



Wellbore stability analysis and safe mud weight window selection in the Halfaya oil field

Maytham Ismael Saddam ^{a, b, *}, Ghanim M. Farman ^a, Dhifaf Sadeq ^{a, c}

a Department of Petroleum Engineering, College of Engineering, University of Baghdad, Iraq

b Missan Oil Company, Missan, Iraq

c Department of Petroleum Engineering, College of Engineering, Al-Naji University, Iraq

Abstract

Drilling operations in the Halfaya oilfield frequently encounter severe wellbore instability challenges. When navigating shale deposits, wellbore instability remains the primary operational concern. Based on the analysis of the wellbore instability intervals, low-strength shale and marlstone formations are identified as the principal unstable zones that lead to non-productive time and higher drilling costs. By planning a safe operating mud window, these non-productive times and drilling costs can be mitigated. Several wellbore instability concerns have been found in a southern Iraqi oil field. A problem-diagnostic technique was done by evaluating well log data, drilling reports, mud logging reports, and pore pressure readings. In wellbore stability evaluations, the three rock failure criteria that are used the majority of the time are the Mohr-Coulomb, Mogi-Coulomb and Modified Lade criterion were used to predict a safe mud weight window. The Mogi-Coulomb and Modified Lade criteria provided more accurate predictions than the Mohr-Coulomb model in well H1. The Mohr-Coulomb criterion proved inadequate for this formation because it fails to account for the intermediate principal stress. According to the pore pressure predictions in this study, the unsuitable mud weight of 10.49 ppg is the major cause of wellbore instability during the drilling of the Nahr Umr A formation in this well; therefore, a mud weight of 14.5–15 ppg is recommended. The Formation Micro Imager (FMI) was responsible for determining the orientations of the horizontal stresses. The Halfaya oilfield has an azimuth that corresponds to a maximum horizontal stress of about N20–35 E, the findings indicate that the Nahr Umr formation is characterized by a reversal faulting regime ($S_{Hmax} > S_{hmin} > S_V$). Formation lithology impacts Halfaya oilfield horizontal stress. High-strength, hardened intervals have high horizontal stress, shale and marlstone formations with low strength are the principal unstable wellbore intervals. Ultimately, to prevent breakout failures and minimize drilling fluid losses, it is recommended to either restrict wellbore inclination or employ an optimized, higher mud weight.

Keywords: Wellbore instability; Iraqi Oil Field; Well Log Data; Principal Stress; Mud Weight.

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1- Introduction

Halfaya oilfield lies 400 km south of Baghdad in Missan province. The Halfaya oilfield consists of a relatively flat anticlinal structure measuring approximately 38 km in length and 12 km in width. The nine oil-bearing formations of the Halfaya oilfield are: Tertiary Jeribe and Upper Kirkuk; Upper Cretaceous Hartha; Tanuma; Khasib; Mishrif & Nahr Umr; and Lower Cretaceous Yamama. The presence of an active aquifer within the Middle Kirkuk formation has been verified. These reservoirs are buried at depths ranging from 1900 m to 4300 m.

During drilling, significant impediment to drilling is wellbore instability. High stresses, weak rock, or improper drilling are causes. Therefore, it is necessary to develop a method to prevent wellbore collapse. Sensitivity studies can also reveal if well trajectory and inclination pose extra risks [1]. Instability in the wellbore can cause the drill pipe to become stuck or broken, which can cause the open-hole segment to collapse if left

unchecked [2, 3]. Borehole instability issues that occur while the well is being drilled, completed, or operating are the result of a complicated interaction between various factors. Both the difficult and complex stress conditions, as well as the solid contact (between rock materials and drilling fluid), are examples.

There is the possibility that borehole issues can be reduced by carefully planning the wellbore trajectory and orientation, as well as the directions in which perforations are placed, and by conducting leak-off tests [4]. Halfaya oilfield located on Arabian Shelf near Zagros tectonic zone. The Eurasian Plate collided with the Arabian Plate via Zagros tectonic activity (NNE-SSW). The resulting stress waves generated the anticlinal structures characteristic of the Arabian Shelf. Middle Miocene ended the extrusion. Fig. 1 shows the stratigraphy column of Halfaya oilfield.



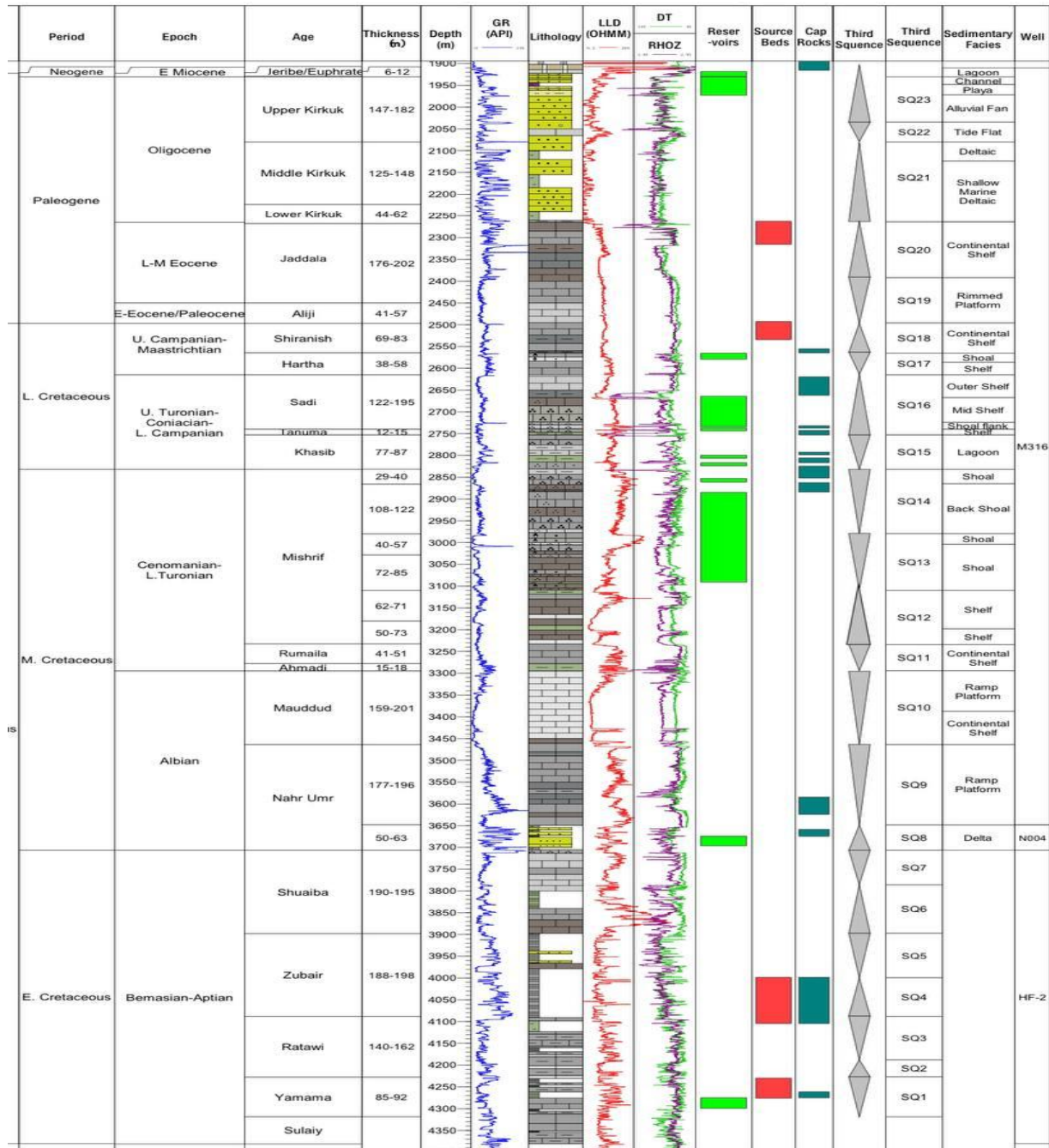


Fig. 1. Stratigraphy column of Halfaya oilfield [5]

2- Background: Rock mechanics applications in Petroleum Engineering

Rock mechanics is an important part of the growth of the petroleum industry, and it is used in almost every step of extracting hydrocarbons. Rock mechanical analysis is adequate for predicting Pore pressure, estimating hydrocarbon column, and evaluating wellbore fluid flow [6, 7]. In drilling, rock mechanical techniques helped with examination of the wellbore stability and the available mud window design as shown in Fig. 2, wellbore trajectory planning, feasibility of underbalanced drilling, fracture and fault evaluation, and drill bit selection. For the hydraulic fracture technique and drilling new

development wells to help get more oil out of the ground, geomechanical models are needed [8, 9]. Furthermore, recent studies have demonstrated the critical value of utilizing 1-D Mechanical Earth Models for geomechanical characterization and mitigating production instability specifically within the Nahr Umr formation of Southern Iraq [10].

3- Methodology

The present work implements an integrated geomechanical diagnosis methodology aimed to assess and prevent wellbore instability problems in Halfaya oilfield. The methodology consists of three main steps

including data acquisition, construction of 1-Dimensional Mechanical Earth Model (1-D MEM), and utilizing rock failure criteria to establish mud window for safe operation.

3.1. Data acquisition and problem identification

To better understand contributing factors to wellbore instability issues, several field and log data were reviewed. The following datasets were used within this study:

- Well Log Data: Wireline bulk density, compressional slowness and shear slowness logs were used to

determine dynamic and static rock mechanics properties.

- Formation Micro Imager (FMI) Logs: Used FMI log interpretation to establish direction of horizontal in-situ stresses and predict breakout directions.
- Field Reports: Reviewed drilling reports, mud logging reports and field pore pressure measurements looking for historical instances of wellbore instability.
- Diagnostic Tests: Data from leak-off tests were incorporated to assist in modeling the stress regimes and establishing safe operational parameters, a practice supported by [4].

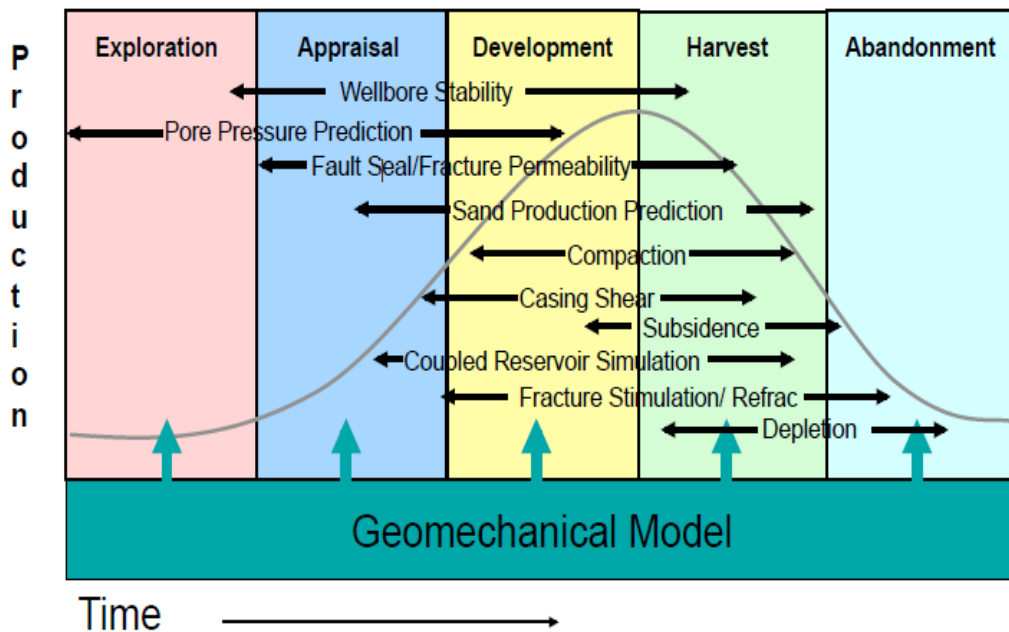


Fig. 2. Geomechanics' history [11]

3.2. Geomechanical modeling and stability analysis

Wellbore instability remains one of the greatest challenges engineers face during drilling operations [12, 13]. Instability during drilling, completion, and production operations can be triggered by tough stress conditions and the solid interaction between rock materials and drilling fluid [14, 15]. Following data collection, the wellbore stability diagnostic workflow proceeded through the following analytical steps:

- 1- 1-D MEM Construction: Using the available well log and field data, a 1-D MEM was constructed. The numerical model predicts the vertical stress, pore pressure, rock strength parameters (UCS, internal friction angle) and magnitude of the minimum and maximum horizontal stresses.
- 2- Failure Criteria Implementation: The following failure criteria were implemented to forecast wellbore failure and determine allowable mud weight windows. The results of each rock failure model were

compared: Mohr- Coulomb, Mogi-Coulomb, Modified Lade.

- 3- Sensitivity Analysis: A wellbore stability sensitivity analysis was performed to determine the effects of wellbore inclination and azimuth on mud weight requirements. Proper planning of the borehole path and orientations can help control the direction of perforations and leak-off tests to reduce borehole problems. This allowed us to optimize the well path for highly deviated and horizontal wells.

4- Model of the Earth's mechanics in one dimension (1-D MEM)

A 1-D MEM is a numerical explanation of rock strength and the stresses in both the vertical and horizontal directions. Rock mechanics is a "theoretical and practical study of rock mechanics" [16]. Rock mechanics started in the 1950s and became its own field in the 1960s. An engineer must know how to remove rocks and understand rock mechanics in order to drill oil wells. When drilling

and completion fluids are used in a stable formation, the wellbore becomes unstable, the casing falls apart, and the borehole doesn't work anymore [4].

4.1. Vertical stress

Vertical stress is induced by rock weight and saturating fluids. The overburden stress can be computed using Eq. 1, which integrates the bulk density log (RHOB). Halfaya's bulk density and vertical stress are shown in Fig. 3.

$$\sigma_v = \int_0^z \rho(z)gdz \approx \bar{\rho}gz \tag{1}$$

Where g:gravity acceleration; z:depth [17].

Alternatively, the density-dependent vertical stress can be expressed as:

$$S_v = \int_0^D \rho Dgd_D \tag{2}$$

Eq. 3 is employed to extrapolate the bulk density profile from the mudline across the air gap to the surface [18].

$$\rho_{\text{extrapolated}} = \rho_{\text{mudline}} + A_o \times (TVD - \text{Air Gap})^\alpha \tag{3}$$

4.2. Pore pressure

Formation pressure refers to the force exerted by fluids within the pores of rock. The formation pressure is an important geological parameter that is used in oil and gas field development. Pore pressure is one of the most essential components that go into formation. There are challenging factors at play here that affect the overall success of drilling operations [19]. Eq. 4 predicts the pore pressure gradient in shales by utilizing a resistivity log as an analytical tool [20, 21]. If pore pressures are miscalculated before drilling, blowouts and lost circulation can occur [22]. Field measurements and estimated pore pressure agreed well. Eaton's method and Slowness logs demonstrate well H1's pore pressure in Fig. 4, a predictive methodology that has proven highly effective for evaluating the Nahr Umr formation across Southern Iraq (Ayal, 2025 #876).

$$P_{pg} = OBG - (OBG - P_{ng}) \left(\frac{R}{R_n}\right)^n \tag{4}$$

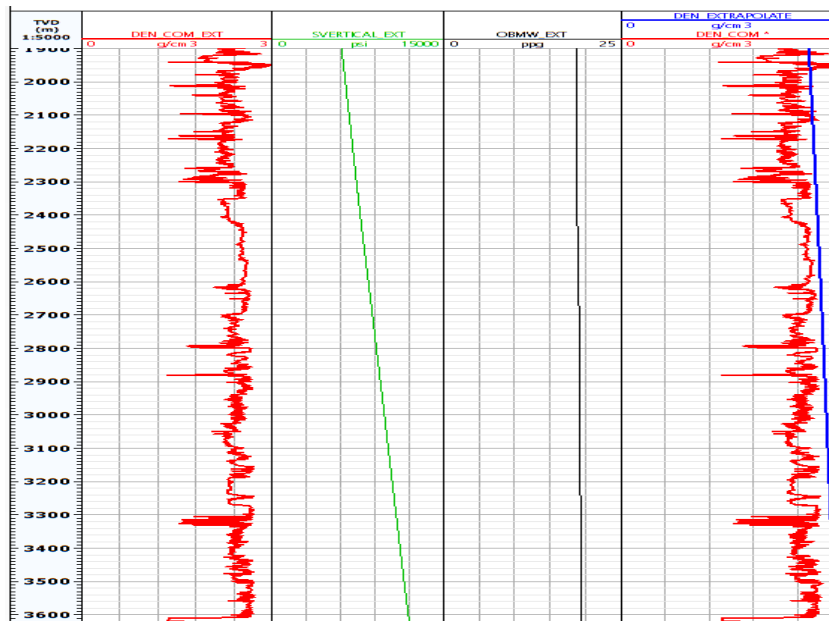


Fig. 3. Vertical stress

4.3. Rock mechanical strength and deformation

Wellbore stability is mostly determined by mechanical rock properties, such as unconfined compressive strength (UCS), cohesion (Co), tensile (Ts), and friction angle (FANG). Depending on how the rock is deformed, its mechanical properties can be either elastic (linear elastic modulus) or inelastic (rock strength). In this study, a variety of mechanical characteristics were evaluated, including features such as Young's modulus, UCS, friction angle, and Poisson's ratio. Calculations for the dynamic shear modulus were performed with the assumption that the formation was elastic, homogenous, and isotropic [23].

$$G_{dyn} = \frac{\rho_b}{DTSMS^2} \tag{5}$$

$$K_{dyn} = \frac{\rho_b}{DTCO^2} - \frac{4}{3}G_{dyn} \tag{6}$$

$$E_{dyn} = \frac{9G_{dyn} \times K_{dyn}}{G_{dyn} + 3K_{dyn}} \tag{7}$$

$$v_{dyn} = \frac{3K_{dyn} - 2G_{dyn}}{6K_{dyn} + 2G_{dyn}} \tag{8}$$

Where: ρ_b is bulk density (g/cm3). $DTCO$ is compressional slowness us/ft. $DTSMS$ is shear slowness us/ft. K_{dyn} and G_{dyn} are in MPa.

Shear modulus and dynamic bulk estimation, Young's Modulus and the Poisson ratio dynamic profiles as show in Fig. 5.

The dynamic Young's modulus is used in the computation of the static Young's modulus, using the correlation suggested by John Fuller (Fig. 6).

$$E_s = 0.0018 \times E_d^{2.7} \tag{9}$$

As can be shown in Fig. 7, the static Poisson's ratio can be approximated using the dynamic Poisson's ratio.

$$PR_s = PR_d * PR \text{ multiplier} \tag{10}$$

In this analysis, a multiplier of 1.0 was applied; therefore, the static Poisson's ratio is assumed to be equivalent to the dynamic Poisson's ratio.

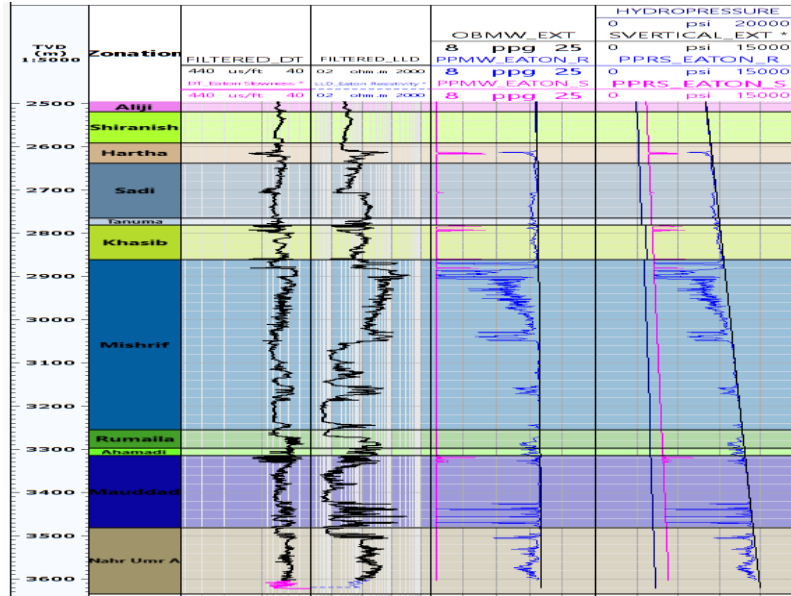


Fig. 4. Pore pressure by to Eaton’s method

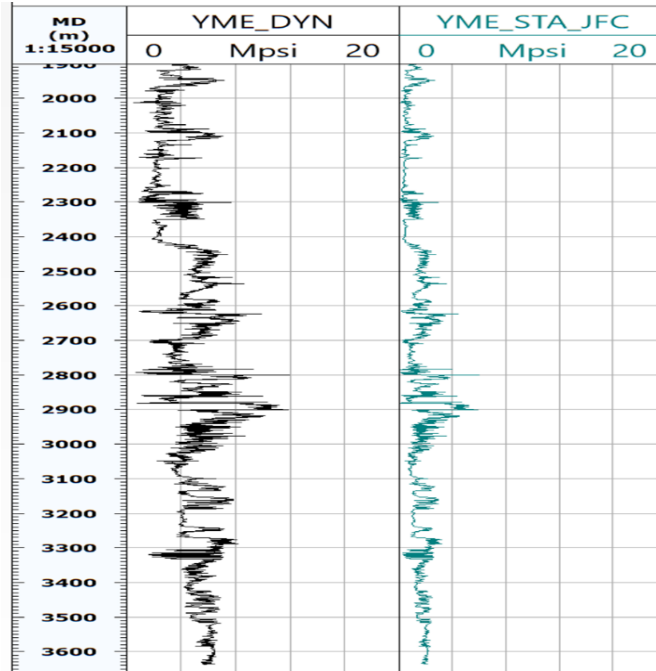


Fig. 5. Isotropic properties

4.4. Rock compressive strength

Rock resistance to in-situ stress around a borehole is determined by cohesion strength (Co), Internal Friction

angle (ϕ) and Unconfined compressive strength (UCS). UCS and ϕ are applied to predict borehole collapse during drilling (Fig. 8).

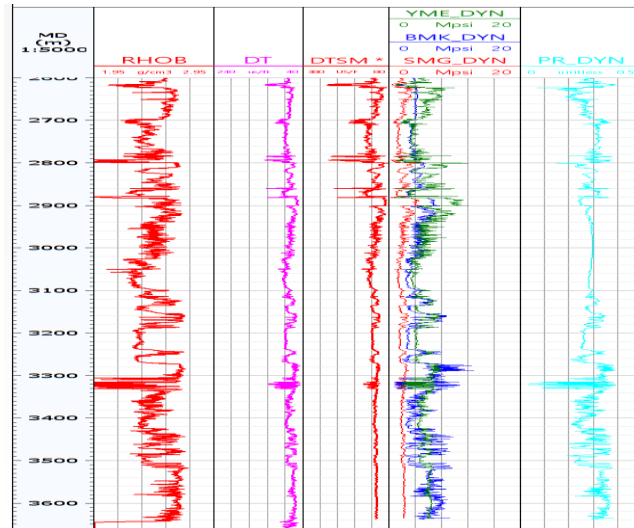


Fig. 6. Static YM by John Fuller

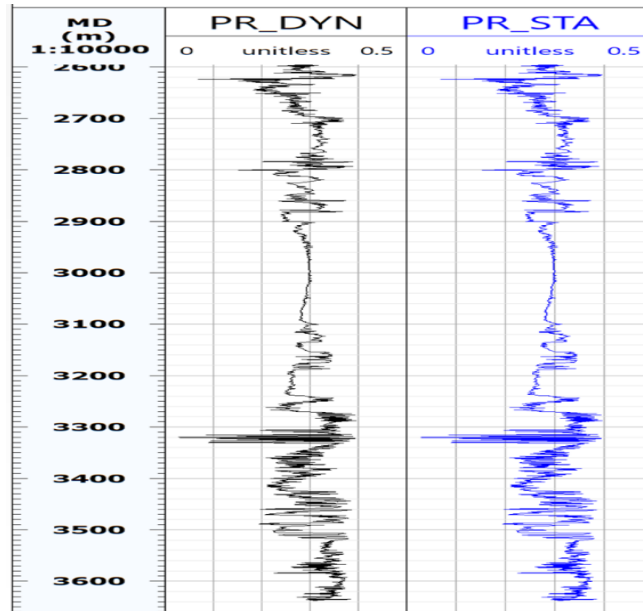


Fig. 7. Static poisson ratio estimation

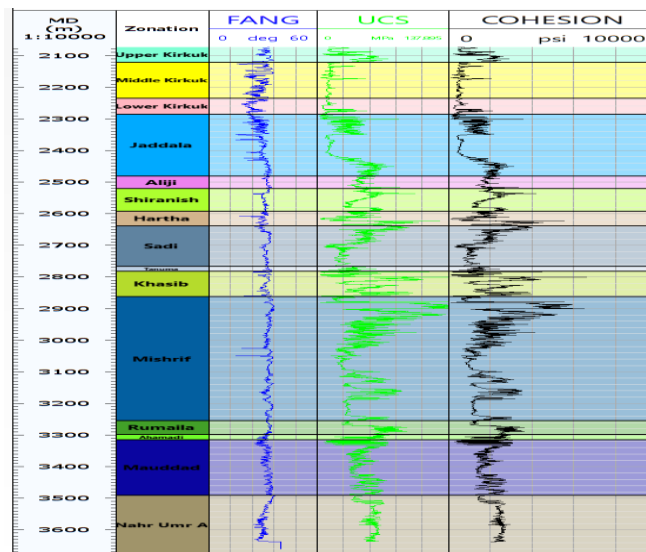


Fig. 8. Rock compressive strength

4.5. Unconfined compressive strength (UCS)

Compressive strength is significant for drilling and wellbore stability. In this study, we employ Plumb Generic Young's modulus correlation with static data (YME STA). To calculate the Unconfined Compressive Strength (UCS) shown in Fig. 9, the empirical correlation developed by Plumb (Eq. 11) is applied:

$$UCS = 4.242 \cdot E_{sta} \quad (11)$$

4.6. Internal friction angle (ϕ)

Friction angle is employed in drilling and wellbore stability. It measures a rock's shear stress. Fig. 10

illustrates the friction angle profile derived using the Gamma Ray (GR) log as an indicator.

4.7. Tensile strength - function of UCS correlation

Tensile strength is derived from UCS in this approach, as shown in Fig. 11.

$$TSTR = K \cdot UCS \quad (12)$$

K = Facies and zone-based factor, default: 0.1.

This value is the one that is used by default, and it is derived from the Griffith Elastic-Brittle theory. This theory provides the ratio of tensile strength to compressive strength to for 8 ~ 12.

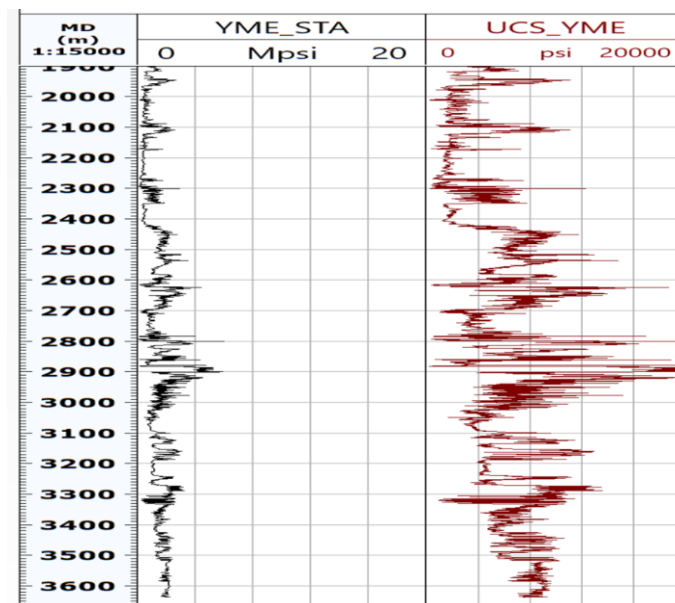


Fig. 9. Unconfined compressive strength

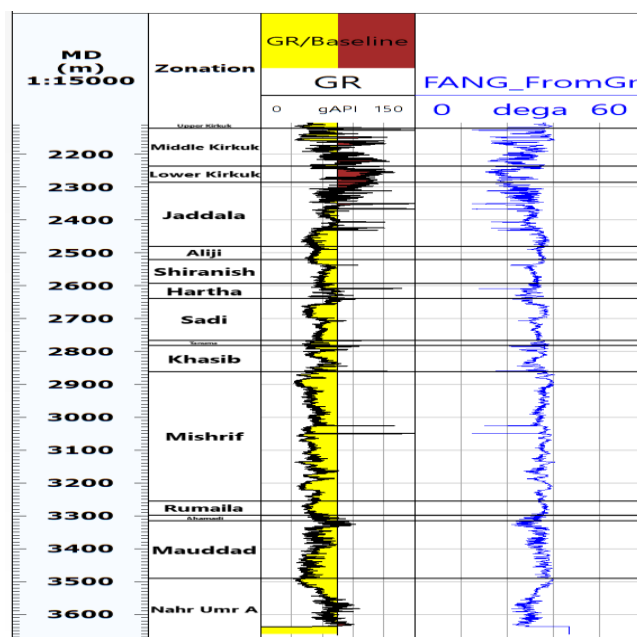


Fig. 10. Friction angle

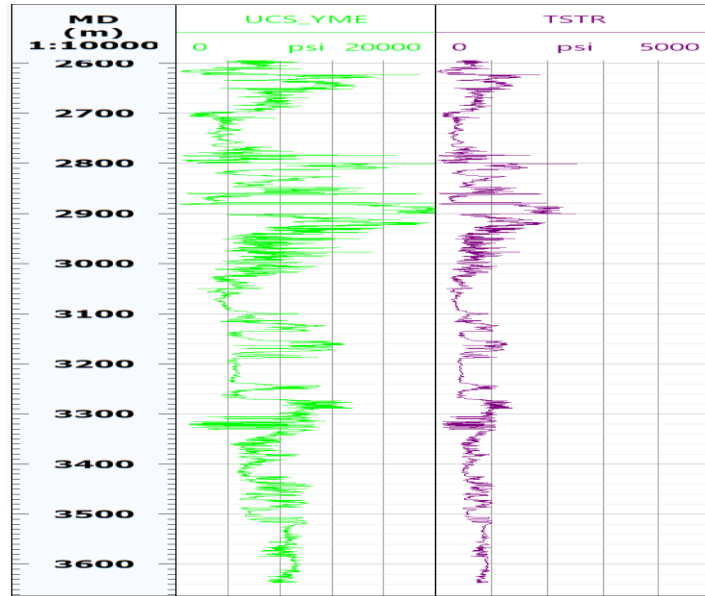


Fig. 11. Function of UCS correlation

4.8. Minimum and maximum horizontal stresses

Hydraulic fracture testing is the best method to determine of S_{hmin} is in a wellbore [17]. The poroelastic model calculates minimal horizontal stress [24]. The minimum horizontal stress (S_h) is calculated using Eq. 13, which incorporates elastic parameters, pore pressure, and vertical stress.

$$S_h = \frac{\nu}{1-\nu} \sigma_v + \frac{1-2\nu}{1-\nu} \alpha P_p + \frac{E}{1-\nu^2} \epsilon_x + \frac{\nu E}{1-\nu^2} \epsilon_y \tag{13}$$

Directly forecasting maximum horizontal stress is difficult. Numerous technological methods predict maximal horizontal stress. Eq. 14 determines the maximum horizontal stress (S_H) using the poroelastic

model, incorporating the Mohr-Coulomb criterion and the theory of elasticity:

$$S_H = \frac{\nu}{1-\nu} \sigma_v + \frac{1-2\nu}{1-\nu} \alpha P_p + \frac{E}{1-\nu^2} \epsilon_y + \frac{\nu E}{1-\nu^2} \epsilon_x \tag{14}$$

ϵ_x and ϵ_y : tectonic strains in the directions of maximum and minimum horizontal stress., respectively. The tectonic strains ϵ_x and ϵ_y can be estimated utilizing Eqs. 15 and 16:

$$\epsilon_x = \frac{\nu \sigma_v}{E} \left(1 - \frac{\nu^2}{1-\nu} \right) \tag{15}$$

$$\epsilon_y = \frac{\nu \sigma_v}{E} \left(\frac{1}{1-\nu} - 1 \right) \tag{16}$$

As can be seen in Fig. 12.

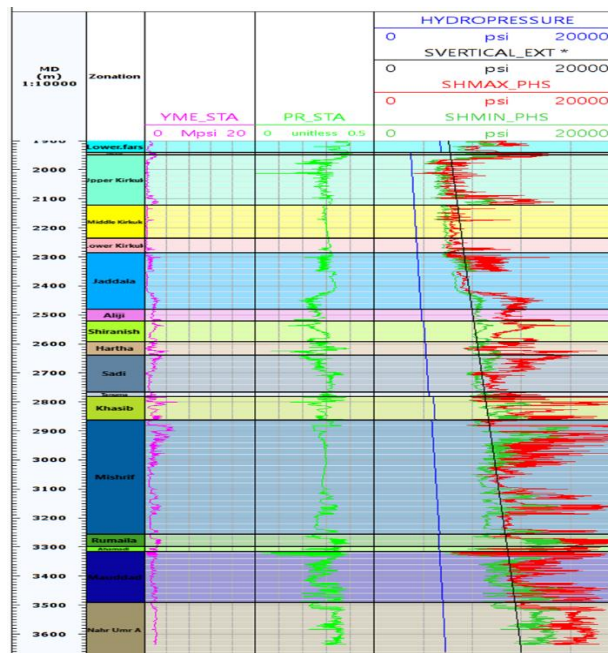


Fig. 12. Min. and Max. horizontal stresses

4.9. Orientation of horizontal stresses

tensile fractures provides in-situ horizontal stress directions and magnitudes.

Fig. 13 shows how detecting breakouts' position and extension around the wellbore and/or drilling-induced

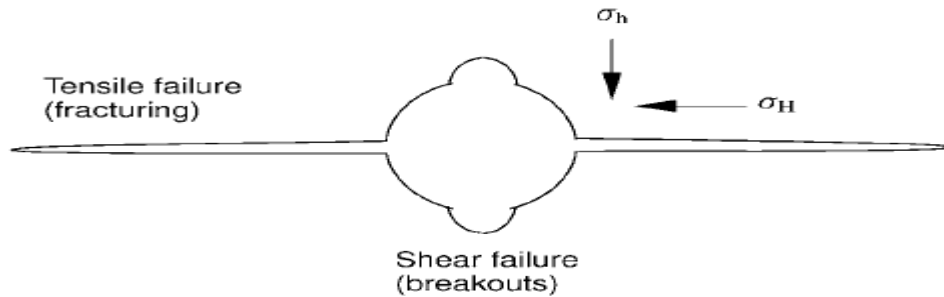


Fig. 13. Failure modes include compression and tension all around a vertical borehole

Fig. 14 illustrates the maximum horizontal stress direction over the Nahr_Umr clastic intervals, derived from the

FMI logging interpretation for well H1 (N2-7E for the entire 8.5-inch section).

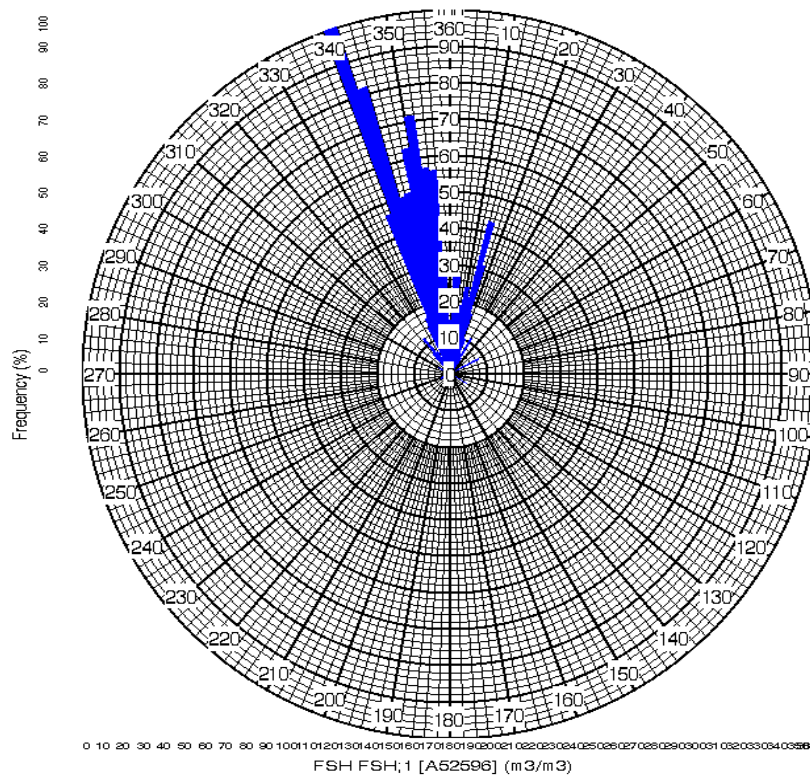


Fig. 14. Maximum horizontal stress direction [5]

5- Results and discussion: Wellbore stability analysis

Modeling results of wellbore stability study which included drilling mud weight data and implemented on the created Mechanical Earth Model (MEM). Images of modeled borehole failure and allowable mud weight window were produced as results. Wellbore instability occurs when the stresses around a borehole exceed the strength of the formation. Three widely used failure criteria were used to predict wellbore instability: Mohr-Coulomb failure criteria, Mogi-Coulomb failure criteria and Modified Lade criteria. According to the results of

this study, Mogi-Coulomb failure criteria and Modified Lade criteria are more effective than the Mohr-Coulomb model. The reason Mohr-Coulomb failure criterion did not match up well is because this model does not take into consideration the intermediate principal stress, which made it ineffective on this formation. Modeled borehole failure using the current mud weight of 10.49 ppg and modeled borehole failure with new mud weight of 14.5-15 ppg can be seen below (Fig. 15 - Fig. 20).

Fig. 21 also depicts the sensitivity of wellbore stability at ONE DEPTH (3600 m):

1. Shear Failure Minimum MW(Breakout) vs. Borehole Orientation: This plot (Fig. 21a) shows wellbore breakout versus borehole orientation (degrees of azimuth and deviation), starting from 11.3ppg mud weight. The point being plotted represents what deviation and azimuth the borehole has at that chosen depth.
2. Breakdown MW vs. Orientation: This plot (Fig. 21b) shows breakdown mw versus borehole orientation, starting from 20.4ppg mud weight.
3. MW Window vs. Deviation: This plot (Fig. 21c) shows safe operating mw window versus deviation at a set azimuth. As you can see from this plot wellbore

inclination affects the required mud weight to stabilize the wellbore. As the plot shows the safer mud weight window becomes smaller as deviation increases.

4. MW Window vs. Azimuth: This plot (Fig. 21d) shows safe operating mw window versus azimuth at a set deviation. Looking at this plot you can see that an azimuth of 50 or 225 degrees is favorable because it is in the direction of the minimum horizontal stress.

Based on this sensitivity analysis avoid highly deviated well trajectories unless appropriate mud weights can be used to offset breakout failure and mud loss.

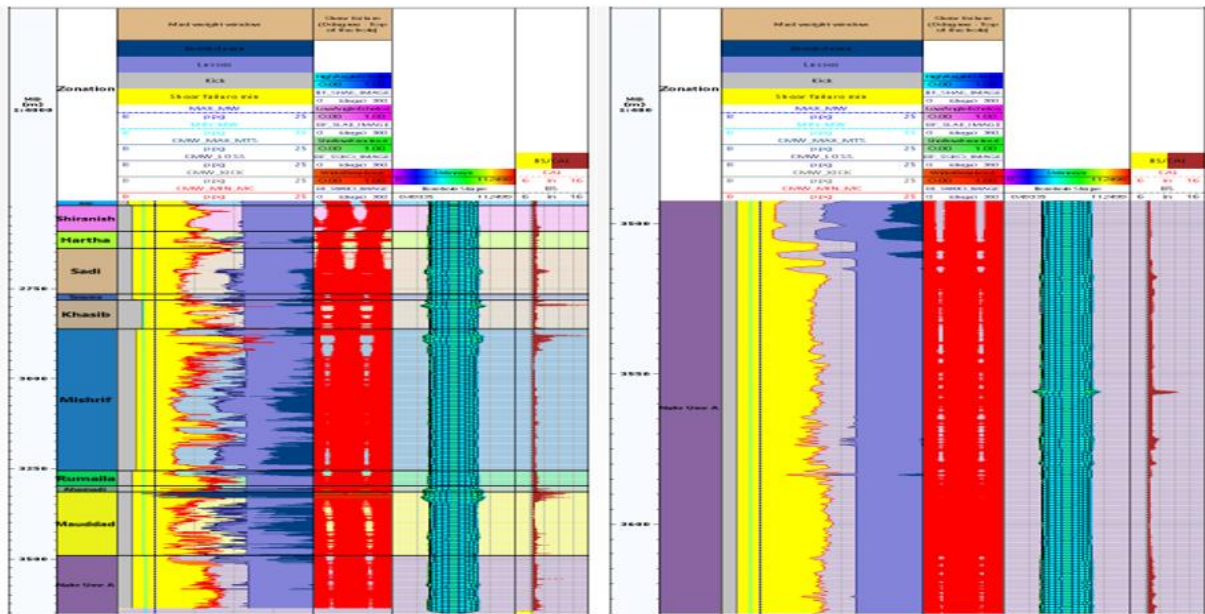


Fig. 15. Mohr-Coulomb criterion with actual MW (10.49) ppg

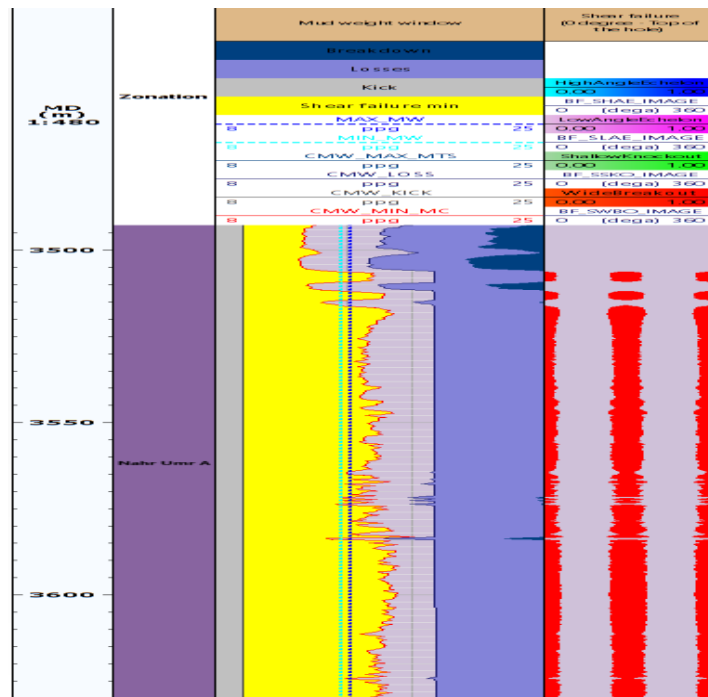


Fig. 16. Mohr-Coulomb criterion with new MW (14.5- 15) ppg

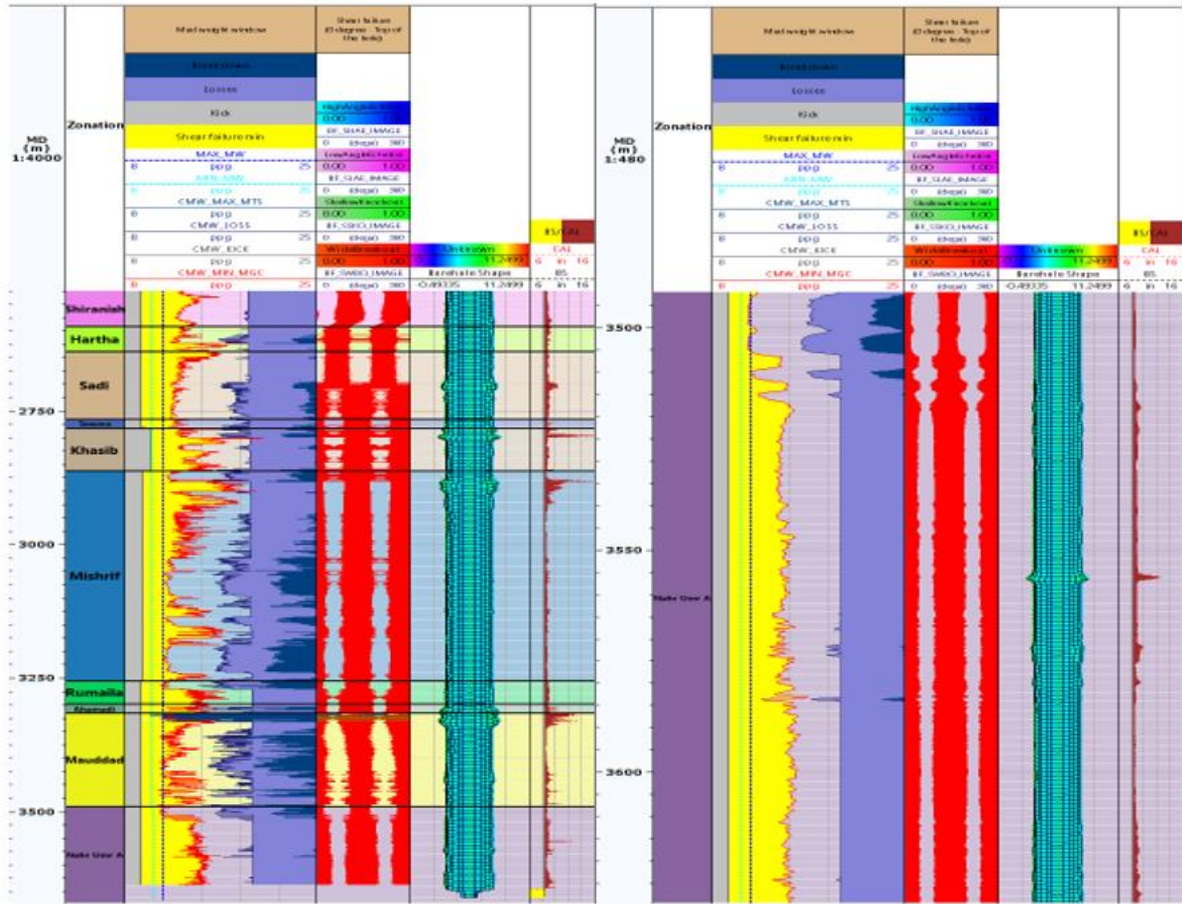


Fig. 17. Mogi-Coulomb criterion with actual MW (10.49) ppg

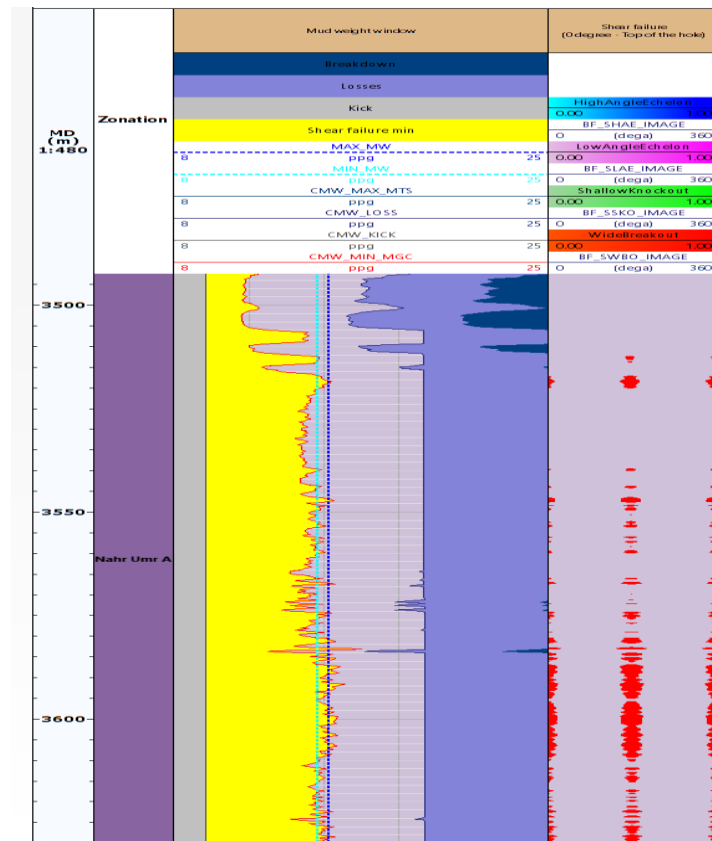


Fig. 18. Mogi-Coulomb criterion with new MW (14.5- 15) ppg

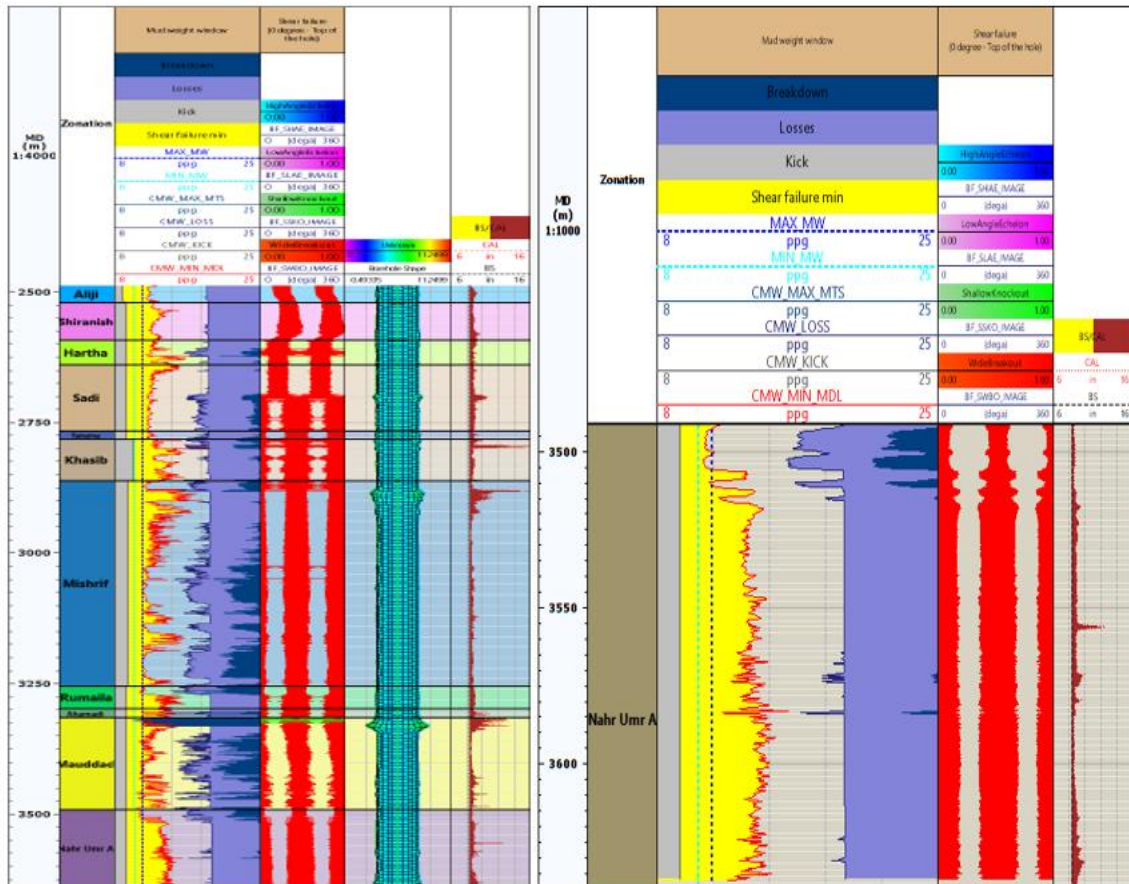


Fig. 19. Modified lade Coulomb criterion with actual MW (10.49) ppg

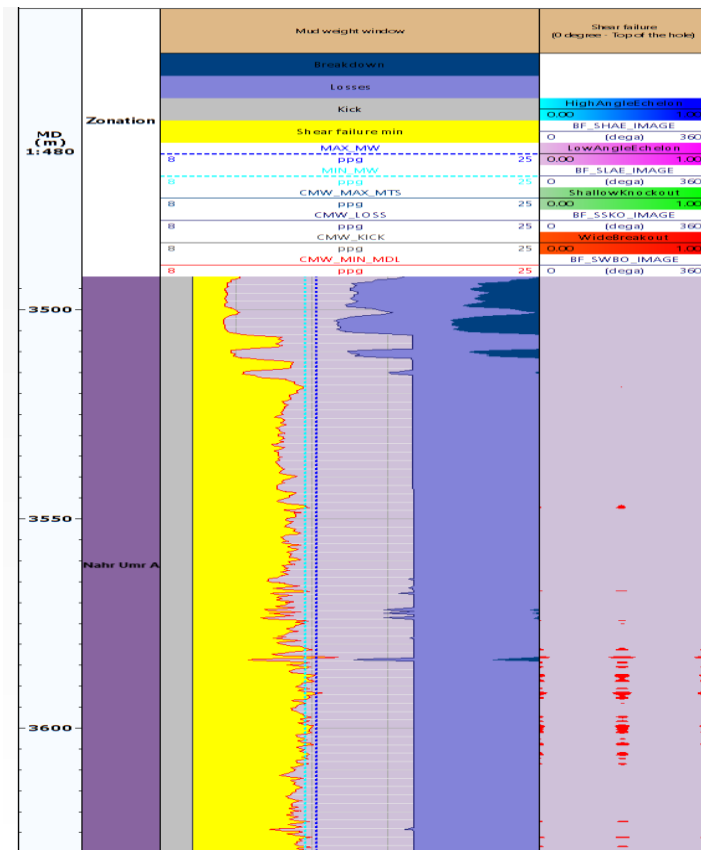


Fig. 20. Modified lade Coulomb criterion with new MW (14.5- 15) ppg

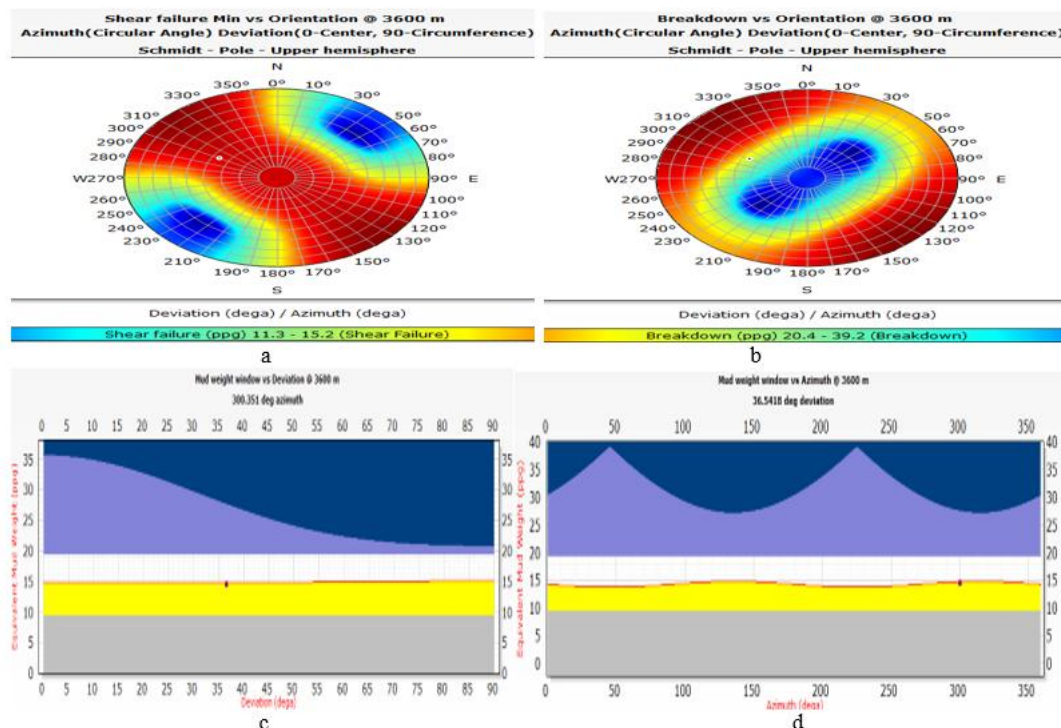


Fig. 21. Wellbore stability sensitivity analysis at single depth using modified lade criterion at Nahr Umr B formations

6- Conclusions

Mechanical strength, in-situ stresses and pore pressure were assessed to understand wellbore stability issues experienced in highly deviated and horizontal wells completed in the Halfaya oilfield. A 1-D MEM was constructed, and failure around the wellbore was assessed with the Mohr-Coulomb failure criteria, Mogi-Coulomb failure criteria, and Modified Lade failure criteria. The results indicate that as inclination increases, the mud weight window becomes increasingly smaller until it reaches horizontal well orientation where the wellbore is most prone to instability. The study concluded that the mud weight being used in the field of 10.49 ppg is one of the leading causes of instability issues within the Nahr Umr A formation. It is highly recommended that an optimized mud weight between 14.5–15 ppg be utilized.

However, any mud weight increases must be coupled with excellent fluid properties to avoid invading the formation with drilling fluid and causing further instability issues. Lithology was found to be controlling horizontal stresses in the Halfaya field where high strengths and hardened intervals were associated with higher horizontal stresses. Low strength shale and marlstone formation were identified to be the main culprit of where instability occurs. If future wells want to avoid breakout failure or mud losses they should limit well inclination or utilize the higher optimized mud weights. The drilling azimuth should be planned with the well trajectory such that the drill bit is always drilling parallel to the minimum horizontal stress. If this geomechanical characterization is taken into consideration during well planning, an optimized well trajectory can be designed.

Nomenclature

σ	Stress
E	Young Modulus
G	Shear Modulus
Φ	Friction Angle
ν	Poisson Ratio
Sh	Minimum Horizontal Stress
SH	Maximum Horizontal Stress
Pp	Pore Pressure
σ_v	Vertical Stress
UCS	Unconfined Compressive Strength
MEM	Mechanical Earth Model

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استقرار جدار البئر وتحديد نافذة الوضع الآمن في حقل الحلفاية النفطي

ميثم اسماعيل صدام^{١،٢،*}، غانم مديح فرمان^١، ضفاف جعفر صادق^{٣،١}

١ قسم هندسة النفط، كلية الهندسة، جامعة بغداد، العراق

٢ شركة نفط ميسان، وزارة النفط، العراق

٣ قسم هندسة النفط، كلية الهندسة، جامعة الناجي، العراق

الخلاصة

في حقل الحلفاية النفطي ، يكون الحفر صعباً لأن حفرة البئر غير مستقرة. عند الحفر في رواسب الصخر الزيتي ، فإن الشيء الرئيسي الذي يدعو للقلق هو عدم استقرار حفرة البئر ، استناداً إلى تحليل فترة عدم استقرار حفرة البئر ، فإن تشكيلات الصخر الزيتي والمارلستون ذات القوة المنخفضة هي الفترات الرئيسية غير المستقرة التي يمكن أن تؤدي إلى وقت غير منتج وتكاليف حفر أعلى. من خلال التخطيط لنافذة التشغيل. تم العثور على العديد من المخاوف من عدم استقرار حفرة البئر في حقل نفط جنوب العراق. تم إجراء تقنية تشخيص المشكلات من خلال تقييم بيانات سجل الآبار وتقارير الحفر وتقارير تسجيل الطين وقرارات ضغط المسام. معايير فشل الصخور الثلاثة الأكثر استخداماً في تحليلات استقرار حفرة البئر هي موهر كولوم، تم استخدام معيار موجي كولوم وليد المعدل للتنبؤ بنافذة وزن طينية آمنة. تم العثور على موجي كولوم وليد المعدل لتكون الأنسب من موهر كولوم في بئر H1. معيار فشل موهر لا يعطي تطابق، وهذا التكوين ليس جيداً لذلك لأن معايير فشل موهر تتجاهل الإجهاد الرئيسي المتوسط. ووفقاً لهذه الدراسة تم التنبؤ بضغط المسام ووزن الطين الغير مناسب (١٠,٤٩) باوند/جالون هو السبب الرئيسي لعدم الاستقرار البئر أثناء حفر تكوين نهر عمر الوحدة A في هذا البئر ويوصى أن يكون وزن الطين (١٤,٥-١٥) باوند/جالون. تم تحديد اتجاهات الضغوط الأفقية من قبل تكوين التصوير الجزئي (FMI). الحد الأقصى من السمات الأفقي للإجهاد في حقل الحلفاية النفطي هو حوالي N20-35E ، وتشير النتائج إلى أن تكوين نهر عمر يتميز بنظام التصدع العكسي ($S_{Hmax} > S_{Hmin} > S_V$). لبيولوجية التكوين يؤثر على الإجهاد الأفقي في حقل الحلفاية النفطي. الفواصل الزمنية عالية القوة والمتصلبة لها إجهاد أفقي وتشكيلات الصخر الزيتي وحجر المارلستون ذات القوة المنخفضة هي الفواصل الزمنية الرئيسية غير المستقرة لحفرة البئر. في الختام ، تجنب الآبار المائلة للغاية أو استخدام وزن الطين العالي لمنع فشل الاختراق وتقليل فقد الطين.

الكلمات الدالة: عدم استقرار حفرة البئر ، حقول النفط العراقية، بيانات مجسات الآبار، مبادئ الاجهادات، وزن الطين.