Journal of Science and Technology Research

Journal homepage: www.nipesjournals.org.ng

Influence of In-Situ Stresses on Wellbore Trajectory and Stability

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Article Info

***Keywords*:**
Wellbore, stress, Stability, Mud, Pressure, drilling

Received 01 August 2021
Revised 17 August 2021
Accepted 24 August 2021
Available online 31 August 2021

https://doi.org/10.37933/nipes/3.3.2021.19

https://nipesjournals.org.ng

Abstract

Wellbore stability is of critical importance in the success of drilling operations. One of the main goals of any drilling operation is to drill the well as cost-effective as possible. During drilling, there are two major instability problems namely, borehole collapse and fracture. The consequences of these drilling problems are severe, they can lead to serious non-productive time and loss of huge amounts of money. Wellbore instability has become an increasing concern for horizontal and extended reach wells, open hole lateral section, and in some cases, open hole build-up section through shale cap rocks. More recent drilling innovation such as underbalanced drilling techniques, high pressure jet drilling, re-entry horizontal wells and multiple laterals from a single vertical or horizontal well often gives rise to challenging wellbore stability questions. In this paper, a geomechanical software "Optiwell" was utilized to perform stability analyses and calculations for different inclinations and azimuths. Results obtained showed that wellbore stability is a function of several factors such as inclination and azimuth, in-situ stresses, mud weight, rock strength parameters, etc. Some of these factors are controllable, while some are not. It was established that stability problems can be significantly reduced by appropriately varying these parameters. Knowledge of the in-situ stress state in a field is a prerequisite for varying these parameters, and hence, a very essential component for well design.

1.0. Introduction

Well bore trajectory planning plays an important role in the development and optimization of any petroleum field. The placement of a well bore may not only influence the amount of hydrocarbons contacted, but will also influence the ease at which a well is drilled [1,2], its long-term integrity [2] and affect hydraulic fracture stimulations [3]. With the advent of new drilling techniques, the enhanced accuracy during the drilling process and the ability to drill various types and shapes of wells, a demand of the understanding of well bore trajectory planning has resulted [4,5,]. Stable well bore conditions with respect to mechanical failure are a function of the geometrical trajectory within the 3D state of stress [1]. Well bore stability can be predicted by determining safe mud pressures preventing either borehole breakdown or collapse [1,2,4,5,6,7,8,]. Thus, a thorough knowledge of the in-situ stresses in the subsurface and how they change during the life of a petroleum field is a crucial input parameter for planning stable wellbores. Figure 1 shows the well bore stresses after drilling. The black arrows signify the in-situ stresses, while the red arrows signify the induced stresses. These are described as radial stress, tangential stress (circumferential or hoop stress) and axial stress. The radial stress acts in all directions perpendicular to the wellbore wall, the tangential stress circles the wellbore and the axial stress acts parallel to the well bore axis [9].

The local stress distribution around a well bore is controlled by mechanical, chemical, thermal, and hydraulic effects.

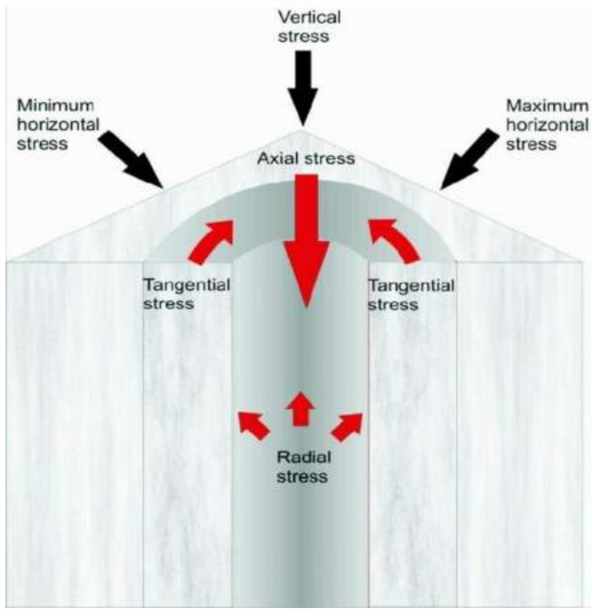

Figure1: Wellborestresses

The in-situ stress regime in a field is defined by the magnitude and orientation of the three principal stresses (σ_1, $\sigma_2$and σ_3) in terms of σ_V, σ_H, σ_h. Where,

Σ_V is the vertical principal stress, $\sigma_H$is the maximum horizontal stress, $\sigma_h$is the minimum horizontal stress.

The magnitudes of the vertical and horizontal principal stresses have no specified order such that σ_V may vary from larger than σ_H to smaller than σ_h depending on the faulting regime currently active in a region.

The relative magnitudes of the greatest, intermediate and least principal stress at depth (σ_1, σ_2 and σ_3) in terms of σ_V, σ_H, $\sigma_h$was originally proposed by Simangunsong et al. [10] and is illustrated in Figure 2 and Table 1.

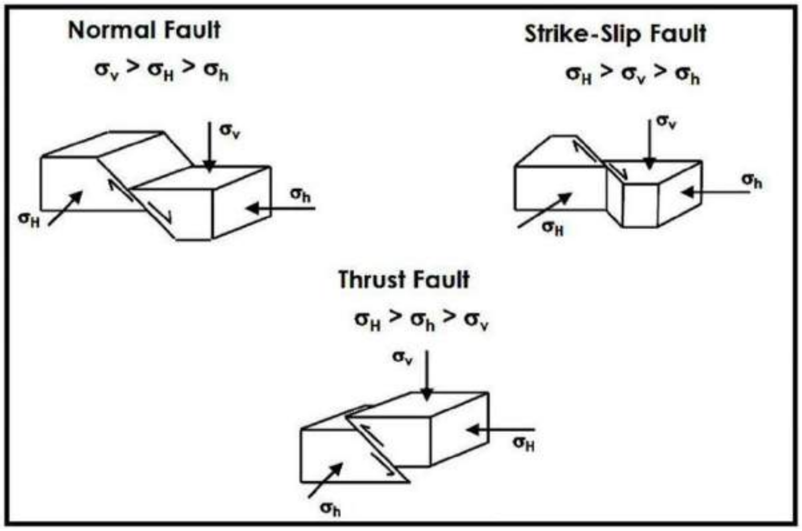

Figure2: Fault classification [Source: [10]

Table 1: Relative stress magnitudes and faulting regimes

Fault regime	**σ1**	**σ2**	**σ3**
Normal	σv	σH	σh
Strike-slip	σH	σv	σh
Reverse/Thrust	σH	σh	σv

Many well bore instability problems, such as well bore collapse and lost circulation, occur in laminated and naturally fractured shales. These instability problems often lead to difficulty with hole cleaning, tripping, logging, and casing running, resulting in significant non productive time and increased costs. Lack of well bore stability brings a reduction in the quality of well log records and consequently leads to difficulties in their interpretation. It also causes mechanical problems such as stuck pipes, high torque and back-reaming, instigating further dangers when setting the casing and removing cuttings.

Furthermore, recent drilling innovation such as underbalanced drilling techniques, high pressure jet drilling, re-entry horizontal wells and multiple laterals from a single vertical or horizontal well often gives rise to challenging wellbore stability questions. In this work, we will identify and examine the effects of the parameters that affect the integrity of a well, and examine the effects of in-situ stresses (magnitude and orientation ofthe3 principal stresses) on well bore stability to optimize well trajectory design for safe drilling and finally examine the effects of inclination and azimuth on well bore stability with respect to in- situ stress state.

2. Methodology

The method adopted to achieve the objectives of this project is an analytical method which involved the use of a geomechanical software called **Optiwell**. Optiwell can predict important features that affect the stability of a well in order to compute accurately the safe operating mud weight window required to keep the well stable. It can perform many kinds of sensitivity analyses which yield different results on varying the input parameters. In this project work, some sensitivity analyses were done for 2 wells from the Niger delta, the results obtained shows how the in-situ stresses influence the stability of the wells.

The sensitivity analyses carried out in this work include:

1. Mud weight tracker to indicate whether stresses deviate from normal conditions.
2. Determination of optimum mud weight window for safe drilling.
3. Effect of inclination on borehole stability with respect to differences in magnitude and orientation of in-situ stresses.
4. Variation of stress magnitude with depth.
5. Failure function plot.

There are various geomechanical software that can perform the above listed sensitivity analyses, but the reason why Optiwell was utilized in this project is because of the principle on which it is based. The failure criterion in which a well bore stability software is based on is very crucial to the collapse pressure predictions made by the software. Most of the geomechanical software that can run these analyses are based on the Mohr-Coulomb failure criterion, but Optiwell is based on the Mogi-Coulomb failure criterion.

The Mohr-Coulomb failure criterion assumes that the intermediate principal stress has no effect on failure, it only considers the strengthening effects of the maximum and minimum principal stresses. But from literature, it has been proven by some authors that the strengthening effect of the intermediate principal stress cannot be ignored in estimating borehole collapse risk under strong anisotropic in–situ stress state. Hence, the Mohr-Coulomb failure criterion is too conservative in its predictions, and hence, reduces the safe operating mud weight window required to keep a well bore stable. On the other hand, the Mogi-Coulomb failure criterion considers the strengthening effects of all three principal stresses, and hence, predicts a better safe operatingmud weight window than the Mohr-Coulomb failure criterion.

3. Results and Discussion

To study the effects of in-situ stresses (magnitude and orientation) on wellbore stability, two wells which experienced serious instability issues at the time they were drilled were analyzed. Some sensitivity analyses were done with Optiwell to observe the causes and severity of instability for these wells. Methods that could be adopted to significantly minimize and solve the instability issues were also shown. The results from the sensitivity analyses and their interpretations presented in the following subsection.

3.1. WELL XX006, OJERO FIELDXX

The input data for well XX 006 are given in the Table 2.

Table 2: Input data for well XX 006

Depth (ft)	Collapse gradient (psi/ft)	Optimum mud weight (ppg)	Optimal stress direction (degree)	Maximum principal stress, σ1 (psi)	Intermediate principal stress, σ2 (psi)	Minimum principal stress, σ3 (psi)
7640	0.52	10.10	45° N/E	7181.60	6876.00	5730.00
7758	0.53	10.12	45° N/E	7292.52	6982.20	5818.50
7860	0.53	10.12	45° N/E	7388.40	7074.00	5895.00
7934	0.53	10.12	45° N/E	7457.96	7140.00	5950.50
8013	0.53	10.14	45° N/E	7532.22	7211.70	6009.75
8137	0.53	10.14	45° N/E	7648.78	7323.30	6102.75
8273	0.53	10.25	45° N/E	7776.62	7445.70	6204.75
8304	0.54	10.71	45° N/E	7805.76	7473.60	6228.00
8461	0.54	10.80	45° N/E	7953.34	7776.90	6345.75
8564	0.54	10.87	45° N/E	8029.48	7707.60	6423.00
8642	0.54	10.96	45° N/E	8123.48	7777.80	6481.50

3.1.1 Mud weight tracker

The Figure 3 shows a mud weight tracker for well ojero 006. The mud weight tracker plot is usually the first analysis carried out by a geomechanist. It is basically designed to give an insight in the ability of the stresses to deviate from normal stress conditions. It shows the pressure variations and indicators which explain the level of consistency between the overburden, fracture pressure, pore pressure and the optimum mud weight for each well. The result for this well is consistent with the normal stress condition as reported by [10] where overburden> fracture pressure > mud weight pressure > pore pressure.

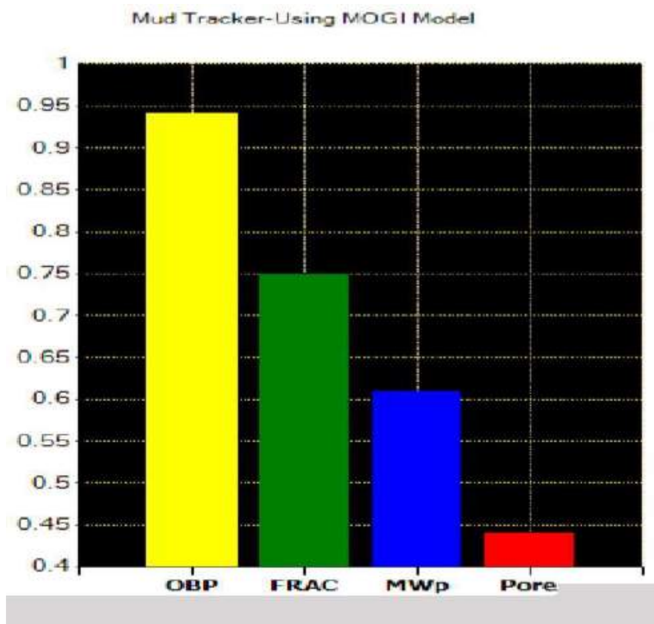

Figure 3: Mud weight tracker plot for well ojero 006

3.1.2 Sensitivity for optimum mud weight

The Figure 4 shows the optimum mud weight window for safe drilling for well ojero 006.

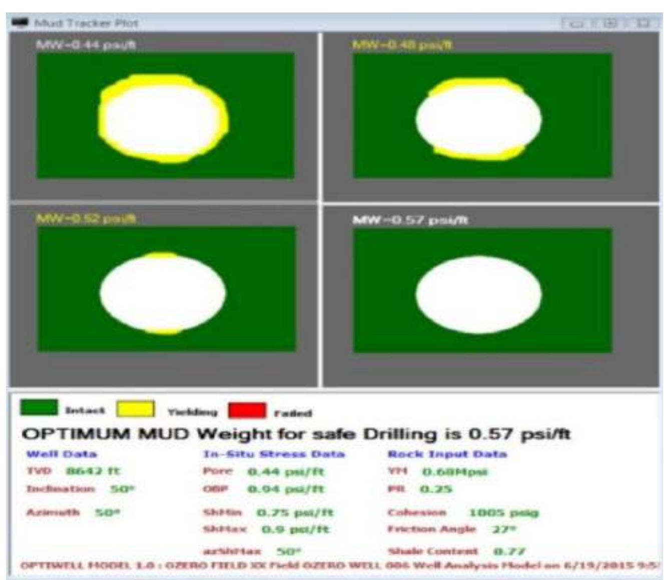

Figure 4: Mud weight window for well ojero 006

The mud weight window used while drilling well ojero 006 (where instability issues persisted) as well as adjustments that could be made to the mud weight to achieve a stable well bore to ensure success while drilling the well.
The well was initially very unstable as a result of non-sensitivity to the effect of inclination and optimum mud weight on its stability. The rose envelopes show the effects of mud weight on the stability of the well from 0.44 psi/ft where breakouts were seen through to 0.57 psi/ft where stability was attained. The yellow portion around the plan of the borehole on the rose envelopes depicts how the wellbore was yielding (breakouts)and it is seen that with increasing mud weight, the yielding effects significantly decreases and on attaining the optimum mud weight, the wellbore becomes entirely stable. This implies that for stability to be achieved, the rose envelopes must be entirely white with green colouration around it [9]. Red colouration signifies failure (collapse or fracture).
Hence, breakouts will be experienced while drilling well ojero 006 until a well-defined envelope is identified to mitigate instability issues as shown in the Figure 4 and Table 3. For this well to be stable for easy Pull Out Of Hole(POOH), running of casing and allowable completion strategy, the mud weight required is 0.57 psi/ft this is as reported by Yang et al. [7].

Table 3: Mudweight design criteria for well Ojero 006

True vertical depth (ft)	Collapse gradient (psi/ft)	Mudweight (psi/ft)	Stress direction (degree)
0-4000	0.45-0.50	0.46-0.51	45° N/E
4000-6811	0.50-0.52	0.51-0.54	45° N/E
6811-8642	0.52-0.54	0.54-0.57	45° N/E

3.1.3 Effect of inclination on well bore stability with respect to optimum mud weight

The Figure 5 shows the effect of inclination on the stability of well ojero 006 with respect to optimum mud weight.
The plot shows the optimum mud weight for safe drilling corresponding to any given inclination for the well path. This implies that in order to have an entirely stable well, the optimum mud weight corresponding to any inclination from the plot must be used while drilling.
The well was drilled at an inclination of 50° and from the plot shown in Figure 5, the optimum mud weight corresponding to 50° inclination is 10.96 ppg. It was previously shown from the sensitivity analysis for optimum mud weight that the optimum mud weight for this well at that same depth was 0.57 psi/ft which is equivalent to10.96 ppg. This further supports the result from the analysis of the optimum mud weight for this well. Hence, the initial mud weights could not have supported the well bore against instability but the recently simulated mud weight of 0.57 psi/ft will

keep the hole stable, devoid of all weak planes associated with stress orientation.

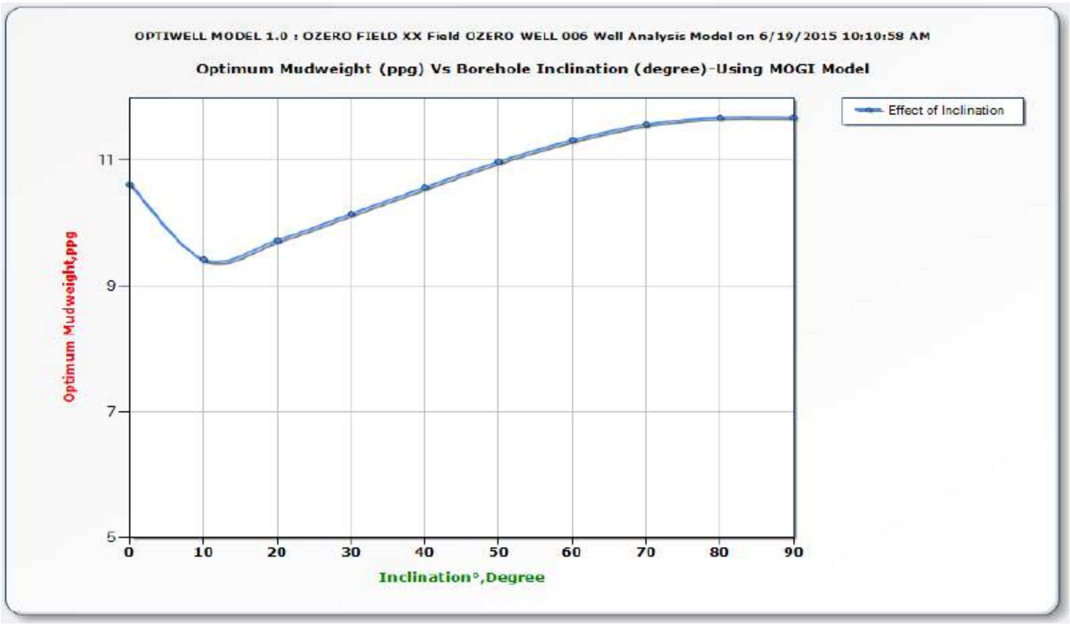

Figure5: Plot of optimum mud weight vs inclination for well ojero 006

3.1.4 Variation of stress magnitude with depth

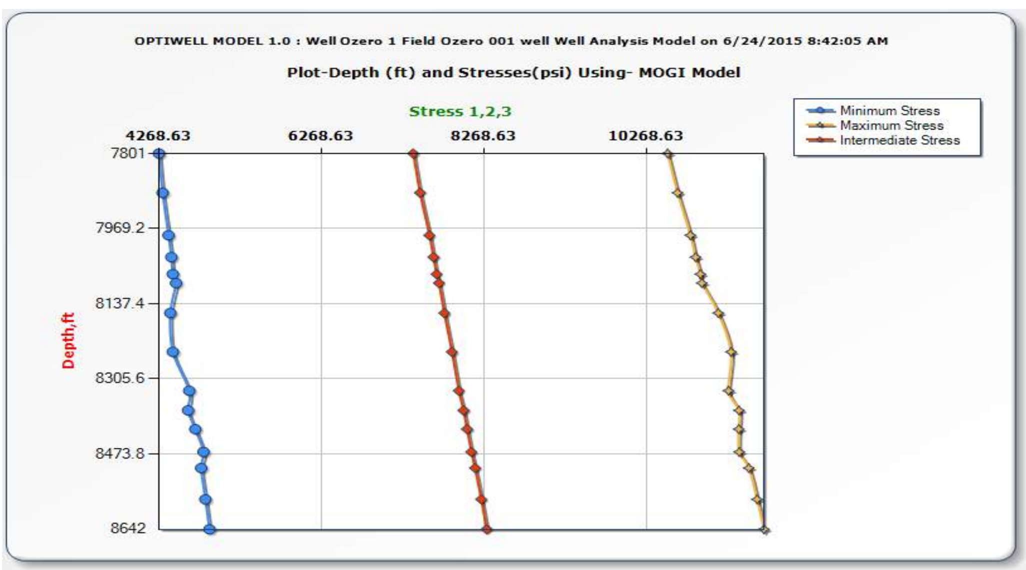

Figure6: Variationofin-situstresses with depth forwellojero 006

The Figure 6 above shows the variation in magnitude for the three principal stresses with depth. The stress magnitude for the well is basically configured to make a judgment on the stress paneling while drilling. This sensitivity plot is very relevant in many ways; it gives the drilling engineer a clear picture of the kind of stresses that the well will be exposed to, and hence, a good choice of casing is made, one that can withstand these stresses throughout the entire life of the well [2].
It is also relevant in casing point selection. The usual practice is to set the casing in a competent formation, which in this case is the top of the E4 shale, because it is the casing shoe that will feel the perturbation that the well will be exposed to as a result of variation of stresses [4]. Figure 6 gives a good insight to the kind of perturbation the casing will be exposed to.

3.1.5 Effect of stress magnitude on well bore stability with respect to casing point selection

The wellbore with inclination of 50° and stress orientation of 45° showed that at a mud weight of 0.57 psi/ft, the shale strength was found within the base of theE4 sand (i.e. top of E4 shale) as shown in Table 4:

Table 4: Stress data at casing point selection for well ojero 006

TVD (ft)	Mud weight (psi/ft)	σ1 (psi/ft)	σ2 (psi/ft)	σ3 (psi/ft)	Stress direction (deg.)
8473	0.57	4900	7900	11750	45

The hydraulic pressure of the drilling mud should not be higher than the stress that the casing will feel as is shown in the Table 4. The pressure of the mud at 8473 ft is (0.57x8473 = 4829.6 psi), which is less than the three principal stresses.

3.1.6 Failure envelope

Figure 7 shows the failure envelope for well ojero 006. From Figure 7, the failure envelope envisages the tight spot zone within the top of the E4 shale due to stress orientation variation, there by causing critical instability along the failed path due to strength anisotropy configuration. A negative failure function signifies instability as is represented on the horizontal axis in the figure. The blue lines signify severity of instability with depth, and the area enclosed in the failure envelope spans over a wide range of depth. Hence, the action for mitigating this instability issue is to increase the mud weight to match the prone section and maintain hole integrity within that zone.

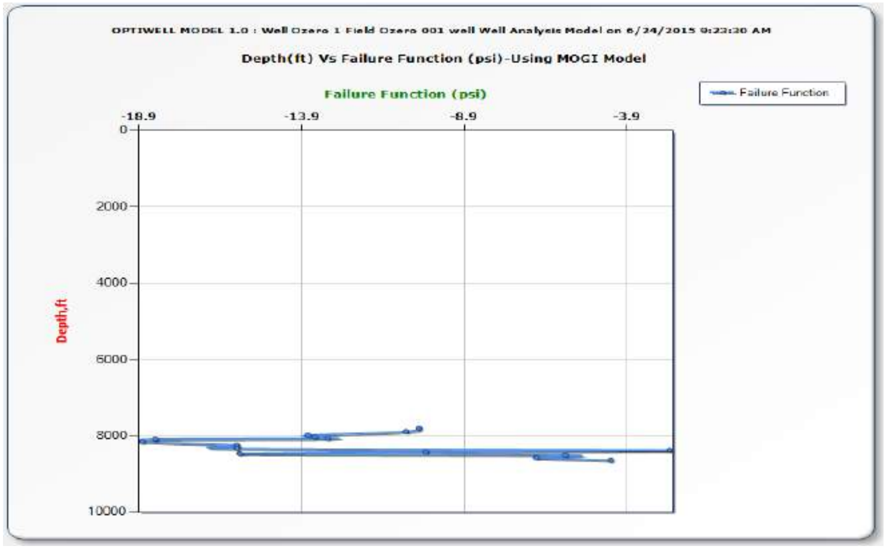

Figure 7: Plot of depth vs failurefunction forwellojero 006

The mud weight tracker plot which is designed to give an insight in the ability of the stresses to deviate from the normal stress condition shows the pressure variations and indicators which explain the level of consistency between the overburden, fracture pressure, pore pressure and the optimum mud weight for each well. The result for this well is consistent with the normal stress condition where overburden > fracture pressure >mud weight pressure > pore pressure.

Figure 9 shows the mud weight window used while drilling well field XR (where instability issues persisted) as well as adjustments that could be made to the mud weight to achieve a stable well bore to ensure success while drilling. Again, the well was initially very unstable as a result of non-sensitivity to the effect of inclination and optimum mud weight on its stability. The rose envelopes show the effects of mud weight on the stability of the well from 0.44 psi/ft where breakouts were seen through to 0.59 psi/ft where stability was attained. The yellow portion around the plan of the borehole on the rose envelopes depicts how the wellbore was yielding (breakouts)and it is seen that with increasing mud weight, the yielding effects significantly decreases and on attaining the optimum mud weight, the wellbore becomes entirely stable. This implies that for stability to be achieved, the rose envelopes must be entirely white with green colouration around it. Red colouration signifies failure(collapse or fracture).

Hence, breakouts will be experienced while drilling well field XR until a well-defined envelope is identified to mitigate instability issues as shown in the Figure9 and Table 5. For this well to be stable for easy Pull Out Of Hole (POOH), running of casing and allowable completion strategy, the mud weight required is 0.59 psi/ft.

3.2 WELL FIELD XR, FIELD XR

The input data for well field XR are given in the Table 5.

Table 5: Input data for well field XR

Depth (ft)	**Collapse gradient (psi/ft)**	**Optimum mud weight (ppg)**	**Optimal stress direction (degree)**	**Maximum principal stress, σ1 (psi)**	**Intermediate principal stress, σ2 (psi)**	**Minimum principal stress, σ3 (psi)**
3914	0.51	10.40	45° N/E	3757.44	3600.88	2974.64
4075	0.52	10.45	45° N/E	3912.00	3749.00	3097.00
4236	0.52	10.53	45° N/E	4066.56	3897.12	3219.36
4397	0.53	10.60	45° N/E	4221.12	4045.24	3341.72
4558	0.53	10.69	45° N/E	4375.68	4193.36	3464.08
4719	0.54	10.80	45° N/E	4530.24	4341.48	3586.44
4880	0.54	11.02	45° N/E	4684.80	4489.60	3708.80
5041	0.55	11.18	45° N/E	4839.36	4637.72	3831.16
5202	0.56	11.30	45° N/E	4993.92	4785.84	3953.52
5363	0.57	11.40	45° N/E	5148.48	4933.96	4075.88
5526	0.57	11.47	45° N/E	5304.96	5083.92	4199.76

3.2.1 Mud weight tracker

Figure 8 shows a mud weight tracker for well field XR.

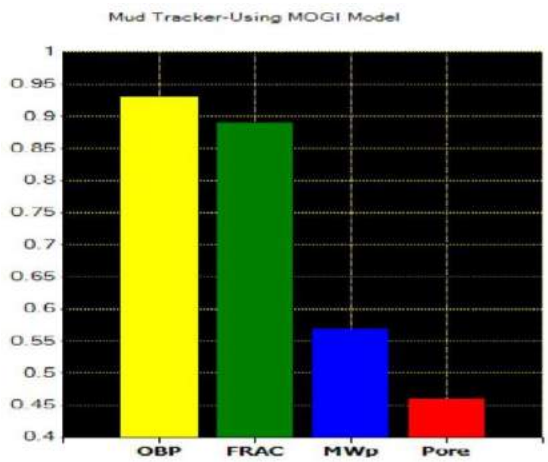

Figure 8: Mud weight tracker plot for well field XR

3.2.2 Sensitivity for optimum mud weight

Figure 9 shows the optimum mud weight window for safe drilling for well field XR.

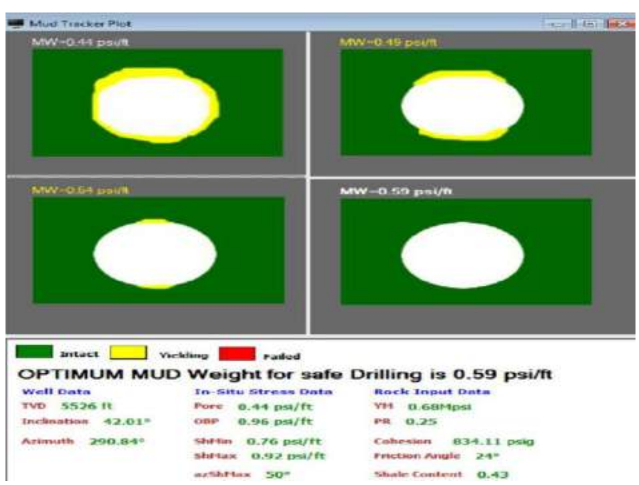

Figure 9: Mudweight window for well field XR, showing the optimum mud weight for safe drilling

Table 5: Mud weight design criteria for well field XR

True vertical depth (ft)	Collapse gradient (psi/ft)	Mud weight (psi/ft)	Stress direction (degree)
2600-4253	0.45-0.50	0.46-0.53	50° N/E
4300-5526	0.50-0.54	0.53-0.59	50° N/E

3.2.3 Effect of inclination on well bore stability with respect to optimum mud weight

Figure 10 shows the effect of inclination on the stability of well field XR with respect to optimum mud weight.

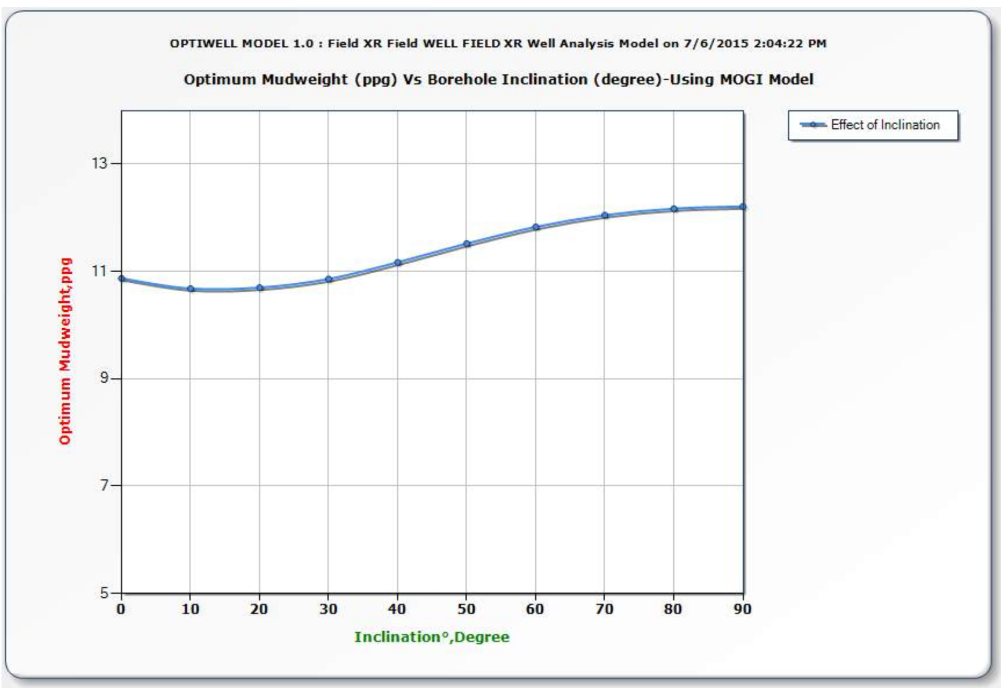

Figure10: Plot of optimum mud weight vs inclination for wellfield XR

The plot on Figure 10 shows the optimum mud weight for safe drilling corresponding to any given inclination for the well path. Well field XR was drilled at an inclination of42.01° and from the plot shown in figure10, the optimum mud weight corresponding to 42.01° inclination is 11.346 ppg. It was previously shown from the sensitivity analysis for optimum mud weight that the optimum mud weight for this well at that same depth was 0.59 psi/ft which is equivalent to 11.346 ppg. This further supports the result from the analysis of the optimum mud weight for this well. Hence, the initial mud weights could not have supported the well bore against instability but the recently simulated mud weight of 0.59 psi/ft will keep the hole stable, devoid of all weak planes associated with stress orientation.

3.2.4 Variation of stress magnitude with depth

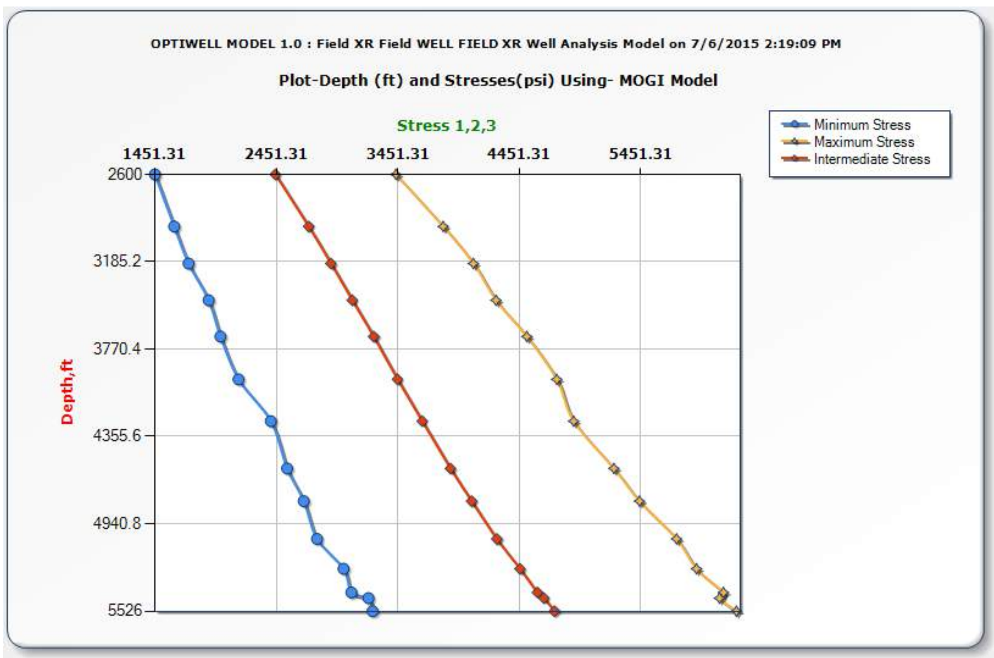

Figure 11: Variation of in-situ stresses with depth for well field XR

Figure 11 shows the variation in magnitude for the three principal stresses with depth. The stress magnitude for the well is basically configured to make a judgment on the stress paneling while drilling. The relevance of this sensitivity plot has been previously stated; it is relevant in casing type selection and casing point selection among others, and hence, is very valuable to the drilling engineer.

4.0. Conclusion

In this paper, well bore stability is a function of several factors such as inclination and azimuth, in-situ stresses, mud weight, rock strength parameters, etc. Some of these factors are controllable, while some are not. The controllable factors are mud weight, inclination and azimuth. Stability problems can be significantly reduced by appropriately varying these parameters. A well should not face any instability problem if the optimum mud weight corresponding to any given trajectory is adopted. Concrete knowledge of the in-situ stress state in a field is a prerequisite for varying the parameters stated above. Hence, the in-situ stress state in a field is a very essential component for well design. Well bore stability can be significantly improved by adopting an optimum inclination and drilling direction at which the shear stress anisotropy around the wellbore wall is minimized.

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