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Borehole Stability Control

Nehad Elhemali*, Jim Somerville** and Brain Smart**

Abstract: Wellbore stability is one of the biggest challenges for drilling engineers. The main question is how to keep the wellbore stable to assure a safe drilling operation. Optimizing borehole pressure, hence the equivalent circulating density (ECD) within the limit between collapse pressure and fracture pressure is important to avoid borehole failure.

In this study, the drilling induced wellbore failure in two wells in one of the North Sea fields was examined. Four-arm caliper log was used for observation of wellbore failure where density log, sonic log and leak-off test were used to estimate elastic parameters and the magnitude of the three principal in-situ stresses. The typical problems encountered in both wells have included washout and breakout sections. Due to lack of data such as: laboratory test measurements and shear wave in one of the wells, empirical formulas were used.

An analytical model was constructed in order to optimize the mud weight requirements to drill through instable zones, and mud weight ranges were identified to minimize wellbore instability. The key parameters were imported from Excel sheet including elastic properties, in-situ stresses and rock strength.

The collapse pressure, fracture pressure and mud weight, which can be used safely while drilling, were calculated. As the appropriate mud weight range was estimated ECD has been predicted for different assumed pressure losses.

INTRODUCTION

Wellbore stability is one of the most serious problems in the oil industry. It can lead to delays in the drilling

Process, increases in drilling cost, and in some cases even to abandonment of the well[1],[2]. It is estimated that this problem costs the oil industry one billion U.S. dollars per year[3].

Wellbore instability is an important factor that should be considered while drilling and maintance of boreholes. Drilling problems frequently occur due to severe mechanical instabilities at the borehole wall where stress amplification has exceeded the strength of the rock [4]. This is because the rock surrounding the hole must support the stress previously supported by material removed in the drilling process. To prevent wellbore failure the stresses around the wellbore should be minimized.

In order to achieve a successful drilling operation, the drilling fluid pressure should be maintained to stay within a tight mud weight window defined by the pressure limits for wellbore stability [5].

Pore pressure or collapse pressure is the lower pressure limit of drilling fluid and the upper limit is the fracture pressure. If the drilling fluid pressure is less than the pore pressure then formation fluids could flow into the borehole, with the subsequent risk of a blowout [5]. An increase in drilling fluid pressure more than the upper limit pressure, there will be a risk of fracturing the formation.

The Equivalent Circulating Density (ECD)

The equivalent circulating density (ECD) is defined as the effective mud weight at a given depth created by the total hydrostatic pressure (including the cutting pressure) and dynamic pressure (hydrostatic pressure plus friction pressure)[6],[7]. ECD can be represents by the following equation:

$$ECD = \frac{P_{hyd} + \Delta P_{fric}}{D}$$

High ECD is responsible for many problems while drilling that have direct relation with wellbore pressure.

*Libyan Petroleum Institute.
** Heriot –Watt University, UK

Management of borehole pressure is a critical part in the drilling operation, in which static and dynamic fluid pressure are the main key in containing formation pressures and assuring wellbore stability. For successful drilling operation, drilling fluid should be well selected and optimized, which will affect the equivalent ECD. When circulation is established, the equivalent mud weight slowly builds up to the ECD as a result of friction pressure losses. Measurement of ECD while drilling will give an indication of possible cuttings/carvings build up in the wellbore [8].

ROCK MECHANICAL PROPERTIES AND STRENGTH

Definitions of Rock Mechanics Parameters

Stress

Stress is an applied external force on solid body that causes internal resulting forces to exist within the body whose resultant force will be equal in magnitude but opposite in direction to the applied force. A stress could be tension if it tends to elongate the subjected body or compression if it tends to contact the subjected body.

$$\sigma = \frac{F}{A}$$

Stress is measured in Pascal (N/sq.m), atm, bar, psi and/or dyne/sq.cm.

Strain

Strain is the resultant deformation of a body, as a function of its original dimension; caused by an applied force (stress).

$$Tensile\ \ strain = \frac{L_O - L}{L_O} = \frac{\Delta L}{L_O}$$

$$Shearing\,strain = \tan\phi = \phi$$

Where:

ϕ : Deformation angle.

$$Volume\ \ strain = \frac{\Delta V}{V_O}$$

Elasticity Modulus

When a body is subjected to a specific stress, it will undergo a specific strain. If the body returns to its original dimension upon removal of the stress, the action is said to be elastic. However, if upon the removal of the stress the body does not return to its original dimensions, and there is a residual strain, the action is said to be inelastic.

Poisson's Ratio

It is the ratio of the absolute value of stain in the lateral direction to the strain in the axial direction. The Poisson's ratio is defined as:

$$\upsilon = -\frac{\varepsilon_X}{\varepsilon_Z} = \frac{Lateral\ strain}{Axial\ strain}$$

Young's Modulus

A measurement of the opposition of a substance to extensional stress is determined by:

$$E = \left[2G(1+\upsilon)\right]$$

Poisson's ratio and Young's modulus are function of rock's hardness and elasticity.

Shear Modulus

The opposition of a substance to shear stresses, is determined by

$$G = C\left[\frac{\rho_b}{\left(\Delta t_s^2\right)}\right]$$

FAR FIELD STRESSES

The stresses that exist in the rock mass are related to the weight of the overburden and also to its geological history. Knowledge of the in-situ stress in rocks is important in drilling stable borehole. The magnitudes of stresses in the rock generally increase with depth. Rock stress can be divided into virgin or in-situ stress and induced stress. The in-situ stresses are existing as the rock is stable, at which the rocks are supporting each other, without any disturbance that created by induced stresses such as drilling [8].

The In-situ Principal

Stresses. Total stress components are defined vertically and horizontally. A simple linear coordinate system requires a vertical stress component ($ó_z$), and two horizontal components $ó_x$ and $ó_y$ as shown in Fig.1.

Vertical Stress $ó_v$

It is normally the maximum principal stress, and fundamentally due to the weight of overlaying rocks (overburden) and often called lithostatic stress. In geologically relaxed areas having little tectonic activity, the overburden gradient is taken as 1.0 psi/ft. In tectonically active areas, as in sedimentary basins which are still undergoing compaction or in highly faulted areas, the overburden gradient varies with depth, and an average value of 0.8 psi/ft is normally taken as representative of the overburden gradient.

For elastic solid:

$$\sigma_V = \rho g z$$

Where: ñ: is the density of the overlaying rock
g : acceleration of gravity.
z : is the depth

Horizontal Stress

This is a summation of tectonic and nontectonic stresses, the first related to plate motions and the second related to lateral expansion due to overburden load. Two mutually perpendicular horizontal stresses ($ó_H$ and $ó_h$) can be calculated, and it is therefore necessary to determine the orientations and magnitude of the two principal horizontal stresses.

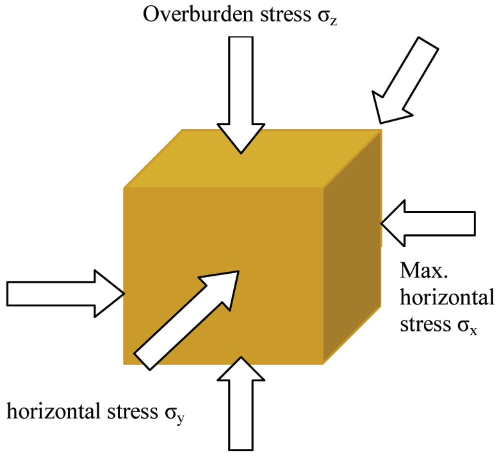


Fig. 1. The principal stresses.

Pore Pressure

Pore pressure plays a crucial role in wellbore stability exerted by the formation fluids on the walls of the rock pores. Pore pressure supports part of the weight of the overburden, while the other part is supported by the grains of the rock. The terms pore pressure; formation pressure and fluid pressure are synonymous, referring to formation pressure. Hydrostatic pressure due to weight of a column of water

$$P_p = \rho_w g z$$

FAILURE CRITERIA

Borehole walls may fail when the surrounding stress exceeds the tensile, the compressive, or the shear strengths of the rock formation, whichever is reached first. To analyse the initiation of failure, the effective stress concentration near the wellbore due to the far-field stresses and the specific borehole orientation should be taken into consideration.

Tensile Failure

Tensile failure occurs if the minimum principal stress becomes sufficiently negative; ó3d≤-To

Shear Failure

This type of failure is most often described by Mohr-Coulomb criterion:

$$\tau = S_o + \sigma \tan \phi$$

WELLBORE INSTABILITY PROBLEMS

The wellbore instability caused by imbalance between the near wellbore stresses and the rock strength can be classified into [9], [10]:

Washout

Washout while drilling can be observed from LWD calliper (Four-arm calliper) and some other states such as: excess of cuttings return to surface, excessive hole fill after tripping and an increase in mud volume. Washout occurred by either collapse of borehole due to insufficient mud weight and/or erosion of the borehole wall due to inappropriate mud chemical design.

Hole Collapse (Breakout)

Hole collapse or breakout occurs when the stress around the borehole exceeds that required to cause compressive failure of the borehole wall. Breakout can be observed from four-arm calliper log data. Breakouts are zones of spalling and fracture on opposite sides of the wellbore, which elongate it in cross section from circular to approximately elliptical.

Hole Tight

Hole tight or undergauge hole occurs when there is a reduction in the annular clearance, and this causes an increase in torque and drag, stuck pipe, an increase in swab and surge pressure and overpull.

Mud Losses

Mud losses or lost circulation caused by the initiation of hydraulic fracturing due to high mud weight which causes a tensile failure. Propagation of fracture may occur depending on the maximum pressure in the borehole.

STRESSES AROUND BOREHOLES

Before a well is drilled, the rocks are pressed by overburden and horizontal stresses as well as formation pore pressure. After the well is drilled, the drilling fluid in the borehole will provide the support for the borehole stability instead of the rock that drilled off, causing an alteration in the stress state of the rock around the wellbore [11]. When a vertical well is drilled in a formation subjected to maximum and minimum horizontal stresses, the state of local principal stresses around the borehole wall are expressed by the following equations:

$$\sigma_r = \Delta P$$

$$\sigma_\theta = \sigma_H + \sigma_h - 2(\sigma_H - \sigma_h)\cos 2\theta - 2p_p - \Delta P$$

$$\sigma_z = \sigma_v - 2\nu(\sigma_H - \sigma_h)\cos 2\theta - P_p$$

Where: ÄP: is the pressure difference between the borehole pressure and pore pressure.

When the local stresses exceeds the rock strength the rocks around borehole will undergoes failure.

WELLBORE INSTABILITY ANALYSES

Case History

Two deviated wells were drilled in the North Sea with KCl polymer mud (C64 and C80).

Well C64, the $12^1/_4$in hole was drilled smoothly with no problems at angle degree of 45^0. An $8^1/_2$ in hole drilled smoothly to 10760 ft (MD) without problems using static mud weight of 9.3ppg, at this point hole failure continued throughout drilling operation until 10880 ft (MD) causing a enlargement in the original designed borehole size.

Well C80, the well was drilled without any drilling problems until reaching a depth of 15565 ft (MD) in a hole size of $8^1/_2$ in. Another hole failure problem while drilling $8^1/_2$ in hole was encountered from 16060ft (MD).

Area Geology

Based on the formation evaluation (Gamma ray log and SP log) a general description of the lithology could be discerned. The formation interval from 10760 to 10820 ft in well C64 is characterized by dipping beds of about 32^0, and interval from 15565 ft to 15660 ft with dipping bed of about 28^0 and from 16230 ft and 16350 ft with bedding dip of 20^0 in well C80 can be described as shale or mudstone with shale beds interspersed in a few layers.

Detection of Wellbore Failure

Four-arm caliper log is the only tool used to detect the wellbore failure in both wells. Two caliper measurements (C1 and C2) were available as recorded by dipmeter tool and the caliper analysis focused on data in the shale unit above the reservoir.

Figure 2 shows that caliper reading versus depth for well C64. From the caliper data, it is clear that the borehole has undergone significant failure below 10760ft, MD (7747ft, tvd). A large washout zone is encountered in the intervals from 10760 to 10806ft, MD (7747 to 7780ft, tvd) and caliper two (C2) gives the large reading. A peak value in washout reaches up to 18.85in for caliper C2 which is almost the double of the bit size (8.5 in) and caliper C1 has a similar peak value distribution to the C2, and is generally about 16.88 in.

Below 10806 to 10824ft, MD (7780 to 7793ft, tvd) caliper one C1 has approximately constant value which is close to the bit size (8.5in) with an increase in the reading of caliper C2 to 10.65in this interval can be considered as breakout zone.

Below 10824ft, MD (7793ft, tvd) both C1 and C2 have similar values (8.6-8.8in). In this well a good breakout is hard to find because none of the two calipers are constant while the other is increased.

Figure 2 shows that the hole deviation increases along the hole from 17.7^0 to 73^0 and the hole azimth ranges from 255^0 to 340^0.

Figure 3, represents the reading of C1 and C2 for well C80, Both caliper readings show a washout zone from 15569 to 15604ft, MD (8423 to 8441ft, tvd) where the large caliper peak reading value is about 16.5in while the smaller one is 12.86in. From 15604 to 15637ft, MD (8442 to 8460ft, tvd) the calliper C1 becomes constant at 8.5in and calliper C2 reading ranges between 8.7 and 9.4in.

Below 16174ft, MD (8750ft, tvd) repeated breakout zones are encountered with a large a breakout intervals from 16246.5 to 16413.5ft, MD (8789 to 8880ft, tvd) and the tool rotated 90^0 causing caliper C1 to become larger and give a reading of 15.46 in.

From Figure 3, the hole deviation increases from 17.5^0 to 31^0 and the hole azmith ranges from 91^0 to 209^0.

CONSTRUCTION OF ANALYTICAL MODEL

In order to understand, control the wellbore instability (breakout) and mud weight window for conducting safe drilling operation, an analytical model has been derived. The key parameters for evaluating stability and those needed to construct an analytical model are the three principal in-situ stresses and rock strength parameters defining the two common failure criterions (tensile and compressional failure). Once these parameters were calculated the three principal stresses at the wellbore wall and predictions of failure can be obtained (Fig. 4).

The model is derived from conventional Leak-off test and logging (density log and, Acoustic waves) from which variables can be calculated such as: Young's moduls, Poisson's ratio, unconfined compressive strength and the in-situ stresses.

Determination of Elastic Properties

Due to the absence of laboratory data, Poisson's ratio and Young's modulus were derived using density log and acoustic velocities of compressional velocity (Vp) and shear velocity (Vs) which recorded in monople data [12]

$$\nu = \frac{v_p^2 - 2v_s^2}{2\left(v_p^2 - v_s^2\right)}$$

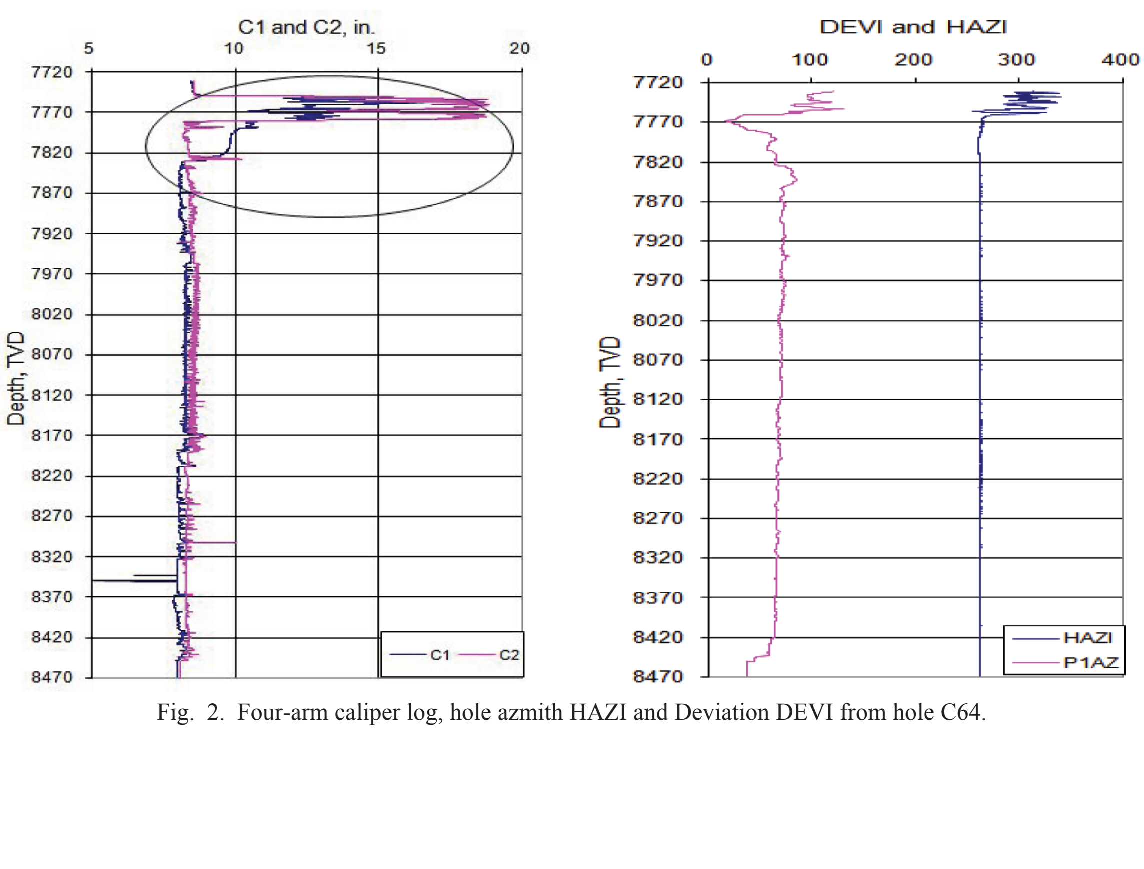


Fig. 2. Four-arm caliper log, hole azmith HAZI and Deviation DEVI from hole C64.

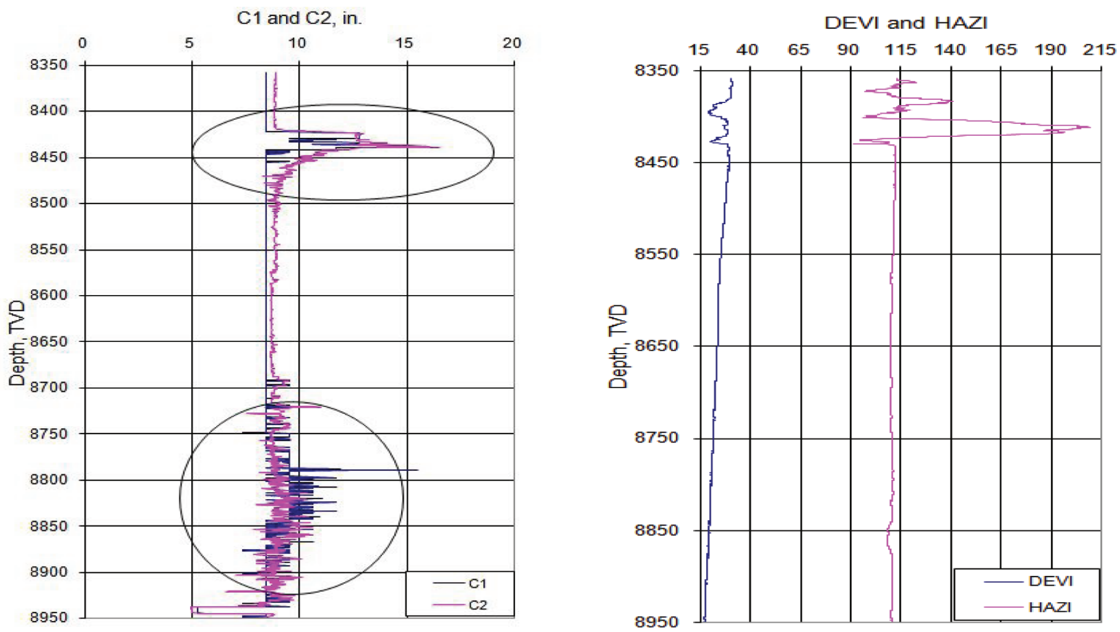


Fig. 3. Four-arm caliper log, hole azmith HAZI and Deviation DEVI for hole C80.

and

$$E = \rho v_s^2 \frac{3v_p^2 - 4v_s^2}{v_p^2 - v_s^2}$$

In well C64, only monopole sonic was used in the hole which measured the compressional velocity and there is no direct measurement of the shear waves. In order to estimate Vs in this well, two methods were tested for Vs prediction, and the result from the two methods was checked using the available Vs from well C80.

The most common method of shear velocity prediction is Castagna's relationship, which is known as mudrock equation (ARCO mudrock line) has been used[13]

$v_p =$

The second method gave a better match with the measured Vs than the Castagna's relationship and gives the same results when used to determine the elastic properties (Fig.5).

$$v_s = 0.73 v_p - 767$$

Determination of Rock Mechanics

In order to predict the wellbore stability, the mechanical properties of the rock, in particular the unconfined compressive strength (UCS) should be known. Due to the unavailability of laboratory

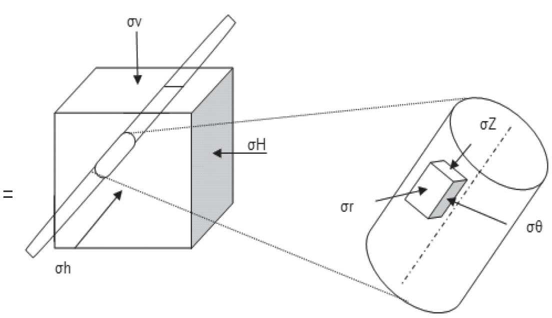


Fig. 4. Stresses acting on the wellbore.

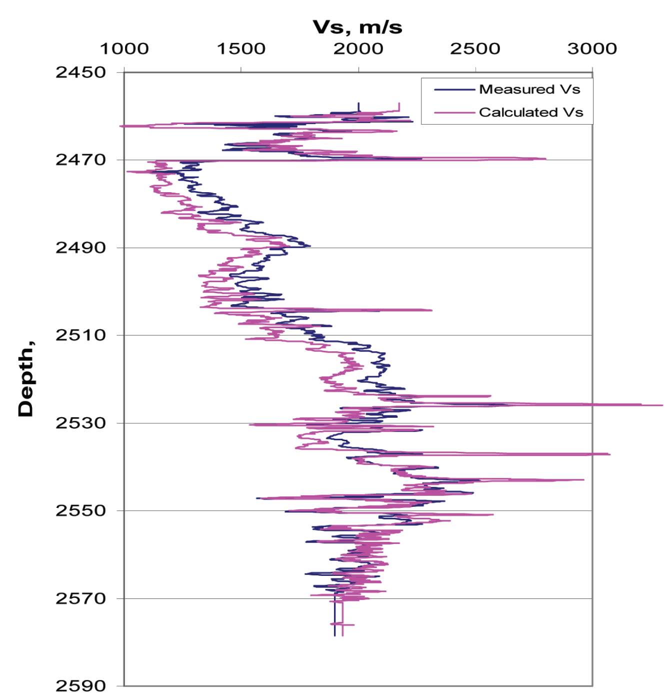


Fig. 5. The measured and calculated shear wave versus depth relationship for well C80.

measurements an alternative approach for deriving UCS is used based on well log data. The following relationship was developed in North Sea for high porosity (Ø>0.27) shale [13]:

$$UCS[MPa] = 0.286\,\phi^{-1.762}$$

Figure 6 shows the plots of bulk density, sonic transit time, calculated dynamic elastic properties and unconfining compressive strength. From these plots, the trends are strongly correlated between the rock stiffness and rock strength.

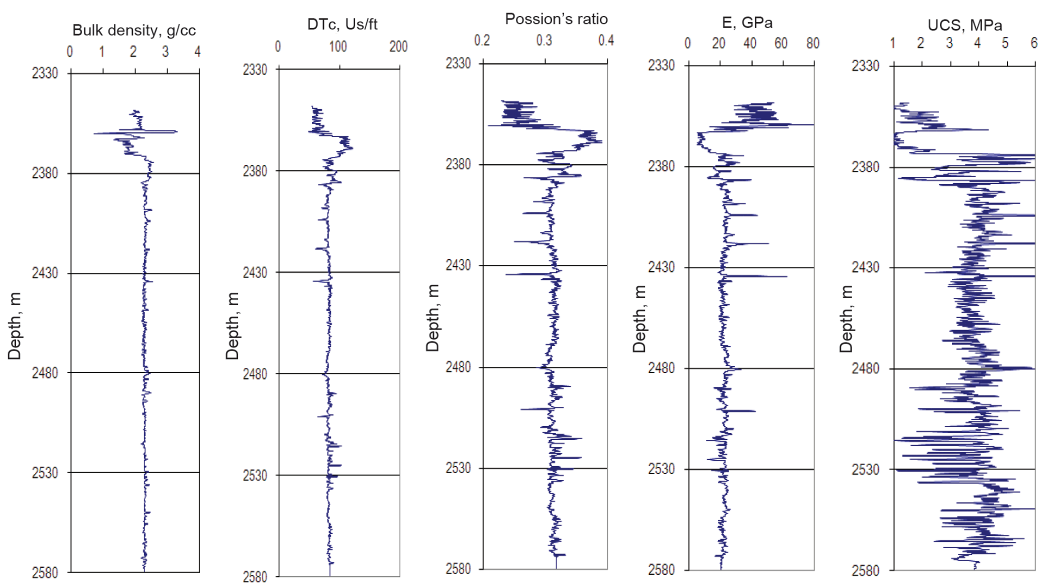
IN-SITU STRESS

Determination of Vertical Stress

Vertical stress was derived for both wells from integration of density log data taken into account the hydrostatic pressure due to water depth:

$$\sigma_v = \int \rho_b g\, D_s + \int \rho_w g\, D_w$$

A linear trend was established for the upper several meters up to the seafloor.



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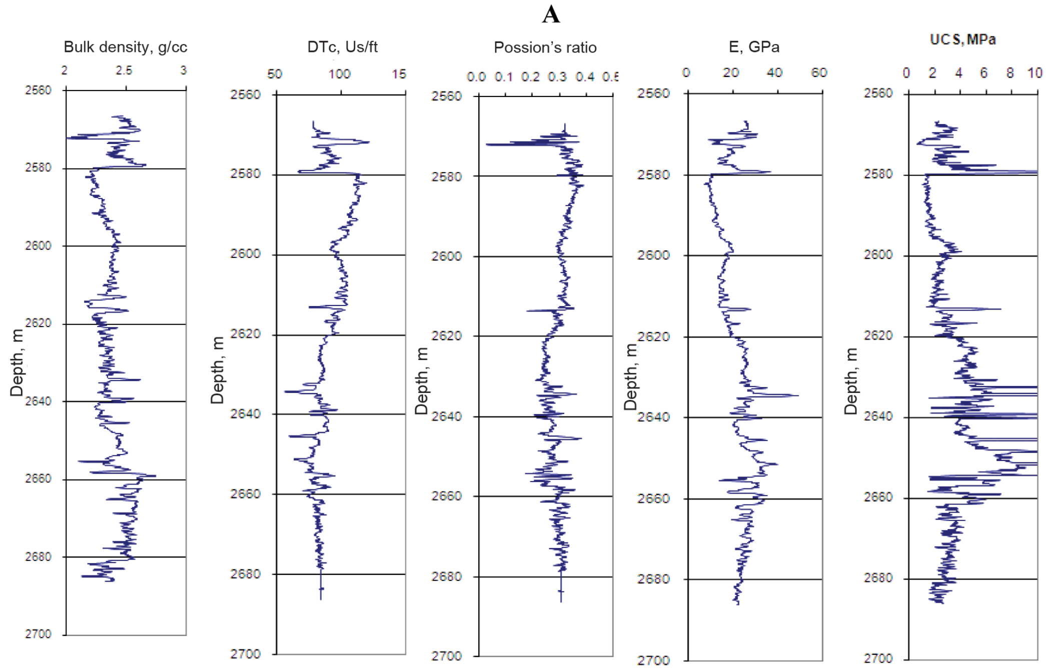

B

Fig. 6. Bulk density, transit time, calculated elastic properties and calculated UCS, A for well C64 and B for well C80.

The magnitude of Horizontal Stresses

Full LOTs and XLOTs are rarely conducted, and pressure decline following leak-off test is not universally monitored [14]. In our case there are no extended leak-off tests conducted in both wells, therefore the determination of the minimum horizontal stress in both wells was based on conventional leak-off tests.

In both wells the leak-off tests were conducted in depths above the depths of the interest. In order to overcome the lack of LOTs in the regions of interest, a linear stress gradient was assumed and the linear stress gradient to the depth of interest was extrapolated.

Determination of Minimum Horizontal Stress

The minimum horizontal stress was derived from the conventional LOTs in both wells using Leak-off pressure:

$$\sigma_h = p_{lot} + p_{hyd}$$

Determination of Maximum Horizontal Stress

With only conventional Leak-off tests available, the only method of determination of the maximum horizontal stress is to use the leak off pressure P_{lot}

$$\sigma_H = 2P_{lot} + T_o - P_p$$

The tensile strength is ignored since the rock is assumed to be as a weak rock.

DISCUSSION

In order to optimize mud weight and to predict mud weight window, some parameters such as: elastic properties, in-situ stresses, pore pressure and rock strength have to be determined.

This study is mainly based on density log, sonic log, leak-off test and four arm caliper to derive formation mechanical properties, magnitude of in situ stresses and identification of wellbore instability. No laboratory test measurements were used in this study.

The results of four arm caliper analysis show that both holes C64 and C80 undergo mechanical induced borehole enlargement and elongation. Both washout and breakout are observed in the two wells. Breakout candidate that fulfilled the breakout condition which encountered in well C64, is shown in Table 1. In well C80, four breakout candidates, where one calliper increases while the other is constant, are found in this well and these breakout sections are shown in Table 2. Since that four-arm calliper is the only tool used in this study the orientation of the maximum horizontal stress can not be made.

Figures 7 and 8 show the relationship of depth versus in-situ stresses and pore pressure data for both wells. The pore pressure gradient determined from the RFT is 0.28psi/ft for oil and 0.49psi/ft for water column. The vertical stress of each well was derived by the integration of bulk density log data taken after drilling.

In order to assess wellbore stability, the minimum and maximum horizontal principal stress should be measured. Extended leak-off test and minifrac tests are the common and more reliable tests used to constrain minimum and maximum horizontal stress. Due to the unavailability of XLOT and/or minifrac testes in this field, two conventional leak-off tests (a single test in each well) were used to constrain the least principal stress. The two leak-off tests were conducted at depths above the depth of interest. To overcome this, a linear gradient trend was assumed between the LOT and area of interest as mentioned before.

The magnitude of the maximum horizontal stress is the most difficult stress to be determined. As a result of lack of tests which are commonly used to constrain the magnitude of maximum horizontal stress, conventional leak-off tests were used by equalizing the least principal stress with the leak-off

Table 1. Summary of borehole breakout sections in well C64.

Depth, MD	Breakout depth	Hole angle
10806 to 10824, ft	2.24 in.	34°

Table 2. Summary of boeakout sections in well C80.

Depth, MD	Breakout depth, in.	Hole angle
15565 to 15568.5, ft	1.93 in.	27.7°
15585.5 to 15588, ft	4.184 in.	28.98°
15604.5 to 15637, ft	3.3 in.	29°
16246.5 to 16413.5, ft	1.1 – 9.95 in.	20.5°

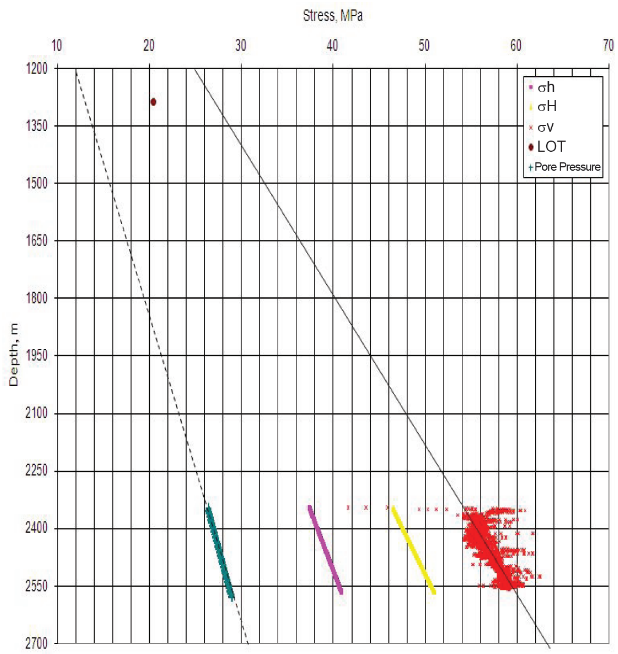

Fig. 7. Stress and pore pressure versus depth, well C64.

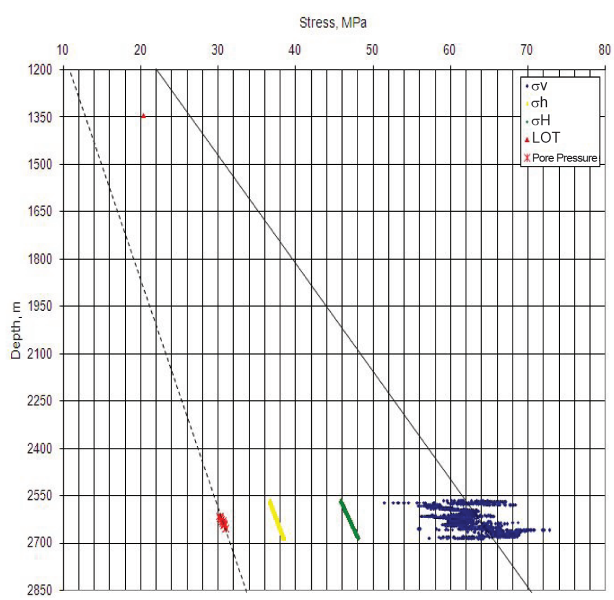

Fig. 8. Stress and pore pressure versus depth, well C80.

pressure. Tables 3 and 4 show the calculated rock mechanical parameters and Tables 5 and 6 show the stresses and pressure form both wells.

The data in these Tables such as in-situ stresses pore pressure gradients, elastic properties and rock strength are taken from the prepared Excel sheets for the depth where borehole breakout starts.

Prevention of wellbore failure requires that the stresses around the wellbore be minimized. An example of the calculations and equations for determining the borehole pressure limits and minimum and maximum mud weight for well C80 are illustrated in Appendix A.

Tables 7and 8 show the minimum, median and maximum mud weight for wells C64 and C80. These tables show that the actual mud weight used in drilling the instable zones in both wells is less than the minimum mud weight (collapse mud weight). Figures 9 and 10 display the profile of predicted minimum and maximum mud weight, the in-situ stresses and pore pressure (expressed in pound per gallon) with depth for both wells.

Table 3. Rock mechanical properties and strength for well C64.

Depth,MD	υ	E, MPa	UCS MPa	T_o	Φ, degree	β
10806 ft,MD 7780 ft, tvd	0.3	13.6	2.5	-	30	60

Table 4. Rock mechanical properties and strength for well C80.

Depth,MD	υ	E, MPa	UCS, MPa	T_o	Φ, degree	β
15565 ft,MD 8421 ft, tvd	0.3	26.1	2.4	-	30	60
15585.5 ft,MD 8432 ft, tvd	0.3	30.1	2.6	-	30	60
15604.5 ft,MD 8442 ft, tvd	0.3	24.1	3.9	-	30	60
16246.5 ft,MD 8789 ft, tvd	0.3	23.2	2.4	-	30	60

Table 5. The principal stresses and pore pressure for well C64.

Depth, MD	σ_v, MPa	σ_H,MPa	σ_h, MPa	Pore pressure gradient, psi/ft
10806 ft,MD 7780 ft, tvd	53.9	46.7	37.6	0.49

Table 6. The principal stresses and pore pressure for well C80.

Depth, MD	σ_v, MPa	σ_H, MPa	σ_h,MPa	Pore pressure gradient, psi/ft
15565 ft,MD 8421 ft, tvd	61.6	45.8	36.7	0.49
15585.5 ft 8432 ft, tvd	66.4	45.9	36.8	0.49
15604.5 ft 8442 ft,tvd	66.9	46	36.8	0.49
16246.5 ft 8789 ft, tvd	65.5	48	38.4	0.49

Table 7. Predicted and actual mud weight for well C64.

Depth	Min. mud weight, ppg	Max. mud weight, ppg	Median mud weight, ppg	Actual mud weight, ppg
10806 ft, MD 7780 ft, tvd	11.97	14.2	12.6	9.3

Table 8. Predicted and actual mud weight for well C80.

Depth, TVD	Min. mud weight, ppg	Max. mud weight, ppg	Median mud weight, ppg	Actual mud weight, ppg
15565ft, MD 8421 ft, tvd	11.06	11.88	11.47	9.3
16246.5ft, MD 8432 ft,tvd	11.09	11.94	11.5	9.3

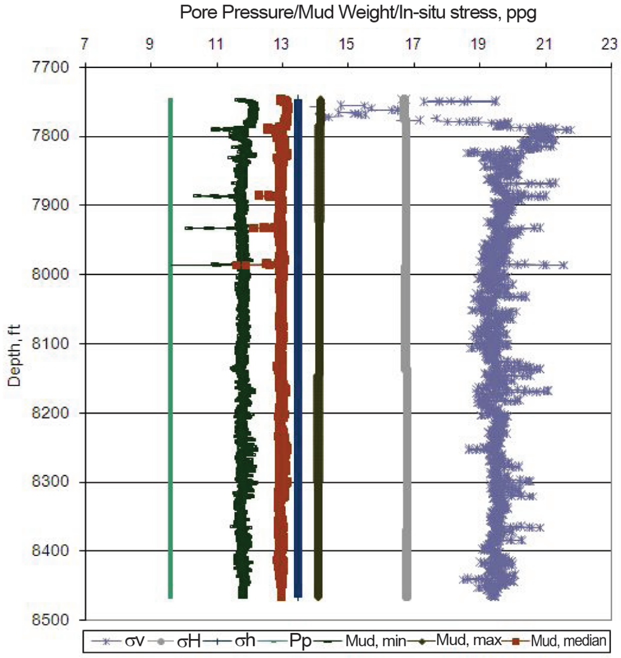

Fig. 9. Mud weight and in-situ profile, C64.

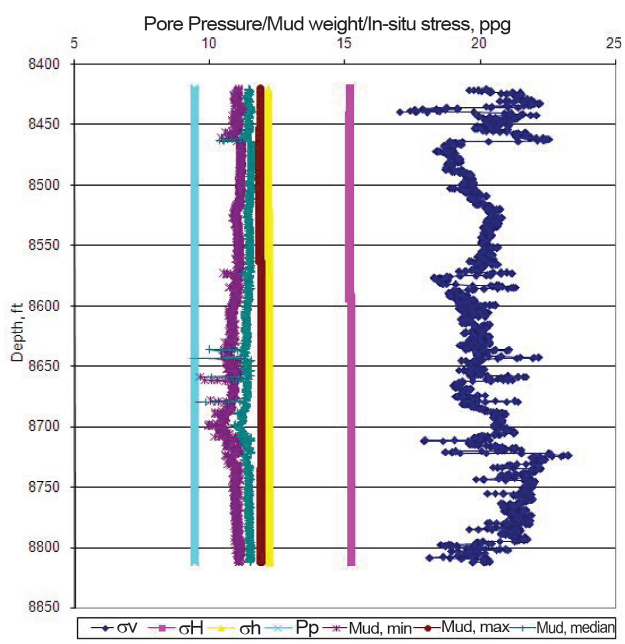

Fig. 10. Mud weight and in-situ profile, C80.

As the drilling operation proceeds, the static mud weight will increase (ECD) as a result of friction pressure which will cause an increase in the borehole pressure (Tables 9 and 10). In order to predict the increase of mud weight while drilling (ECD) different pressure losses are assumed, 200, 300, and 500psi. No ECD measurements are available for both wells to compare with the calculated ECD.

The local stresses around the well bore $ó_{è}$, $ó_{z}$ and $ó_{r}$ have been calculated and Tables 11 and 12 show the results at which $ó_{è}>ó_{z}>ó_{r}$ for well C64 and C80, respectively.

Table 9. Predicted equivalent circulating density for well C64.

Depth	Mud weight, ppg	ECD, ppg		
		200 psi	300 psi	500 psi
10806 ft, MD 7780 ft, tvd	11.09 (min.)	11.58	11.8	12.3
10806 ft, MD 7780 ft, tvd	12.6 (median)	13.09	13.34	13.8

Table 10. Predicted equivalent circulating density for well C80.

Depth	Mud weight, ppg	ECD, ppg		
		200 psi	300 psi	500psi
15565ft, MD 8421 ft, tvd	11.06 (min.)	11.52	11.76	12.2
16246.5ft, MD 8432 ft, tvd	11.09 (min)	11.55	11.77	12.23
15565ft, MD 8421 ft, tvd	11.47 (median)	11.9	12.2	12.6
16246.5ft, MD 8432 ft, tvd	11.5 (median)	11.96	12.18	12.64

Table 11. The local stresses around the borehole, well C64.

Depth	σ_θ, MPa	σ_z,MPa	σ_r, MPa
10806 ft, MD 7780 ft , tvd	68.24	40.6	33.3

Table 12. The local stresses around the borehole, well C80.

Depth	σ_θ, MPa	σ_z, MPa	σ_r, MPa
15565 ft, MD 8421 ft, tvd	80.41	41.89	33.33
16246.5ft,MD 8432 ft, tvd	86.95	43.42	34.9

CONCLUSIONS

1) Formations of breakout and washout are successfully observed using four arm caliper log data.

2) The key parameters (in-situ stresses and formation material properties) for model construction were derived using density log, sonic log and leak-off tests.

3) Due to the lack of laboratory measurements, impirical relationships where used to derive the unconfined compressive strength.

4) The mud weight window (minimum and maximum mud weight) has been calculated in order to keep the borehole pressure within this window to assure successful drilling operation.

5) The minimum mud weight predicted is higher than the actual mud weight used in drilling through the instable zones for both holes.

6) Minimum and maximum equivalent circulating densities (ECD which represent the borehole pressure

and pressure losses) have been calculated using different assumed pressure losses in both holes.

NOMENCLATURE

ECD: equivalent circulating density.
P_{hyd}: hydrostatic pressure.
ΔP_{fric}: frictional pressure losses.
D: depth
F: applied force.
A: cross sectional area.
Lo: original length.
L: elongated length.
ΔL: the longitudinal strain.
ΔV: change in volume.
Vo: original volume.
εx: lateral strain.
εz: axial strain.
E: Young's modulus.
ν: Poisson's ratio.
G: Shear modulus.
ρ_b: bulk density.
Δts: Shear wave transit time.
ε: strain.
σx,σy,σz : Stress tensor as function of location (x,y and z).
σv: vertical stress.
σ_h: minimum horizontal stress.
σ_H: maximum horizontal stress.
g: acceleration of gravity.
P_p: pore pressure.
α: Biot constant.
K_m: rock matrix compressibility.
K_b: bulk rock compressibility.
To: tensile rock strength.
τ: shear stress.
τ: normal stress.
So: Cohesion.
φ: friction angle.
LWD: logging while drilling.
UCS: unconfined compressive strength.
σr: radial stress.
σ_θ: tangential stress.
σz: vertical stress.
θ: azmith angle with respect to minimum horizontal stress.
KCl: Sodium Chloride.
MD: measured depth.
tvd: true vertical depth.
m: meter.
ft: feet.
in.: inch.
C1: caliper one.
C2: caliper two.
V_p: compressional wave.
V_s: shear wave.
Ø: porosity.
ρ_w: sea water density.
D_w: sea water depth.
LOT: leak-off test.
XLOT: extended leak-off test.
Plot: leak-off pressure.
FIT: formation integrity test.
RFT: repeat formation test.
P_w: borehole pressure.
Co: unconfined Compressive Strength, UCS.
P_f: fluid pressure.

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Appendix A

Borehole failure in well C80 (15565 to 15637 ft) MD, (8421 to 8460ft) tvd

The maximum stress is greater than minimum stress: $\sigma_H > \sigma_h$

In case of: $\sigma_\theta > \sigma_z > \sigma_r$

The minimum borehole pressure that failure may occur

$$p_{w,\min} = \frac{2\sigma_h - C_o + P_f(\tan^2\beta - 1)}{\tan^2\beta + 1}$$

$$p_{w,\min} = \frac{2*36.7 - 2.4 + 28(0.89)}{3}$$

$$p_{w,\min} = 33.19MPa$$

To examine the solution the local around the wellbore can be determined as following:

$$\sigma_r = p_w$$

$$\sigma_r = 33.19MPa$$

$$\sigma_\theta = \sigma_h + \sigma_v - 2\cos 2\theta(\sigma_v - \sigma_h) - p_w$$

$\sigma_\theta > \sigma_z e > \sigma_r$

$$\sigma_\theta = 80.41MPa$$

$$\sigma_z = \sigma_h - 2v\cos 2\theta(\sigma_v - \sigma_h)$$

$$\sigma_z = 41.89MPa$$

The minimum mud weight can be calculated as follows:

$$\rho_{\max} = \frac{33.19MPa}{9.8\, {}^{m}\!/\!{}_{s^2} * 2567m} = 1.32\, {}^{gm}\!/\!{}_{cc} = 11ppg$$

The maximum borehole pressure and mud weight for impermeable formation:
The maximum borehole pressure for initiating hydraulic fracture in the wellbore wall:

$$p_{w,\max} = 3\sigma_h - \sigma_H - P_p$$

$$p_{w,\max} = 3*36.7 - 45.8 - 28 = 36.3MPa$$

The maximum mud weight from impermeable formation:

$$\rho_{\max} \frac{36.3MPa}{9.8\ {}^{m}\!/_{s^2} * 2567m} = 2.05\ {}^{gm}\!/_{cc} = 12.04\,ppg$$

Borehole failure in well C80 (16246.5 to 16370 ft) MD, (8764 to 8856ft) tvd

In case of: $\sigma_\theta > \sigma_z > \sigma_r$

$$p_{w,\min} = \frac{2\sigma_h - C_o + P_f(\tan^2\beta - 1)}{\tan^2\beta + 1}$$

$$p_{w,\min} = \frac{2*38.4 - 3.9 + 29.6(0.89)}{3}$$

$$P_{W,\min} = 34.34MPa$$

$$\rho_{\min} = \frac{34.34MPa}{9.8\ {}^{m}\!/_{s^2} * 2679} = 1.31\,gm/cc = 10.9\,ppg$$

The maximum borehole pressure:

$$p_{w,\max} = 3\sigma_h - \sigma_H - P_f$$

$$p_{w,\max} = 3*38.9 - 48 - 28 = 39.2MPa$$

$$\rho_{\min} = \frac{39.2MPa}{9.8\ {}^{m}\!/_{s^2} * 2679} = 1{,}49\,gm/cc = 12.45\,ppg$$