Modern Well Design

Bernt S. Aadnøy

Second Edition

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Preface

The current trend in the oil industry is to drill more difficult wells in a more cost effective way. To be able to reach these goals, both the planning and the drilling operation need continuous improvement. Although modern computer systems give us access to more data than ever, both cost and well failure statistics show that there is a considerable potential for improvements. It is my belief that the basic understanding of both the geology and the wells is the most important element in making progress. The purpose of this book is to present a unified picture of the well process.

The main idea behind this book is to provide a systematic approach to improve the planning and the design of wells. To be able to improve, each new well should be designed individually, and should be based on experiences from earlier wells. This book will treat the subject as a design process, attempting to bring forward some of the improvements seen in recent years.

In particular, practical borehole stability analysis, and methods to derive geomechanical prognosis, are new subjects. Also, the book suggests ways to present well design, for easy verification and modification. Therefore, in addition to being used as a textbook, it is also intended to be used as a guide by well designers.

Many people have stimulated the writing of this book. First of all the many students that I have trained in well design over the years, and also my many friends and former colleagues at Saga Petroleum, have made significant contributions as many of the topics of this book have been implemented in the field.

Stavanger, August 2010
Bernt S. Aadnøy

Symbols and units

Symbols

The general symbols used in this book are listed below. In addition, specific nomenclature and subscripts are listed in each chapter to quickly identify the variables used.

D	depth (m)
P	pressure (bar) or pressure gradient (s.g.)
h	distance or height (m)
Diam.	Diameter (m)
d	pressure gradient as specific gravity to water
s.g.	specific gravity relative to water
V	volume (m^3)
A	area (m^2)
L	length (m)
T	temperature (°C)
σ	stress (N/m^2)
q	flow rate (litres/min)
μ	viscosity (cP)
F	force (N)
E	modulus of elasticity (N/m^2)
ν	Poisson's ratio
LOT	leak off pressure test (s.g.)
FIT	formation integrity test (s.g.)
RKB	drill floor depth reference point
MSL	mean sea level depth reference
SF	sea floor depth reference
ROP	rate of penetration for drill bit (m/hr)
WOB	weight on drill bit (N)
N	rotational speed (revolutions/min)
ECD	equivalent circulating density
HP	hydraulic horsepower at drill bit
t	time (hrs), or thickness (m)
γ	wellbore inclination (degrees)
ϕ	wellbore azimuth (degrees)

δ difference between two readings of a parameter
s.g. specific gravity relative to water
ρ density (kg/m^3)
q flow rate (litre/min)
f Fanning friction factor
α temperature expansion coeficient (1/°C)
c fluid compressibility (1/bar)

Units

In this book we have adapted the units commonly used in drilling operations. Because pressures often are related to the density of the drilling fluid in the well, we are usually referring to equivalent mud density or specific gravity instead of a pressure or a pressure gradient. The following equation is used for these calculations throughout this book:

$$P\ (\text{bar}) = 0.098 \times d\ (\text{s.g.}) \times D(\text{m})$$

Chapter 1

Introduction to the well design process

Petroleum wells have changed character in recent decades, as compared to earlier times. We have had a considerable improvement in equipment and technology, but we are also facing wells which are more difficult to drill, and we are required to make the wells more cost effective. The result of these requirements is to put more emphasis on the well design process. Wells should preferably be designed for easy implementation. The design should also provide flexibility if changes are introduced during the drilling operation. One of the key elements in any design is cost-effectiveness. This is of course an element that should be considered in all parts of the design process.

There are many computer programs available for well design purposes. However, the quality of designs from software depends on the knowledge of the well designer. The objective of this book is to provide basic knowledge and design examples, and to approach the construction of the well as a systematic design process. First, the objectives and the design premises have to be established before the actual design is carried out. In the numerous examples given in this book, certain assumptions are made. It is the intention that these should always be re-evaluated and changed when new conditions arise. This book also uses simple physics principles. Usually this is adequate. However, in certain instances more detailed studies are required. It is fully in line with the intention of the book to start the design process in a simple way, but to increase the complexity when needed.

The second chapter deals with two important elements when drilling a well; mud weight and hydraulic design. The mud weight schedule is designed from a simple principle called the median line principle. By keeping the mud density close to the virgin in-situ stress, it has been demonstrated that borehole stability problems have been minimised. The main intention of the hydraulic design is to provide sufficient flow rate to obtain good hole cleaning. The two elements covered in chapter two are very critical for a successful and problem-free drilling operation.

Chapter three deals primarily with borehole stability-related issues. Firstly, methods to normalise field data to the same reference level are derived. The second sub-chapter defines methods to derive field stresses and fracture gradients. The basic idea is to normalise the data and obtain correlations, rather than carry out conventional modelling. A fracture model for shallow depth is also given. If a borehole caliper log is available, simple correlations are defined to obtain the critical mud density required to minimise mechanical hole collapse. The drillability log is discussed as an important tool for field interpretation. Finally a generalized fracture model is presented which is applicable at any water depth. All these elements serve to provide a simple basis for well design and to give simple tools to analyse drilling problems.

The design premises are treated in chapter four. Of particular interest is the connection to the geomechanical evaluation. In addition to defining the minimum fracture pressure and kick margins required to drill a section of the hole, the maximum leak-off value is also used. Part of this chapter is devoted to demonstrating various methodologies to select depths for casing strings, and finally the long term perspective of the well is considered by defining completion and production requirements.

In casing design, chapter five, the design criteria and the failure mechanisms are first defined. Design of the casing test pressure is also covered, with an example of ways to test critical wells. A complete well design example is presented. The last section of chapter five deals with 3-dimensional tubular design.

Chapter six is a continuation from the previous chapter. Here the particular considerations for critical wells are discussed. A high-pressure high-temperature (HPHT) well is used as a design example. It is handled in three parts, the shallow casing strings, the intermediate, and the deep casing strings. Part of the chapter is devoted to establishing fracture prognosis for use in design and operation. This chapter is intended to identify many of the problems encountered in the design of HPHT wells.

There are certain operational issues also to consider. Therefore chapter 7 is intended to define issues related to platform types, execution of drilling operations and aspects of well friction. The emerging issue of well integrity is also presented.

In order to improve well planning, post analysis of earlier failures is required. Appendix A shows an evaluation of six wells. This is used to establish a drilling time curve based on realistic data. This chapter also shows a summary of borehole stability-related problems, and gives a simple system for experience transfer.

Appendix B discusses another aspect of these wells, namely the volumetric behavior of the drilling fluid, which may disturb kick control, and also change the effective bottom-hole pressure of the well.

Chapter 2

Drilling design

2.1 SELECTION OF OPTIMAL MUD WEIGHT

2.1.1 Introduction

The specific nomenclature used in Section 2.1 is as follows:

ECD = equivalent circulating density
$\sigma_r = P_w$ = borehole pressure
σ_θ = tangential (hoop) stress
σ_v = vertical stress
σ_a = average horizontal in-situ stress
P_{wf} = fracturing pressure
P_o = pore pressure.

In this section borehole problems such as fracturing, collapse, lost circulation, differential sticking and others are discussed in a rock mechanical context. It is shown that by maintaining the mud weight close to the level of the in-situ stresses, most of the borehole problems will be minimised. A design methodology called "the median line principle" is derived. The field case included in this chapter also demonstrates a reduction in drilling problems by using this methodology. In addition to problems during drilling, zonal isolation in the reservoir is identified as a crucial consequence of hole problems.

Figure 2.1 specifically shows the aim of this chapter. The low mud weight schedule has traditionally been used mainly for pore pressure estimation purposes, but also because one believed that a low mud weight increased the drilling rate. The high mud weight schedule has been used in problem wells, and in highly deviated wells, but to a limited extent because of fear of losing circulation, and of differential sticking. We will demonstrate that neither of these two approaches are preferred from a borehole stability point of view. In fact, the "median line" mud weight also shown in Figure 2.1 is beneficial, and will provide a common optimum for many of the parameters of the drilling process.

2.1.2 Borehole problems

Many elements affect the success of a drilling operation. Since the main function of a drilling rig is to penetrate and to seal off formations, any single technical failure

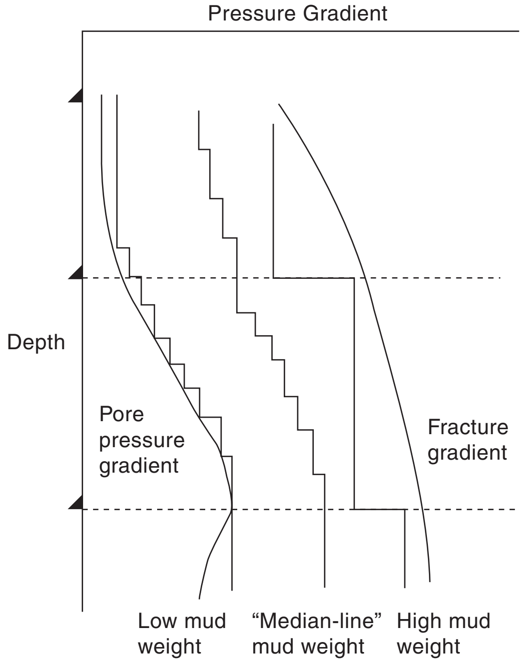


Figure 2.1 Typical mud weights used.

may halt this progress thereby causing additional expenditure. The cost of an offshore drilling operation is dictated by the rig rate. Therefore, the success of a drilling operation is strongly dependent on avoiding problems which cause down time.

Bradley et al (1990) brought borehole problems into a wider perspective by identifying the human element as a key factor in avoiding stuck pipe situations. In addition to sound engineering practices, the operational culture may therefore also strongly affect the outcome of a potential borehole problem. Furthermore, we will point out technical aspects of borehole problems not covered in this chapter. Although the mud weight selection is a key factor, related elements require good planning as well. Examples are torque and drag considerations in well path planning as discussed by Sheppard et al (1987), and evaluation of stuck pipe experience as discussed by Hemkins (1987). Of course hole cleaning and reaming practices must also be adequate. We will not give a detailed discussion of all the other elements, only point out the fact that no single element will replace good overall well planning.

With the above view in mind, we will proceed to the main topic, optimal mud weight selection.

Higher mud weight, the whole truth?

The mud weight is a key factor in a drilling operation. The difference between success or failure is nearly always tied to the mud weight program. Too low a mud weight may result in collapse and fill problems, while too high a mud weight may result in

Table 2.1 Effects of high mud weight.

Element	Advantage	Debatable	Disadvantage
Reduce borehole collapse	X		
Reduce fill	X	X	
Reduce pressure variations	X		
Reduce washout	X	X	
Reduce tight hole	X	X	
Reduce clay swelling	X	X	
Increase differential sticking		X	X
Increase lost circulation			X
Reduced drilling rate		X	X
Expensive mud			X
Poor pore pressure estimation		X	X

mud losses or pipe sticking. In an attempt to tie effects of high mud weight to drilling problems, Table 2.1 was defined, showing some beneficial effects of mud weight.

The elements of Table 2.1 will briefly be discussed below:

Borehole collapse. It is well known that borehole collapse occurs when the mud weight is too low because the hoop stress around the hole wall is very high, often resulting in rock failure (Aadnoy & Chenevert, 1987). The most important remedy is often to increase the mud weight.

Fill. Fill is the problem of cleaning the well. Cuttings or collapsed fragments may accumulate in the lower part of the well and lead to problems such as inability to reach bottom with the casing. Fill is commonly associated with the flow rate and the carrying capacity of the mud. There is also a strong connection to mud chemistry.

An increased mud weight should therefore reduce the potential for borehole collapse, thereby reducing the potential for fill.

Pressure variations. If the mud weight is kept more constant, the well is subjected to more static pressures. As pressure variations may lead to borehole failures (a fatigue type effect), a higher and more constant mud weight should be preferred. In addition to maintaining a more constant mud weight, the equivalent circulating density (ECD) and the surge and swabbing pressures should be kept within limits.

Washouts. The theory behind borehole washout is that the jet action through the bit nozzles hydraulically erode the borehole wall away. The result is often believed to be an enlarged borehole of considerable size.

We believe that it is difficult to hydraulically wash out a consolidated rock at several kilometres depth. What sometimes may happen is that the mud weight is too low, resulting in a failed hole wall. The washout is therefore often actually a collapse. The hydraulic action just removes already broken fragments. Field studies have shown that by increasing the mud weight by a small amount, the result is an in-gauge hole, despite the same high flow rate.

Tight hole. A high mud weight will balance the rock stresses and keep the borehole more in-gauge. However, it is still likely that the hole will decrease in diameter the first day after it is drilled by swelling, still requiring wiper trips or back-reaming. Therefore, we propose to allow for an increase in mud weight, but not a reduction. Tight hole may also be caused by fill packing around the bottom-hole-assembly, combined with doglegs.

As shown later in this paper, the tight hole conditions may be reduced or eliminated by increasing the mud weight. However, sound wiping or back-reaming practices should still be maintained.

Clay swelling. Changes in fluid chemistry philosophy have been seen (Clark (1976), O'Brien & Chenevert (1973), Simpson et al (1989) and Steiger (1982)). A good review of fluid chemistry is given by Santarelli & Carminati (1995). One key problem has been to inhibit reactive clays, as they often contribute to borehole problems such as collapse. However, field experience indicates that a sufficiently high mud weight may in some wells keep the hole stable even with a reduced degree of chemical inhibition, provided that the open hole exposure time is short. Therefore, the clay swelling problem should be reduced by increasing the mud weight. However, some wells seem to show hole enlargement irrespective of borehole pressure.

Differential sticking. An increased mud weight will lead to a higher pressure overbalance, and the drilling assembly will be more easily subjected to differential sticking. From this point of view a high mud weight is detrimental.

However, it is also becoming clear that what we sometimes believe is differential sticking is often something else. Collapse and fill may pack around the bottom-hole-assembly resulting in sticking, and tight hole may be another contributor. Also, if we have intermittent layers of shales and sandstones, the shales may often collapse, exposing the sands directly towards the drilling assembly.

Figure 2.2a illustrates a borehole section where there are breakouts in the shale layers, but in-gauge sand stringers in between. This situation is highly sensitive to differential sticking due to sand exposure. Figure 2.2b illustrates the same situation with an ingauge hole. Since all layers now are in-gauge, it is possible that the contact between the hole and the drilling assembly occurs in the shale layers as well, reducing the potential for differential sticking in the sand layers.

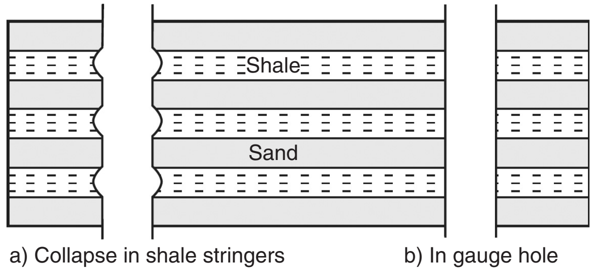


Figure 2.2 Partial collapse in mixed lithology.

A high mud weight is preferred from a collapse point of view. However, a high mud weight may, in general, increase the likelihood for differential sticking. Here is a potential conflict, which can be handled by keeping the mud weight below the critical level for differential sticking.

Lost circulation. Sometimes a weak stringer or a fault is penetrated resulting in loss of drilling fluids. In general, the mud weights must be kept below this critical limit. Also fractured formations may set restrictions on the mud density, as discussed by Santarelli & Dardeau (1992).

Reduced drilling rate. It is commonly believed that a high overbalance results in a slow drilling. It is our opinion that the drilling rate is mainly a formation characteristic and that the effect of overbalance is of lesser significance. A reduction in drilling rate should also be measured against the cost of borehole problems.

Mud cost. A higher weight mud program is often more expensive. This additional cost is usually negligible if it results in less drilling problems.

Pore pressure estimation. During drilling the geologist estimates the pore pressure using various criteria. One factor of particular concern is the recording of excess gas. This helps to quantify the pore pressure at the particular depth. A high mud weight may suppress high gas readings. A high mud weight may therefore not be preferable during wildcat drilling. During production drilling this requirement is often relaxed.

Mud Weight Summary. From the above discussion it may be concluded that a relatively high mud weight is acceptable and preferable from many points of view. However, particular concern has to be paid towards:

- lost circulation
- differential sticking
- background gas readings in exploration drilling
- naturally fractured formations

Also, the mud chemistry must not be neglected. We have assumed an inhibited mud system in the above discussion. Table 2.2 summarises some likely connections between various borehole problems. Please observe that the mud weight is a common denominator between these.

From the above discussion, it is clear that the mud weight should preferably be on the high side. However, we still have a wide mud weight window. Figure 2.3 shows the allowable mud weight range. In many wells this allowable range may be very wide, so there is a definite need to limit this range further. This will be pursued in the following.

Mud properties

Important mud properties to minimise hole wall problems include:

- chemical inhibition
- low filtrate loss in permeable zones
- coating in impermeable zones

Table 2.2 Likely relations between some borehole problems.

Problem	Collapse	Fill	Washout	Tight hole	Diff. stick	Lost circ.
Collapse	X					
Fill	X	X	X			
Washout	X		X			
Tight hole	X	X		X		
Diff. stick.	X	X		X	X	
Lost circ.						X

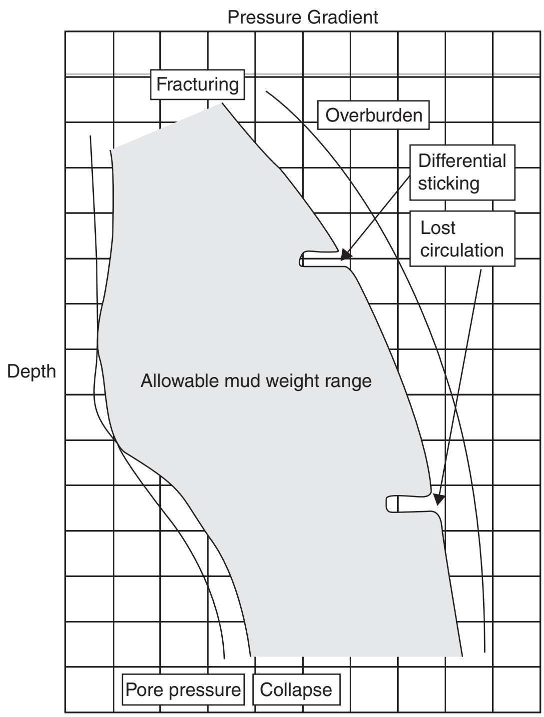


Figure 2.3 Allowable mud weight range considering common borehole problems.

Another very important property of the drilling fluid can be described as follows. Experience shows that new drilling fluid exacerbates fracturing/lost circulation situations. During leak-off testing it is our experience that used mud gives higher leak-off values than new mud. This is believed to be caused by the solids content from drilled cuttings. Therefore, one design criterion applied is to increase mud weight gradually to ensure that there are drilled solids present. In a new hole section one therefore usually starts out with a lower mud weight. After drilling out about 100 m below the previous shoe, the mud weight is gradually increased. It is believed that by using this procedure we have avoided potential lost circulation situations. In Section 2.1.3 the practical applications of these observations will be demonstrated.

2.1.3 Rock mechanics

Stresses acting on the borehole wall

The Kirsch equation is commonly used to calculate the stresses around the borehole. The stress level defines the loading on the borehole wall, and the rock strength defines the resistance to withstand this load. A number of publications have been written on this subject, and McLean & Addis (1988) and Aadnoy & Chenevert (1987) give a good overview.

It is well established that the stability of a borehole falls into two major groups:

- Borehole fracturing at high borehole pressures. This is actually a tensile failure, where the consequence may be loss of circulation. In a pressure control situation this is of concern, and further drilling may be halted until circulation is re-established.
- Borehole collapse at low borehole pressures. This is a shear failure caused by high hoop stress around the hole, exceeding the strength of the rock. There are many variations of the collapse phenomenon. In some cases the rock may yield resulting in tight hole. In other cases a more catastrophic failure may occur resulting in collapse, which again may lead to hole cleaning problems.

Figure 2.4 illustrates the stresses acting on the borehole wall when the mud pressure is varied. Figure 2.4a shows the three main stresses acting on the borehole. The radial stress acting on the borehole wall is actually the pressure exerted by the drilling fluid. The axial stress is equal to the overburden load for a vertical well. However, around the circumference of the hole the tangential stress is acting. This is also called the hoop stress. This stress depends strongly on the borehole pressure. As equations, these three stresses can in their simplest form be expressed as:

$$\begin{aligned} &\text{Radial stress:} && \sigma_r = P_w \\ &\text{Tangential stress:} && \sigma_\theta = 2\sigma_a - P_w \\ &\text{Vertical stress:} && \sigma_v = constant \end{aligned} \tag{2.1}$$

Figure 2.4b helps to understand the borehole failure mechanisms in the context of the borehole stresses. The three stress components are plotted as a function of borehole pressure. The vertical stress, or the overburden, is not influenced by the mud weight and remains constant. The radial stress is equal to the borehole pressure and has therefore a unit slope in the diagram. The tangential stress decreases with increased borehole pressure.

At low borehole pressures, the tangential stress is high. Since there is a significant difference between the radial and tangential stress, a considerable shear stress arises. It is this shear stress that ultimately results in borehole collapse. At high borehole pressure, on the other hand, the tangential stress goes into tension. Since rocks are weak in tension, the borehole will fracture at high borehole pressures, usually resulting in an axial fracture. These two failure types are indicated in Figure 2.4b. More complex failure modes can be evaluated (Maury, 1993), but this will not be pursued here.

From the discussion above, we observe that low and high borehole pressures produce high stress conditions, and bring the hole towards a failure state. By further

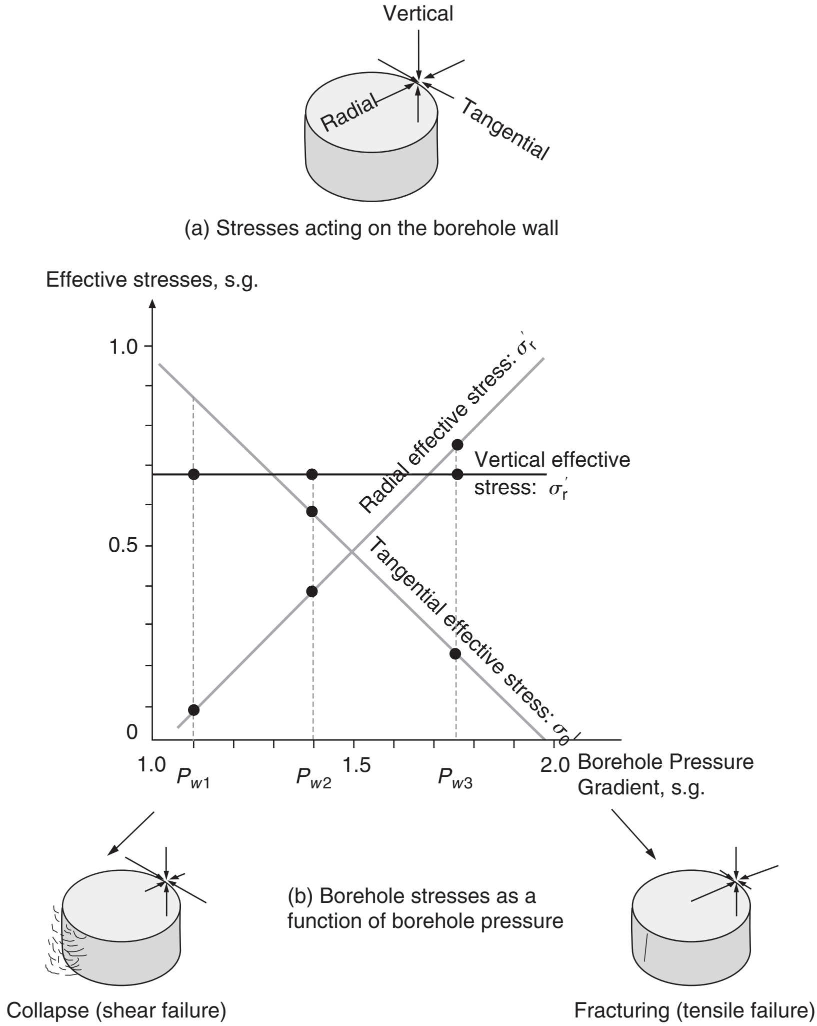


Figure 2.4 Borehole stresses with varying mud weight.

inspection of Figure 2.4b we see that at a given point the radial and the tangential stresses are equal. Here the mud weight is equal to the in-situ stress, and there are no longer abnormal stresses. This will be further discussed in the following section.

The in-situ stress state

We will assume a relaxed depositional basin with a so-called hydrostatic stress state. That is, around a vertical hole, the horizontal stress level is the same in all directions.

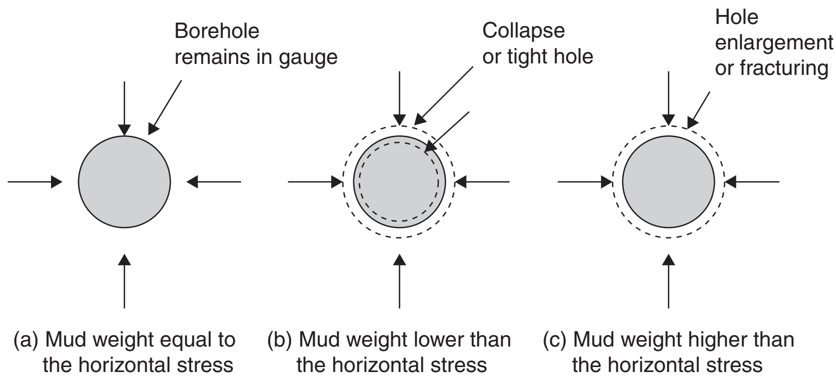


Figure 2.5 Effects of varying the borehole pressure.

Having a leak-off pressure and a pore pressure, the fracturing pressure is reached when the effective hoop stress is zero, or $\sigma_\theta - P_o = 0$ from Equation (2.1). The following equation results (Aadnoy & Chenevert, 1987):

$$\sigma_a = \frac{1}{2}(P_{wf} + P_o) \tag{2.2}$$

The average horizontal stress is equal to the average pressure between the fracturing and the pore pressure. A tectonic stress situation with non-hydrostatic horizontal stresses gives a more complex picture. A short example is given at the end of the chapter. However, the proposed method could also be used in this case, as the fracturing gradient implicitly takes both the actual stress situation and the borehole inclination into account. For example, for a deviated well the design fracture gradient may be corrected for borehole inclination (Aadnoy & Larsen, 1989). This will be further discussed in Section 3.2.

Equation (2.2) can explain several of the borehole problems we have just discussed. Let us first discuss the implications. We assume that the elements of Equation (2.2) are known, and will, in the following, discuss what happens if the actual mud weight is equal to, lower than, or higher than the in-situ stress of Equation (2.2). Figure 2.5 illustrates the responses of varying mud weight.

Fig. 2.5a. Using a mud weight *equal to* the horizontal stress σ_a, the immediate surrounding rock is undisturbed by the drilling of the hole. This is the ideal mud weight, and the hole diameter will remain constant.

Fig. 2.5b. Using a mud weight *lower than* the horizontal stress σ_a, the stress will locally change. A hoop stress is created causing the borehole to decrease in diameter. This can result in either:

- borehole collapse, or
- tight hole

Fig. 2.5c. Using a mud weight *higher than* the horizontal stress σ_a, the borehole pressure will tend to increase the hole diameter, ultimately causing fracturing if the mud weight becomes too high.

As implied from the above discussion, mud weight/borehole stress relationships can be used to describe common borehole problems. This can be defined as the median line principle, which is defined by Equation (2.2):

> The mid-point between the fracturing pressure and the pore pressure defines the borehole pressure that is equal to the ideal in-situ stress. Maintaining the mud pressure close to this level causes least disturbance on the borehole wall.

The median line principle will in the following be used to define the actual mud weights to be used in a drilling operation.

The median line principle

Figure 2.6 shows pressure gradient plots for a well. This will first be used to give a general description, then be used in a discussion of drilling problems in Section 2.1.4. Shown are five pressure gradients. The median line is drawn using the previously defined Equation (2.2). The casing seats are selected based on:

- Fracture gradient and pore pressure gradient prognosis
- Kick scenario
- Seal off likely lost circulation intervals
- Minimising effects of borehole stability problems
- Casing landing considerations

In the following the mud weight selection for each of the intervals will be described. Details on the geology can be found in Dahl & Solli (1992).

The 26/24 in. hole. The 30 in. conductor casing is set with about 100 m penetration. The fracture gradient below the 30 in. casing is fairly low. Therefore, in the 26/24 in. hole the mud weight is below the median line during most of the interval.

The 16 in. casing interval. Drilling out below the 18-5/8 in. casing, the mud weight of Figure 2.6 is below the median line for two main reasons:

- To give the open hole time before increasing mud weight to minimise the risk of breaking down below the casing shoe.
- It is preferable to have a low mud weight during leak-off testing. The leak-off pressure plot covers a larger pressure range, improving the interpretation.

After drilling below the 18 5/8 in. casing at about 100 m, the mud weight is gradually increased to exceed the median line, and kept above for the rest of the section. The main reason for staying above the median line is to minimise tight hole conditions.

The 12-1/4 in. hole. When drilling out below the 13-3/8 in., casing circulation was lost in several wells. Figure 2.6 shows the current approach where the mud weight is initially below the median line. After drilling out 100 m, one attempts to keep the mud

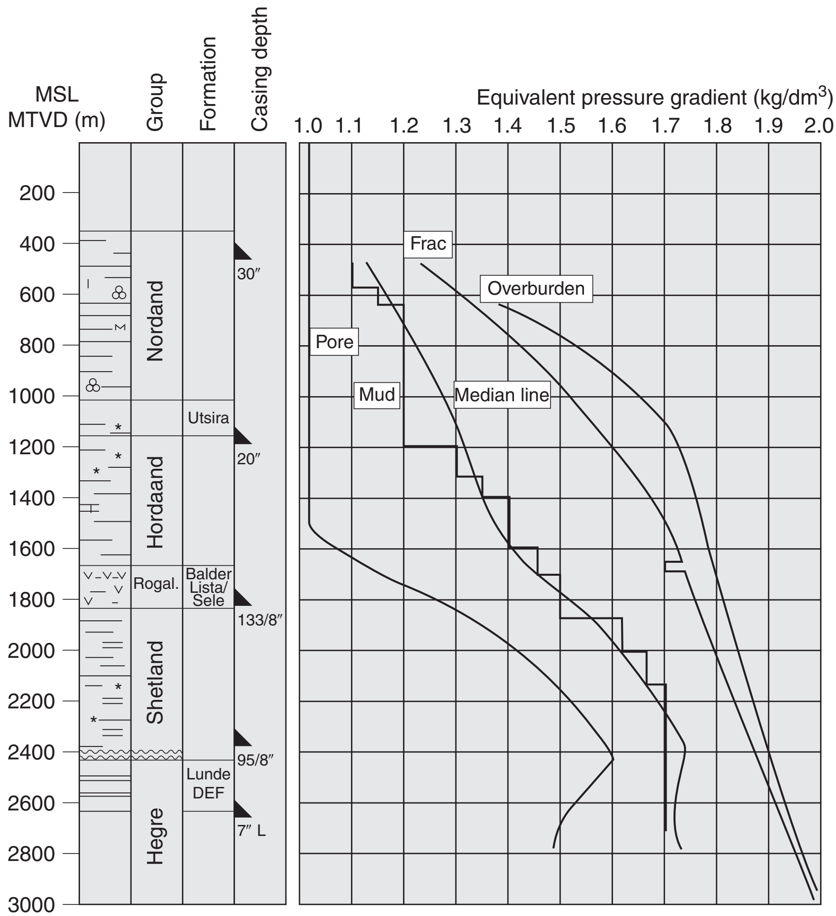


Figure 2.6 Pressure gradients for a well.

weight above the medium line for the rest of the section. However, at the bottom, the mud weight of Figure 2.6 drops below the medium line for the following reasons:

- To minimise the risk of lost circulation.
- To minimise the risk for differential sticking.

The 8-1/2 in. hole. The last section of Figure 2.6 penetrates the reservoir. In this case the mud weight is maximum, and it is kept constant throughout the section. Lost circulation and differential sticking experiences has resulted in using a mud weight lower than the median line in the reservoir section.

A final comment on the application: In an open hole section the mud weight should only be increased, and not decreased, as tight hole may result. Furthermore, we have chosen to increase the mud weight in steps of 0.05 g/cm^3, for the convenience of the mud engineer.

2.1.4 Field case studies

Of the six pre drilled wells, three were drilled according to the high mud weight profile shown in Figure 2.1, and the last three wells were drilled according to the median line principle. In the following, the three bottom sections of one of each group will briefly be discussed from a drilling problem point of view.

Well 3 (high mud weight profile). In the 16 inch section, the mud weight was initially 1.2 s.g., but increased towards 1.45 s.g. at about 1300 m. Tight hole was not observed during drilling, but at about 1500 m a wiper trip showed a 50 ton overpull. After drilling to final depth of the section, a wiper trip to 1400 m showed a 30 ton overpull. A final wiper trip after logging resulted in severe tight hole problems, and the hole had to be reamed. After increasing the mud weight to 1.51 s.g., the hole was not tight, except for the bottom 100 meters. Because of these problems, the casing was installed 79 m above planned shoe depth.

It was believed that a more gradual mud weight increase would successively push the hole open, resulting in less tight hole. Actually this strategy was used on wells 4, 5 and 6, the latter being discussed in the following.

Well 6 (median line principle). The pressure gradients for this well are shown in Figure 2.6. This was the last of the six wells pre-drilled. Therefore, many parameters are optimised such as the drilling mud composition, chemistry, operational practices, and many other factors. The mud weight schedule is also optimised based on previous experiences.

Figure 2.6 shows the resulting pressure gradients on well 6. Just before finishing this well the casing program was altered to eliminate the 7 in. liner, which resulted in setting the 9 5/8 in. casing to TD. In addition, the coring program was dropped.

The 16 in. section was drilled and cased off with no reported problems. The mud weight was gradually increased, contrary to well 3 where a more constant high mud weight gave tight hole conditions.

In the 12 1/4 in. section, only minor tight hole conditions were reported, but a slight mud weight increase and reaming cured the problems. The mud weight was kept below the median line during most of the 12 1/4 in. section because of the fear of differential sticking. No lost circulation incidents were reported. The tight hole conditions identified in well 3 are much more severe than those reported in well 6. In well 3, the casing point had to be changed, but similar effects were not observed in well 6.

In the reservoir section, the mud weight was also kept below the median line. Significant tight hole was not reported. However, there were several signs of possible differential sticking, which indicates that the mud weight is possibly on the high side. However, the riser margin (at a water depth of about 300 m) restricts the mud weight reduction possibilities considerably, because it limits the operating window between the pore pressure and the fracturing pressure gradients. The riser margin is discussed in Section 4.2.4.

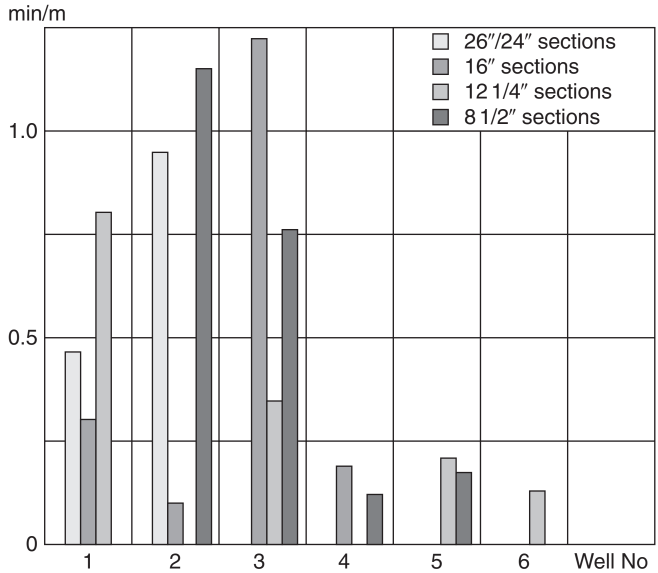


Figure 2.7 Specific reaming time for each well.

The mud weight schedule has been varied during drilling of the six production wells. The last three wells have been drilled using the median line mud weight design. Figure 2.7 shows the specific reaming time for each of the six wells. A considerable time was spent reaming the open hole sections of the first three wells, while the last three wells only needed a little reaming. A gradual reduction is apparent, with the last well having only minor reaming. We believe that the mud weight program is a significant contributor here. The amount of reaming necessary is considered a measure of the general condition of the borehole.

2.1.5 Application of the median line principle

Common borehole problems are discussed and evaluated in a rock mechanics context. The result is the "median line principle", which simply says that the mud weight should be kept close to the in-situ stress field in the surrounding rock mass. In this way the borehole problems are minimised since a minimum of disturbance is introduced on the borehole wall.

The mud weight methodology was applied in the three last wells in a field study of six wells. The enclosed field study shows a considerable reduction in tight hole conditions, which is considered a good indicator of the general condition of the hole.

The median line mud weight design methodology can be summarised as follows:

1 Establish a pore pressure gradient curve and a fracturing gradient curve for the well. The fracture gradient curve should be corrected for known effects like wellbore inclination and tectonic stresses.

2 Draw the median line between the pore and the fracture gradient curve.
3 Design the mud weight gradient to start below the median line immediately below the previous casing shoe.
4 Mark out depth intervals prone to lost circulation and differential sticking, and their acceptable mud weight limits, if known.
5 Design a stepwise mud weight schedule around the median line, that also takes into account limitations from 3 and 4 above.
6 Avoid reducing the mud weight with depth. If a median line reversal occurs, keep the mud weight constant.

2.1.6 Tectonic stresses

This section is intended for those who are more interested in the rock mechanics aspect, and who want to work in more detail.

In this chapter the mud weight is designed based on an assumption of equal horizontal stresses in the formation. This should always be a starting point, and will for most applications provide a reasonable mud weight schedule.

However, the reader will observe that in Section 3.2, methods are given to determine anisotropic stresses. For these cases, the median line principle can be modified. Assuming that the two horizontal stresses are of different magnitude and given by σ_H and σ_h, the fracturing pressure is given by (Bradley, 1979, Aadnoy & Chenevert, 1987):

$$P_{wf} = 3\sigma_h - \sigma_H - P_o \tag{2.3}$$

An example will demonstrate the effect of stresses. The first case assumes equal horizontal stresses and the optimal mud weight is defined by Equation 2.2, which is:

$$\sigma_a = 0.5(P_{wf} + P_o) \tag{2.2}$$

This will be compared to the second case. Now assuming anisotropic horizontal stresses, for example $\sigma_h = 0.8\sigma_H$, Equation 2.3 can be solved for the smallest horizontal stress as follows:

$$\sigma_h = 0.571(P_{wf} + P_o)$$

Assuming all factors are equal, except the horizontal stresses, the two cases illustrates that for an anisotropic stress state the ideal mud weight should be higher. However, for this case, the difference between the fracturing pressure and the minimum horizontal stress is smaller than for the first case.

For anisotropic, or unequal horizontal in-situ stresses, the mud weight should actually be higher than for equal horizontal stresses. However, the example above also demonstrates that this situation may easily be subject to circulation losses. In general, high in-situ stress anisotropy usually leads to a smaller mud weight window.

2.2 MUD LOSSES DURING DRILLING

2.2.1 Introduction

The two most costly drilling problems are stuck pipe and circulation losses. Statistics show that these unplanned events may take 10–20% of the total time spent on a well. Very high cost is therefore associated with these problems.

We will in this section address the problem of circulation losses. They can occur at any time during a drilling operation and are very common in depleted reservoirs. Usually the loss problem must be cured before drilling can resume. Using water-based drilling fluids the problem is often reduced by pumping lost-circulation-materials (LCM) into the wellbore. In some cases cementing is required. Using oil-based drilling fluids is much worse. If circulation losses occur with oil mud it can be difficult to control the losses, and large amounts of mud may be lost before control is regained. This is believed to be related to wettability contrast between the rock and the mud. A capillary barrier prevents filtrate losses to the rock, maintaining the low viscosity of the mud and thereby allowing for further fracture propagation.

Mud companies have many recipies to stop mud losses. Basically all of these use particles in various combinations as bridging materials. These are often proprietary and will not be addressed further here. Instead we will explain the mechanisms believed to cause circulation losses. A research program has been carried out at the University of Stavanger over many years. Some of this work is described by Aadnoy et al (2008). This section will mainly report results from this work. A new mechanistic model for fracturing called "the elastoplastic barrier model" evolved from this work.

Nomenclature

σ_y = yield stress of bridging particles
σ_a = horizontal in-situ stress
t = barrier thickness
a = borehole radius
P_{wf} = Fracturing pressure
P_o = Pore pressure
LCM = Lost Circulation Material

2.2.2 Experimental work

Figure 2.8 shows a fracturing cell where specially prepared hollow concrete cores are fractured. The setup also allows for mud circulation to ensure that mud particles are well distributed inside the hole. The cell is rated to 69 Mpa, and the axial load, the confining pressure and the borehole pressure can be varied independently. Many oil- and water-based drilling fluids have been tested, as well as novel ideas like changing rock wettability or creating other chemical barriers. Cores with circular, oval and triangular holes have also been tested to study effects of hole geometry.

Figure 2.9 shows typical results from the fracturing experiments. The commonly used Kirsch equation is used as a reference. The Kirsch equation defines the theoretical fracture pressure with a non-penetrating situation such as when using drilling muds. From Figure 2.9 it is seen that only one of the measured fracture pressures agrees with

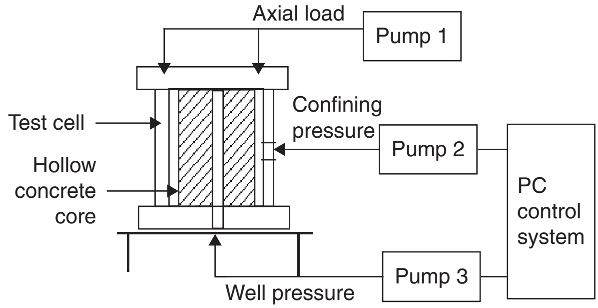


Figure 2.8 Fracturing cell for testing of concrete cores.

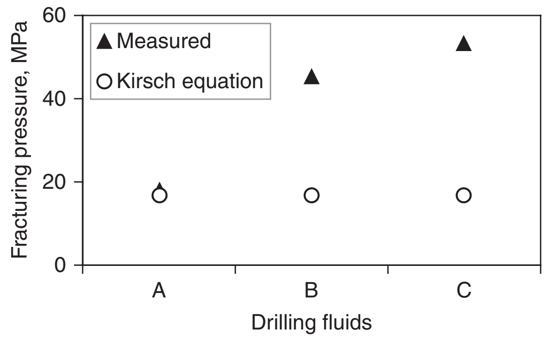


Figure 2.9 Examples of theoretical and measured fracture pressures.

the theoretical model, the two others are much larger. Several conclusions have come out of this research:

- The theoretical Kirsch model underestimates the fracture pressure in general, and
- There is significant variation in fracture pressure depending on the quality of the mud.

This shows that the fracture pressure can potentially be increased by designing a better mud. Actually the results of Figure 2.9 explain the variability we observe in the field – sometimes a higher leak-off is observed. For some reason the mud is more optimal in these cases. Aside of standard mud measurements like filter cake thickness, the types of measurements taken nowadays do not adequately show the fracturing resistance of a drilling mud.

Figure 2.10 shows a mud cell provided with six outlets containing artificial fractures of various dimensions. The mud is circulated with a low-pressure pump to develop a filter cake across the slots. At this stage a high-pressure pump increases the pressure until the mud cake breaks down. In this way we can study the stability and the strength

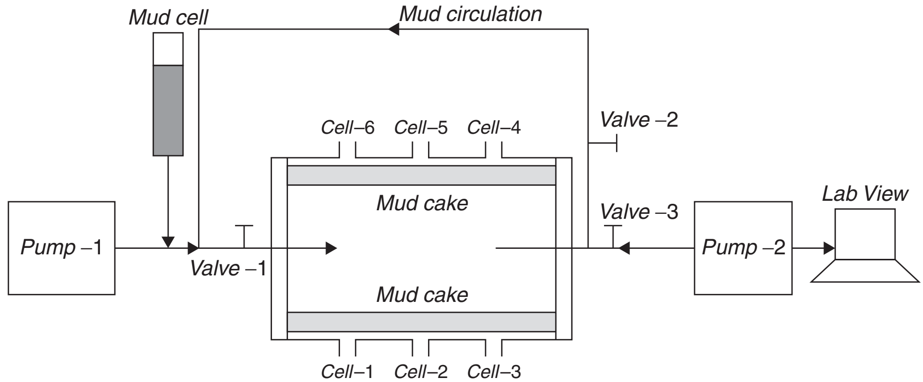


Figure 2.10 Apparatus to determine fracture strength of mud cake.

of the mud cake. We have used common muds and additives and observed that reducing the number of additives often gives a better mud. We have also studied non-petroleum products to look for improvements. Some of this will be discussed later.

2.2.3 Fracturing models

The socalled Kirsch equation is almost exclusively used to model fracture initiation in the oil industry. It is a linear elastic model which assumes that the borehole is penetrating, that is fluid is pumped into the formation, or, it is non-penetrating which means that a mud cake prevent filtrate losses. The latter gives a higher fracture pressure. In the following we will only presents the simplest versions of the fracturing equations, applicable for vertical holes with equal horizontal stresses, typically for relaxed depositional basin environments. Tensile strength assumed negligible in the following.

Penetrating model

This is the simplest fracture model, which is defined as:

$$P_{wf} = \sigma_a \tag{2.4}$$

For well operations like hydraulic fracturing and stimulation, the penetrating model applies. It requires a clean fluid with no filtrate control such as water, acids and diesel oil. It simply states that the borehole will fracture when the minimum in-situ stress is exceeded.

All of our fracturing experiments confirm that this theoretical model works well using pure fluids. It should therefore be used in well operations involving clean fluids such as stimulation and acidizing. Please note that Equation 1 is valid for fracture initiation. Fracture propagation requires other models.

Non-penetrating model

In a drilling operation the fluids build a filter cake barrier. For this case the Kirsch equation becomes:

$$P_{wf} = 2\sigma_a - P_o \tag{2.5}$$

This equation in general underestimates the fracture pressure as demonstrated in Figure 2.9. The problem rest with the assumptions of a perfect (zero filtrate loss) mudcake.

We found that the mud cake behaves plastically. The new model therefore assumes a thin plastic layer which is the mud cake, followed by a linearly elastic rock. This is called an elasto-plastic fracture model. The explanation for the higher fracture pressure is that when a fracture opens, the mud cake does not split up, but deforms plastically maintaining the barrier. This model can be described as(Aadnoy and Belayneh, 2004):

$$P_{wf} = 2\sigma_a - P_o + \frac{2\sigma_y}{\sqrt{3}} \ln\left(1 + \frac{t}{a}\right) \tag{2.6}$$

The additional strength obtained with the elasto-plastic model is directly proportional with the yield strength of the particles forming the barrier. This model describes accurately the measured data shown in Figure 2.9.

2.2.4 Description of the fracturing process

In Figure 2.11 we have shown the various steps in the fracturing process.

Event 1: Filter cake formation. A small filtrate loss ensures formation of a filter cake. During mud flow a thin filter cake builds up. The thickness of the cake depends on the equilibrium between the filtrate attraction and the erosion due to the flow.

Event 2: Fracture initiation. By increasing the borehole pressure, the hoop stress in the rock goes from compression towards tension. The filtrate loss ensures that the filter cake is in place. The in-situ stresses, which control the borehole hoop stress, resist the pressure. At a critical pressure the borehole starts to fracture.

Event 3: Fracture growth. A further increase in borehole pressure results in an increase in fracture width. In-situ stress is opposing this fracture growth. The filter cake will remain in place because a stress bridge is formed across the fracture. This is the plastic part of the elasto-plastic model. This bridge acts as a natural rock road bridge, the higher the top load, the higher the compressive forces inside the curvature. The factor that prevents this bridge collapsing is the mechanical strength of the particles of the filter cake. In this phase both the rock stress and the filter cake strength resist failure.

Event 4: Further fracture growth. Further pressure increase leads to further fracture opening. The stress bridge expands and become thinner. Due to the geometry increase it becomes weaker.

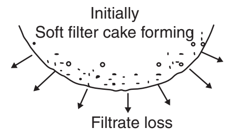
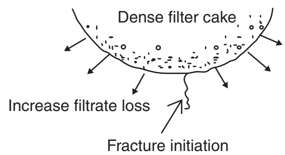
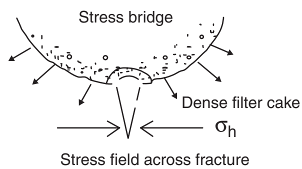
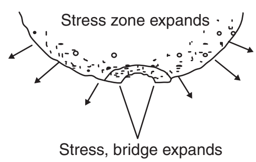
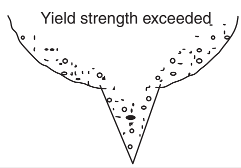
Event	Fig	Main controlling parameters
Filter cake formation		Filtrate loss
Fracture initiation		Filtrate loss, Stress
Fracture growth		Bridge stress Rock stress
Further fracture growth		Bridge/rock stress Particle strength
Filter cake collapse		Particle strength

Figure 2.11 Qualitative description of the fracturing process.

Event 5: Filter cake collapse. At a critical pressure the filter cake is no longer strong enough, and the "rock bridge" collapses. This occurs when the yield strength of the particles is exceeded. At this point communication is established and we have mud losses towards the formation.

2.2.5 Some research findings

Properties of the mud cake

Our research has concluded that two main characteristics of a filter cake can give a high fracture pressure. These are related to the filtrate properties required to form a filter cake, and also the strength of the particles in the mud. The bridge model