POLITECNICO DI TORINO

Department of Environment, Land and Infrastructure Engineering

Master of Science in Petroleum and Mining Engineering

Analyzing and Detection of abnormal pressure using the D exponent method

Submitted to Politecnico Di Torino as a Partial Fulfilment of the Requirements for the Degree of Master of Science in Petroleum Engineering

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DEDICATION

This M.SC Thesis is dedicated to my father, mother, and family, who have encouraged me all the way and have made sure that I give it all to finish what I have started. Also, I dedicate this M.SC. Thesis to all staff and students in POLITECNICO DI TORINO department of environment, land, and infrastructure engineering (DIATI).

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ABSTRACT

Usually, the pore pressure which is the fluid pressure inside the pores of the reservoir is the hydrostatic pressure or in other words, the pressure that is exerted by the fluid column of water from the depth of the formation to the sea level. When the impermeable formation (rock) such as shale form as sediments are in compaction, the fluids inside the pores is able to escape and the overlying rock column must be supported, leading to anomalously high formation pressure. The pressure must be described as measured at a specific time because the pressure of the reservoir various with the production of the fluid from the reservoir.

The **"MYM"** Field was selected as a real case to perform the pore pressure and fracture pressure estimation from Metlaoui Group formation. Wells that selected are **TT4** and **TT5**. The D-Exponent was executed by using a drilling program for each well to make an estimation of the formation pore pressure and fracture pressure.

Using oil base mud while drilling is not always a solution to the wellbore instability problems without applying adequate mud parameters like what happened in **TT5**. Also, well planning should incorporate Geomechanics to reduce wellbore instability and lost circulation risk.

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NOMENCLATURE

API	American Petroleum Institute
BHP	Bottom Hole Pressure
BHT	Bottom Hole Temperature
DC	Drill Collar
DP	Drill Pipe
DDR	Daily Drilling Report
LWD	Logging While Drilling
ROP	Rate of Penetration
RPM	Rotations Per Minute
THP	Tubing Head Pressure
TVD	True Vertical Depth
WHP	Well Head Pressure
WOH	Weight On Hook
WOB	Weight On Bit

Chapter One

Introduction and Overview

1.1 Introduction

In normal conditions, the pressure of the fluids inside the pores is assumed to be stable and in equilibrium, this pore pressure is also known as the formation pore pressure, In several areas of well planning and development operations, this is an important consideration. Combining unconsolidated clay, sediments of shale, as well as in-situ pore pressure above hydrostatic levels, will lead to a very adverse environment for the integrated top-hole well. This will affect the design of the casing and the choice of mud weight and raise the probability of the pipe getting stuck and problems of control (well control). It is very important to try to know or forecast abnormal pressure regions because, if not well completed, there may be a risk of blowing out[1].

Besides forecasting the pressure of the pores in a subsurface formation, stress which is under rocks fracture point must be estimated. So in the subsurface formation knowing and predicting the pressure that the rocks will be fracted at is one of the important essential considerations. The pressure at which open-hole formation collapse is called the "fracture pressure.". These fractures may lead to the loss of massive volumes of mud or drilling fluid and these fluids may move all the way up to the ground level in the environment of a shallow formation possibly Tends to cause a blowout, something else is that hydraulic fracture treatment must be planned for improving the oil or gas efficiency. In such a system, the most critical pressure is the "horizontal minimum stress". Hydraulic fracturing is a mechanism in which pressure is used to fracture or break a reservoir rock. . These fractures are referred to as hydraulic fractures which are necessary to crack the rock. Unfortunately, in most literature, this is sometimes referred to as the "fracture pressure," which can often be mistaken with the fracture pressure measured for open-hole conditions.

The Abnormal pressure or Abnormal pressure zones is a subsurface phenomenon in which the sedimentary rock formation's pore pressure is greater or less than the anticipated or natural formation's pore pressure. If impermeable rocks, including shales, are readily compressed, then the fluids cannot escape their pores normally and then sustain the complete overlying rock layer, contributing to an abnormally high degree of pore pressure. this pressure, known as overpressure, can lead to a well blowout or become uncontrollable during the drilling process. The drill pipe could be stuck to the under-pressured formation through extreme under pressure.

By predicting the pressure of the pores (fluid pore pressure) and the pressure of the fracture, We are able to manage and operate the well or wells in order not to have instability that is by making the pressure of the drilling (mud pressure) neither exceed the fracture pressure nor goes below the formation pore pressure[2].

1.2 Pressure Concepts

Before starting to drill any well in any location in the world the driller must know and understand the different pressure within the subsurface that will come into contact with during the drilling operations.

The different pressure within the subsurface that will come into contact with during the drilling operations.

The various formation pressures in a region is a major role in the exploration and use of future hydrocarbon reservoirs and their reserve

The different types of reservoir pressure that normally occur while drilling operations are commonly classified into three types[6]:

- Hydrostatic
- Pore (formation)
- Overburden

1.3 Hydrostatic Pressure

The pressure of the column of water (fluid) acting on any certain point that is the Hydrostatic Pressure it can be represented in the field of petroleum engineering as the following[7]

Equation

$$Hydrostatic\ pressure = pressure\ gradient * true\ vertical\ depth$$

The Vertical Depth below the ground level until the point of interest is called the True Vertical Depth (TVD) it is shown in Figure 1.1 the difference between the TVD & MD, Measured Depth or (MD) is the total length of the well starting from ground level until the point of interest including the angels along the well (curves)[8]

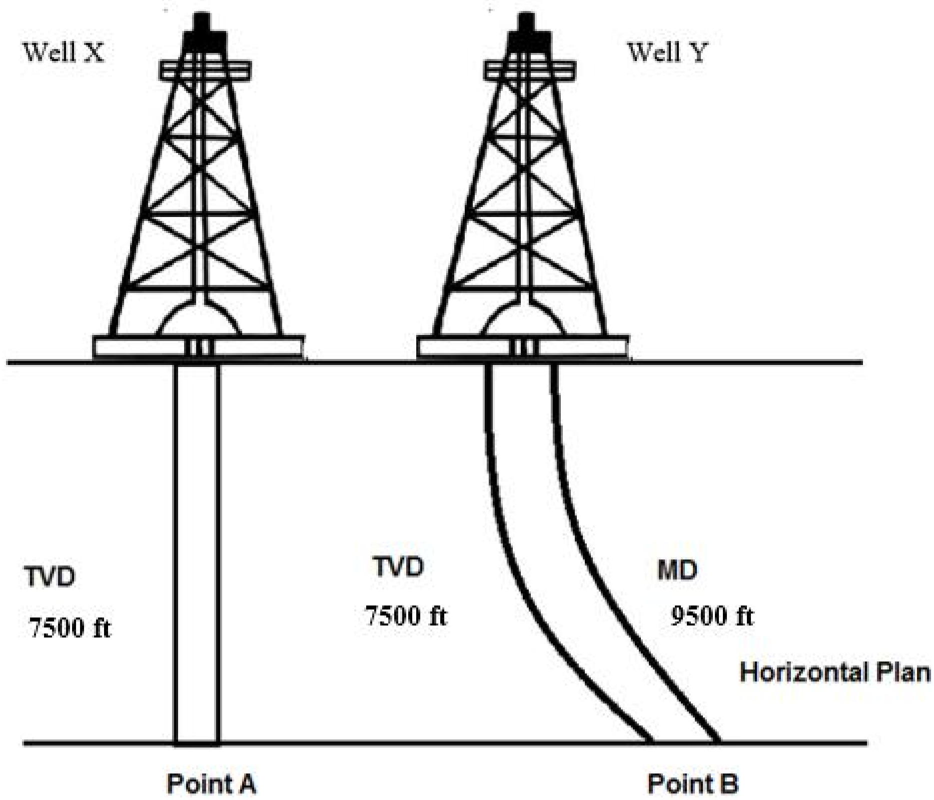


Figure 1.1 the difference between TVD and MD[8]

As it can be seen in the Figure 1.1 well x and well y are look the same from the surface point of view but the main difference is that the well x has 7500 ft Measured Depth and the same True Vertical Depth of 7500 ft (since it has no curvature) but well y as it is shown has 9500 ft of Measured Depth and 7500 ft of True Vertical Depth. In order to calculate the bottom hole pressure in any well we tend to use the TVD because the gravity works vertically down the well.

It can also be described as follows[9]:

$$\boldsymbol{p = 0.052 * \rho * h} \qquad (\mathbf{1.1})$$

Where:

$p = Hydrostatic\ pressure$ ρ = density $h = depth\ (TVD)$

It also required to be known that gradient if the hydrostatic pressure is influenced by dissolved solids and gas concentrations in the column of fluid at changing temperatures. A rise in dissolved solids raises the normal pressure gradient slightly[10]

1.4 Overburden Pressure:

The total vertical pressure (stress) at a certain point in the subsurface that what is called the Overburden Pressure, in other words, it's the weight of the upper formation which include the matrix (grain to grain compaction) pressure and the pressure of the fluids inside the pores (formation pores pressure)[11]

The advantage of overburden pressure is that it helps us to estimate the pressure at which the rock will be break or crack at known as the Fracture Pressure.

Figure below shows a visual representation of what OB stress is:

The following figure provides a representation of the overburden Pressure (stress):

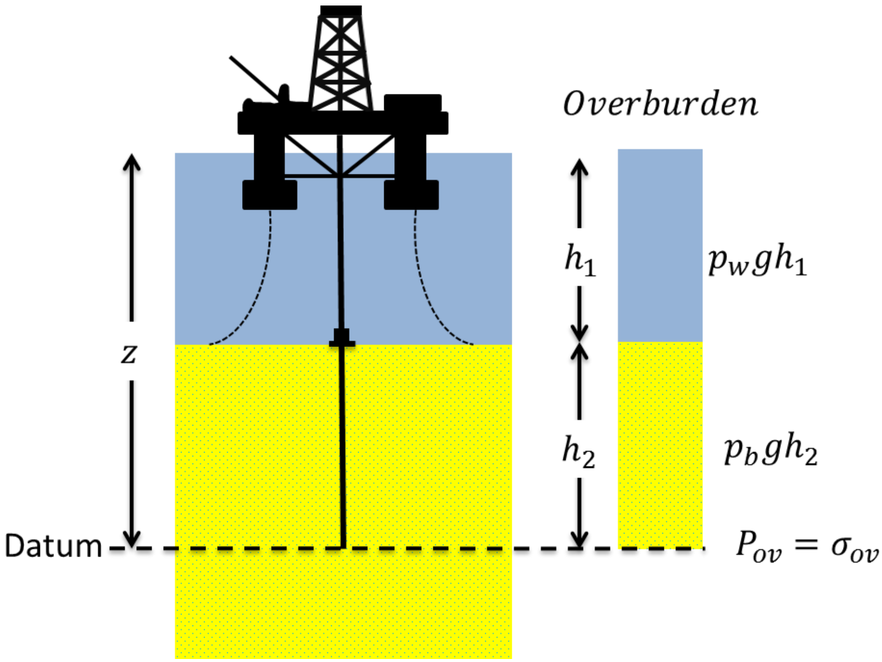


Figure 1.2 (The Overburden pressure factors)[13]

From the above Figure , it can be seen that the stress that is overburden pressure at a certain depth (datum) is like it was mentioned the overall summation of the all the pressure above that datum which caused by the weight of the fluid column and the caused by the rock matrix, it's also must be known that the pressure can be calculated at the exact point using the ρ_b Bulk density not the grain or fluid density[14].

Now the overburden gradient comes from a crossed plot of overburden pressure versus depth as it is shown in Figure 1.3.to be more accurate when describing the overburden pressure it can be said that at any point in the earth, the overburden pressure is a summation of the stresses of the rock mass and the fluid above a certain point of interest, and as we mention it cannot be used ethine the rock or the fluid density but the Bulk density must be used the equation of the bulk density is shown below[2]:

$$\boldsymbol{pb = pf * \Phi + pm * (1 - \Phi)} \qquad (1.2)$$

also,

$$\boldsymbol{pb = pm - (pm - pf) * \Phi} \qquad (1.3)$$

Where:

$pb = bulk\ density\ of\ porous\ rocks$ $\qquad pm = density\ of\ rock\ matrix$

$pf = density\ of\ pores\ media\ fluid$ $\qquad \Phi = Porosity$

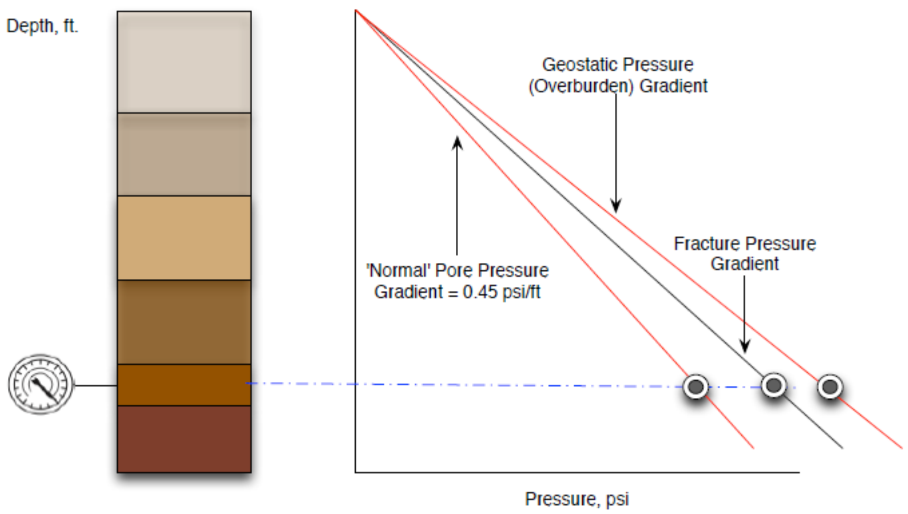


Figure 1.3 (The subsurface pressures and the gradients for each pressure)[7]

Since the Porosity, Type of rocks, and the fluid portion is varying with increasing depth, as a result, the total density which also called Bulk density will change as it goes down in the borehole, so in order to know what is the overburden at a certain point in the earth the bulk density must integrate all over from the sea level (surface) until reaching a certain point of interest the equation below illustrates the situation[13]:

$$\sigma_{ov} = \int_0^{h_1} p_w(z) g dz + \int_{h_1}^{z} p_b(z) g dz \qquad \textbf{(1.5)}$$

Where:

$\sigma_{ov} = the\ overburden\ stress$ $g = gravitationl\ constant$

$z = depth$ $p_b(z) = the\ bulk\ density$

$p_w(z) = densityof\ fluid\ coulmn$

Since the bulk density varies with depth in the real world i.e the deeper you go in the earth, porosity normally decreases because of the rock compaction effect on the pore space, but to make life more simple normally a value of 1.0 psi/ft is assumed as a general gradient for the OB pressure gradient, this will be helpful in case we have lack of data.

In figure1.4, it's shown that in the normal condition the pressure will always follow the trend of pore pressure, once the depth increase and the compaction start the pressure at that point will deviations from hydrostatic pressure especially if the fluid has no open throat to escape from in this case the abnormal region start to occur[15].

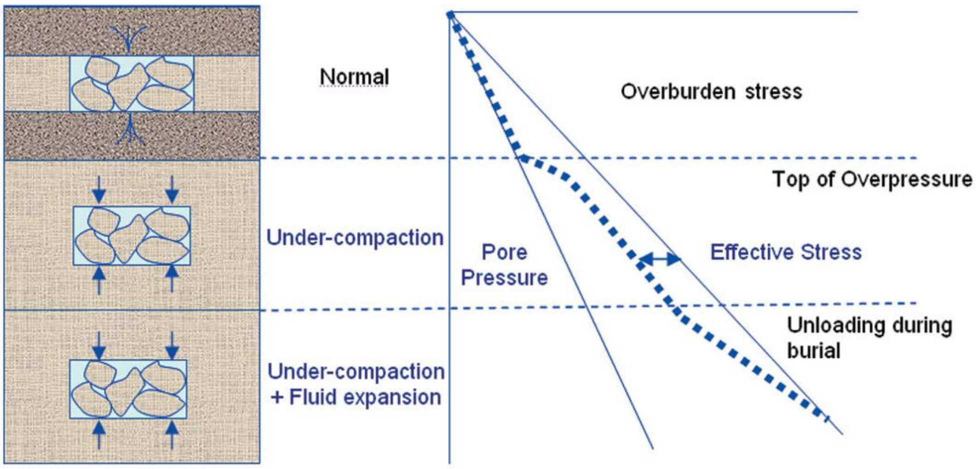


Figure 1.4 (the formation compaction versus depth)[15]

In general, hydrostatic pressure variations arise once the formation fluid is limited and cannot balance with surface pressure. Usually, the over-pressuring is created by[15]:

1. The compression of tectonic

2. Compaction during the geological event

3. Generation and migration of hydrocarbons.

1.5 Formation pore pressure:

Grains of rocks are continually Stocking up on one another during a time of erosion and sedimentation, usually in an environment that has water. The grains of the rocks are packed closely together as the sediment layer thickness rises, and the water begins to exceed out of the pores, although when the pore throats are interconnected in the rock structures the water will escape normally when the pressure of the compaction is applied that leave the pressure of the structure in a condition similar to the normal fluid column[15].

Normally the pore fluids are assumed to be in equilibrium (hydrostatic equilibrium) all over the way from the surface level until the depth of interest. This gives a comprehensive estimate of the pore pressure besides some variation in the porous density. (for water the gradient will be 0.47 psi/ft) it is still below a reasonable gradient of mud pressure since the mud is denser than water[7].

The pressure of the fluids in the pores in the subsurface structure-dependent only on fluid density and depth, it is independent of the geometry of the pores or pores. Figure shows a diagram that is called the P-Z diagram this plot illustrates Pp versus D(depth)[6].

When the drilling operation take a place the pressure of the formation to be drilled is usually converted into a pressure gradient. Which is known as the pore pressure gradient which can be obtained from the movement of the trendline by certain pore pressure and datum depth. Generally, drillers during the operation use the datum, which is the evaluation of the drill floor, but there is a universal datum that is in use which is Mean Sea Level.

The pressure of the fluids that are held in the interconnecting pore throats of the sediments will be the same at any depth, the same value of the pressure that will be found fluid column, and this is the reason that Figure it is shown that the gradient of the pore pressure is a straight line, the gradient (trendline) is a representation of density (fluid density), which mean that normally the fluid density inside the pores many times is conveyed in the units of psi/ft[7].

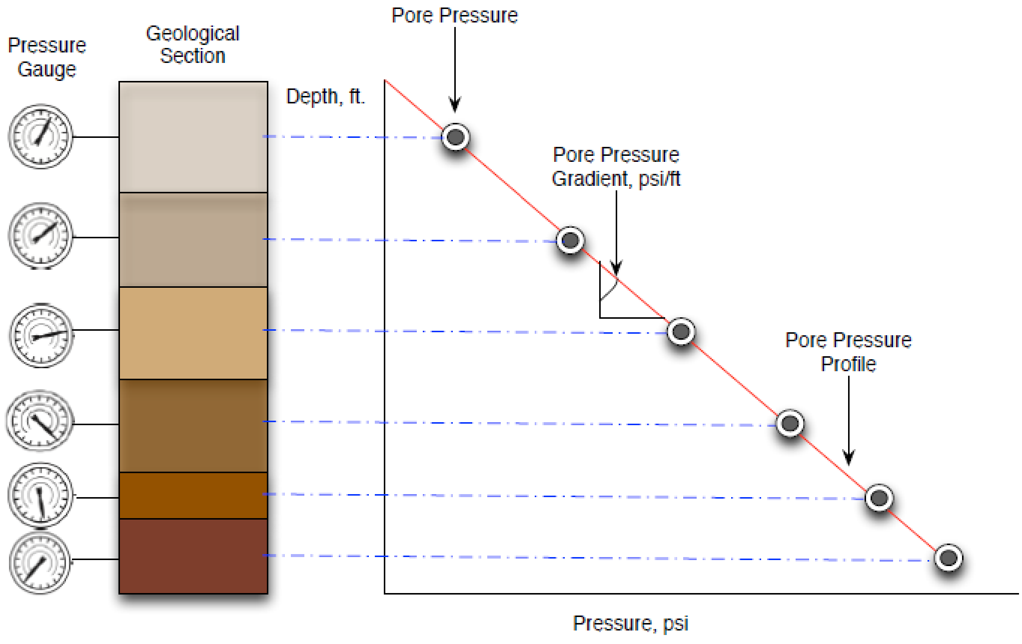


Figure 1.5 pore pressures represented in P-Z Diagram[7]

The unit of psi/ft it's very helpful and convenient representation since the pressure of the formation (pore pressure) can be easily approximated using the formation pressure gradient multiply by the depth of interest, now it will be also very important to calculate the density of the fluids that will be used for drilling operation (mud or drilling fluids), and this information about the density fluid will affect the whole drilling operation because one of the main objects is to make sure that the mud pressure (drilling fluid) is always above the pore pressure (some cases it might have underbalanced drilling with precautions), this way will reduce the probability to have a kick or blow out[16].

The overbalance pressure at a certain depth can be described as the variation between the pressure of the mud during the drilling operation and the formation (pore pressure). Figure 1.6 Demonstrate it If the pressure of the formation (pore pressure) is greater than the pressure of the drilling fluids (mud) in this case this difference will refer to the under-balance pressure.

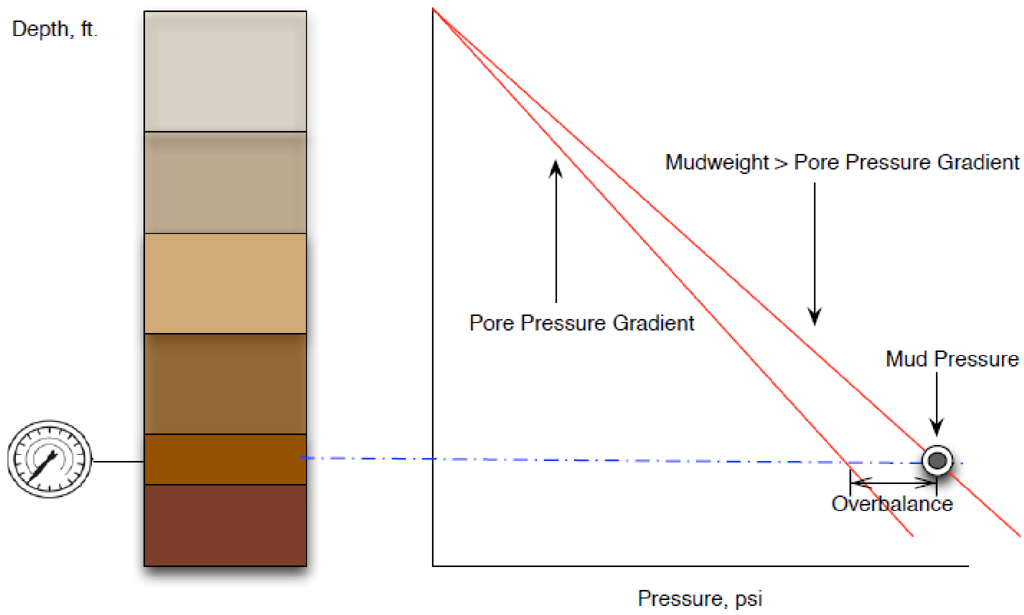


Figure 1.6 (The density of the mud versus the gradient of pore pressure)[7]

Normally the fluid that is found in the pores of the rocks is not water(freshwater) but it is known as brine which is a fluid that has a percentage of salt in it, the proportion of salt in the brines can be changing from zero up to 200,000 part per million **(ppm),** so as a result the formation (pore) pressure will also change from 0.43 psi/ft which is the gradient for freshwater to 0.5 psi/ft , but as an average value in the most geological areas the 0.465 psi/ft is considered (taking into account the salt content is 80,000 ppm) and this value is knowing as the pore pressure gradient or normal pore pressure gradient, so when the formation pressure in the subsurface is more or less than this value (0.465 psi/ft) that pressure will consider abnormal pressure also, one important thing that the pore pressure it can be called the hydrostatic pressure since they have the same value and follow the normal trend line[17].

If we consider the problems that will happen if the drilling fluid (mud) pressure falls below the normal pore pressure or at least the pore pressure at the depth of drilling we will find that kick or blow out is one of the serious problems that will cost both economically and humans lost, also the well may collapse but regardless these problems nowadays drills are able to drill in underbalanced conditions with taking the maximum safety procedure as possible, this underbalanced drilling will increase the penetration rate ROP and that is the main target of doing it[18].

It is must be cleared out that the fundamental theory behind the detection and prediction of the formation(pore) pressure is based on the law of Terzaghi's and Biot's effective stress, it is shown below the equation that Terzaghi and Biot derive which indicate the formation pressure as a function of the overall overburden stress and the effective stress[2]:

$$p = (\sigma_V - \sigma_e)/\alpha$$

Where

$p = the\ pore\ pressure$ $\sigma_V = the\ overburden\ stress$

$\sigma_e = the\ vertical\ effective\ stress$ $\alpha = the\ Biot\ effective\ stress\ coefficient$

1.6 Abnormal Pressure:

When defining the abnormal pressure in simple words it can be defined as the pressure or formation pressure that is higher or lower than the formation pore pressure (normal pore pressure) at that certain depth, sometimes it is called surpressure, geopressures, overpressure, but in most of the conditions it is called abnormal pressur.

Abnormally pressure it's a worldwide phenomenon it was predicted that the age of it comes from the Pleistocene age (more than 1 million years ago), this phenomenon may found very deep in the ground (more than 20,000ft) or simply below a couple of hundred ft and the rocks or structural can be sand/shale, evaporite-carbonate sequences

The origin of the abnormal pressure is Associated with a combination of physical, geochemical, and geomechanical processes[19].

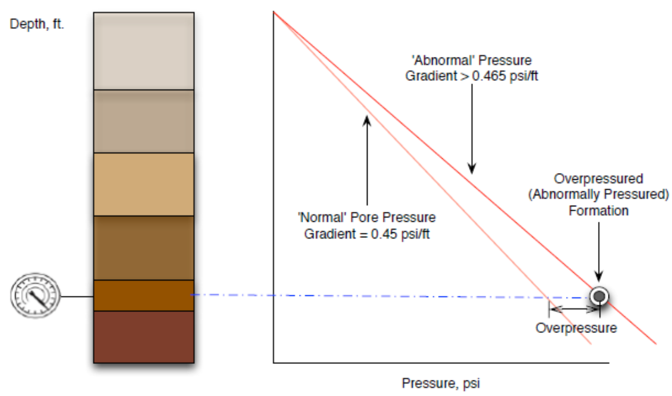


Figure 1.7 (Overpressure Formation)[7]

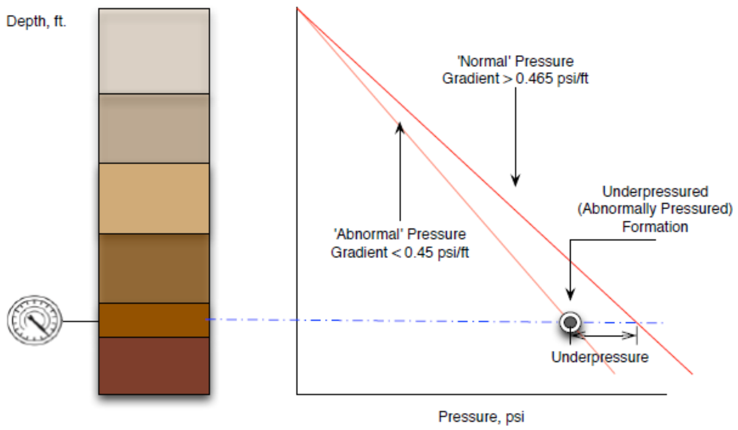


Figure 1.8 (Under pressured (Subnormal pressured) formation)[7]

As we mentioned above that the pressure of the formation inside the pores is found higher or lower than the normal pore pressure (pressure gradient is considered to be abnormal pressure the Figure and Figure shown it. Also, one of the most common mechanisms for the phenomena of the abnormal pressure zones is under compaction[7].

Figure shows the mechanism of compaction which has an empty vessel that is filled with fluid (this represent the fluid in the pores media) and also a spring (which is represent the matrix rocks) and the overburden pressure(stress) can be replaced by the piston being pus downward and compress the vessel, the equation below is an illustration of what happened in the subsurface[2]:

$$\boldsymbol{S = \sigma + p} \qquad \textbf{(1.6)}$$

Where

$(S) = overburden\ stress \quad (\sigma)\ spring\ stress \quad p = the\ fluid\ pressure\ (pore)$

This model will simulate the procedures that happened during the phenomena of the abnormal pressure When the sediments start to compact above each other the overburden will increase the rock grain and the fluids inside the pores must bear the overburden extra load as a result, now in normal condition when compaction happened the fluid will escape through the pores in order to formation be in equilibrium condition but if the fluid cannot leave the pores because the path is blocked for example, then the fluid pressure will increase above normal (i.e. hydrostatic pressure), this formation called the overpressure formation, in the figure below a representation of the process of the trapped fluid and the occurring of the pressure increase due to closing the valve and not let the fluid escape, that what happened in the subsurface in the abnormal region. If we open the valve the extra fluid will find its way out of the vessel and the pressure will be in equilibrium which is the normal pressure or hydrostatic pressure[19].

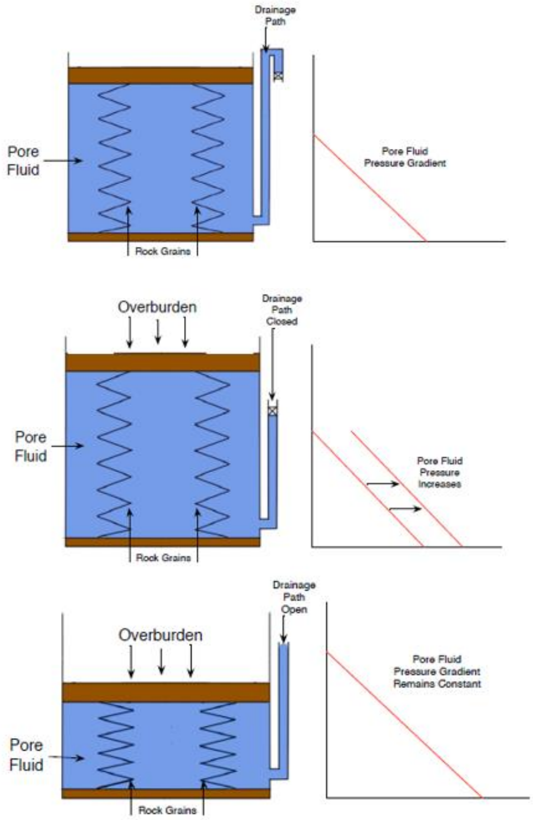


Figure 1.9 (Overpressure Generation Mechanism)[20]

1.6.1 Original of Abnormal Pressure:

As was mention before the abnormal pressure is any subsurface pressure that deviates from the normal trend of the hydrostatic pressure at a certain depth A pressure is called an abnormal pressure when it is different from a normal pressure gradient, or it could be lower than the normal pressure (formation pore pressure) in this case it is known as the sub-normal pressure. Even though the subnormal pressure causes some issue in good control, well planning problem, but for simplicity, we will refer to the abnormal pressure with the pressure that is greater or higher than the normal formation pore pressure, as for the pore pressure as it was mention it will be called formation (pore) pressure usually gas or brine (saltwater) is the kind of fluid that is kept inside the pores of the rocks, then we come again to define the overburden stress a the mass of the rock grain and the fluids above a certain point that is what produces the overburden pressure, if we want to know just the stress of the rock grain (matrix), it is the subtraction of the pore pressure from the total overburden pressure at a certain depth, as a value the overburden pressure value is 1.0 psi/ft with a density of 19.2 lb/gal these numbers is for general calculations[15].

As it is known that the hydrostatic pressure must be the same as the pore pressure of the formation at a certain depth, and the number is from 0.43 psi/ft (8.33 lb/gal) in (freshwater) up to 0.47 psi/ft (9 lb/gal)for saltwater with (200,000 ppm salt content), it was found that in some reports around the world that normal pore pressure (density) can be greater than 0.47 psi/ft (9 lb/gal), but whatever the fluid density, the normal formation pore pressure is an open hydraulic system, means that the pressure transmits through the system[19].

Overburden pressure that is the result of compaction of the rocks plus the fluids inside the pores can be calculated if it was taken into account that the compact of the rocks does not happen beneath the barrier, so what must be supported the overburden pressure is rock grain matrix and the formation fluid, this pressure can be estimated using the following formula[2]:

$$\mathbf{P = 0.465\frac{psi}{ft}DB + 1.0\frac{psi}{ft}(D_i - DB)} \qquad \textbf{(1.7)}$$

Where:

$Di = depth\ of\ interest\ below\ the\ barrier, ft$

$DB = depth\ of\ barrier, ft$ $P = formation\ pressure\ at\ Di, psi$

The phenomenon of the abnormal pressure zone has happened all over the world, and as a result, it adds more difficulties in petroleum exploration when drilling in these zones the results of abnormal pressures may be in beneficial and unbeneficial way.

The drilling strategy effectiveness can depend on the knowledge and good estimation of the formation pressure from the top ground level until the depth of interest, wherever there is a chance of abnormal pressure to occur a different kind of method need to include continuously assess the pressure of the formation as[2]:

- In comparison, abnormally high formation pressure systems are primarily “closed”, which makes the fluid in non-communication conditions.

- Practically, any difference in the normal formation pressure from the consideration of the "normal" hydrostatic pressure gradient is the abnormal pressure.
- "abnormal pressure" is usually referred to as overpressure sometimes as sur-pressure, trapped pressure, geo-pressure.
- In many cases, low pressure can be called "normal pressure" and sub-pressure.

1.6.2 The Origin generation of subnormal formation pore pressures:

Most of the mechanisms that the subnormal pressure phenomena is caused by are sum up as follows[2]:

a) Temperature effect Expansion due to thermal activity

The temperature will keep increase while the sediments buried the pore fluids if the fluid has enough space to move and expand then the pressure will reduce[21].

b) Formation strata foreshorten

As a result of the compression process, the strata will start bending, the lower beds will bend downwards, while the upper beds will bend upwards leaving the intermediate bed to expand to fill the void that the upper and lower beds left, as a result, subnormal pressure zone is created as shown in the Figure1.10, hence the upper and the lower beds will have overpressure zones correspondingly.[7]

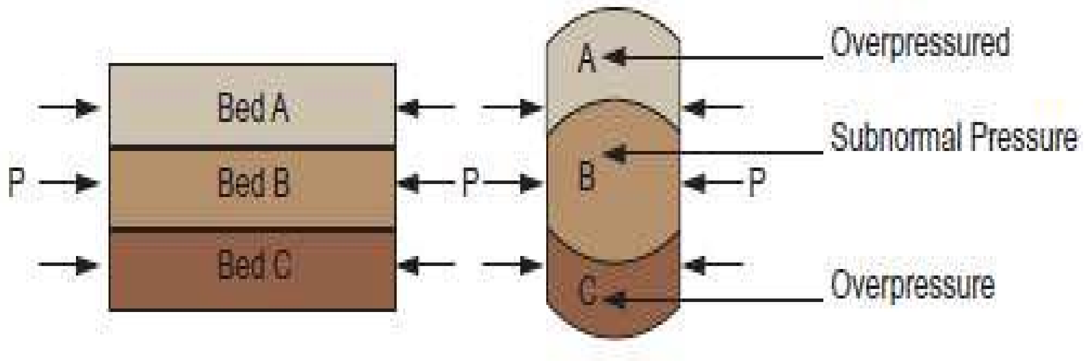


Figure 1.10 (The different layout of the beds)[7]

c) Depletion:

A sub-normal pressure may create when the production of hydrocarbon or water from a particular formation that has no caving in or subsidence occurs, this will have a huge impact On the development well drilling operation in the oil field that was producing for a certain amount of time[6]

d) The surface of Potentiometric:

This mechanism Describes the formation of structural relief And the result would be in the over-pressured and subnormal zone, the potentiometric surface can be described by the level that the water can reach in the same aquifer of the reservoir when the wells are drilled. the potentiometric then can be up or down the ground level Figure **.**

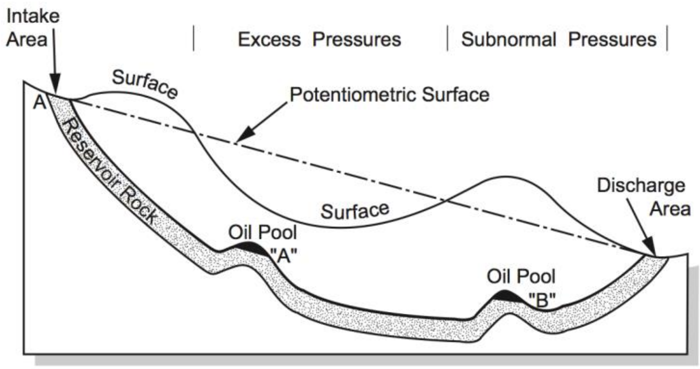


Figure 1.11 (The effect of the potentiometric surface causing abnormal pressure)[6]

Changing in depth can lead to abnormal pressure in the formation or structure that is in contact with the surface but in other conditions, it is sealed. If the edges of the rocks go up overpressure will occur in this case, if it goes down it will cause subnormal pressure zones Figure 1.1illustrate this, the pressure difference rarely caused by changes in the depth alone since there are other things associated like erosion and deposition is also huge impact, the losing or gain of the sediments that are saturated with water is important. The under-pressure level is generally so small that it is not practical taking into account. The largest abnormal pressures recorded were by far overpressures, not subnormal pressures[23].

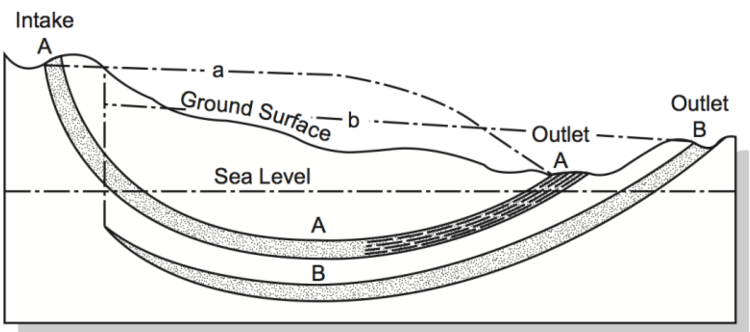


Figure 1.12 potentiometric surfaces related to reservoir[22]

1.6.3 Origin of Over-pressured Formations:

The overpressured formations are formations with pressure more than the normal pore pressure trend line which is $0.465\ psi/ft$ Figure shows the different pressure points for several European fields which represent a plot of normal (pore) pressure gradient versus the overburden.

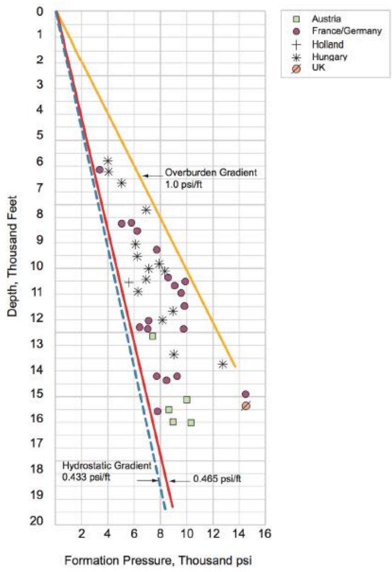


Figure1.13 Overpressures observed in European Wells[24]

There are several mechanisms that cause the pressure to not to follow the normal trend line of hydrostatic pressure, some of these mechanisms have been discussed under subnormal pressure and those are potentiometric surface and formation foreshortening because in these conditions both the subnormal and abnormal pressure can occur, and the other mechanisms that related to the overpressure zones are[25]:

a) Incomplete sediment compaction or under compaction:

It is considered as the significant mechanism that causes the overpressures. Under the fast compaction of clays of low permeability (sometimes even shales) the fluids have no time to escape, normally the primary high porosity (around 50%) is reduced due to the expelling of the water across the permeable sand structures, however, the fast compaction of the rocks layers and the sand is trapped by the impermeable barriers as shown in Figure it does not allow the process to take enough time for the fluids to expelled normally which will support the pressure to be overburden[26].

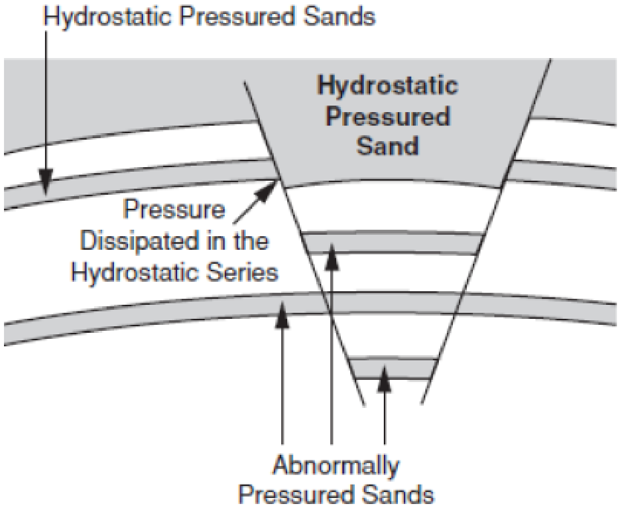


Figure 1.14 Origin of the overpressure sand and barriers to flow[24]

b) Fault formation:

When the mechanism of fault happened or occurred in the subsurface the sediments are cross over each other, causing barriers for the fluid to move because the permeable zones will be opposite the impermeable zones, this will prevent any fluids inside the pours to expelled out as it should in normal condition, this will cause an increase in the porosity and the pressure to be an overburden.

c) Deposition of the Rock Salt:

The deposition of salt is commonly found in large places around the world, The abnormal pressure is commonly found below the formation of the salt directly, this happened because as it is known the salt is impermeable and the formation that is underlying becomes over-pressured.

d) Diaperism of the salt:

The layering of the structural (sediments) is a result of the buoyancy effect which makes the upper movement of the low-density salt and as a result, the abnormal pressure zones occur, also the salt can also serve as a not permeable barrier for clay drainage.

e) Compression of the tectonic:

The horizontal compression of the sediments may result in uplift the weathered formation or fracture of sediments, as a consequence, the formation is compressed down at a certain depth can be uplifted to a new level, and the formation will be over-pressured now if the original pressure kept uplifted[24].

f) Deeper Levels Repressuring:

The main reason for this phenomenon is the movement of the fluid from the high-pressure zone to the low-pressure zone at shallow depth, this could have varied reasons it may be because of faulting or from poor cement job. This unexpected high pressure one of the reasons that cause a kick, since the lithology has no apparent change. In shallow sands, high pressure may occur if from lower formation the gas was charged[25].

g) The origin of the Hydrocarbon:

The over-layering of the hales formation with the compaction of the organic material will produce the hydrocarbon (oil and gas) this is due to the degrades of the material under the compaction, in normal condition the gas and oil will Migrates throughout the pours but if it is trapped then the overpressure or overburden pressure will occur. Salts can be formed from organic products and will be precipitated in the pore's space, as a consequence this will help to reduce porosity and seal creation[27].

1.7 The drilling problems related to the abnormal pressure:

the maintaining of the drilling fluids pressure during the drilling operation is essential in order to:

- Make sure that the collapse will not happen in the wellbore.
- The formation fluid will not inflow into the well.

To maintain the borehole stability and have the problems mentioned the drilling fluids (mud) pressure required to be kept above the formation pressure. This is called overbalance drilling. But if the overbalance is too high (means the pressure is too large) it may lead to:

- The Rate of penetration will be less or decreasing, that is because of the “chip hold down” effect.
- Because when the mud pressure exceeds the fracking pressure this will conduct to a loss in the drilling fluid through the circulation
- The stuck of the pipe might happen because of the too much differential pressure

When designing casing strings, the formation pressure must be taken into account. If we have two pressure zones one is high and the other is low, we cannot drill with the same mud pressure through both zones because the zone with the lower pressure might be fractured.

The zone with the high pressure in the casing design let us say that is the first zone that the drilling string will be encountered with, so in this case, it must “cased off” Because in order to be able to drill throughout the next zones which has a lower pressure the mud pressure must be decreased, one of the common problems is that the surface casing is set at high-level such action will affect the circulation of the mud because when encountered with an overpressured zone the influx of the formation will be mixed with the heavier mud and it will not be able to circulate out of the borehole.

It is important to set each of the casing string to the maximum depth that is allowed with taking into consideration the formation gradient pressure, if these procedures do not done properly an extra protective casing string will be required, this will affect the economic part of view because it will cost more and also will affect on the final or inner diameter that will be reduced, As the output tubing size will have to be reduced, this will have repercussions when the well is to be completed[2].

Having considered some of these issues, it should be clear that it is important to locate any abnormally pressurized zone and to accommodate the drilling program.

1.8 Transition Zone:

Looking at the “P-Z diagram” it would be noticed how the formation (pore) pressure in the region where the over-pressure will be like, at the shallower formation the pressure will follow the normal tren line that is the hydrostatic fluid gradient, after that it starts to drift out of the normal trend line of the pressure until it reaches the “overpressure” formation zone. The zone between the normal hydrostatic pressure and the over-pressure is known as the transition zone.

It can be a notice from the “P-Z diagram” that the pressure of the transition zone and the over-pressurized zone not following the normal (hydrostatic) gradient line. The transition zone, in this case, will represent the caprock or the seal that is lying on the over-pressure zone formation, also at is shown in Figure that by knowing the transition zone the thickness of the shale or the caprock can be estimated, the shale will have very low permeability that is the reason for a generation the overpressure zone because the fluid will not be able to flow across the shale and it is not able to migrate and move (trapped), the caprock is not necessary to be with zero permeability (that is impermeable but it is very low[2].

The transition zone can be detected in the cases that the caprock is had low permeability. After all, the pores pressure gradient will increase gradually, which will give enough time and visualize to the detecting of the caprock or transition zone, in the other hand if the caprock is hard crystalline rock (the permeability is zero) the transition zone will not be detected because the pressure will be sudden drop.

In the abnormal pressure zones when the drilling operation starts the drillers have to monitor all of the drilling parameters such as the mud and cutting to know and detect the increase of the pore pressure which leat to the start of the transition zone. the thing that must be clear is that during the transition zone drilling although that the pressure increasing but the fluid will not enter the wellbore because of the low permeability, but once we reach the overpressure formation the fluid can easily enter the wellbore if the mud pressure does not change and precautions have been taken, in some companies, the operating have to approve to the policy of intentionally, that is reducing the pressure (overbalance in this case) so that the transition zone can be detected, even if that mean to have some problems like a kick[28].

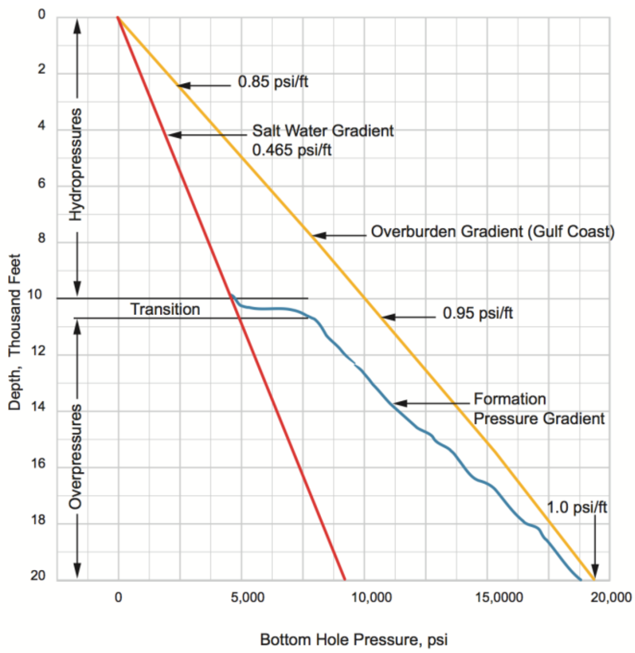


Figure 1.15 Transition from normal pressures to overpressures

Chapter Two

Prediction and detection of Abnormal Pressure

2.1 Data Classification for Abnormal Pressure Detection:

It is well known that the predictive techniques for prediction and detection of abnormal pressure rely basically on surface measurements, for instance; geophysical measurement, or through performing analysis of data extracted from drilled wells in adjacent locations (offset wells). It is normal to use geophysical to determine geological conditions that may suggest overpressure potential, like salt domes, associated with over-pressured areas. Generally, engineers use seismic data to detect transition zones and gas presence as a fluid content function. The history of offset wells can provide details on the utilized mud weights, stuck pipe issues, any circulation losses or kicks. During the process of predicting over-pressurized zones, any relevant wireline logs or information extracted from mud logging is of great value[29].

Table 1 General classifications can be proposed for overpressure techniques[2]

Source of Data	Parameters	Time of Recording
Geophysical methods	• Formation velocity (Seismic) • Gravity • Magnetics • Electrical Prospecting Methods	Prior to spudding well
Drilling Mud	• Gas Content • Flowline Mud weight "kicks" Flow line Temperature Chlorine variation • Drill pipe pressure • Pit volume • Flowmeter • Hole Fill up	While drilling
Drilling parameters	• Drilling rate • D Dc exponent • Torque • Drilling rate equations • Drag Drilling	While drilling Delayed by the time required
Drill Cuttings	• Shale cuttings • Bulk density • Shale factor • Electrical resistivity • Volume • Shape and Size • Novel geochemical, physical techniques	While drilling Delayed by time required for sample return
Well Logging	• Electrical survey • Resistivity • Conductivity • Shale formation factor • Salinity variations • Interval transit time • bulk density • hydrogen index • Thermal neutron • caption cross section • Nuclear Magnetic Resonance downhole gravity data	After drilling
Direct Pressure Measuring Devices	• Pressure bombs • Drill stem test • Wire line formation test	When well is tested or completed

2.2 Detection Techniques

During the Drilling program, the detection techniques (mention above) are used. are used mainly to monitor and sense any pressure increase within the transition zone. The definition of the following data is based on their type:

- Parameters of Drilling: it is done by monitoring different drilling parameters (e.g. Rate of Penetration ROP) and implementing empirical equations in order to generate a dependent term on the pore pressure.
- Drilling mud: basically, by observing and reporting the influence of an over-pressurized formation (zone) that affects the drilling mud (i.e. influx of oil/gas, temperature).
- Drilled cuttings – Monitoring drilling cuttings, with the aim of detecting the sealing zone's cuttings.

Many approaches are used for forecasting, detecting, evaluating, and analyzing formation fluid pressures, The **Table 2.22.2** shows the approaches which are categorized in qualitative and quantitative methods of detection(the following table includes solely these methods which are relevant to the well drilling phase)[31].

Table 2 Different methods for detecting abnormal pressures during the drilling phase of a well[2]

Pressure detection method while drilling	
Qualitative methods	Quantitative methods
paleontology	Log analysis
Offset well correlation	Porosity detection
Temperature anomalies	Resistivity (conductivity)
Gas counting	Sonic
Mud and/or cutting resistivity	Bulk density
Delta chlorides	Drilling equation
Cutting Character	dc exponent
Hole condition	Computerized drilling models
Cutting content (shale factor)	Kicks

Table 3 General classifications can be proposed for overpressure techniques in different time[2]

	Source of Data	Parameters	Time of Recording
Predict	Geophysical methods	• Formation velocity (Seismic) • Gravity • Magnetics • Electrical Prospecting Methods	Prior to spudding well
Detect	Drilling Mud	• Gas Content • Flowline Mud weight "kicks" Flow line Temperature Chlorine variation • Drill pipe pressure • Pit volume • Flowmeter • Hole Fill up	While drilling
	Drilling parameters	• Drilling rate • D Dc exponent • Torque • Drilling rate equations • Drag Drilling	While drilling Delayed by the time required
	Drill Cuttings	• Shale cuttings • Bulk density • Shale factor • Electrical resistivity • Volume • Shape and Size • Novel geochemical, physical techniques	While drilling Delayed by time required for sample return
Confirm/evaluate	Well Logging	• Electrical survey • Resistivity • Conductivity • Shale formation factor • Salinity variations • Interval transit time • bulk density • hydrogen index • Thermal neutron • caption cross section • Nuclear Magnetic Resonance downhole gravity data	After drilling
	Direct Pressure Measuring Devices	• Pressure bombs • Drill stem test • Wire line formation test	When well is tested or completed

Predictive Techniques

These techniques include different geophysical techniques used during the early exploration phase. They will predict and forecast the presence of conditions of any possible abnormal pressure[29].

Detection techniques

These techniques are the ones that can be monitored while the drilling operations are going on and with these techniques, the drilling team (crew) will be alert if they have drill across an over-pressurized zone or transition zone.

This refers to factors and characteristics that can be tracked during the process of drilling. These parameters play a significant and crucial role in giving an alarm to the drilling crew that a transition/over-pressurized zone has been encountered.

Confirmation techniques

These techniques are related to techniques used to confirm and detect any abnormal pore pressures of the encountered formations. These techniques are applicable after the completion of the well drilling successfully.

In order to detect the presence of abnormal pressure zones, three different categories of data sources must be mentioned as follows[32]:

- **Drilling Parameters**
  These parameters are related to drilling parameters monitoring, and utilizing the drilling rate empirical equation which takes into consideration the pore pressure as a dependent term.
- **Drilling Fluid (Mud)**
  In this section, the effect of the abnormal pressure zone on the drilling fluid is studied. This effect includes for instance influx of quantities of hydrocarbons and an increase in the temperature.
- **Drilling Cuttings**
  In this category, the study of the drilling cuttings from the sealing zone is carried out.

2.3 Detection of Abnormal Pressure Zone Based on Drilling Parameters

The scientific background which illustrates that drilling parameters are used to detect over-pressurized zone/zones is mainly assumed from:

- That whenever we drill downward the whole (increasing in depth) the formation compaction will increase. This leads to the decrease in the Rate of Penetration (ROP) if all other factors are constant.
- The rock characteristics within the transition zone, which are a more porous and less compacted rock in comparison with normally compacted formation. In this case, consequently, ROP will increase. Nevertheless, ROP will continue to increase as drilling goes on due to the reduction of the pressure difference between the hydrostatic pressure of the mud and the pore pressure of the formation.

The concept of using ROP to observe the transition and consequently the over-pressurized zones is a simple conceptual matter, however, it is hard to be applied in practice. The reason for that is other factors such as Rotary speed and WOB has a huge effect on the ROP.

Therefore, precise consideration of the other factors should be considered to have a direct correspondence between (ROP) and the formation pressure as the other factors cannot be maintained constant. This task is basically accomplished by using the empirical equations in order to generate a “normalized” ROP, which afterward is utilized as a detection tool[2].

2.4 Parameters of Drilling

The using of the drilling parameters is based on**:**

That it is probably the barrier or the seal zone will be presented as the greater compaction zone which will decrease the rate of penetration

2.4.1 The rate of Drilling (Rate of Penetration)

The drilling rate was used for several years to differentiate between sand and shale. The obvious relation between the penetration rate and fluctuations in pore fluids pressure was therefore recognized. The drilling rate is basically dependent on Weight On Bit WOB, size of bit and type, hydraulic characteristics, rotary speed Drilling-mud and characteristics of the formation. There is a decrease of ROP (rate of penetration) with depth (because of the compaction) (as long as all parameters above are constant).

2.4.2 The Normalized Rate of Penetration (D exponent)

Since WOB and RPM. are not often feasible to be controlled/kept (as previously described), an innovative system has been created to plot the normalized-penetration rate (d-exp) versus depth.
The penetration rate, bit size, WOB, and rotary speed are required to calculate the dimensionless number (d-exp)[33].

2.4.3 The “D” exponent

The technique of ("d" exponent) of overpressure detection relies on an equation of normalized values of drilling rates made by Bingham in 1964. Bingham suggested the following generalized equation of drilling rate:

$$R = aN^e \left(\frac{W}{B}\right)^d \qquad (2.1)$$

Where

R =penetration rate

N = speed of the rotary table

W = the bit weight WOB

B = diameter of the bit

a = constant of matrix strength

e = rotary speed exponent

d = formation drill ability

"Jordan and Shirley (1966)" did some reorganization to the equation above in order to be obvious with regard to the term "d". afterward, simplification of this equation was carried out by giving the following assumptions: Firstly, That drilling throughout the rocks did not change the formation structure which means the strength constant (a) is equal to 1, secondly the exponent of rotary speed is similar to one[29].

Experimentally, the exponent of rotary speed (e) was found to be close to 1. Which will replace the lithology and rotational speed variables. This means that only one form of lithology and theoretically with a single rotation speed can be used for the resulting equation. The above statements is not limited enough since the (e) value is normally very similar to 1. The following equation was developed on the basis of these assumptions and constraints[34]:

$$d = \frac{\log\left(\frac{R}{60N}\right)}{\log\left(\frac{12W}{10^6 B}\right)} \qquad (2.2)$$

This equation is called the equation of the "d-exponent." As the N, R, B, and W values are either defined or measurable on the surface, the d-exponent value can be estimated and drawn for the entire well versus depth. You will find "d" values using the nomograph that is showed in the figure below. Note that the D exponent value varies in reverse with the drilling rate. As the bit penetrates the ROP will rise an over-pressured zone as differential pressure and compaction will decrease, this will lead to a decrease in d-exponent[35].

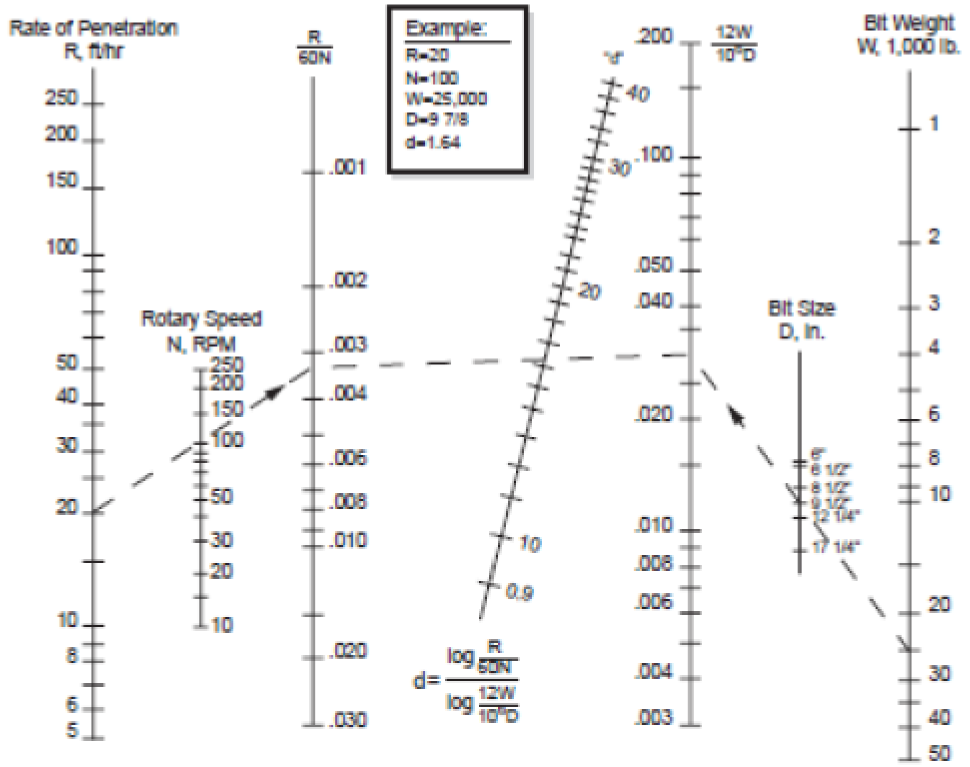


Figure 2.1 Nomogram for calculating D-exponent[36]

Therefore, the d-exponent vs depth plot identifies an over-pressurized zone as the d-exponent is reduced (Figure 2.1).

This equation considers differences in the most common drilling parameters, for that Conditions below should be preserved for exact results[34]:

- keeping RPM and WOB steady and not changing as much as possible (meaning no sudden shift should occur).
- In order to minimize lithology dependency, the equation can only be extended to small depth increments.
- For a reliable "trend" line a good thick shale is needed the d-exponent equation does not take into consideration the weight of the mud. The Mud weight means the exerted pressure which is applied on the bottom hole, so the higher is the value of the mud density, the higher will be the chip hold effect leading to the decreased value of rate of penetration ROP. Therefore, after considering differences and fluctuations in mud weight, another d-exponent (dc) equation is introduced:

$$d_c = d\left(\frac{Mw_n}{Mw_a}\right) \qquad (2.3)$$

As

Mw_n = “normal mud weight”

Mw_a = “actual mud weight”

For detection of the transition zone, it will be more defined and obvious when using the Dc exponent as shown in (Figure 2.2).

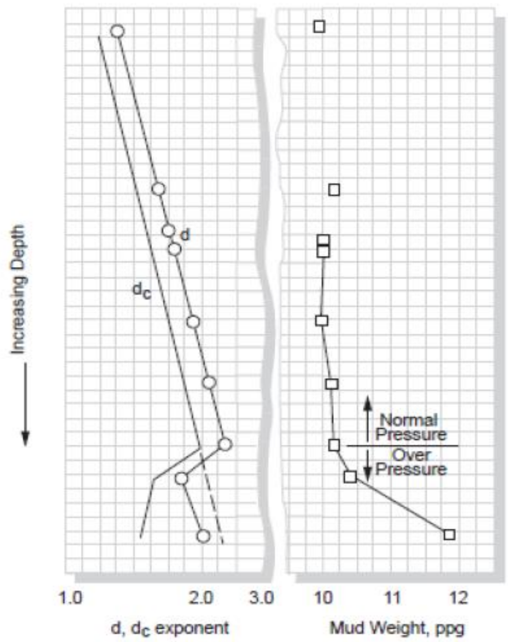


Figure 2.2 The detection of the geo-pressure by using both the D and Dc exponents[36]

Since the D-exponent is normally utilized to define the start (top) of the over-pressurized zone. Eaton (1976) suggested a method that can calculate the formation pressure from the adjusted exponent:

$$\frac{P}{D} = \frac{S}{D} - \left[\frac{S}{D} - \left(\frac{P}{D}\right)_n\right]\left[\frac{dc_o}{dc_n}\right]^{1.2} \qquad (2.4)$$

Where

$\frac{P}{D}$ = “fluid pressure gradient”

$\frac{S}{D}$ = “overburden gradient”

Dc_o = Dc observation at a certain depth

Dc_n = Dc from the trend line (normal) at a certain depth

Eaton states that his equation can be applied globally and the value of ± 0.5 ppg is reliable.

Plotting (de) exponent versus depth can define the over-pressurized field. The following criteria must prevail for correct results:

- There should be no sudden shift in Round per minute (RPM) or the weight on bit (WOB), i.e. keeping them both steady without changing as possible.
- In order to minimize lithology dependency, the equation above can only be extended to small depth increments.

Normally, Plots of de versus depth indicate an increasing pattern against depth. The measured d-value in transition zones and overpressure conditions diverges from the usual pattern towards lower than expected values (Figure 2.3).

Computed De value is influenced by any changes in R, N, W&D, which can affect the d-exponent by variations in bit size & type, bit weight, a shift in lithology, and changes in

Mud density[35].

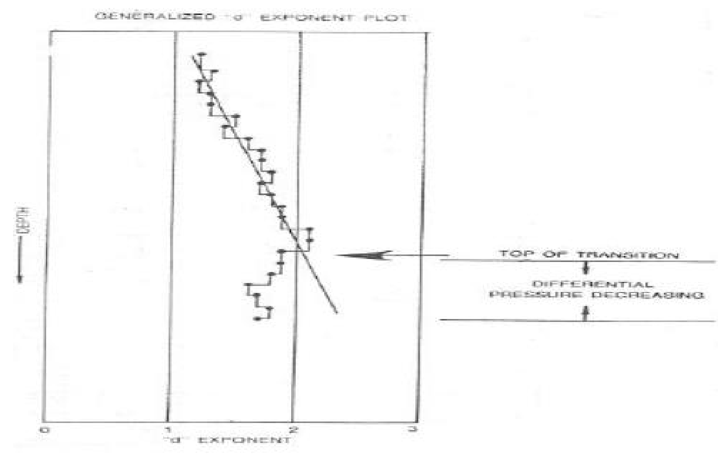


Figure 2.3 D-exponent vs depth[36]

2.4.4 Modified D-exponent

As the de is affected by changes in mud weight, an adjustment was made to normalize the De value with the effective mud density, for instance:

$$d_c = d\left(\frac{\rho_n}{\rho_e}\right) \qquad (2.5)$$

Where

dc = corrected or modified D-exponent

ρ_n = "mud density equal to normal formation pore pressure gradient"

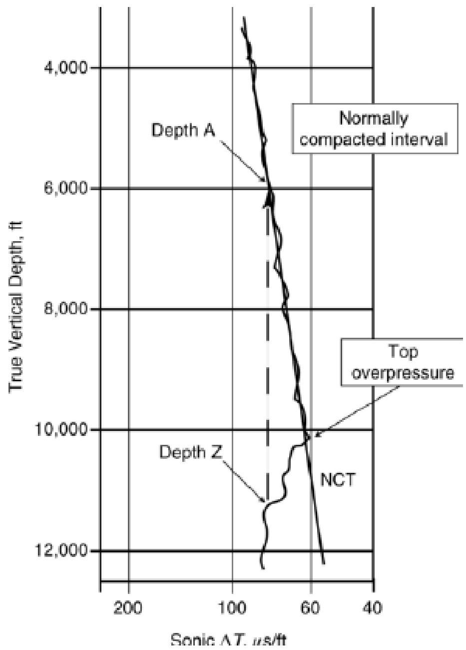
ρ_e = "equilibrium mud density at the bit while circulating"

- **Comparison of d and d-exponents**

  Both exponents can be utilized to measure the top of the over-pressurized zone. However, Dc is more quantitative as it takes account of the influence of the density of mud on the drilling rate

2.4.5 Equivalent Depth Methods

One technique to perform trendline analysis is like the analogous depth approach which is shown in figure2.4. An assumption is made by this approach that over a depth segment, the pores pressure is hydrostatic, and compactions of sediments follow a systematic rise of effective stress with respect to depth. If the log relationship is viewed vs depth, typically compacted section will show direct straight lines which fit the data representing the NCTs (Normal compacted Trend). Given that this physical property measured is a function of effective stresses, at ant depth where the value is not on the NCT, pore pressure can be estimated[37].



2.4 Illustration of the equivalent depth method using sonic ΔT[37]

NCT as mentioned before can be defined as a straight line within a log scale that diminishes versus depth as sediments usually compact. The value of effective stress at depth Z is equal to its correspondent at depth A, therefore pore pressure at depth Z is calculated as below:

$$P_z = P_a + (S_z - S_a) \qquad (2.6)$$

knowing that Pa, z, and Sa are the pressures of the pores and the effective stress at point "z", and at the depth of interest "a" and a depth within the normal pattern of compaction at which the calculated parameter is equivalent to that at the interest depth. The equivalent-depth method considers only one single assumption which is effective stress is a linear depth function[38].

2.4.6 The Ratio Method

The pore pressure in this method is determined by the hypothesis that the Sonic (delta t), Resistivity, and density divided or multiplied by the pore pressure value at the same depth as shown in equation (2.7)[37].

$$P_p = P_{hyd} \frac{\Delta t_{log}}{\Delta t_n} \qquad (2.7)$$

And,

$$P_p = P_{hyd} \frac{R_n}{R_{log}} \qquad (2.8)$$

Where:

P_{p} = the real pore pressure

P_{hyd} = the normal hydrostatic pore pressure

The main meaning of log and (n) value is respectively the recorded value and normal value of resistivity, density, or sonic (delta-t). The calibration for this equation demands that each parameter recognizes the required normal value. In comparison to trendline approaches, it is necessary to notice that the ratio approach is not directly using effective stress, therefore it cannot be considered an effective stress method. As a consequence, unphysical conditions will be met, for instance when estimated pore pressures are higher than the overburden pressuresFigure [37].

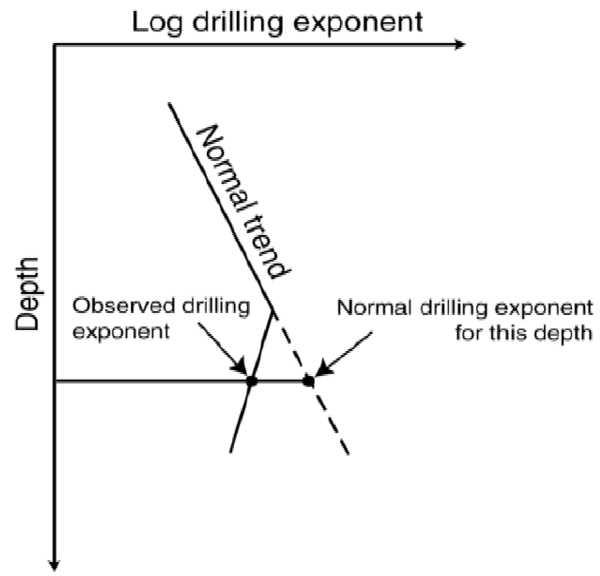


Figure 2.5 ratio method Illustration[37]

2.4.7 Eaton's Method

In 1975, Eaton developed a pressure detection technique focused on numerous well logs, which would use the acoustics velocity, resistivity, or dc for the quantification of the formation pore pressure. The system is an advancement in the equivalent depth method introduced by Hottman and Johnson in 1965. Both methods rely on the commonly agreed assumptions that overburden pressure depends on pore pressure and vertical effective stresses, as seen in Terzaghi's 1948 equation (Eaton, 1975))[38].

$$\boldsymbol{Pore\ Pressure = Overburden\ Pressure - \sigma_{Vertical}} \qquad (2.9)$$

Originally based on acoustic speed and resistivity alone, the dc exponent plots were shown to conform to the resistivity logs of shales, allowing the system to be extended even with the dc exponent (Eaton, 1975). The equations of Eaton are the following[38]:

- despite which used log data to estimate strain, they all depend on the development of a trend line based on data from a formation with a normal pressure behavior and the knowledge of a gradient of overburden-pressure and normal gradients of pore pressure of the region.
- Probably the most commonly known methodology for the estimation of pore pressure is Eaton's process (Figure 2.6). Stress is explicitly included in the calculations below.

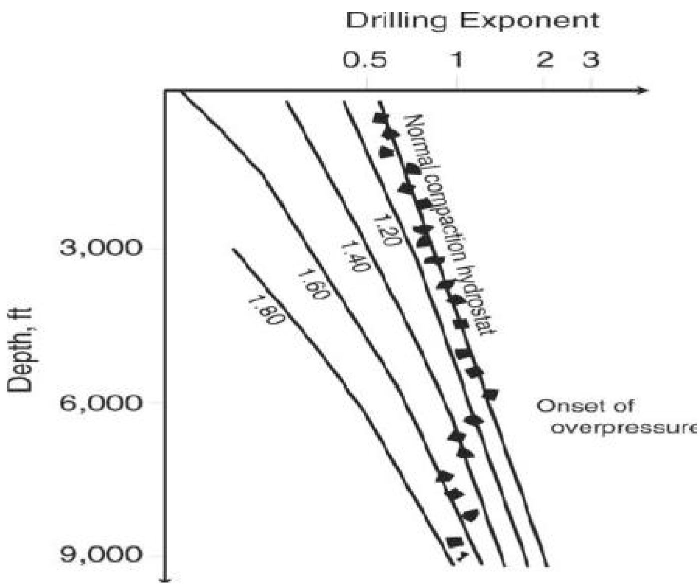


Figure 2.6 Lines for computing pore pressure using Eaton's method[7]

Notice that these "lines" are not linear in semi-log space (modified after Mouchet and Mitchell).

$$P_p = S - (S - P_{hyd})\left(\frac{R_{log}}{R_n}\right)^{1.2} \qquad (2.10)$$

And,

$$P_p = S - (S - P_{hyd})\left(\frac{\Delta T_n}{\Delta T_{log}}\right)^{3} \qquad (2.11)$$

Where

P_p = the real pore pressure

S= the stress

P_{hyd} = the normal hydrostatic pore pressure

The subscripts log and n are showing the standard measured at a certain depth for the resistivity (R) and sonic delta-t values.

The exponents indicated in equation 2.10 are standard values frequently modified for different regions to best fit the estimates for the pore pressures obtained from other results. The biggest issue with both trend lines is that the consumer has to select the right standard trend in the compaction. Too few details are often used to describe the NCT. Unfortunately, the approach can generate the wrong (too low) pore pressure if the

NCT is established at an interval with a high pore pressure, leading to extreme drilling risks[38].

2.4.8 Method of Resistivity versus Depth- Normal Compaction Trend Line dependent

The standard resistivity of the shale or the resistivity of the shale in pores pressures is not easy to be determined in Eaton's original equation. One solution is the presumption that the resistivity of the shale is constant. The standard resistivity (Rn) in the majority of cases, however, is not constant but depends on the burial depth. The compaction trend line needs to be calculated for the estimation of the pore pressure, The equation below for the compaction trend line of resistivity is utilized on the basis of the relation of resistivity measured and normal pressured formation at a deeper depth. (Zhang, 2011)

$$\boldsymbol{Rn = R_o\, exp(bZ)} \qquad (2.12)$$

Where:

Rn = the Normal compaction's shale resistivity

Ro = the shale resistivity under the mud line

Z = represents the depth beneath the mud line

The pore pressure can be determined by substituting the value of Rn in Eaton's resistivity equation.

2.4.9 Sonic with Depth method- Normal Compaction Trend Line Dependent

Based on the data on the calculated Normal pore-pressure sonic transit time of the formations, the following general relation is proposed the compaction pattern of the transit time:

$$\boldsymbol{DT_n = DT_m + (DT_{ml} + DT_m)\, exp(-cZ)} \qquad (2.13)$$

Where:

DT_m = the transit time of compression through the shale matrix (no porosity)

DT_{ml} = the time of transit of the mud line

c = the constant of compaction

Z = the distance below the mud line

The pore pressure can be determined when this DTn is replaced by the Eaton velocity/transit time equation[37].

2.5 Fracture Gradient

2.5.1 Definition

the fracture gradient can be defined as the load or the strength that the rock can handle before breaking down varies with depth

When the mud program takes place, it is very helpful to be able to know what is the max weight of the mud which will be suitable to use at each depth, this mud weight is known as the Fracture gradient, in general (as was mention before) the mud weight must be in the range between formation pressure gradient (using minimum MW) and the fracture gradient (using the max MW), The known of the fracture gradient is necessary when throughout an overpressured zone[39].

2.5.2 Fracture Gradient Predictions

In the past decade's attempts have been made to be able to detect and predict the fracture pressure or fracture gradient from knowing the pore pressure gradient[40]:

- “Hubbert and Willis”
- “Matthews and Kelly”
- “Ben Eaton”

Hubbert and Willis

This method assumes that the fraction occurs when the fluid pressure that is applied is surpasses the minimum effective stress and the formation of pore pressure

$$G_f = \frac{1}{3}\frac{\sigma_v}{D} + \frac{2}{3}\frac{P_f}{D} \qquad (2.14)$$

Where:

Gf: Fracture gradient *σ_v: Overburden pressure*

D: Depth of interest *Pf: Formation pressure*

This method is not suitable for soft rock formation like in parts of north sea, because in the abnormal pressure formation it predicts a higher fracture gradient while in the subnormal pressure formation is predict a lower fracture gradient[40].

Matthews and Kelly

As it was proposed by them the best use of this method in sedimentary rocks:

$$G_f = G_p + \frac{K_i \sigma}{D} \qquad (2.15)$$

Where:

Gf: Fracture gradient *Gp: Pore pressure gradient*

σ: Overburden pressure *D: Depth of interest*

Ki: Matrix stress coefficient

The result can be obtained from charts since the actual matric stress is related to the normal matrix stress[40]

Ben Eaton

This equation (method) is considered the most worldwide used in petroleum industries.

$$G_f = \left(G_o - G_p\right)\left(\frac{v}{1-v}\right) + G_p \qquad (2.16)$$

Where

Gf: Fracture gradient *Gp: Pore pressure gradient*

v: Poisson's ratio

$$\frac{\sigma_1}{\sigma_2} = \left(\frac{v}{1-v}\right) = \frac{1}{3} \qquad (2.17)$$

The Poisson's ratio can show a variation start from 0.25 to 0.5 as the field test shows, at a point in which the rock becomes plastic (stresses equal in all directions[40].

Chapter Three

Calculation and results of Case Study

3.1 Introduction:

In this study, the main objective is to get a prediction and detection of the formation pore pressure and fracture pressure in the "MYM" field.

From the data of two wells that were drilled the pore's pressure gradient and fracture pressure gradient will be detected based on the D-Exponent & Modified D-Exponent.

By known the upper and bottom limit of the pressure (pore pressure & fracture pressure), it is possible to know the range of the Mud weight that will be used in the drilling operation in the same area, this will save much time and money that will be lost if the prediction is not done, as it will be shown in this two wells (TT4, TT5)

And cost analysis was done in order to know how much money was not lost if this method was done.

3.2 Data Gathering:

The first thing to do is to get certain parameters that are needed in the equations that will be used to get to the goal.

The parameters that are needed will be taken get it from the DDR(daily drilling report) which is a report that describes the actions that happened during one day of drilling which consists of well name, field name, rig name, operation description…ect and what we are aiming to get from the DDR is :

ROP(rate of penetration)

Lithology,

Operation description

Bit diameter

Drilled depth

RPM(round per minute)

WOB(weight on bit)

Cost(daily cost for the operation)

3.3 Calculate the D-Exponent:

After we get the parameters that we need from the DDR we now start to apply them in the equation below.

- **To calculate the R(rate of penetration)** $\frac{ft}{hr}$

$$R = aN^e \left(\frac{W}{B}\right)^d \qquad (3.1)$$

Where:

R = penetration rate (ft/hr) B = bit diameter (in.)

W = WOB (lb) N = rotary speed (rpm)

d = formation drill ability e = rotary speed exponent

- **To calculate the D-Exponent:**

$$d = \frac{log\left(\frac{R}{60N}\right)}{log\left(\frac{12W}{10^6 B}\right)} \qquad (3.2)$$

- **Then we calculate the Dc-Exponent:**

We can see from the equation of (3.2) that it does not take the effect of the mud weight, which play a major part in the pressure in the bottom hole, because then when the mud weight increases the chance of the chip hold-down effect increase and as a result, the ROP will decrease

So it is just modified to include the mud weight variation which represents in the equation below

$$d_c = d\left(\frac{Mw_n}{Mw_a}\right) \qquad (3.3)$$

Where:

Mw_n = "normal mud weight"

Mw_a = "real (actual) mud weight"

After getting the Dc Exponent for different depth plot contain Dc-exponent VS Depth is done for each well shown below in Figure and Figure .2.

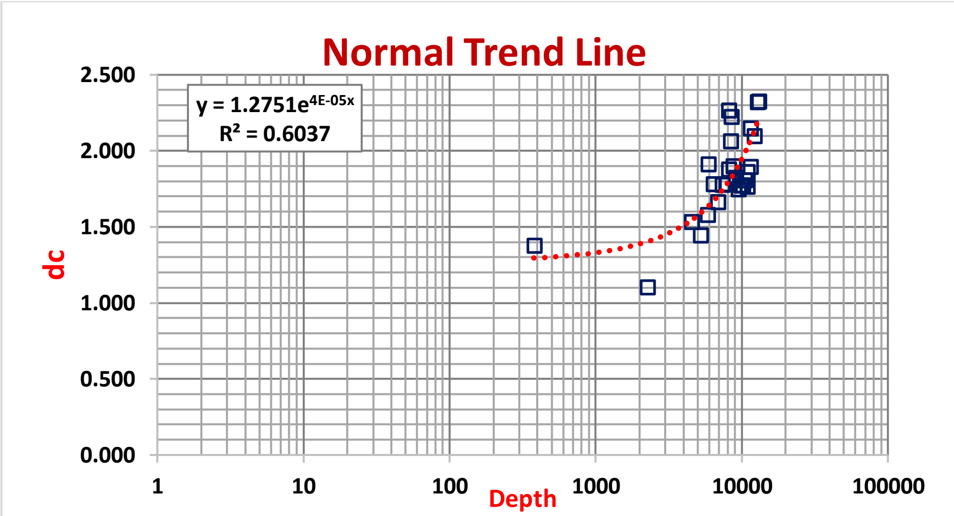


Figure 3.1 Normal trend line for well TT4

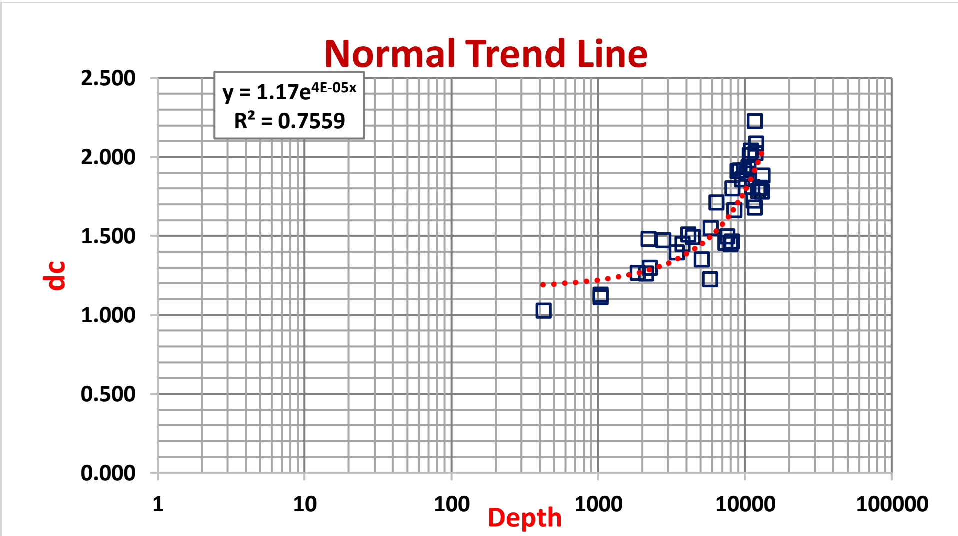


Figure 3.2 Normal trend line for well TT5

In the upper Figures, it can be noticed that the normal trend line is a curve, so the linearization must be applied.

The two plots below show the Dc-Exponent VS Depth after the linearization has been done by using regression analysis

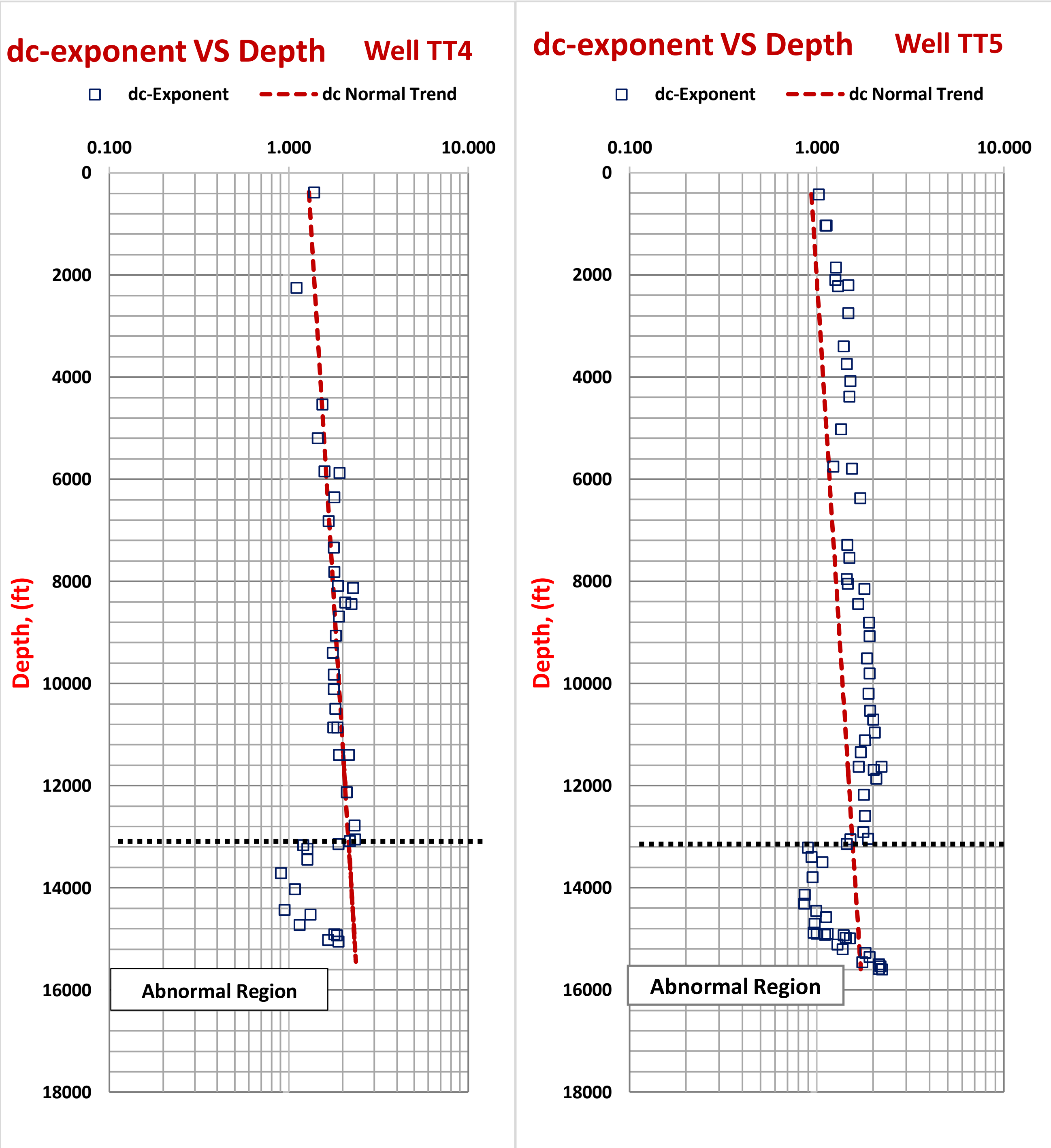


Figure 3.3 D-exponent VS Depth after linearization

From the two upper plots, it can be noticed that the abnormal region starts from about 13040 ft deep, it was possible to obtain the abnormal region by notice at which point the cross-section between the normal tren line (Dcn normal) and the one that was measured (Dco). It also can predict Hydrocarbon reservoirs in some cases.

- **Comparison between D & Dc Exponent**

the two graphs below show the difference between the D and Dc exponent **VS** Depth.

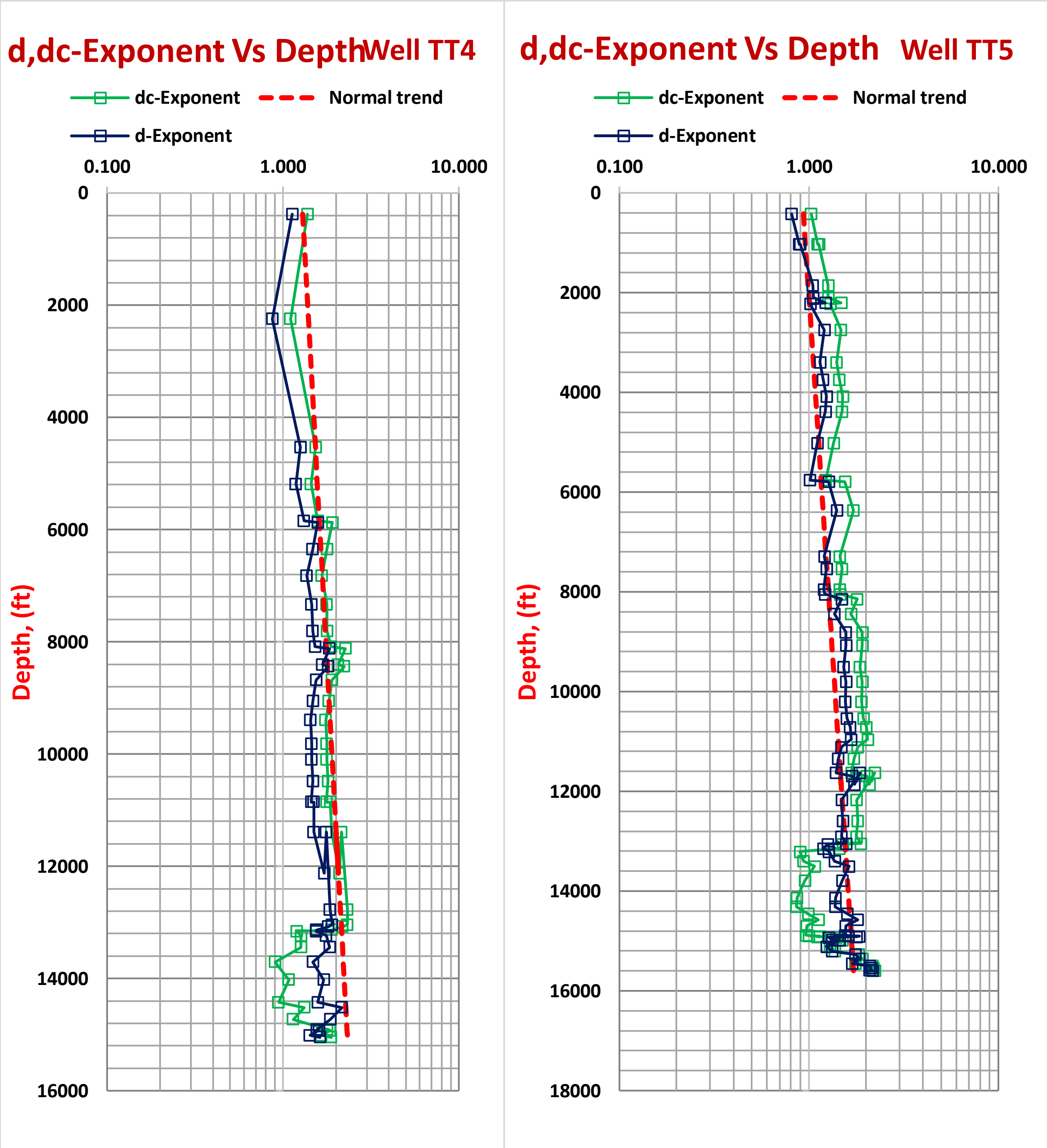


Figure 3.4 comparison between D-exponent and Dc-exponent VS depth

it can be seen that when the Dc-exponent is used, the result will be more accurate because it takes into account the mud weight changing while.

It can be noticed from the graph that when using the modified Dc-Exponent (which including the mud weight effect) the value is greater than in the case of D-Exponent, but after the abnormal pressure zone is reached its vise versa, that is mean that the Dc-Exponent is less than the D-Exponent.

3.4 Calculate the Pressure gradient:

In order to know at which Mud pressure or the range of the mud pressure, the gradient of the Pore Pressure & Fracture pressure must be known.

3.4.1Pore pressure gradient

To get the Pore pressure gradient the following equation is used:

$$\frac{P}{D}=\frac{S}{D}-\left[\frac{S}{D}-\left(\frac{P}{D}\right)_n\right]\left[\frac{dc_o}{dc_n}\right]^{1.2} \qquad (3.4)$$

Where

$\frac{S}{D}$ = *"overburden gradient"* $\left(\frac{P}{D}\right)_n$ = *Normal fluid pressure gradient*

dc_o=Dc observation at a certain depth

dc_n = Dc from the trend line (normal) at certain depth

3.4.2 Fracture pressure gradient

To get the Fracture pressure gradient the following equation is used:

$$G_f=\frac{1}{3}\frac{\sigma_v}{D}+\frac{2}{3}\frac{P_f}{D} \qquad (3.5)$$

Where

G_f: Fracture gradient σv: Overburden pressure (psi)

D: Depth of interest P_f: Formation pressure

After the pore pressure gradient and the fracture pressure, the gradient is estimated the Trip margin and the Kick margin must be included in the plot

- **The Trip margin** is an increase of drilling mud density to provide overbalance so as to compensate for the swabbing effect while pulling out of the hole.

- **The kick margin** A kick margin is subtracted from the upper-bound mud weight to overcome the pressure-increase effects caused by a surge when a trip into the hole is made.

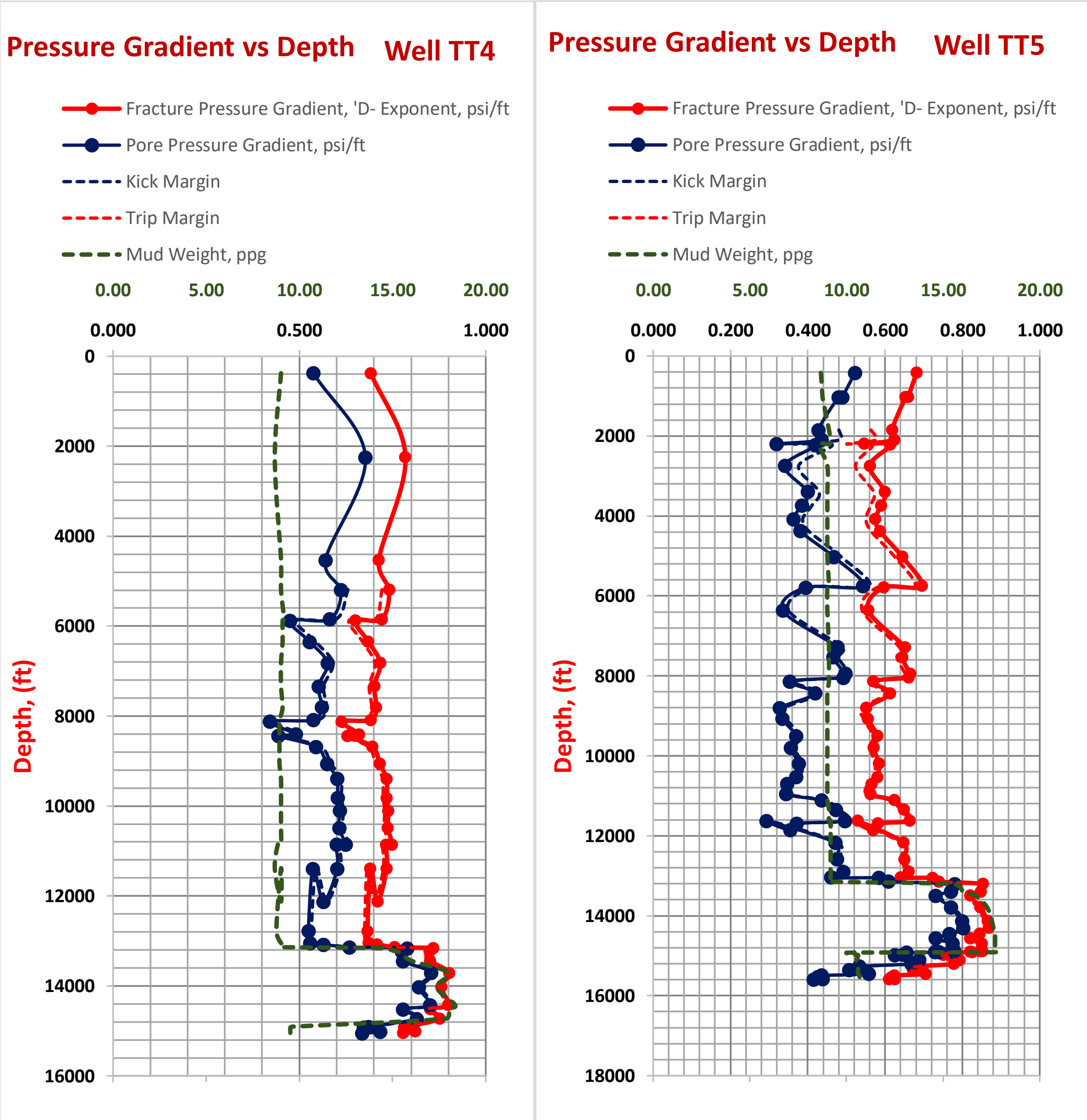


Figure 3.5 pressure gradient vs depth for two wells

The two plots before illustrating the whole drilling program from the surface until the zone of interest.

Also after getting the gradiant it's possible to plot the pressure at each depth as it's shown in the graphs below.

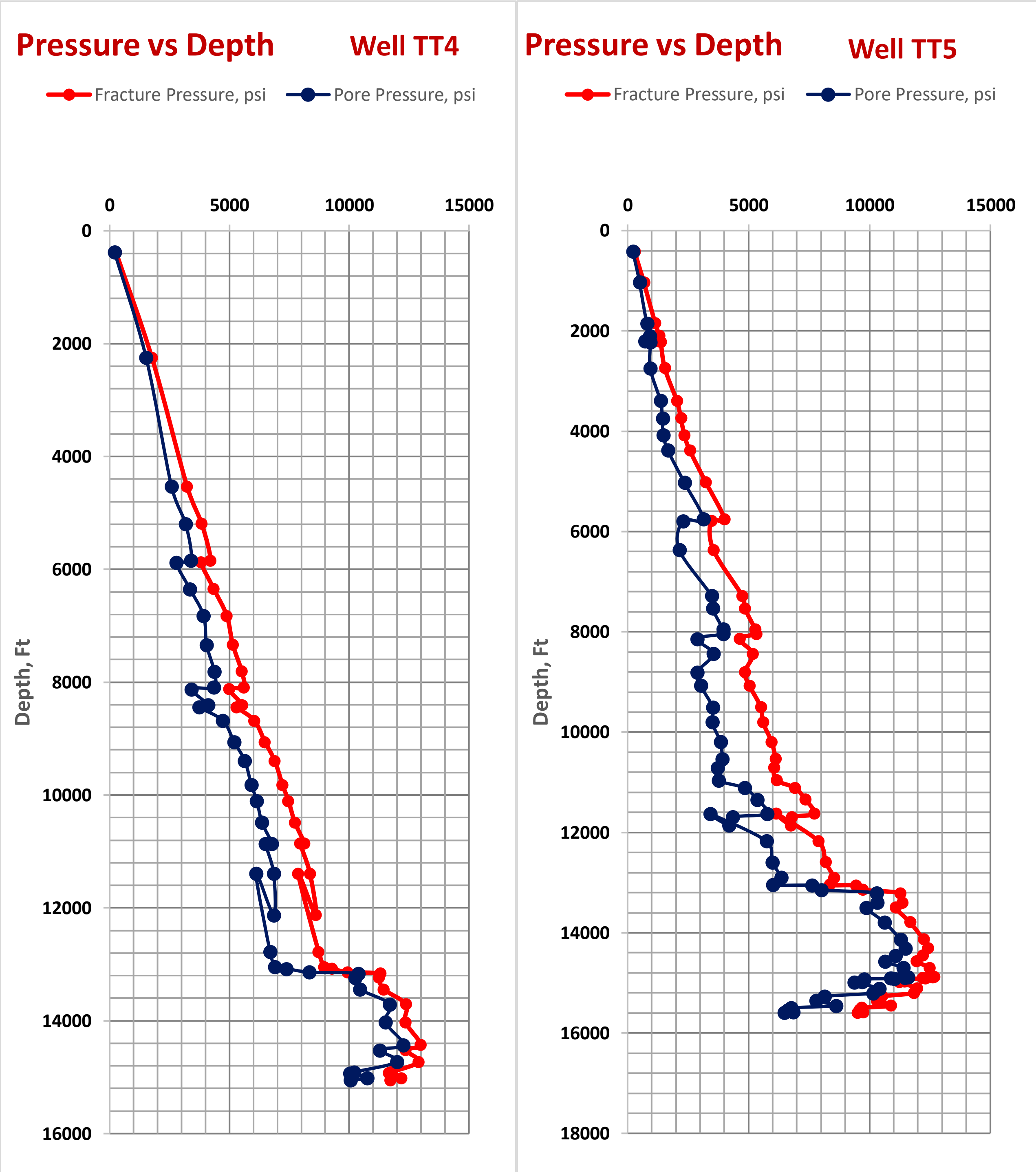


Figure 3.6 Pressure vs the depth for two wells

From the pore pressure and fracture pressure that have been obtained from wells **TT4 and TT5**. We notice the pore pressure and fracture pressure for each well are take the same trend which led to making the right decision about the proper mud weight that should be used to drill any well in the Metlaoui Group formation structure.

Table 4 the various mud type that was used

Depth	Mud Type	Mud Weight
ft		ppg
Surface - 13214	WBM	8.68 - 8.85
13214 - 15014	OBM	15.44 - 18.36
15014 - 15810	OBM	9.43 - 10.43

3.5 Economic Analysis:

The well TT5 was taken to make an economic analysis on, from the report of the DDR Figure below was obtain which shown the whole drilling program and the problems that happened.

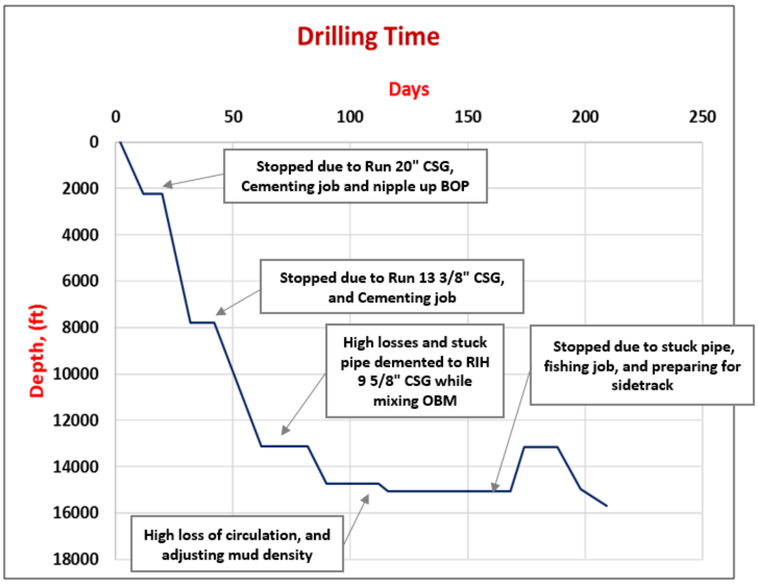


Figure 3.7 (The drilling program Time program)

The drilling operation of the well KK5 was carried out on July 20th, 2012, and was going smoothly.

At depth of 13,137 ft, a stuck pipe & high losses, RIH 9⅝ CSG, changing the drilling fluid from WBM to OBM.

At depth of 14,878 ft, partial loss and adjusting mud density from 13.7 PPG to 9.5 PPG.

At 15,048 ft, a stuck pipe led to cutting off the drill string, fishing job, plug the hole and proceed to a side track.

Based on the problems that happened during drilling and the time and money consuming during these opticals, the below chart illustrate how much money is lost.

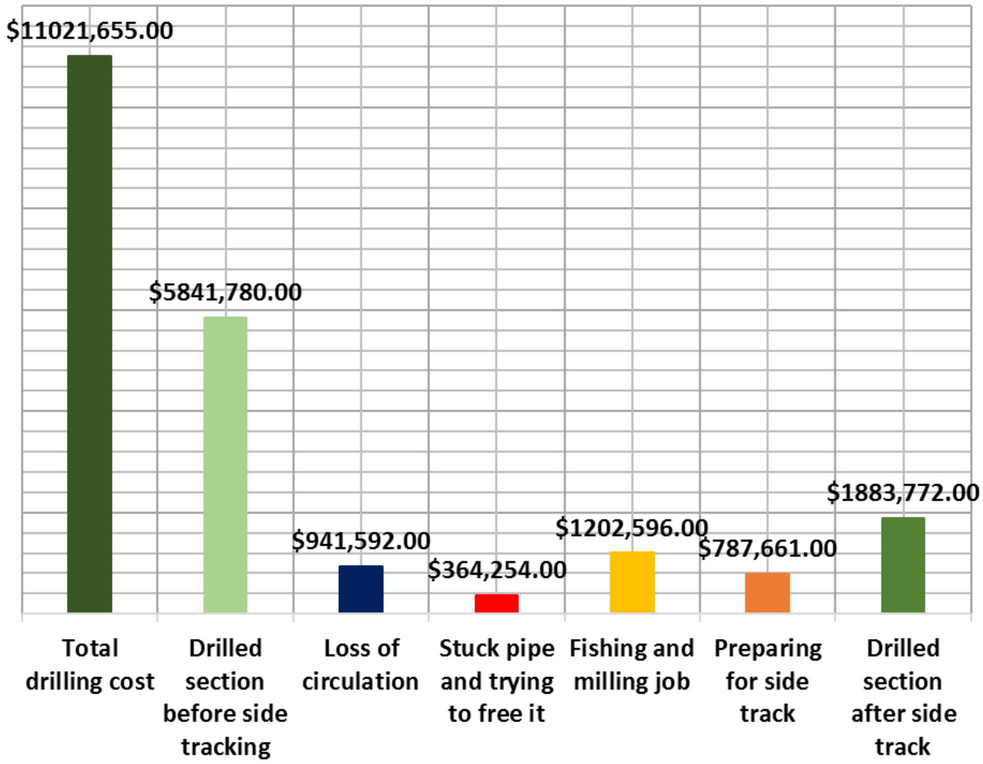


Figure 3.8 (The different costs for the Drilling program)

- We have concluded that the total drilling cost of this well was approximately **11.1 million $**.

The Wasted money is about **3.3 million $**.

Chapter Four

Conclusion and Recommendation

4.1 Conclusions

- The D-Exponent is a useful method to predict the formation of pore pressure and fracture pressure.
- The designing of the mud weight should be probably to avoid wellbore instabilities (lost circulation, stuck pipe, etc.), and for preventing wellbore instability using the oil-base mud will be more effective, if the mud-system that is been used has the mud weight as it was predicted by mechanical earth model and wellbore stability evaluation.
- The mud weight design used in drilling the KK5 well, especially in the over-pressured interval (12,818.5 ft – 15,000 ft) was insufficient to drill this section
- Using the oil-based mud while drilling without applying the adequate mud parameters is not a solution to the wellbore instability.
- Well planning should incorporate Geomechanics to reduce wellbore instability and lost circulation risks.
- Mechanical earth models are valuable for proper mud design, which helps in minimizing drilling cost and operation time, also it supports real-time decision while drilling sensitive formation.

4.2 Recommendations

- It is recommended to use well logging (Porosity Logs) to estimate the pore pressure and fracture pressure in order to make sure the results that have been obtained are valid.

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