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Determination of Optimum Mud Weight Window for Tanuma Formation in Southern Iraq

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ABSTRACT

Problems with borehole instability contribute to an increase in non-productive time, mostly when drilling shale rocks. Drilling in this layer has several issues, including mud loss, tight holes, mechanically stuck pipes, caving, and large holes collapsing. The purpose of this paper is to construct a mechanical earth model (MEM) to evaluate the wellbore's stability. Through the application of MEM, the paper is focused on determining a range of mud weights that would ensure safety and optimize the drilling operation of new wells. The study of wellbore instability indicated that the main factor contributing to these complications was inadequate mud weight during the drilling process in the Tanuma shale formation. Moreover, as the wellbore inclination changed, the quantity of drilling density necessary to penetrate the Tanuma formation also changed substantially. In the Tanuma formation, wellbore angles surpassing 20° should be avoided, according to the model. The model issue that primarily refers to the shear failure in the Tanuma formation was comparatively reduced in the NW-SE direction (in the direction of the minimum horizontal stress). Furthermore, the sensitivity analysis showed that the mud window narrows when the deviation exceeds 10° and that the optimum design range for mud weight in vertical wells is between 11.2 and 14.9 ppg. The outcomes of this study can significantly contribute to the understanding of how to analyze the drilling operations and choose the appropriate mud weight parameters to maintain stability and reduce wellbore instability against shaly formations.

Keywords: Mud window, Mechanical earth model, Wellbore stability·

1. INTRODUCTION

A major issue that arises during drilling operations is wellbore instability, which can result in stuck pipes, caving, well kick or blowout, and loss of circulation. These problems take extra time to treat and increase the Nonproductive Time **(Faraj and Hussein, 2023; Edan and Hassan, 2023)**, as shown in **Fig.1** which illustrates the percentage of Nonproductive time

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for well X. More than 1000 million Dollars annually for the oil industry is due to Wellbore instability during drilling **(Mansourizadeh et al., 2016; Abbas et al., 2019)**. Wellbore stability is affected by several parameters such as formation pore pressure, wellbore strength, rock strength, in situ stress field, drilling fluid chemical characteristics, drilling techniques, vibration impact, frequency of excursions, drag, and torque. The geomechanical study attempts to enhance the safety of drilling new wells. By achieving the ideal mud weight **(Cui et al., 2020; Liu et al., 2021; Ma et al., 2022a, b)**. Heterogeneity significantly impacts wellbore stability and must be considered when creating a mechanical earth model **(Ma et al., 2022a, b)**. By using this data and selecting appropriate failure criteria, one may determine the mud weight window, encompassing both lower and upper limits.

Shale formation is one of the most exciting careers due to the high risk of wellbore instability, more than 75% of all geological formations (the root cause of 90% of wellbore stability issues) are due to Shale formations. Shale is a sedimentary rock of tiny mineral particles collected with clay and has a fine-grained consistency. The fissility in the rock or its tendency to split along flat planes of weakness is indicated by the existence of thin, parallel bedding layers that are less than one centimeter thick. Among the challenges faced during the drilling process in Tanuma Shale raised from the interplay between the drilling fluid and the formation are Sloughing, swelling, caving, cementing, and casing landing problems. It is considered one of the most inspiring creations to drill wells **(Mohammed et al., 2019)**. **(Aadnoy and Looyeh, 2019)** indicated there are two different kinds of failure mechanisms in boreholes, namely the breakout and tensile. The first rock failure is considered the most frequent problem with wellbore stability in vertical types. The fracturing of rocks away from the outside edge of the wellbore is known as "breakout" **(Neeamy and Selman, 2020; Gough and Bell, 2017).** Using a low-density drilling fluid with less pressure than breakout might lead to shear failure and fluid inflow into the hole due to the existing compressive conditions. Using high-density drilling fluid might cause tensile failure, resulting in weak formation fracture and lost circulation. Therefore, choosing suitable failure criteria is crucial in geomechanical modeling **(Darvishpour et al., 2019; Yang et al., 2020)**. The wide Mohr-Coulomb criterion appears incorrect because the intermediate primary stress is absent. To ensure safe drilling, it is, therefore, prudent to exercise caution when determining the required density of the drilling fluid **(Zimmerman and Al-Ajmi, 2006)**. More studies have demonstrated that this criterion has problems in many cases as it fails to consider intermediate stress and non-linear strength **(Vernik and Zoback, 1992)**. As a result, numerous criteria for actual triaxial or polyaxial failure have been established to evaluate the effects of Stress intermediate. However, the majority of these criteria possess constraints and produce poor outcomes, frequently necessitating the implementation of numerical methods. A novel three-dimensional criterion known as the Mogi failure criterion integrates two parameters that are related to the friction angle of strength and cohesion **(Al-Ajmi and Zimmerman, 2005; Ma et al., 2015)**.

The shaly formation in the southern Iraqi oilfields comprises the Upper Zubair, Tanuma, Nahr-Umr, and Ahmadi Shales **(Awadh et al., 2018; Awadh et al., 2021).** The drilling operations have increased challenges when dealing with these formations **(Alsultan et al., 2021; Awadh et al., 2021**). By addressing problems associated with wellbore instability, such as caving, mud losses, tight holes, mechanically stopped pipes, and severe hole collapse, this study provides valuable information for well-planning decision-making. The purpose of this paper is to construct a geomechanical model for a field in southern Iraq to understand and discuss the source and nature of problems that can occur during drilling practice, and to use results to guide future well drilling plans that are devoid of complications and study centered on the shale formation (Tanuma shale formation) that offers significant challenges (mostly caving problem) in achieving an appropriate resolution. Due to the instability of the Tanuma shale formation, significant mud weight is required; however, this may put the Mishrif reservoir at risk and increase the possibility of circulation loss. This study attempts to identify the causes of wellbore instability. It is important to modify the operational mud window for vertical wells to avoid or reduce instability issues. The data from offset wells is normally used to develop the mechanical earth model (MEM) to identify the optimal range of mud weight window during the predrill phase **(Neeamy and Selman, 2020)**.

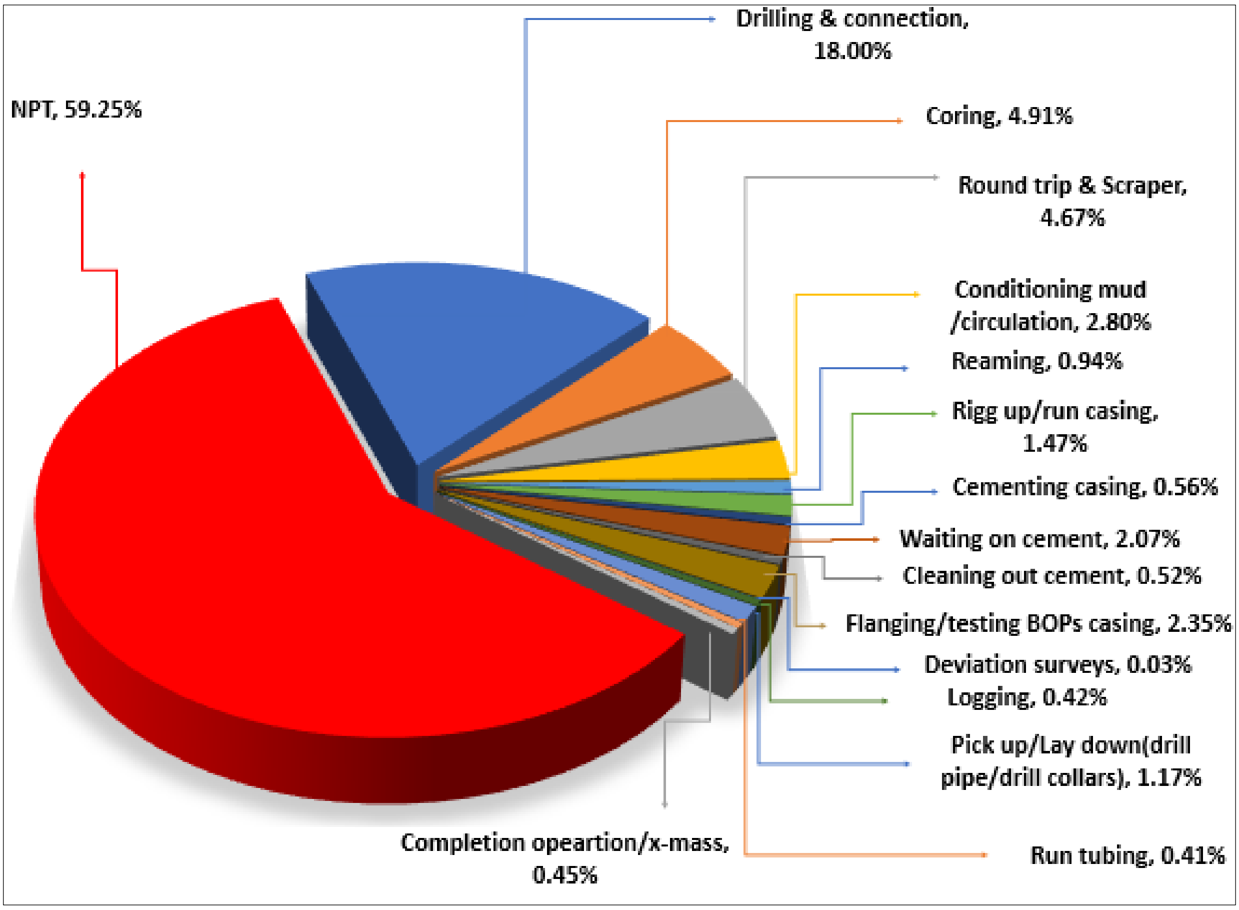


Figure 1. Nonproductive time for well X.

2. GEOMECHANICAL MODELING

A geomechanical model provides a thorough understanding of the factors related to wellbore instability. This model helps in accurate formation measurement. The model was built using data from offset wells that showed significant non-productive time (NPT) and frequent instances of wellbore instability. The model was developed utilizing the comprehensive method, as shown in **Fig.2** Laboratory tests were performed to calibrate and determine the fundamental parameters of the model. A mechanical properties evaluation was conducted on the formation. **(Aadnoy and Looyeh, 2019; Zoback, 2010)**. In this study, the geomechanical model was applied to one well (well X), and the model was calibrated with 11 core samples.

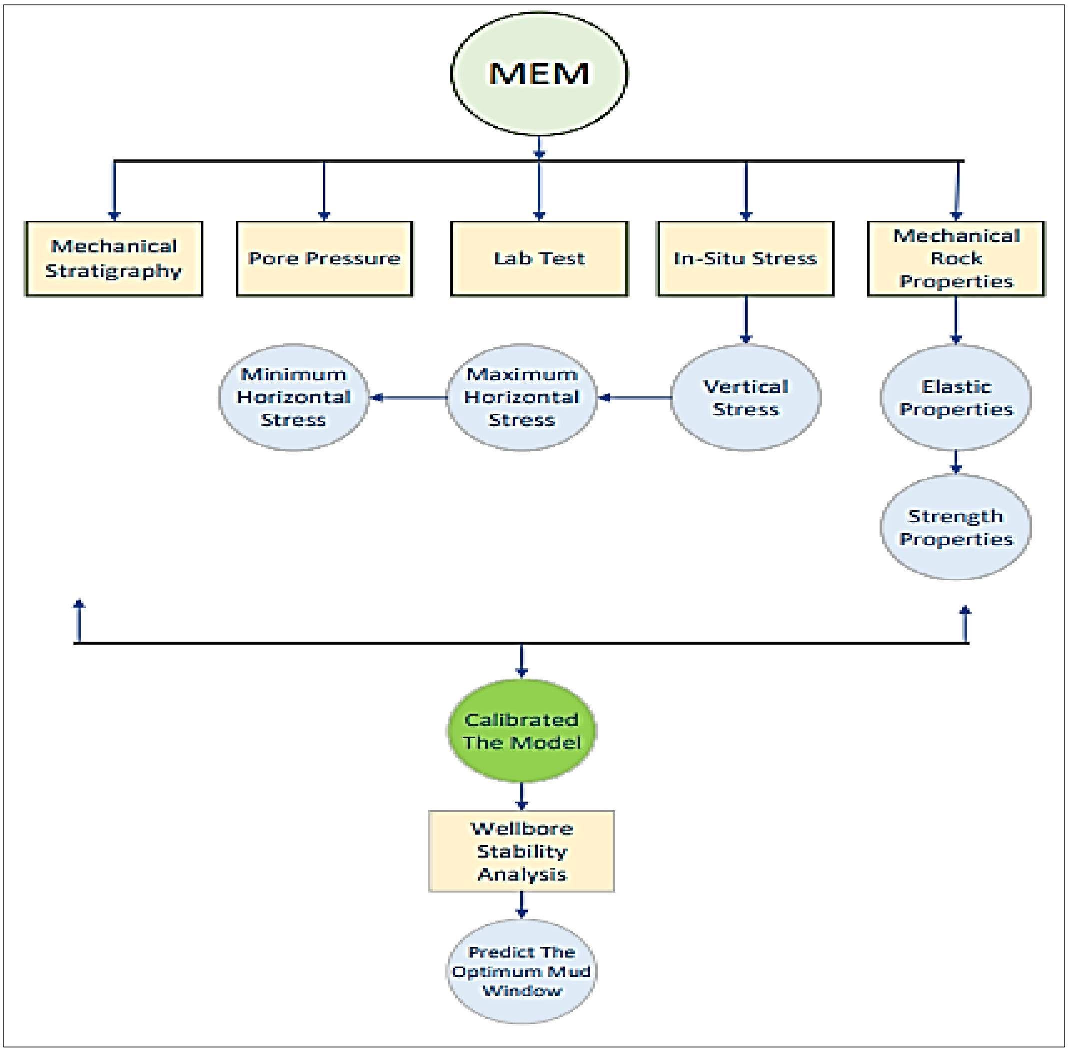


Figure 2. Workflow of MEM.

3. MECHANICAL STRATIGRAPHY

Shale and non-shale formations typically exhibit distinct differences in their mechanical response and properties. Mechanical stratigraphy can determine the rock's mechanical properties by using various correlations, if necessary. The study's lithology primarily consisted of carbonate, shale, and Dolomite. Non-shales were distinguished from shales by setting a threshold of 75 GAPI on the gamma-ray log in the well that was studied by **(Abbas and Hassan, 2021)**. Furthermore, master/mud log data was utilized to confirm the mechanical stratigraphy.

4. MECHANICAL PROPERTIES OF ROCK

Elasticity and strength are essential mechanical properties of materials for constructing the mechanical earth model (MEM). These characteristics may be identified by using different correlations based on well logs **(Aziz and Hussein, 2021; Abbas et al., 2019; Fjaer, 2008)**. Before calculating the dynamic elastic properties, conventional good logs must be available that include gamma ray, density log, compressional slowness, shear slowness, caliber log, and bit size, as shown in **Fig.3** Dynamic elastic properties (Explained from Eq. 1 to Eq. 4) often differ from static elastic properties and they must be converted into static elastic values using the relevant relationships **(Harrypersad et al., 2022; Adelinet et al., 2010)**. **Fig.4** in the sixth track uses the John Fuller correlation calculated from Eq. 5 to represent static Young's modulus and demonstrates a strong agreement with the direct measurements. Similarly, the seventh track in the same figure displays the static Poisson profile calculated from Eq. 6, which also shows good agreement with the direct measurements. The Poisson ratio calculation indicates moderate levels in shale formations and elevated values in limestone, but Young's modulus calculation suggests lower values in shale formations and increased values in limestone. Tracks eighth, ninth, and tenth exhibit rock strength characteristics that match well with the direct measurements. The parameters consist of the friction angle, unconfined compressive strength, and tensile strength calculated from Eqs. 7 to 9.

$$G_{dyn} = 13474.45 * \frac{\rho b}{(\Delta t_{shear})^2} \quad (1)$$

$$K_{dyn} = 13474.45 * \left[\frac{\rho_b}{(\Delta t_{comp})^2}\right] - \frac{3}{4} * G_{dyn} \quad (2)$$

$$E_{dyn} = \frac{9 * G_{dyn} * K_{dyn}}{G_{dyn} + 3 * K_{dyn}} \quad (3)$$

$$\upsilon_{dyn} = \frac{3K_{dyn} - 2G_{dyn}}{6K_{dyn} + 2G_{dyn}} \quad (4)$$

$$E_{sta} = 0.032 * E_{dyn}^{1.632} \quad (5)$$

$$\upsilon_{sta} = \upsilon_{dyn} * PR_{\ multiplier} \quad (6)$$

$$UCS = (4.242 + E_{sta}) * 145.037 \quad (7)$$

$$\varphi = 70 - 0.417 \times GR \quad (8)$$

$$T_S = UCS * K \quad (9)$$

Where:
Gdyn: shear modulus, Kdyn: bulk modulus, ρb: formation bulk density from density log, $\Delta tcomp$, and $\Delta tshear$: compressional and shear acoustic travel time, $Edyn$: dynamic Young's Modulus. $vdyn$: dynamic Poisson's Ratio, $E_{\ static}$: static Young's Modulus. UCS: is an unconfined compressive strength, φ: is the internal friction angle, GR: gamma-ray log, T_S : tensile strength, K : Facies and zone-based factor, 0.1unit less.

4.1 Pore Pressure

Pore pressure can significantly influence the stability of boreholes in constructing the mechanical earth model (MEM) **(Abbas et al., 2018)**. Overburden and effective stress are crucial factors in calculating pore pressure **(Allawi et al., 2022)**. Terzaghi initially proposed the concept of effective stress, which was later developed further by Biot **(Biot, 1941)** and Terzaghi **(Terzaghi et al., 1996)**. Pore pressure can be indirectly calculated using Eq. 10:

$$PPRS = \sigma_v - (\sigma_v - Ppn)(\frac{\Delta t_n}{\Delta t_o})^x \quad (10)$$

Where: PPRS: Pore pressure, σv: Vertical stress, Ppn: Normal hydrostatic pressure, Δt_n and Δt_o: Shale slowness

Fig.4 in the fifth track includes pore pressure (PPRS_EATON_S), which is obtained using the Eaton Slowness method, and formation pressure, which is directly measured in the well using the DST method. The calibration of pore pressure was performed using measurements obtained from a formation tester, as seen in **Fig.3**.

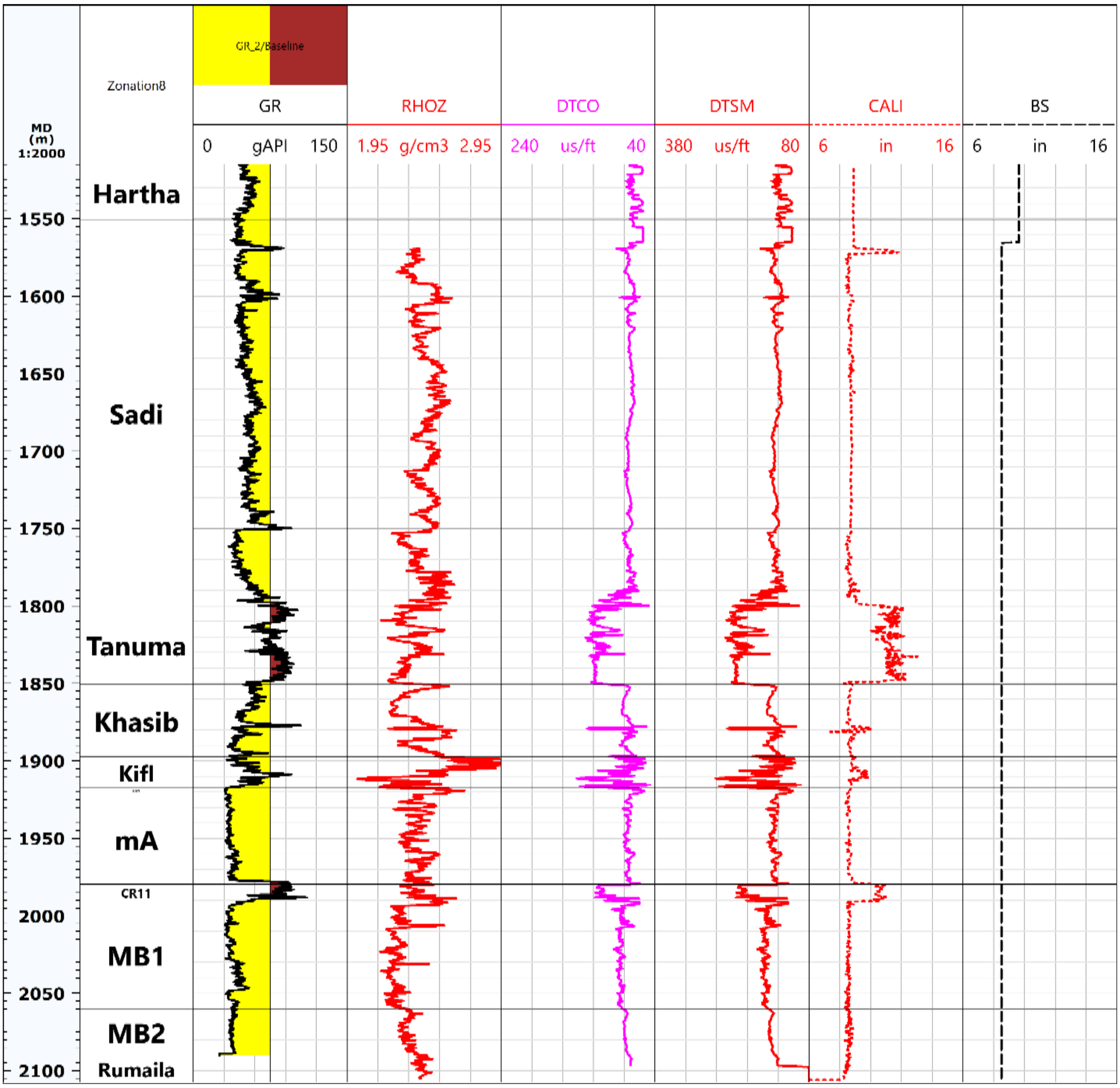


Figure 3. 1D MEM input data obtained from well X.

4.2 IN SITU STRESSES

Overburden stress, maximum horizontal stress, and minimum horizontal stress are the three elements of in-situ stress. The wellbore stability analysis is significantly influenced by these various stress components **(Veatch and Moschovidis, 1986)**.

4.2.1 Vertical Stress Magnitude (Overburden stress)

Vertical stress, which is also known as overburden stress, occurs at a specific location due to the gravitational force exerted by the overlying rock formations. Vertical stress is more efficient since it can be used to calculate pore pressure, horizontal stresses, and their relationship to classify the fault regime of formations. **Fig.4** illustrates the determination of vertical stress including evaluating bulk density and vertical depth, as seen in. The equation for calculating the vertical stress (σv) is as follows:

$$\sigma_v = \int_0^z \rho(z)\, gdz \quad (11)$$

Where: σ_v: vertical stress, Z: vertical depth, g: acceleration, ρ: bulk density

4.2.2 Magnitudes of Horizontal Stresses (Maximum and Minimum Horizontal Stresses)

Principal horizontal stress values are critical inputs in the analysis of the mechanical properties of rocks. When calculating the stress tensor, its maximum horizontal principal stress magnitude is regarded as the most intricate factor **(Reynolds et al., 2003)**. While various indirect methods exist for determining the minimum (Shmin) and maximum (SHmax) horizontal stress magnitudes, only one direct method exists for determining the minimum horizontal stress magnitude. This method is comparable to the microfrac test, leak-off test, and Mini-frac test **(Shaban and Hadi, 2020)**. The magnitudes of the horizontal stresses (SHMIN and SHMAX) were estimated utilizing the poroelastic model **(Thiercelin and Plumb, 1994; Peng and Zhang, 2007)**. The formulae of this model are dependent upon factors such as the static Young's modulus, the pressure exerted by the overburden, the static Poisson's ratio, and the pressure inside the pores, as elucidated in Eqs. 12 and 13.

$$\sigma_h = \frac{\upsilon}{1-\upsilon} * \sigma_v - \frac{\upsilon}{1-\upsilon} * \alpha P_o + \alpha P_o \frac{E}{1-\upsilon^2} * \varepsilon_x + \frac{\upsilon * E}{1-(\upsilon)^2} * \varepsilon_y \quad (12)$$

$$\sigma_H = \frac{\upsilon}{1-\upsilon} * \sigma v - \frac{\upsilon}{1-\upsilon} * \alpha P_o + \alpha P_o \frac{E}{1-\upsilon^2} * \varepsilon_y + \frac{\upsilon * E}{1-(\upsilon)^2} * \varepsilon_x \quad (13)$$

Where: v: Poisson's ratio (static), Pp: formation pressure, E: Young's modulus(static). α: Biot's coefficient is one, ε_x and ε_y can be estimated by using the below Eqs, which mean tectonic strains.

$$\varepsilon_x = \frac{\sigma_v * \upsilon}{E} * \left(1 - \frac{\upsilon^2}{1-\upsilon}\right) \quad (14)$$

$$\varepsilon_y = \frac{\sigma_v * \upsilon}{E} * \left(\frac{\upsilon^2}{1-\upsilon} - 1\right) \quad (15)$$

Fig.4 displays the fifth truck of the SHMIN-PHS, which represents the profile of the minimum horizontal stress in psi. The SHMAX-PHS represents the profile of the maximum horizontal stress in psi. The black circles indicate the closure pressure obtained from the mini-frac test, which is used to calibrate the continuous profiles of the minimum horizontal stress estimated by the poroelastic strain model.

4.2.3 In-Situ Stress Orientation

Wellbore image logs and caliper logs are frequently used in the oil industry, but they do not support all information related to wellbore failure **(Zoback et al., 1985)**. The data from the image log of a vertical well was analyzed, which showed the direction of the breakout zones around the wellbore. Wellbore collapse often occurs in the direction of the minimum horizontal stress. The image of the log reveals several breakouts, indicating an average breakout orientation of 115° in the Tanuma formation, as seen in **Fig. 5**. Therefore, the maximum horizontal stress is 25 degrees **(Allawi and Al-Jawad, 2023)**.

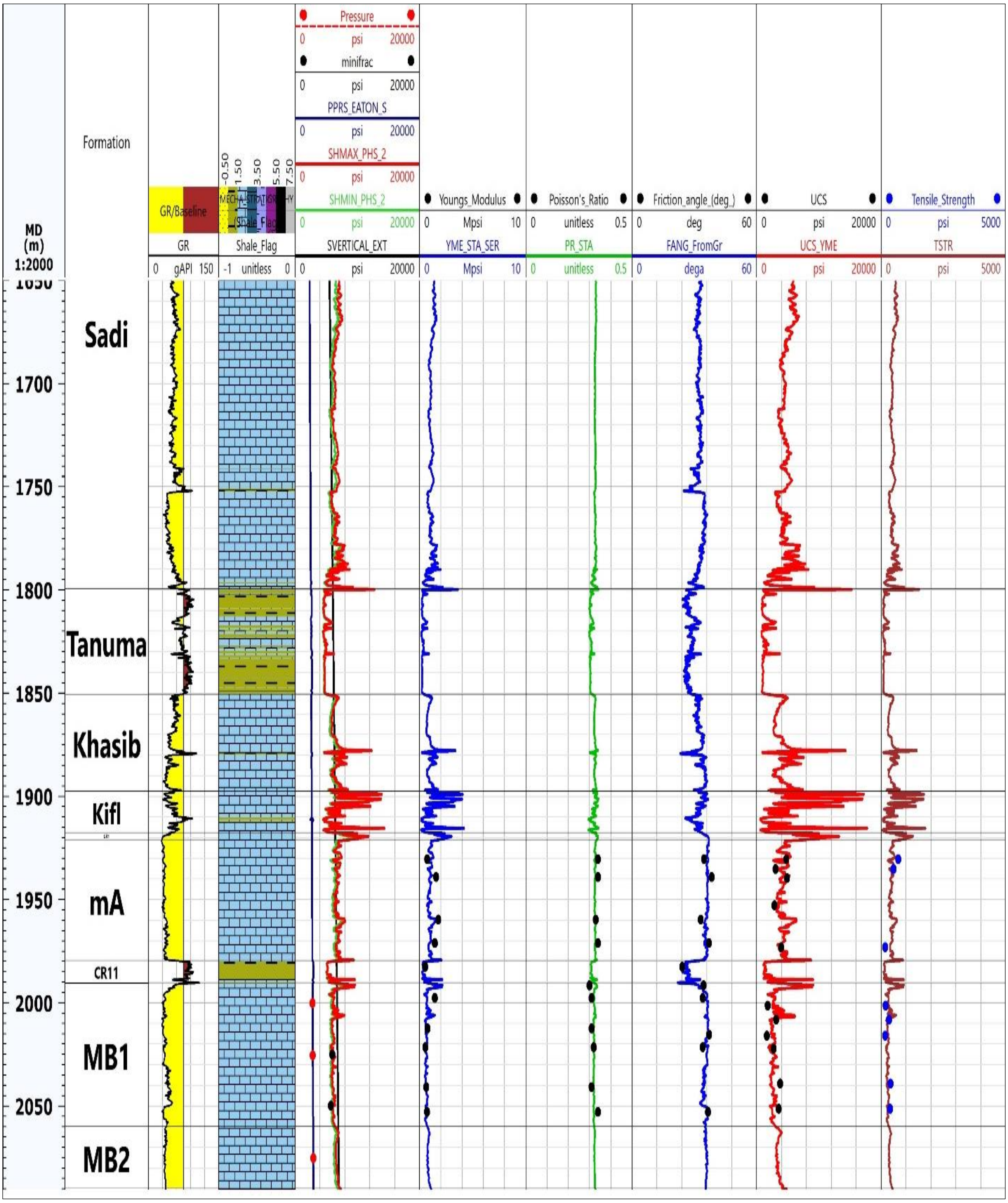
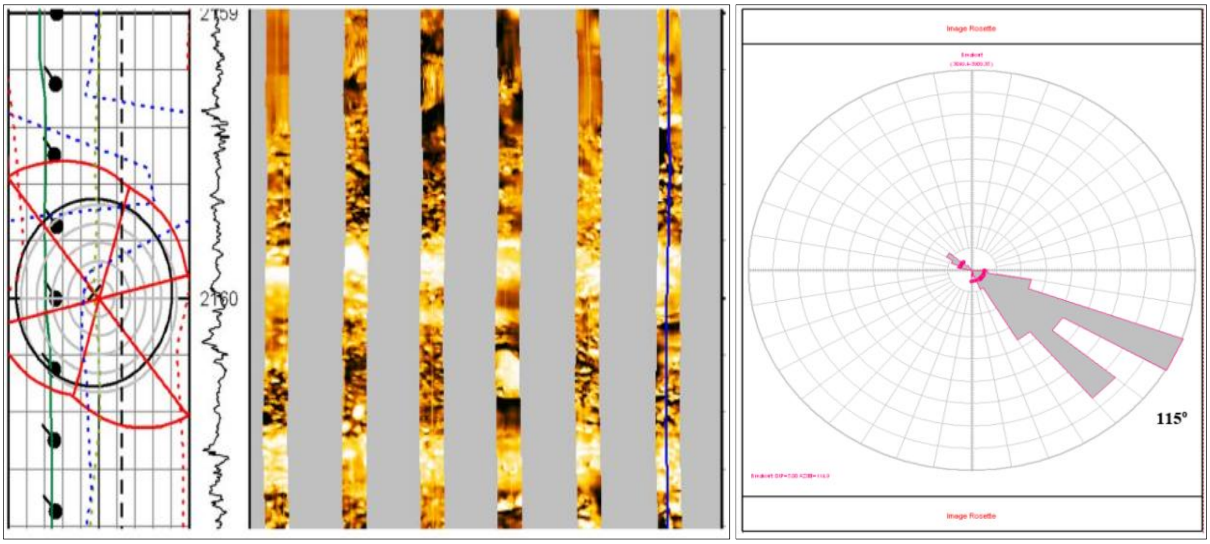


Figure 4. Stress, pore pressure, calibrate points, and strength and elasticity for well X.



(A) (B)

Figure 5. (A) Image log of the Tantuma formation's breakout orientation, (B) A Stereonet offering the orientation of all observed breakouts in an NW-SE direction **(Allawi and Al-Jawad, 2023)**.

5. RESULTS AND DISCUSSIONS

Multiple failure criteria were used in this study, including the Mogi-Coulomb Failure, Modified-Lade Failure, and Mohr-Coulomb criteria. These criteria were used to assess wellbore instability and the possibility of failure to determine realistic limits for wellbore collapse stability. The wells had non-productive time mostly due to instability difficulties resulting from two factors: the weight of the mud and the kind of mud used. The study indicates that the wellbore has the potential to collapse, particularly when shale formations are presented. The purpose of constructing this model was to determine the optimal mud weight and the appropriate failure criterion. Upon thorough evaluation of all the factors, the Mogi-Coulomb Failure criterion was determined to be the most appropriate selection. It showed a strong correlation with shear failure observed in both Tanuma and Mishrif (CR11) formations, as depicted in **Fig.6**, which is compatible with the caliper log. The shear collapse was caused by the mud's low density of 10.3 ppg, it was unable to generate sufficient hydrostatic pressure to prevent the wellbore collapse. The Mogi-Coulomb criterion is widely regarded as a dependable method for studying wellbore stability.

Furthermore, the Modified-Lade failure model was used, and its results nearly corresponded to those of the Mogi-Coulomb criteria in Tanuma formation but it relatively gives a low estimation for share failure against Mishrif (CR11) unit because the Modified Lade failure criterion is considered less conservative than the Mogi-Coulomb criterion, and affects on the intermediate stress when it comes to the prediction of failure impacts, as seen in **Fig. 7**.

However, using the Mohr-coulomb failure criterion, which was an overestimate compared with actual failure, since it was predicted overestimate failure in formations that had actual failure and predicted failure in stable formations such as (Sadi and Khasab), as seen in **Fig. 8**.

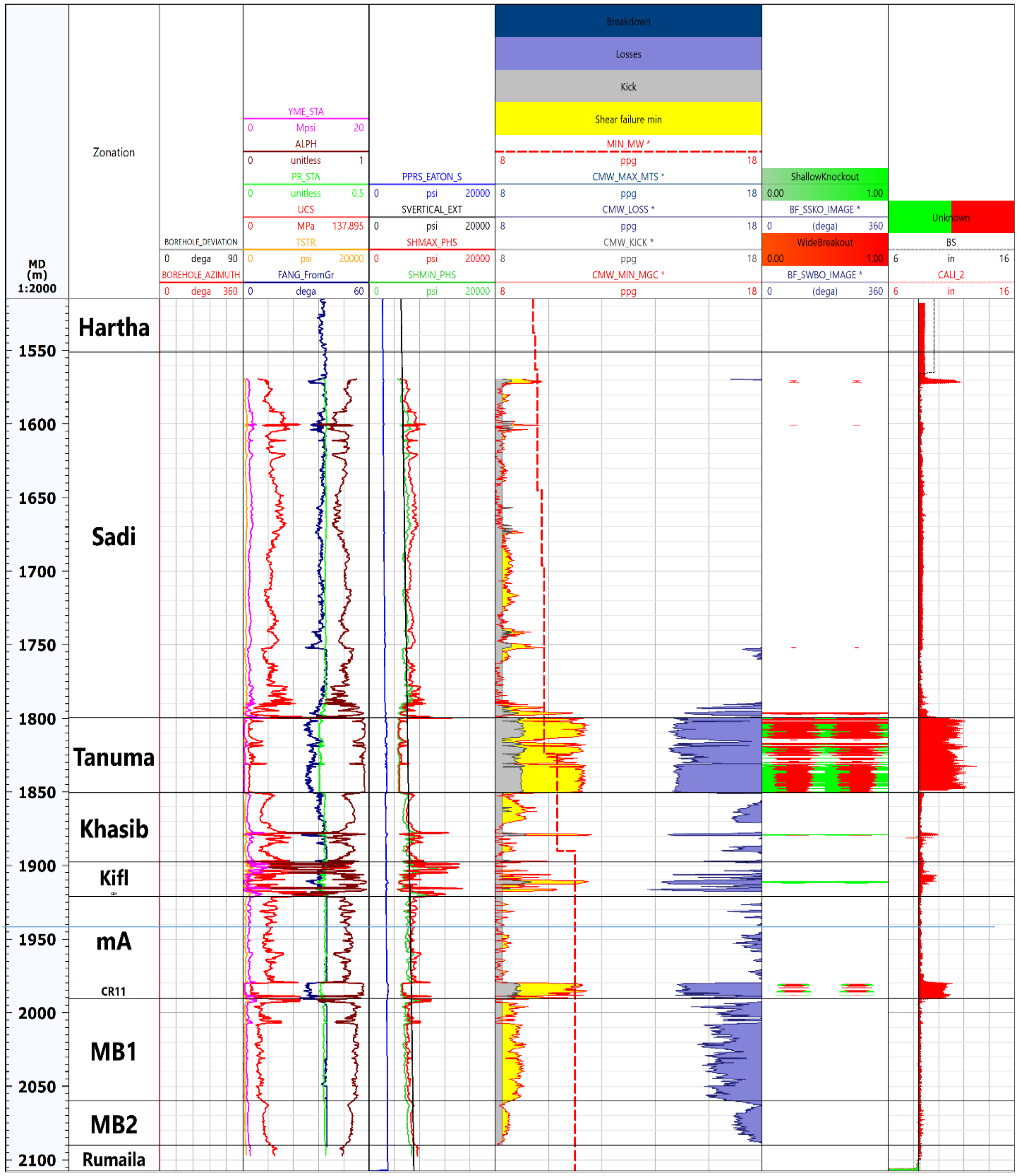


Figure 6. Mogi-Coulomb failure criterion for assessing wellbore instability for well X.

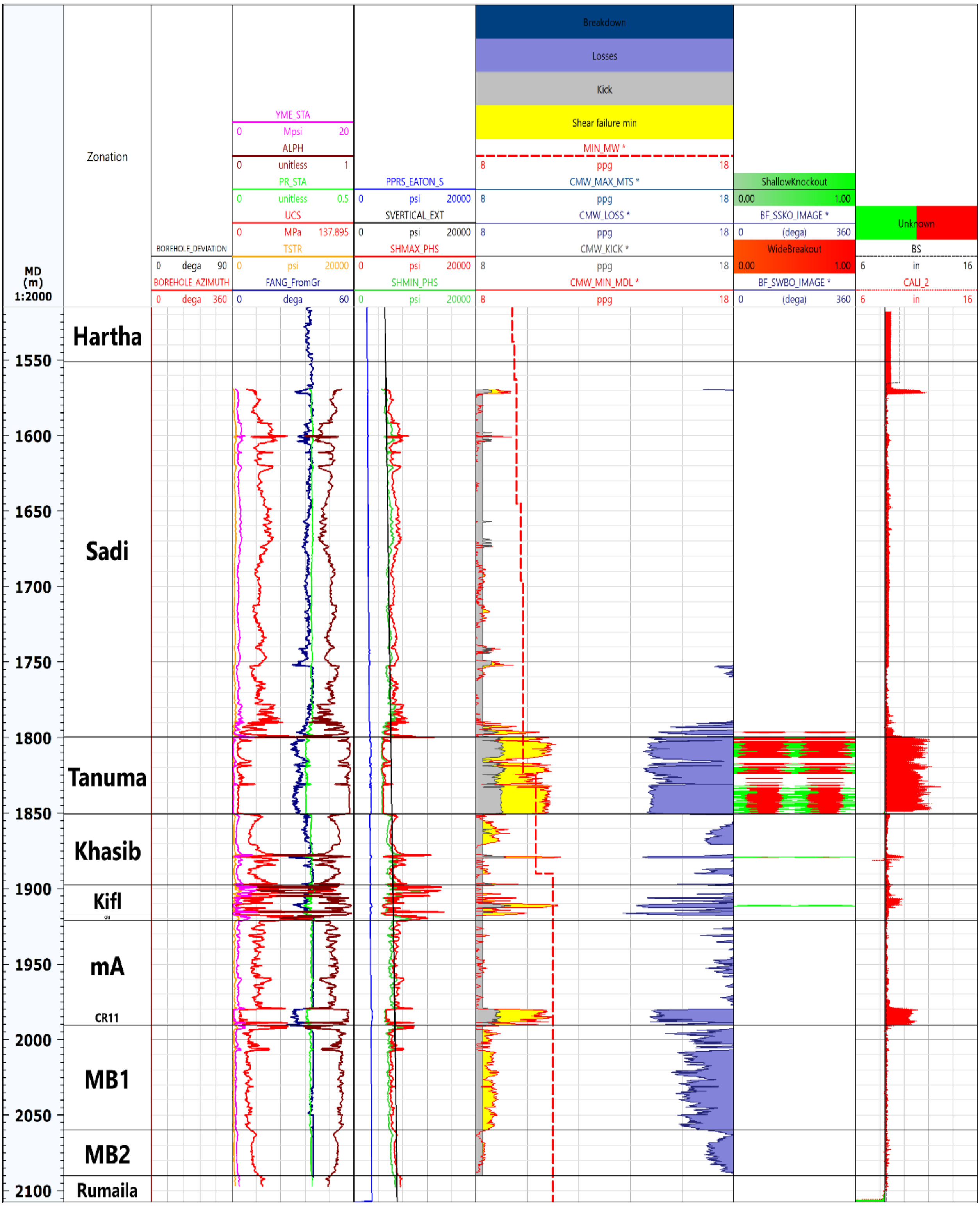


Figure 7. Modified-Lade failure criterion for assessing wellbore instability for well X.

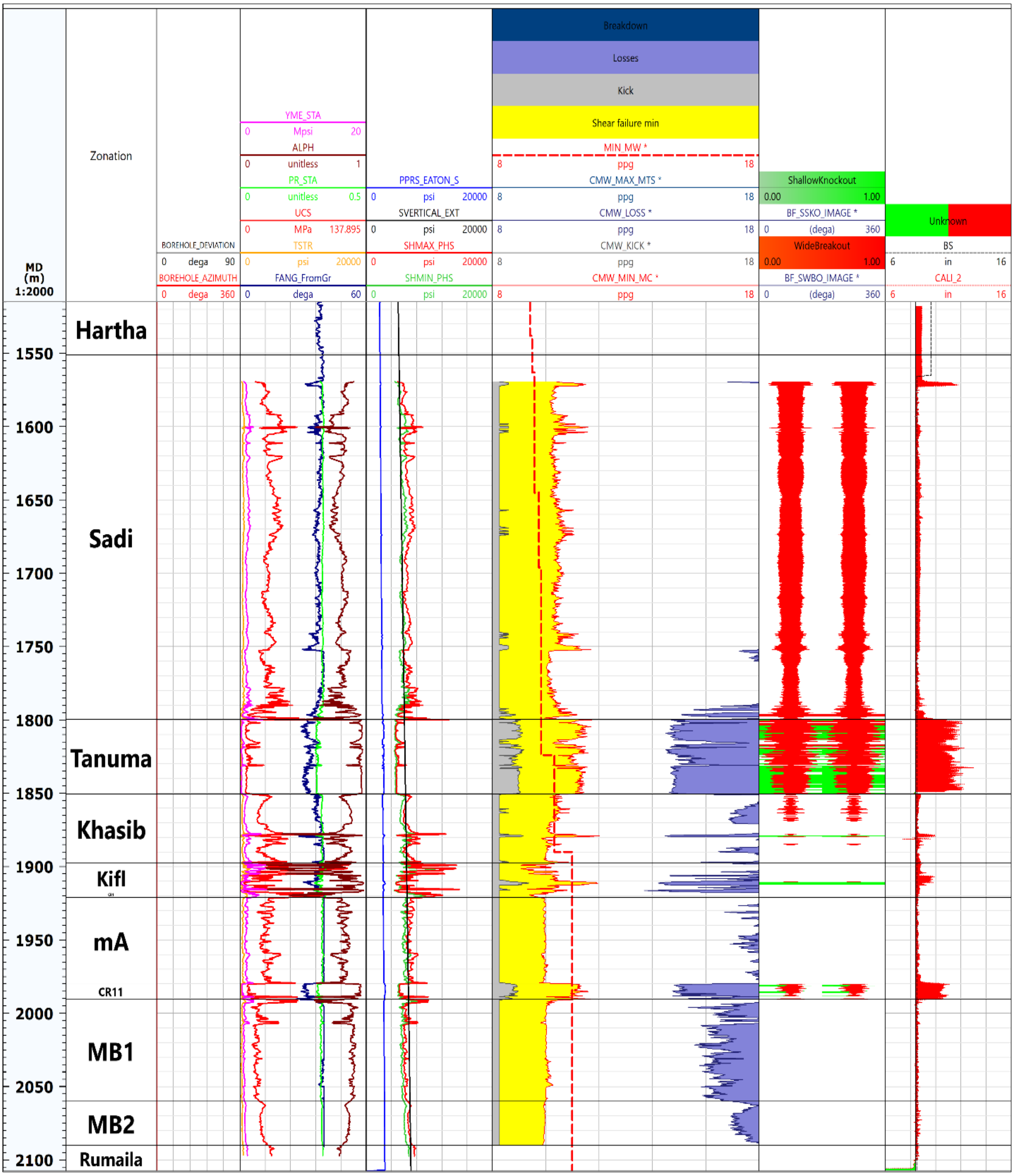


Figure 8. Mohr-Coulomb failure criterion for assessing wellbore instability for well X.

Hence, to ensure a stable wellbore, the safe operating drilling fluid density must fall within the mud weight window's middle region (white area) between yellow color (represents the shear failure) and light blue color (breakdown failure). Therefore, optimal mud density for future wells should be between 11–14.9 pounds per gallon (ppg), as shown in **Fig.9**, since it improves the stability of the wellbore.

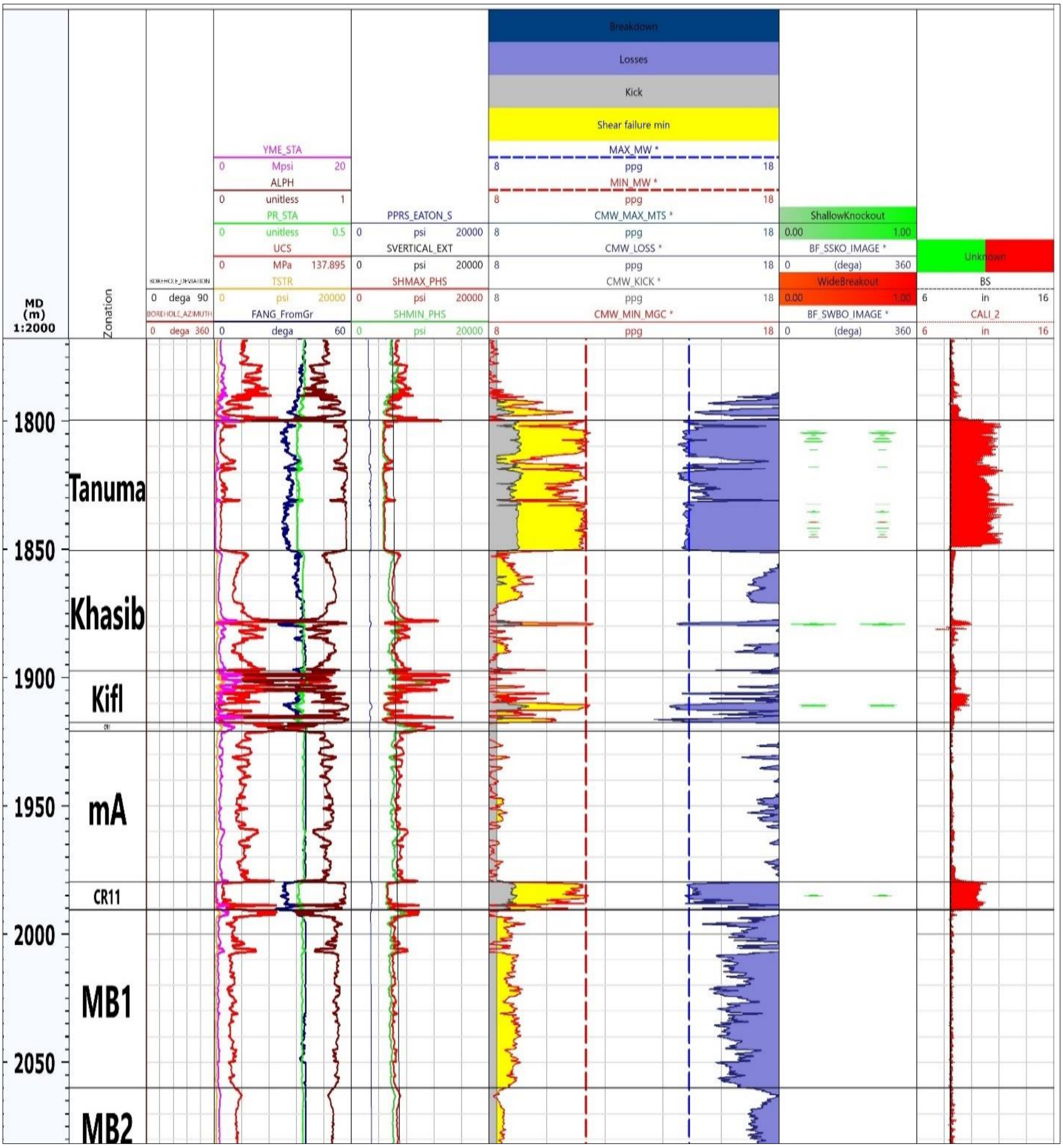


Figure 9. Design of wellbore stability by employing Modified-Lade failure criterion for well X.

6. SENSITIVE POINTS (TANUMA FORMATION)

A sensitivity analysis was performed in this formation at single depths (1804.87 m), focusing on the failure predicted by the Mogi-Coulomb Failure criterion using the actual mud weight. According to the model, the minimum mud weight to maintain stability in the Tanuma formation is 11.2 (ppg), as shown in **Fig.10a**. Tanuma has a greater susceptibility to hole collapse in comparison to other formations. In **Fig.10b,** the breakdown analysis suggests that the probability of tensile failure increases as the inclination exceeds 60° toward the direction of the maximum horizontal stress. However, it is important to note that below 50° in the direction of the minimum horizontal stress, breakdown may not happen. **Fig.10c** illustrates the narrowing of the mud window, which exhibited a deviation of over 10°. Furthermore, the critical areas indicate that to prevent formation from collapsing at this single depth in Tanuma formation, a horizontal well will need to maintain a maximum equivalent mud weight (EMW) of around 14.8 (ppg). In **Fig.10d**, it is shown that the azimuth does not have any impact on the drilling mud weight window.

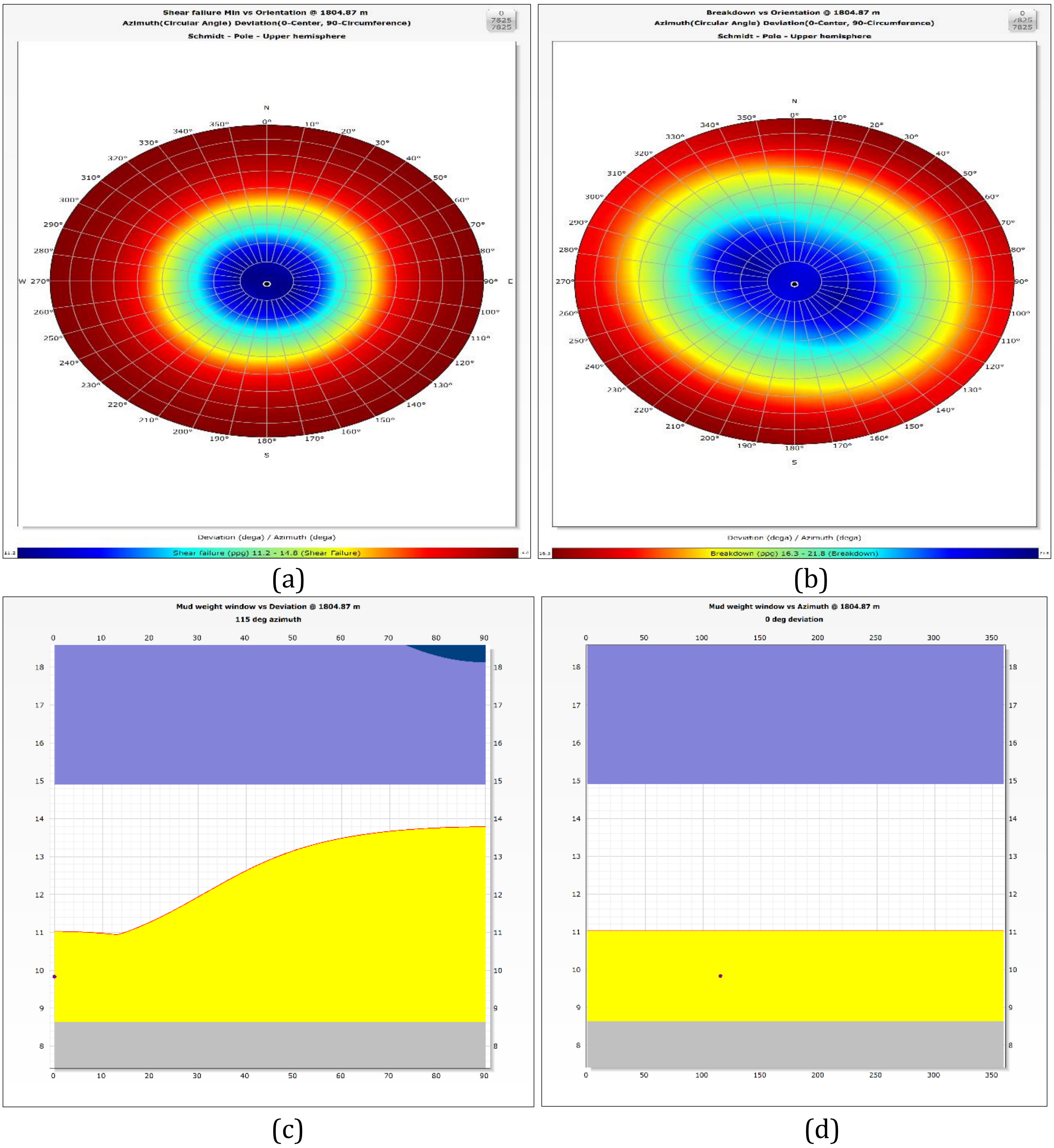


Figure 10. Tanuma formation sensitivity analysis for well X, (a) Mud weight of breakout vs orientation Mogi-Coulomb criteria, (b) Mud weight breakdown vs orientation, (c) Mud window vs deviation, and (d) Mud window vs Azimuth.

7. CONCLUSION

Geomechanics investigations depend significantly on an understanding of mechanical properties and stress characteristics, such as their magnitude and orientation. The MEM model was developed specifically for X field wells for forecasting the rock shear failure, the conclusions can be summarised as follows:

1- The geomechanical analysis showed a strong correlation between the laboratory core data and the static mechanical rock properties obtained based on the relationships described above, also laboratory core data and the static mechanical rock parameters computed by the chosen model was found to be in good agreement, which enhances our understanding of the geomechanical study.
2- The Mogi-Coulomb criterion is better than the Modified Lade and Mohr-Coulomb criterion for predicting rock failure, as determined by comparing the predicted rock failure to the actual failure observed in caliper logs and image logs used to validate the geomechanical model.
3- This study showed that the primary risk is the collapse of the wellbore caused due to the shear failure of Tanuma formation, rather than tensile fracture, which results in fluid losses.
4- The optimal design range for mud weight is determined to be between 11.2 and 14.9 ppg for vertical wells. This range aids in the reduction of wellbore instability for Tanuma formation.
5- The sensitivity study confirmed that vertical and slightly inclined wells exhibit greater stability when the inclination is less than 10° degrees. However, increasing the well inclination above 10° leads to a shrinking in the mud weight window and requires higher mud weight to avoid more complicated shear failure.
6- Based on sensitivity analysis, the azimuth of the wellbore has a more substantial influence, and the orientation that poses less risk is longitudinal to the direction of the minimum horizontal stress 115° (northwest to southeast).

Credit Authorship Contribution Statement

Hussien Luqman Abd: Investigation, Formal analysis, Writing –original draft. Hassan A. Abdul Hussein: Supervision, Writing –review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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تحديد امثل مجال لكثافة الطين لتكوين التنومة في جنوب العراق

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الخلاصة

تساهم مشاكل عدم استقرار الآبار في زيادة الوقت غير الإنتاجي، خاصة عند حفر الصخور الصخرية. في الماضي، كان الحفر يعاني من العديد من المشكلات، بما في ذلك فقدان الطين، والثقب الضيق، والأنابيب الملتصقة ميكانيكيًا، والتجويف، وانهيار الثقوب الكبيرة. الغرض من هذه الدراسة هو بناء نموذج الأرض الميكانيكية (MEM) لتقييم استقرار حفرة البئر. ومن خلال تطبيق MEM، ركزت الدراسة على تحديد مجموعة من الأوزان الطينية التي من شأنها ضمان السلامة وتحسين عملية حفر الآبار التطويرية. أشارت دراسة عدم استقرار حفرة البئر إلى أن العامل الرئيسي الذي ساهم في هذه المضاعفات هو عدم كفاية وزن الطين أثناء عملية الحفر في تكوين تنومة الصخري. علاوة على ذلك، مع تغير ميل حفرة البئر، تغيرت أيضًا كمية كثافة الحفر اللازمة لاختراق تكوين تنومة بشكل كبير. وفي تكوين التنومة يجب تجنب زوايا البئر التي تزيد عن 20 درجة، حسب النموذج. أشار النموذج إلى أن خطر انهيار الحفرة في تكوين تنومة انخفض نسبياً في اتجاه الشمال الغربي–الجنوبي (في اتجاه الحد الأدنى من الإجهاد الأفقي). علاوة على ذلك، أشار تحليل الحساسية إلى أن النطاق الأمثل لوزن الطين في الآبار العمودية يتراوح بين 11.2 إلى 14.9 ppg. بالإضافة إلى ذلك، تصبح نافذة الطين أضيق عندما يكون الانحراف أعلى من 10 درجات. تمثل نتائج هذه الدراسة مساهمات كبيرة في فهم كيفية اختيار معايير الوزن الطيني المناسبة وتخطيط عمليات الحفر لضمان الاستقرار وتقليل عدم استقرار حفرة البئر في التكوينات الصخرية (تكوين تنومة).

الكلمات المفتاحية: ثبات حفرة البئر، النافذة الطينية، نموذج الأرض الميكانيكية.