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Research Paper

Geomechanical Modeling for Determining Safe Mud Window and Evaluating Wellbore Wall Stability Using Numerical Simulation: A Case Study

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ABSTRACT

Mohr-Coulomb and Mogi-Coulomb failure criteria and caliper logs were utilized to determine the safe mud window. The results demonstrated that the formations located at the north wing of the studied oil field are more stable than the other zones. Among the investigated zones, Zone 5 is the most stable and Zone 6 is the least stable zone in terms of shear stability. Zones 1 and 2 in the south wing and Zones 3 and 4 in the middle wing of the oil field are also highly unstable. The Mohr-Coulomb failure criterion is more competent in predicting the stability of the wells compared to the Mogi-Coulomb failure criterion. The main reason for instability in the wells of this oil field is the selection of non-proper mud weight (usually far smaller than optimal mud weight) while drilling. The least mud window is in the middle zone in Well 3, and the safe mud window is about 15 Mpa in other parts of the field. In Zones 6 and 7 of the field, the safe mud window is 22.95 and 32.92 MPa, respectively. A 40-degree azimuth is the safe drilling route to decrease the instability of wells during drilling operations in this field.

Keywords: Wellbore stability; Azimuth; Mohr-Coulomb failure criterion; Mogi-Coulomb failure criterion; Safe mud window.

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1 INTRODUCTION

DRILLING oil and gas wells is one of the most fundamental elements of the oil industry. The advancement of drilling engineers' goals is one of the basic steps in the success of an oil engineering project. Maintaining the wellbore wall stability using the safe mud window is among the crucial influencing factors on the efficiency of the drilling operation.

Geomechanics of hydrocarbon reservoirs is among the influential factors in the development and management of oil and gas reservoirs. How to design and advance the drilling operation is affected by reservoir geomechanics. Besides, the drilling operation in fractured reservoirs possessing enormous heterogeneity, in deep reservoirs having high pressure and temperature, and in reservoirs suffering from unbalanced mechanical and physical conditions is massively affected by reservoir geomechanics. One of the most important concerns of drilling engineers is the stability of the wellbore wall and the determination of wellbore critical pressure. The lack of an accurate calculation and design of drilling mud results in

the instability of the wellbore wall and its collapse, which in turn can lead to differential sticking, drilling pipe collapse and failure, drilling mud loss, the well's diameter enlargement, and excess cost and time of drilling operation. Different approaches such as empirical, numerical, and analytical methods can be employed to predict the performance of the drilling operation, among which hybrid techniques based on empirical and numerical methods shed light on a better understanding of influencing factors on the stability and instability of wells [1-3].

The drilling operation is one of the most costly operations in the oil and gas industry, such that the success or failure of this operation substantially affects the fate of a well. Hence, the optimization of drilling as the optimization of the whole fate of a well is of paramount significance. The wellbore stability during drilling operations significantly influences the efficiency of drilling. The selection of an inaccurate mud weight is one of the most important reasons leading to wellbore instability. Therefore, the optimization of mud weight and the selection of a safe mud weight window is of vital significance. This correct selection causes an increase in the efficiency of the drilling operation and prevents incurring extra costs. Thus, the knowledge of influencing factors on the mud weight during drilling operation is essential [4-6]. Empirical methods, in which influencing parameters are obtained through the analysis of well logging data, are considered fundamental methods. Moreover, the use of failure criteria such as Mohr-Coulomb and Mogi-Coulomb is also accounted as an analytical method for gaining a better understanding of the influencing factors on the wellbore stability. Finally, the employment of numerical modeling using industrial software like Petrel can help determine the safe mud window for the sake of the optimization of the drilling operation.

Mondal and Chatterjee [7] investigated quantitive risk analysis to determine a safe mud window in one of the Indian oil reservoirs. They used the Mogi-Coulomb failure criterion to calculate mud weight. They matched modeling results with actual operational data and examined the geomechanical model from various standpoints. Mud weight calculations reflected that the mud weight is affected by pore pressure and strength-related parameters of the formation. They argued that horizontal stress has an important role in the mud weight. Darvishpour et al. [8] explored wellbore wall stability in a sandstone reservoir through safe drilling mud weight. Flac3D and drilling reports were utilized to predict the safe mud window. Different parameters such as pore pressure, formation stress, and wellbore stress were investigated. The results demonstrated that decreasing friction angle results in a decrease in mud weight and an increase in wellbore wall instability. Furthermore, a decrease in formation pore pressure and horizontal stress leads to a decrease in wellbore wall instability. These scholars suggested that their model provides more comprehensive information regarding in-situ stresses and fracture networks compared to previous models. Zhang et al. [9] examined mud weight in shale layers and stated that improving the capability of building a high-quality mud cake reduces collapse pressure and increases fracture pressure. As a result, the safe range of mud weight window is improved, which in turn increases wellbore stability time. Through modification of the stress equation, they concluded that the suggested model can calculate safe mud weight using parameters like fracture pressure, pore pressure, and in-situ stresses. Kadkhodaei [10] scrutinized the safe mud window in one of the offshore wells of the Middle East. First, well logging data and rock strength experiments were used and the geomechanical model was built. Afterward, rock mechanics-related parameters were estimated using well logging data. The simulation results demonstrated that the safe mud window is in the azimuth of about 120 degrees parallel to minimum horizontal in-situ stress. The upper limit of mud pressure for overcoming the collapse pressure was at an azimuth of N030E, which was considered the worst drilling scenario. These researchers declared that geomechanical modeling is a reliable and efficient method to check and determine the safe mud window. Beheshtian et al. [11] calculated the safe mud window in a gas reservoir via well logging data including data of Gamma ray, Gamma ray spectroscopy, and porosity logs (i.e., sonic, neutron, and density logs). They investigated the safe mud window during overbalanced drilling by determining the upper and lower pressure limits of the wellhead. Artificial intelligence was also utilized to determine the safe mud window through the analysis of pore pressure and fracture pressure. The coefficient of regression was 0.9948 for pore pressure and 0.9967 for fracture pressure, indicating the high reliability of the proposed model. In the end, these scholars suggested that the use of artificial intelligence considerably helps us in interpreting and determining the safe mud window. Qiu et al. [12] examined the safe mud weight in an offshore well and stated that horizontal drilling in gas hydrate reservoirs is one of the most effective methods for improved oil recovery (IOR), although many operational problems such as wellbore instability and unplanned fracturing exist for the application of this technique. This emphasizes the importance of determining an accurate value for drilling mud weight for such reservoirs. They concluded that increasing mud circulation time and increasing circulation flow rate will affect the temperature profile, especially in the horizontal section of the wellbore, leading to a decrease in fracture pressure and collapse pressure. Ultimately, they declared that the saturation of gas hydrates has a direct impact on fracture pressure and high gas saturation will increase safe mud window width.

Petroleum reservoirs possess special complexities and unique conditions in terms of geology, stratigraphy, and pore pressure. Consequently, the determination of influencing parameters like the safe mud window in these reservoirs is inherently challenging, and therefore, the application of wellbore stability analysis for a given oil field (i.e., case study) may be considered a novelty. In this study, the effect of parameters such as elastic modulus, uniaxial compressive strength, pore pressure, overburden and horizontal stresses, and drilling-induced stresses is investigated from Mohr-Coulomb and Mogi-Coulomb failure's standpoints. Then the effect of these parameters on wellbore wall stability and determination of safe mud window is examined through different numerical models. Initially, well logging data (such as acoustic logs) and well-established empirical relationships are utilized, and then, a geomechanical model is built and prepared for one of the wells of the Middle East. Afterward, the safe mud window is calculated and determined using two failure criteria of Mohr-Coulomb and Mogi-Coulomb. For this purpose, the obtained results of the two models are used to determine the formed fractures in the wellbore and then these results are compared. Ultimately, Petrel software is employed to validate the results of the geomechanical model and failure criteria. The research results can be utilized to cast light on influencing factors on wellbore wall stability in other wells of this oil field.

2 TARGET OIL FIELD

This oil field was discovered in 1961. The field is one of the biggest oil fields in the Middle East, and its length and width are about 72 km and 11 km. This field possesses different formations with different thicknesses. Table 1 presents a summary of information regarding different formations of the field. To analyze and evaluate the wellbore wall stability in this field, well logging data of one of the field wells (which is located at a depth of 3510 m to 3869 m) have been used. Table 2 presents a summary of data on the target well. Fig. 1 shows the geographical position of the field.

Table 1
Different formations of the studied field

Formation	Depth (m)
A	2145
M	2479
G	2758
R	3511

Table 1
Target well information

Well No.	04
Depth (m)	3869
Diameter (in)	8.38
Interval (m)	3510-3869

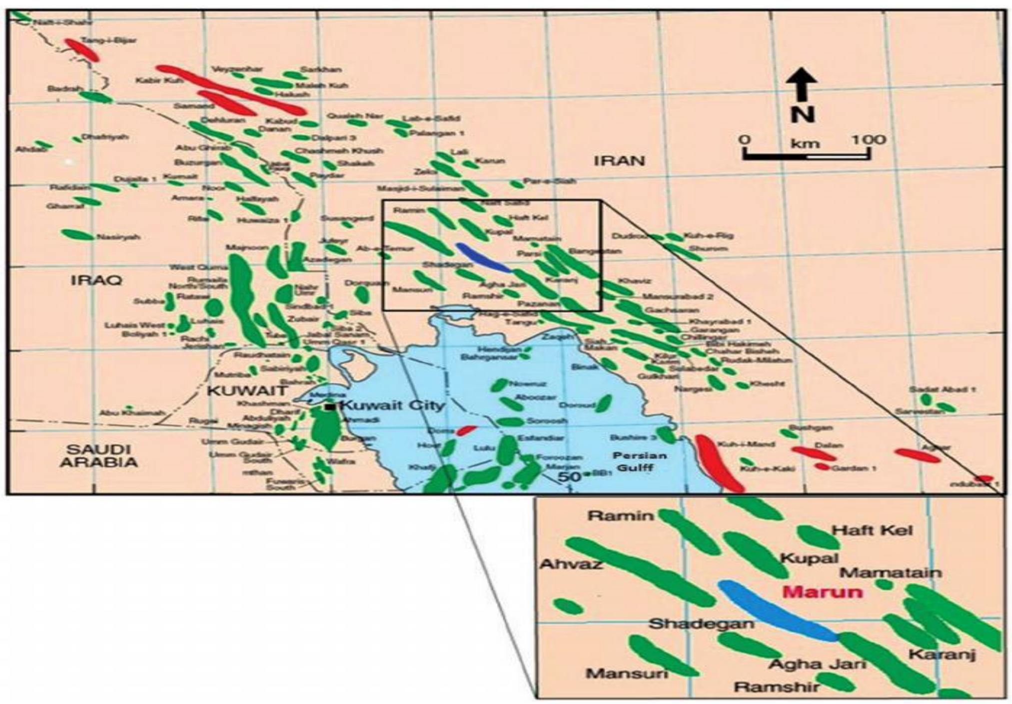

Fig. 1
Geographical position of the studied field.

3 GEOMECHANICAL MODEL

To determine a safe mud window, the preparation of a geomechanical model is necessary. For this purpose, it is possible to utilize the analysis of cores and the interpretation of logs to prepare the geomechanical model. In this research, empirical relationships and the results of porosity logs (sonic log, density log, and neutron log) were employed to build the geomechanical model.

3.1 Formation Elastic Parameters

Formation elastic parameters such as Young's modulus of elasticity, Poisson's ratio, and the shear modulus of elasticity were calculated using empirical relationships (Eqs. 1-5) [11]. Parameters like shear and compressional wave velocity and density are used in these equations.

$$E_{dyn} = \frac{\rho v_s^2 \left(3v_p^2 - 4v_s^2\right)}{\left(v_p^2 - v_s^2\right)} \quad (1)$$

$$E_{sta} = 0.414E_{dyn} - 1.0593 \quad (2)$$

$$\vartheta_{dyn} = \vartheta_{sta} = \frac{\left(v_p^2 - 2v_s^2\right)}{2\left(v_p^2 - 2v_s^2\right)} \quad (3)$$

$$G = \frac{E_{sta}}{2\left(1 + \vartheta_{sta}\right)} \quad (4)$$

$$K = \frac{E_{sta}}{3\left(1 - 2\vartheta_{sta}\right)} \quad (5)$$

where E_{dyn} stands for dynamic Young's modulus, ρ denotes density, v_s represents shear wave velocity, v_p symbolizes compressional wave velocity, E_{sta} indicates static Young's modulus, ϑ_{dyn} signifies dynamic Poisson's ratio, ϑ_{sta} stands for static Poisson's ratio, G denotes the shear modulus of Elasticity, and K represents the bulk modulus of Elasticity.

3.2 Formation Strength

To determine the uniaxial compressive strength of the formation, Eq. (6) was utilized [11]. Tensile strength was assumed to be 0.08 times UCS.

$$UCS = 2.28 + 4.1089\, E_{sta} \quad (6)$$

3.3 Formation Plastic Parameters

To determine formation plastic parameters, Eqs. (7-8) are used to estimate internal friction angle and cohesion, respectively [11].

$$\emptyset = 26.5 - 37.4(1 - NPHI - V_{shale}) + 62.1(1 - NPHI - V_{shale})^2 \quad (7)$$

$$C = \frac{UCS}{2\,tan\theta} \quad (8)$$

$$V_{shale} = \frac{Gr - Gr_{min}}{Gr_{max} - Gr_{min}} \quad (9)$$

$$\theta = 45 + \frac{\varphi}{2} \quad (10)$$

where φ represents formation porosity, *NPHI* denotes porosity obtained through neutron log, V_{shale} stands for shale volume, *C* symbolizes cohesion, *UCS* indicates uniaxial/unconfined compressive strength, *Gr* represents the value of the gamma ray obtained via the gamma ray log, Gr_{min} and Gr_{max} denote the minimum and maximum gamma rays recorded by the gamma ray log, and φ symbolizes the internal friction angle.

3.4 Formation Failure Criterion

To determine formation strength and the role of drilling mud weight, Mohr-Coulomb and Mogi-Coulomb failure criteria were employed. Mohr-Coulomb criterion's parameters are presented in Table 3. It is possible to have an optimal mud pressure using the Mohr-Coulomb criterion in three different cases (see Table 4) [11]. Furthermore, the effect of intermediate principal stress on the reservoir rock strength and wellbore stability is explored using the Mogi-Coulomb failure criterion. Table 5 presents the method for determining the optimal mud pressure by using the Mogi-Coulomb failure criterion.

Table 3
Parameters of Mohr-Coulomb failure criterion

Parameter	θ	UCS	σ_v	σ_θ	σ_h
	Poisson's ratio	Uniaxial compressive strength	Vertical stress	Tangential stress	Min. horizontal stress

Table 3
Parameters of Mohr-Coulomb failure criterion [continued]

Parameter	σ_H	σ_z	σ_r	φ	p_p
	Max. horizontal stress	Axial stress	Radial stress	Friction angle	Pore pressure

Table 4
Determination of optimal mud pressure using Mohr-Coulomb failure criterion [11]

Case	$\sigma_1 \geq \sigma_2 \geq \sigma_3$	Borehole failure will occur if $P_w \leq P_{wb}$, where P_{wb} is given by
1	$\sigma_z \geq \sigma_\theta \geq \sigma_r$	$P_{wb1} = (B - C)/q$
2	$\sigma_\theta \geq \sigma_z \geq \sigma_r$	$P_{wb2} = (A - C)/(1 + q)$
3	$\sigma_\theta \geq \sigma_r \geq \sigma_z$	$P_{wb3} = A - C - qB$

Table 5
Determination of optimal mud pressure using Mogi-Coulomb failure criterion [11]

Case	$\sigma_1 \geq \sigma_2 \geq \sigma_3$	Borehole failure will occur if $P_w \leq P_{wb}$, where P_{wb} is given by
1	$\sigma_z \geq \sigma_\theta \geq \sigma_r$	$P_{wb1} = \frac{1}{6 - 2b'^2}\left[(3A + 2b'K) - \sqrt{H + 12(K^2 + b'AK)}\right]$
2	$\sigma_\theta \geq \sigma_z \geq \sigma_r$	$P_{wb2} = \frac{1}{2}A - \frac{1}{6}\sqrt{12[a' + b'(A - 2P_o)]^2 - 3(A - 2B)^2}$
3	$\sigma_\theta \geq \sigma_r \geq \sigma_z$	$P_{wb3} = \frac{1}{6 - 2b'^2}\sqrt{(3A - 2b'G) - \sqrt{H + 12(G^2 - b'AG)}}$

where

$$A = 3\sigma_H - \sigma_h$$

$$B = \sigma_v + 2\vartheta(\sigma_H - \sigma_h)$$

$$H = A^2(4b'^2 - 3) + (B^2 - AB)(4b'^2 - 12)$$

$$K = a' + b'(B - 2P_o)$$

$$G = K + b'A$$

4 NUMERICAL MODEL CREATION

Petrel software was utilized to build the three-dimensional model. Fig. 2 exhibits the location of the wells of the oil field and Fig. 3 displays the drilling trajectory in this field. Fig. 4 depicts the geometry of the structural model of the studied field. The total number of cells in the field in this modeling was equal to 47,551,185. The number of layerings of the target field is illustrated in Fig. 5.

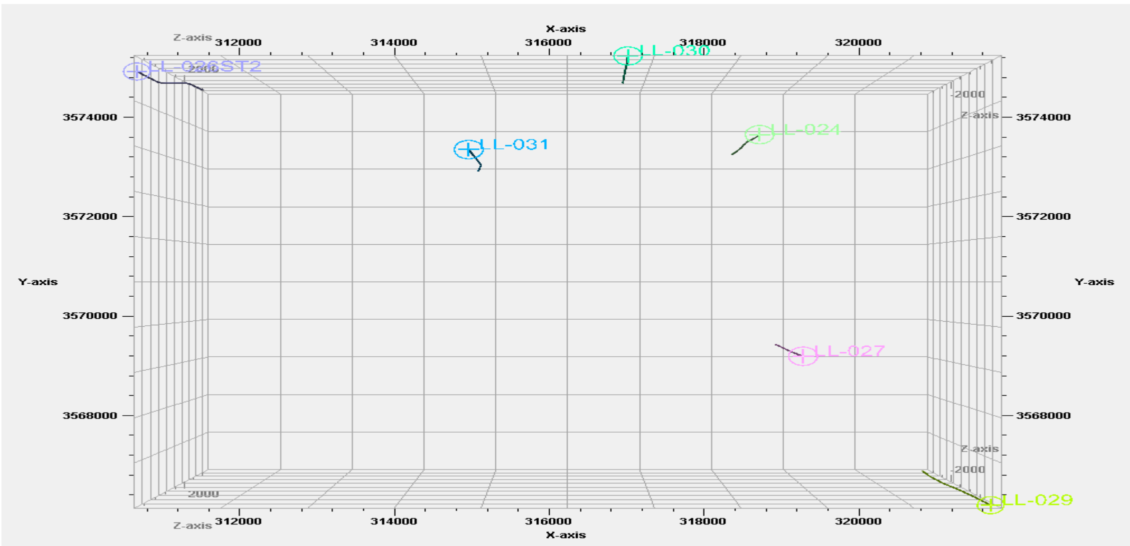

Fig. 2
Location of the wells of the oil field.

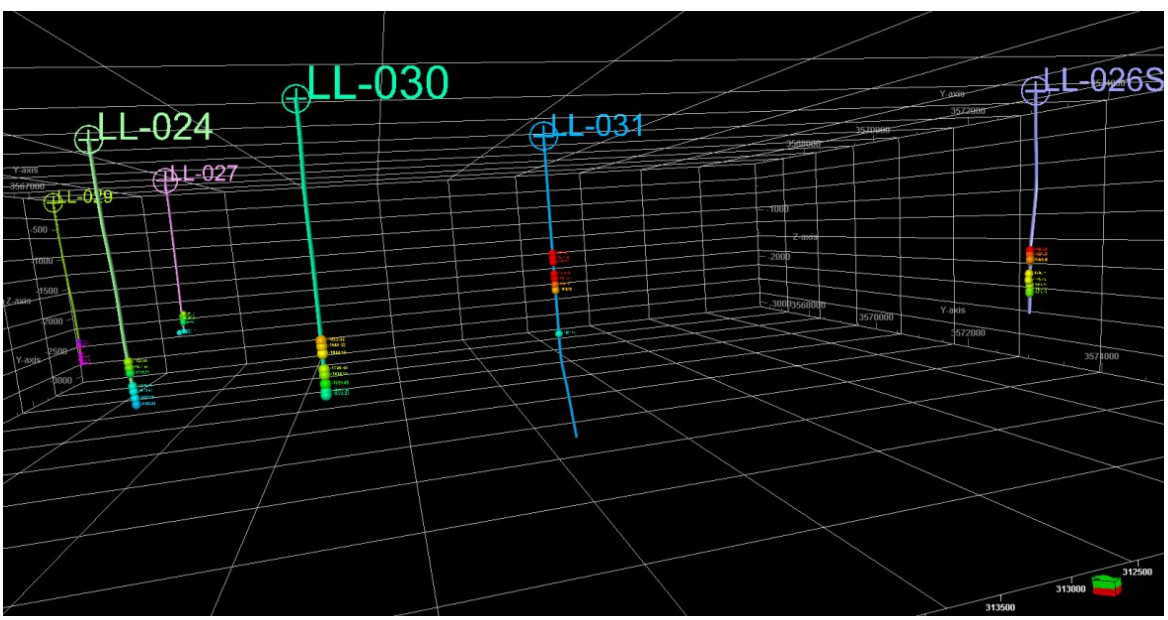

Fig. 3
Drilling Trajectory in wells of the field.

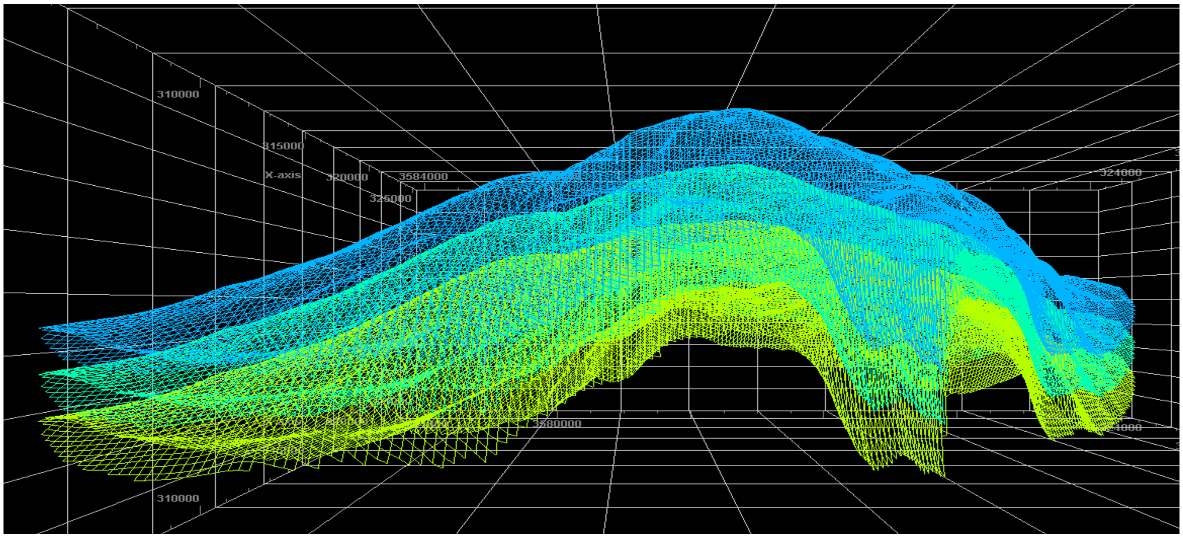

Fig. 4
Geometry of the structural model of the investigated field.

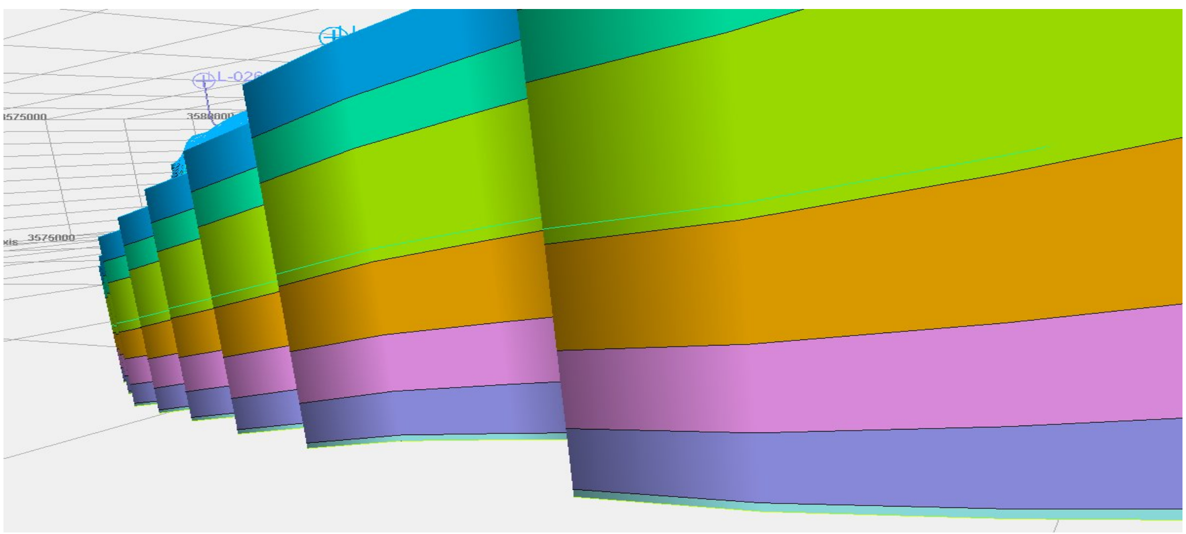

Fig. 5
Field layering.

5 EVALUATION OF IN-SITU STRESSES

The investigation of reservoir rock's in-situ stresses, which were calculated using vertical stress gradient increase with depth in this study, is important during the evaluation of wellbore wall stability. The overburden stress gradient was considered 0.0245 MPa/m. Figs. 6-8 depict three-dimensional modeling of vertical stress, minimum horizontal stress, and maximum horizontal stress. Fig. 6 shows that the depth increase has a direct impact on the value of vertical stress.

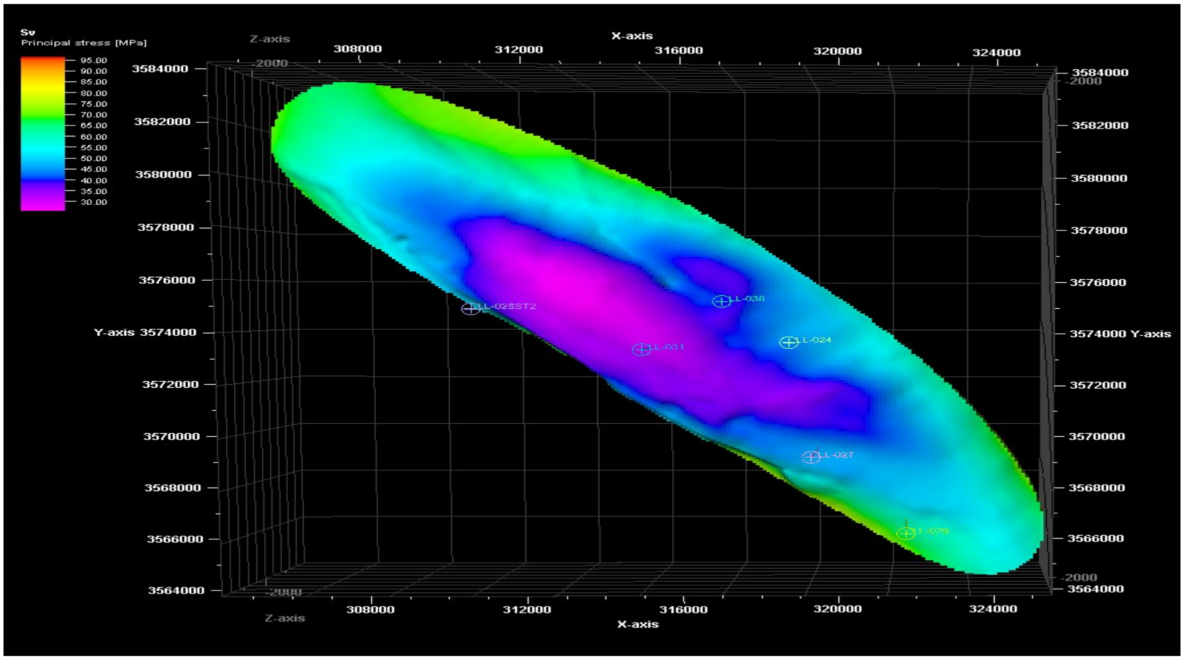

Fig. 6
Moldeld vertical stress.

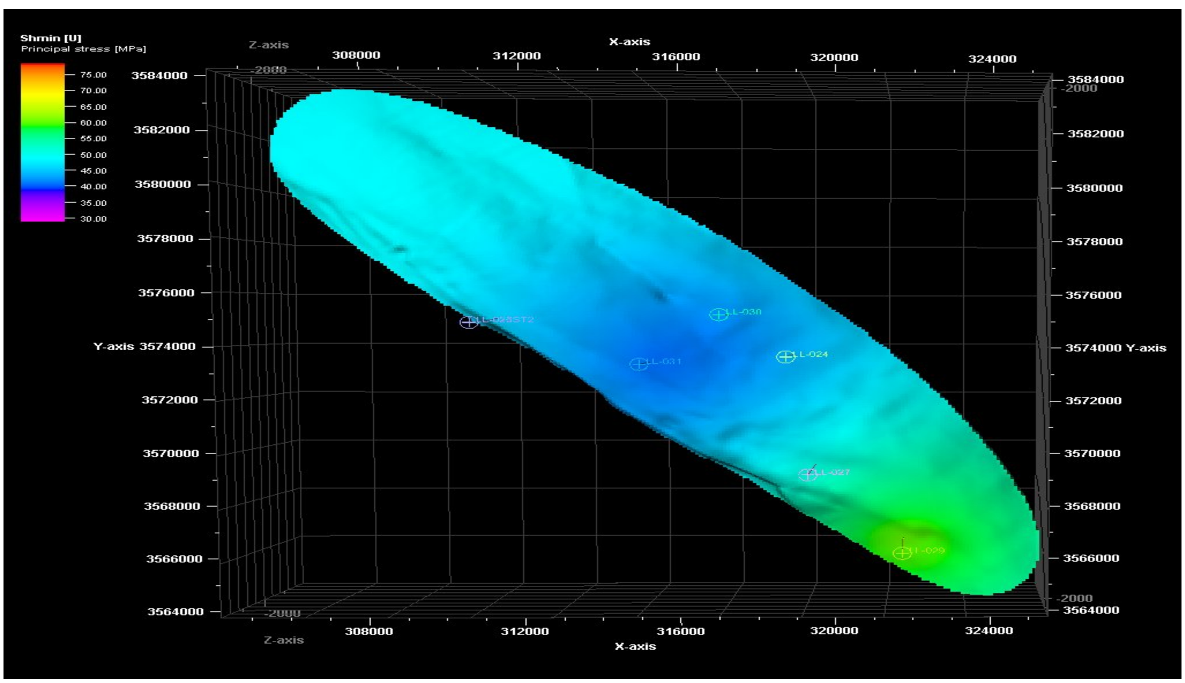

Fig. 7
Moldeld minimum horizontal stress.

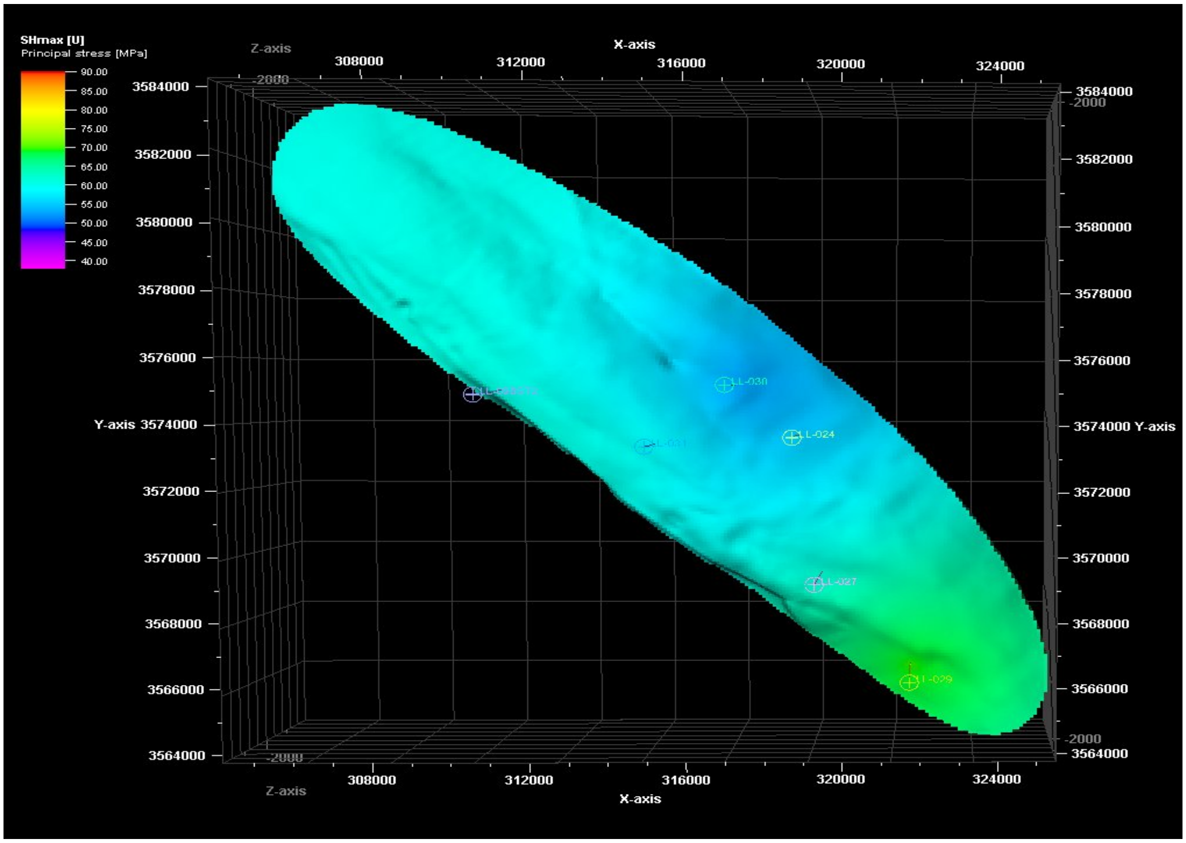

Fig. 8
Moldeld maximum horizontal stress.

6 INVESTIGATION OF WELLBORE WALL STABILITY THROUGH DETERMINATION OF DRILLING MUD WEIGHT

The wellbore wall stability can be evaluated through the determination of drilling mud weight. We employed Mohr-Coulomb and Mogi-Coulomb failure criteria to determine the minimum and maximum pressure of drilling mud. Figs. 9-15 display the lower bound/limit of drilling mud pressure using the Mohr-Coulomb failure criterion. A Breakout Zone with a red color can be observed in some zones of this field. The green color indicates zones in which the wellbore is stable according to applied drilling mud pressure. Zone 1 in this field is composed of limestone, shaly limestone, and dolomitic limestone with a gray to light gray color. Zone 2 consists of limestone, mudstone, calcite, and argillite. Zone 3 comprises wackestone, mudstone, argillite, and limestone. Zone 4 is composed of a shaly layer associated with veins of mudstone, shaly limestone, anhydrite sand, and wackstone. Zone 5 consists of shaly limestone, anhydrite limestone, and shale, and Zones 6-7 comprise marl layers, wackestone, and silt. Therefore, the differences in the geological structure of these zones will noticeably result in differences in terms of wellbore stability during drilling in these zones.

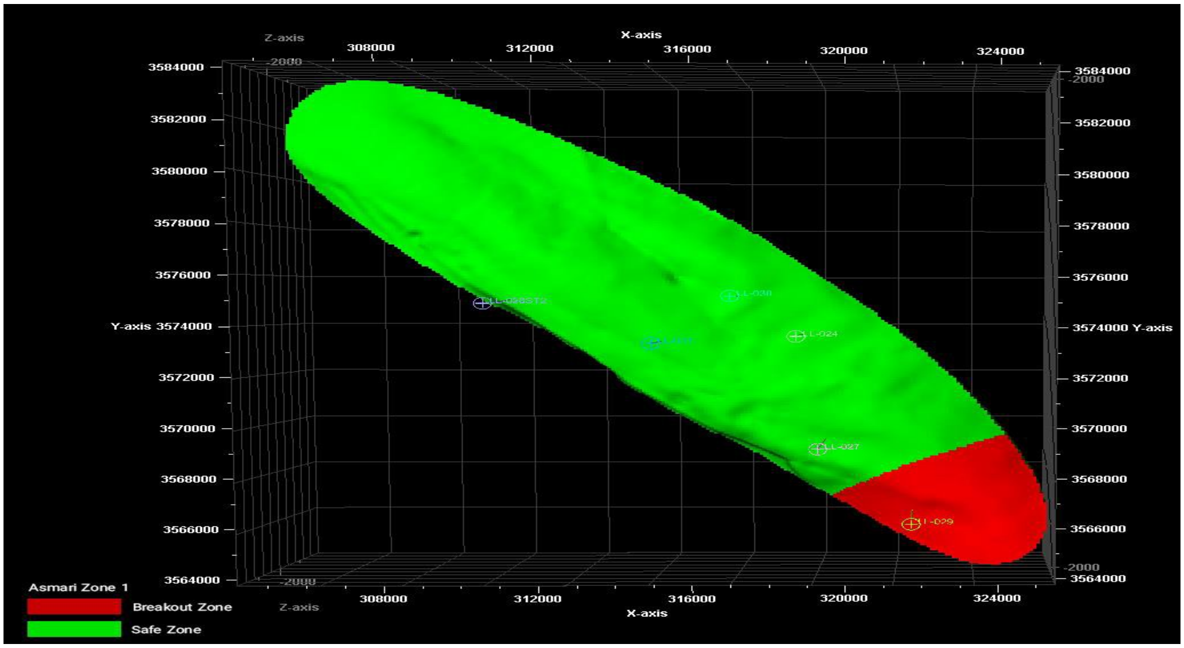

Fig. 9
Investigation of Zone 1 in terms of stability.

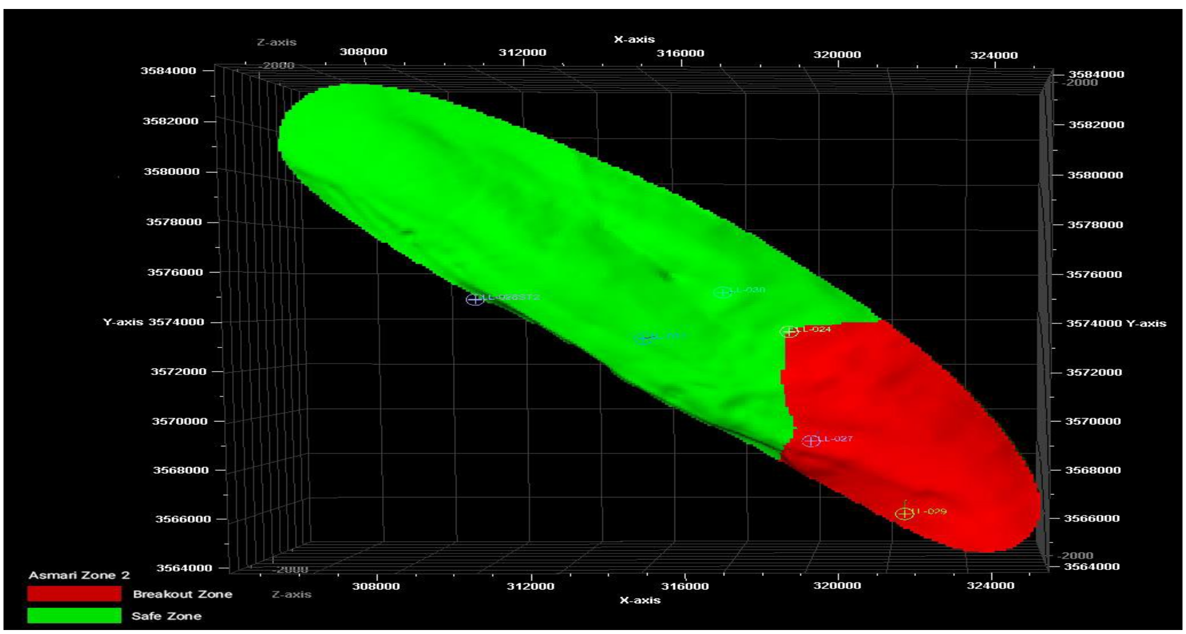

Fig. 10
Investigation of Zone 2 in terms of stability.

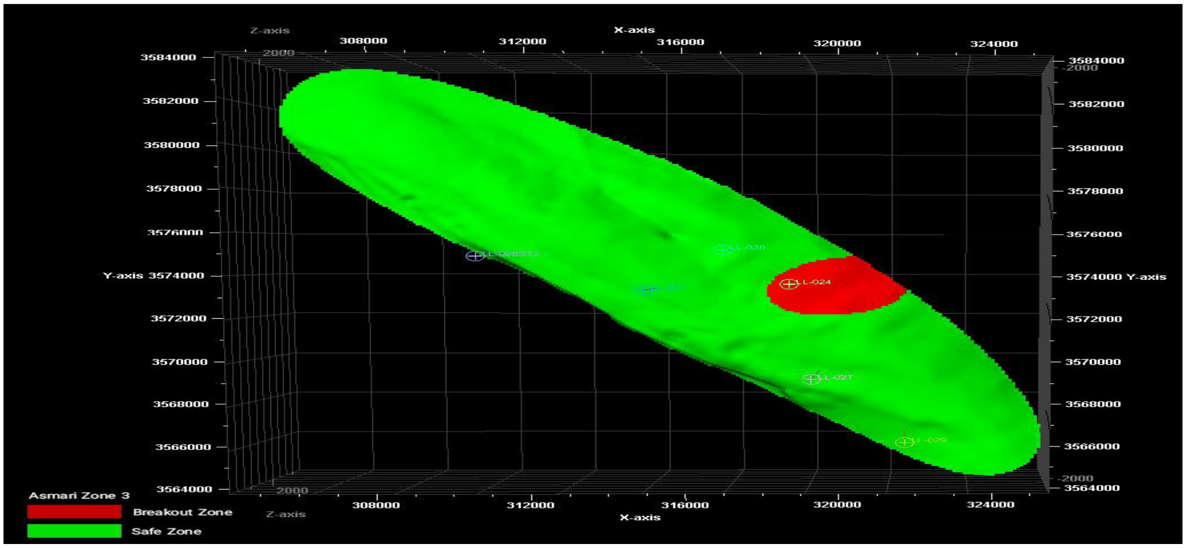

Fig. 11
Investigation of Zone 3 in terms of stability.

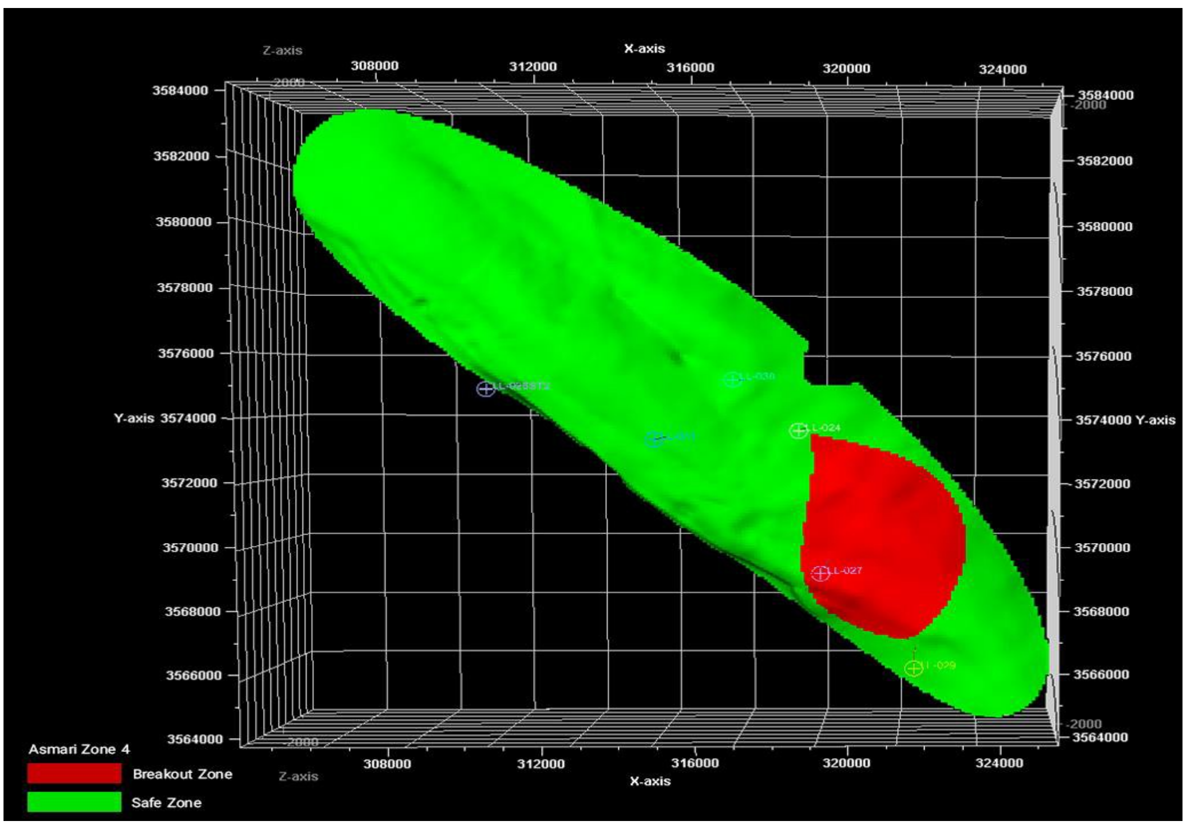

Fig. 12
Investigation of Zone 4 in terms of stability.

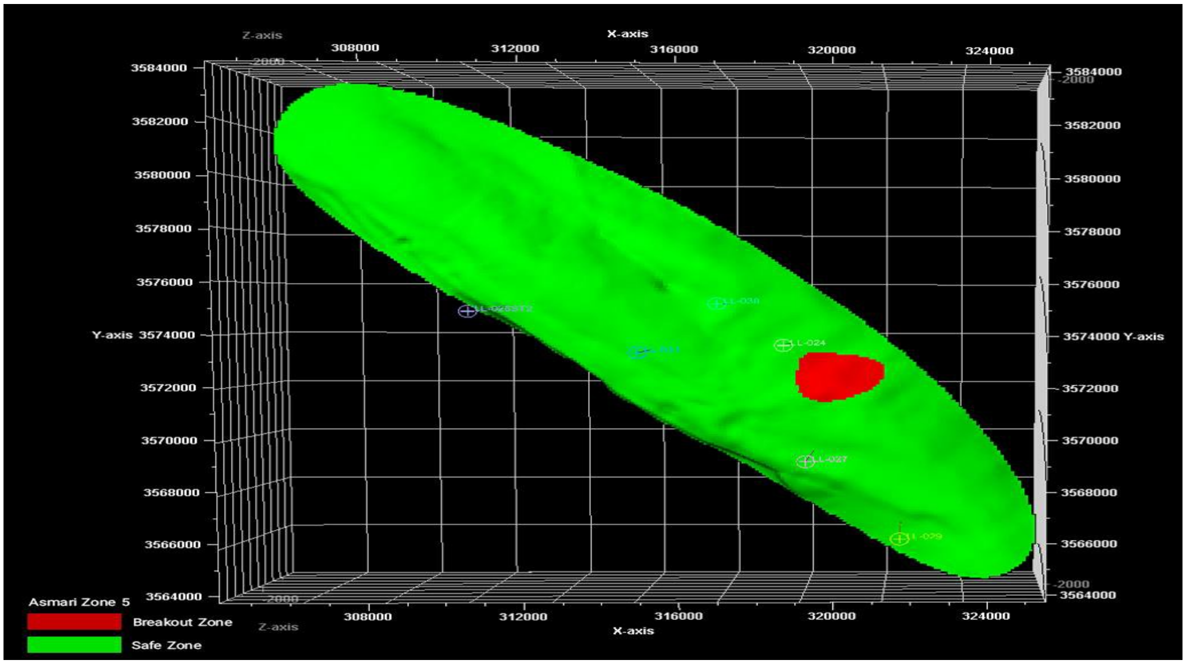

Fig. 13
Investigation of Zone 5 in terms of stability.

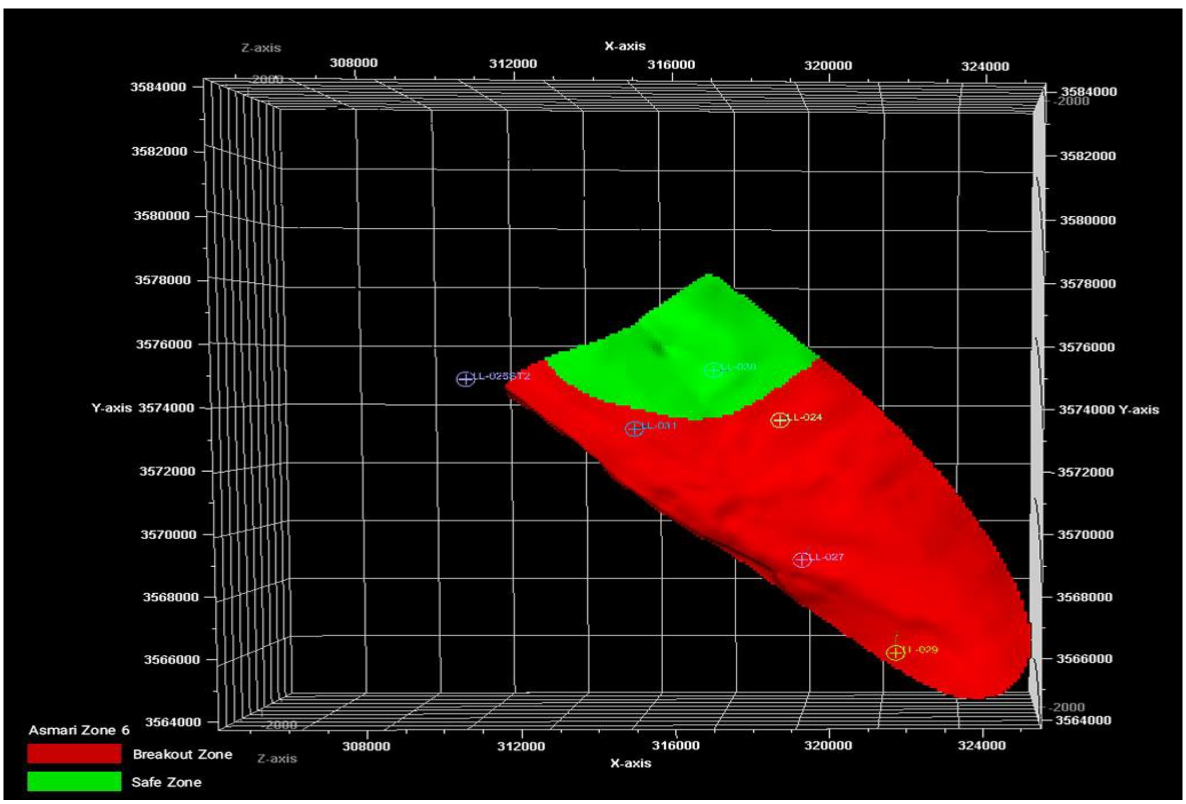

Fig. 14
Investigation of Zone 6 in terms of stability.

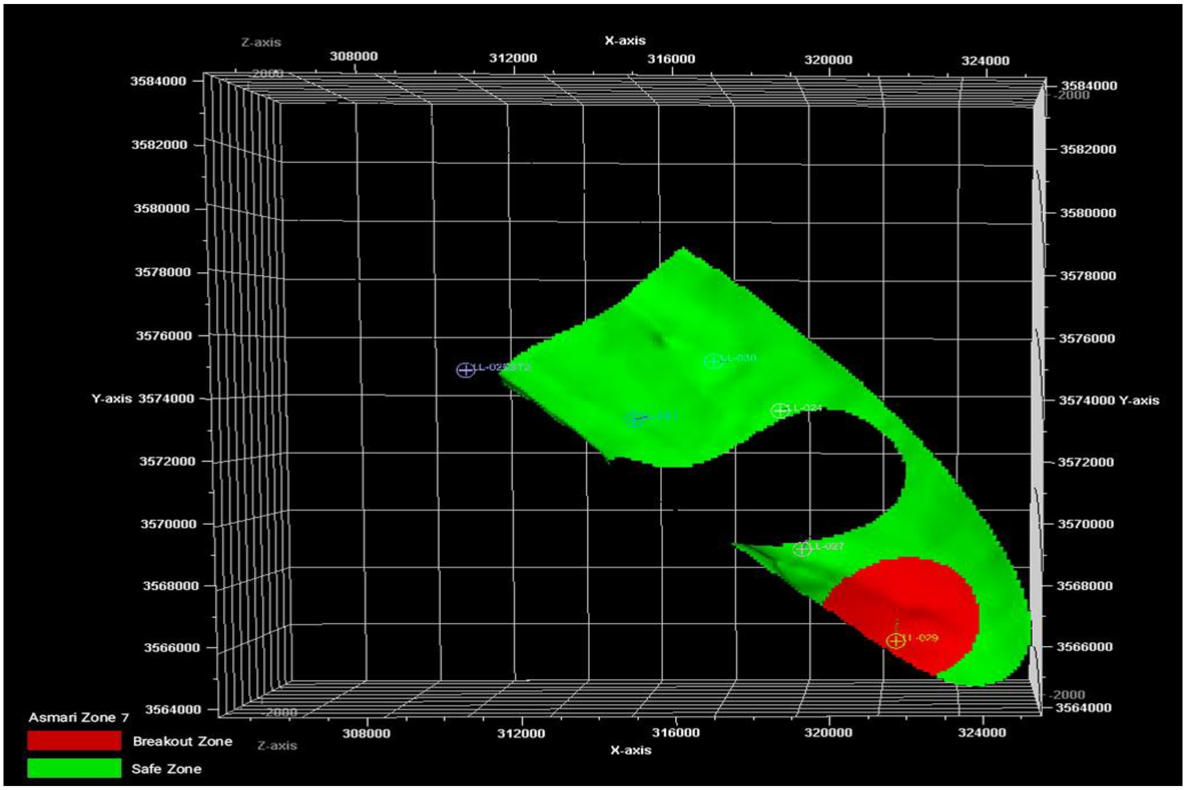

Fig. 15
Investigation of Zone 7 in terms of stability.

To compare the efficiency of Mohr-Coulomb and Mogi-Coulomb failure criteria, the results of these two criteria were integrated with well logging data (Figs. 16-18). Fig. 16 exhibits the results coming from the comparison of these methods in Well 1. Sections with a red color represent the areas that have shear fractures and those with a green color represent safe and stable areas from the mud pressure viewpoint. These two failure criteria have been derived using different assumptions, most notably, the effect of the intermediate principal stress on the rock failure is ignored in the conventional Mohr-Coulomb failure criterion, while the Mogi-Coulomb failure criterion does consider the effect of the intermediate principal stress on the formula of the rock failure. In general, the conventional Mohr-Coulomb failure criterion is based on the shear and normal stresses acting on the failure plane and expresses a linear relationship between these stresses, however, the Mogi-Coulomb criterion incorporates octahedral shear stress and mean effective normal stress into its formula and relates these two stresses linearly as well, but under true triaxial conditions. These differences will result in different predictions when these two well-known rock failure criteria are employed in numerical modeling.

One of the major reasons leading to wellbore instability is the presence of over-pressured layers such as over-pressured shale layers. The excess pressure in shale layers originates from their extremely low permeability preventing the dissipation of pore pressure during the compaction process imposed by the weight of the above-layers. Depth increase causes an increase in horizontal stresses in the wellbore and the lack of an increase in the lower and upper limits of the drilling mud window can give rise to wellbore instability and wellbore wall collapse. Thus, increasing drilling mud weight with increasing depth can prevent wellbore wall collapse, as noticed in Well 3 (Fig. 17). Fig. 18 illustrates the comparison between different methods in Well 2. One of the important points in this well is that the mud weight used in this well is greater than that used in other wells and that increasing mud weight with increasing depth has been utilized in this well. Besides, increasing mud pressure has overcome increasing pore pressure, which in turn has increased drilling mud loss.

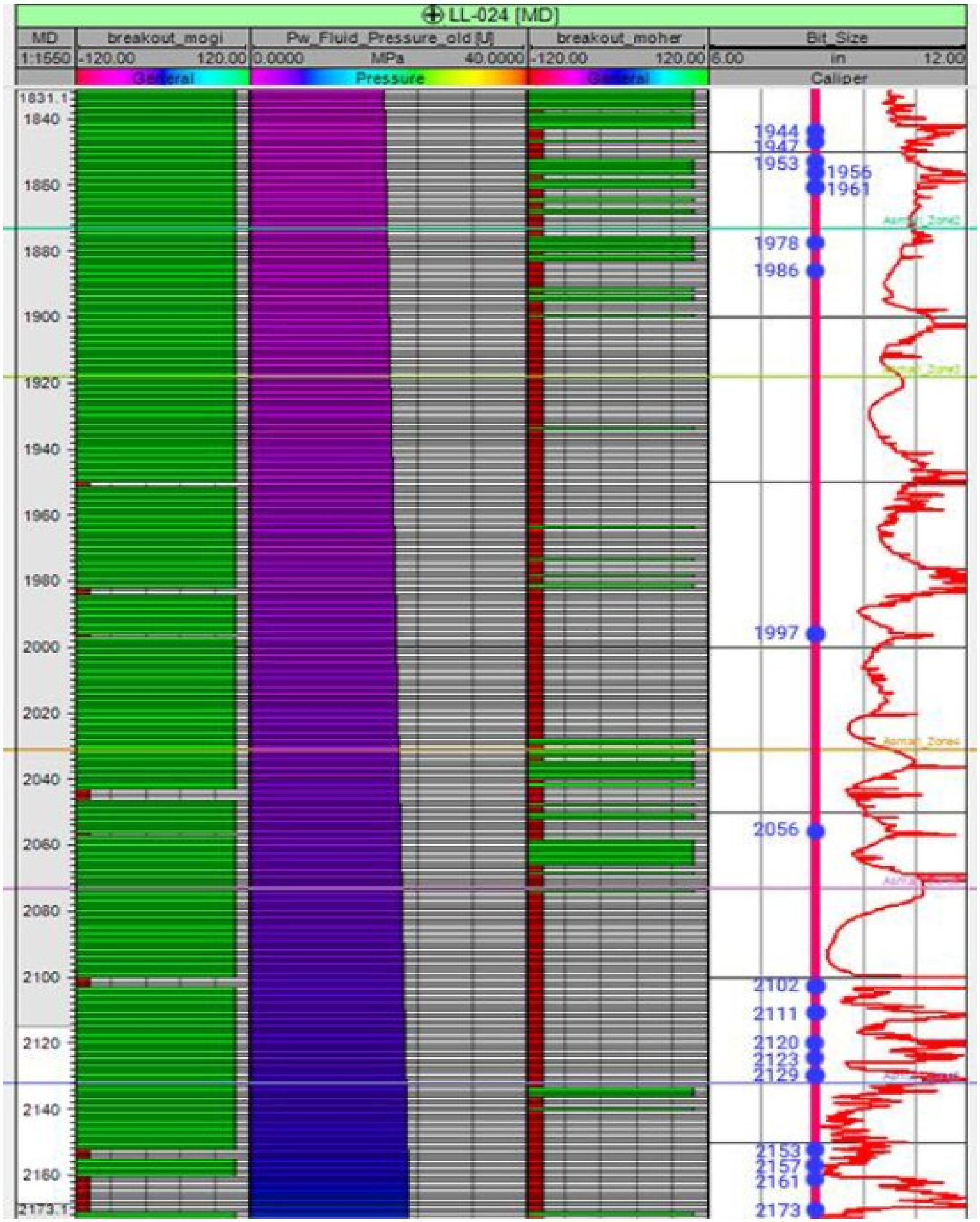

Fig. 16
Investigation of the results of different methods in Well 1.

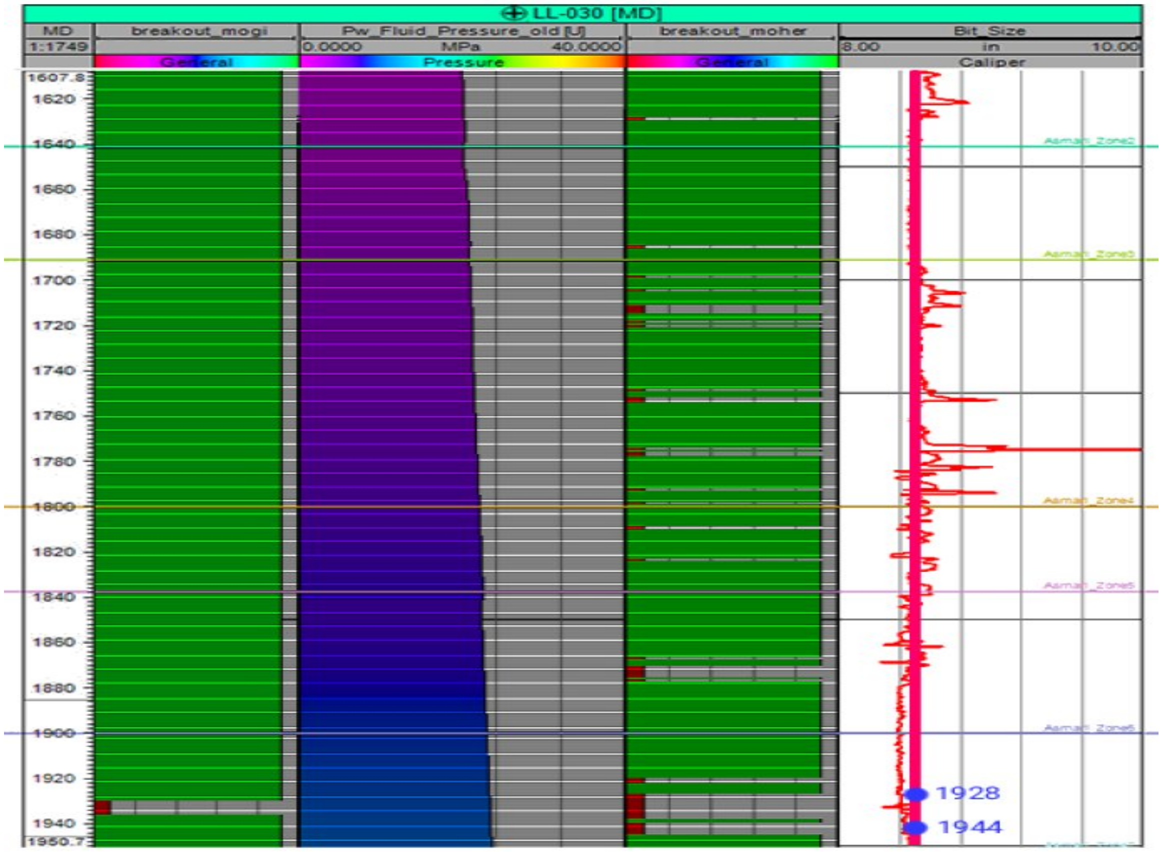

Fig. 17
Investigation of the results of different methods in Well 3.

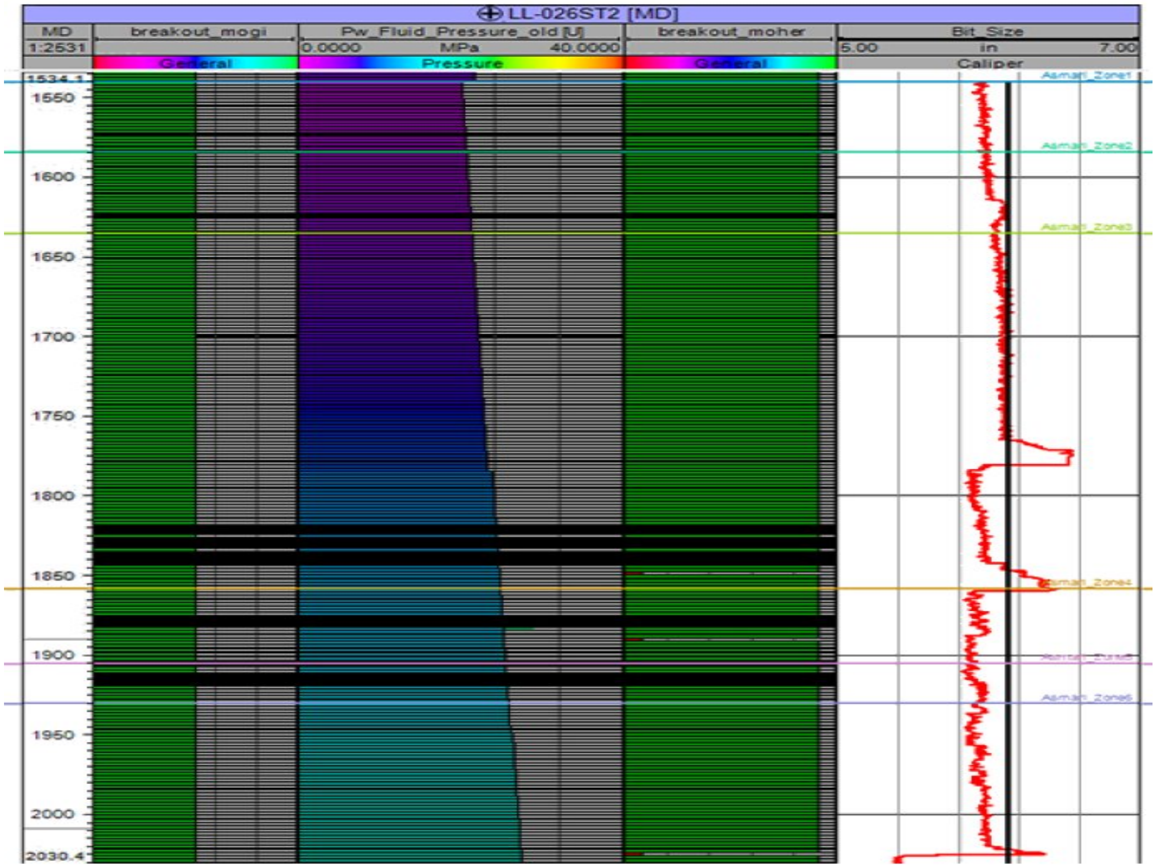

Fig. 18
Investigation of the results of different methods in Well 2.

Fig. 19 shows the safe mud window obtained via the Mohr-Coulomb failure criterion. As observed, the minimum mud weight in different zones ranges from 9.13 to 12.32 MPa, and the maximum mud pressure ranges from 58.32 to 81.9 MPa (Table 6). The minimum and maximum mud pressure in the whole field is equal to 9.13 and 81.9 MPa, respectively, with an average pressure of 32.34 MPa. One of the noteworthy points is that the width of the safe mud window has reduced in the central areas of the field.

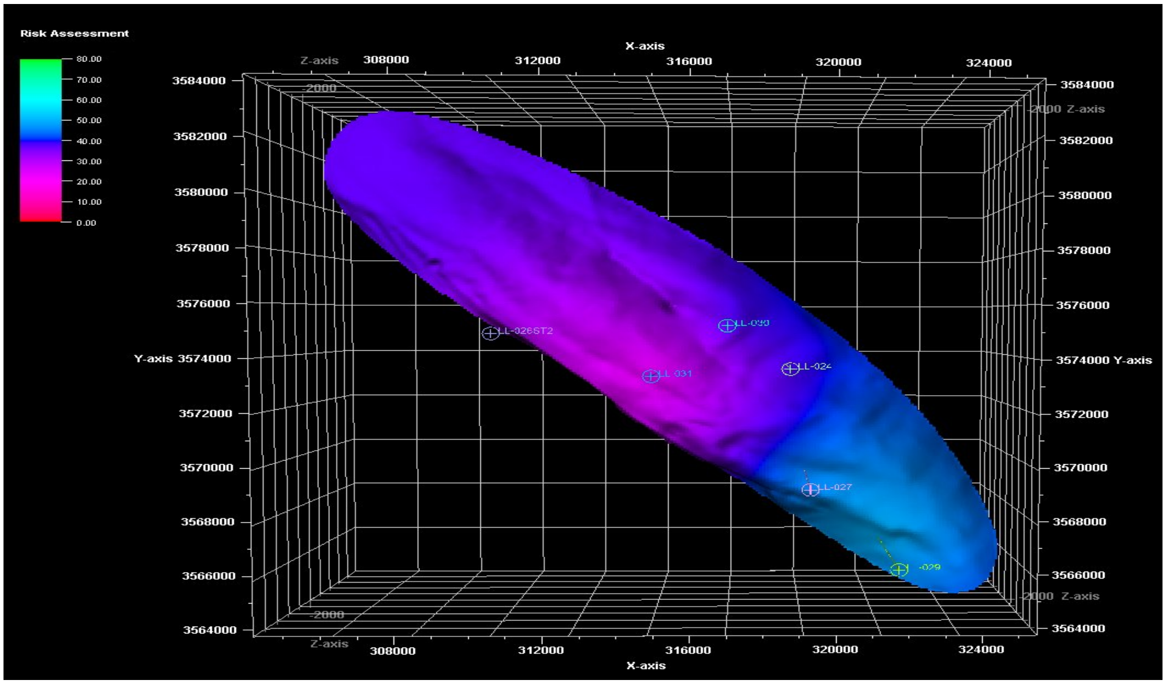

Fig. 19
Width of safe mud window in the field.

Table 6
Width of safe mud window in the field

Zone	Minimum pressure (MPa)	Maximum pressure (MPa)	Mean pressure (MPa)
1	12.32	64.2	37.75
2	10.8	64.98	41.35
3	10.42	69.89	40.85
4	9.53	81.9	40.35
5	9.13	67.6	41.12
6	9.48	64.72	32.92
7	9.27	58.32	22.95
Whole reservoir	**9.13**	**81.9**	**32.34**

7 SAFE DRILLING TRAJECTORY

To determine a safe drilling trajectory, drilling parameters were evaluated in three depths of 1950 m, 1650 m, and 1800 m according to the availability of data existing in drilling reports. The results are presented in Table 7. As observed, the reverse fault regime prevails in all three depths, in which the value of maximum horizontal in-situ stress is the greatest and the value of minimum horizontal stress is larger than that of vertical stress. The lower limit of drilling mud for drilling in depths 1650 m, 1800 m, and 1900 m is shown in Figs. 20-22. The center of the stereonet displays the position of the vertical well. Moreover, its external corners represent the horizontal well and the distance between them represents directional wells. According to these diagrams, to reduce wellbore wall stresses and shear fractures, a 40-degree azimuth is the best drilling direction. Furthermore, directional drilling and vertical drilling possess the highest instability risk and require the highest mud pressure. When drilling is performed in the direction of the maximum horizontal stress, the drilling trajectory will be perpendicular to the well path leading to increasing risk for wellbore collapse and instability.

Table 7
Rock mechanics parameters in the field

Parameter	Depth A (1650 m)	Depth B (1800 m)	Depth C (1950 m)
Poison ratio	0.325	0.298	0.306
Uniaxial compressive strength (MPa)	71.4	90.4	74.1
Internal friction angle (degree)	38.4	32.31	22.49
Pore pressure (MPa)	17.05	18.21	19.4
Minimum horizontal stress (Mpa)	45.02	46.51	49.79
Maximum horizontal stress (Mpa)	53.79	58.32	58.73
Vertical Stress (MPa)	41.4	45.3	49.25

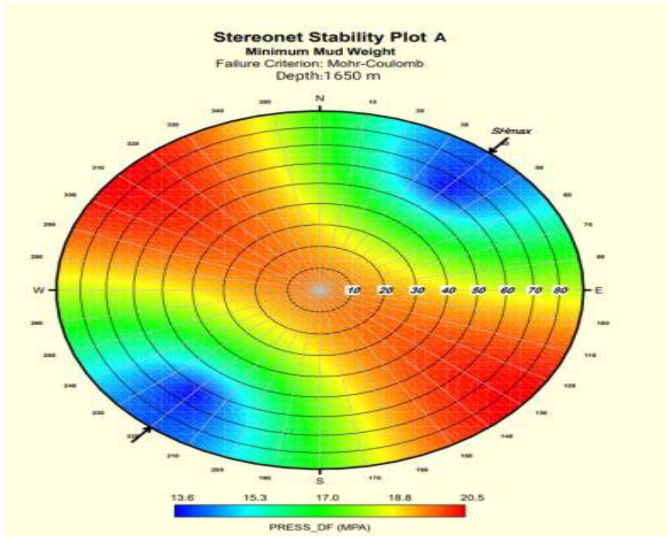

Fig. 20
Minimum mud pressure in the field in depth 1650 m.

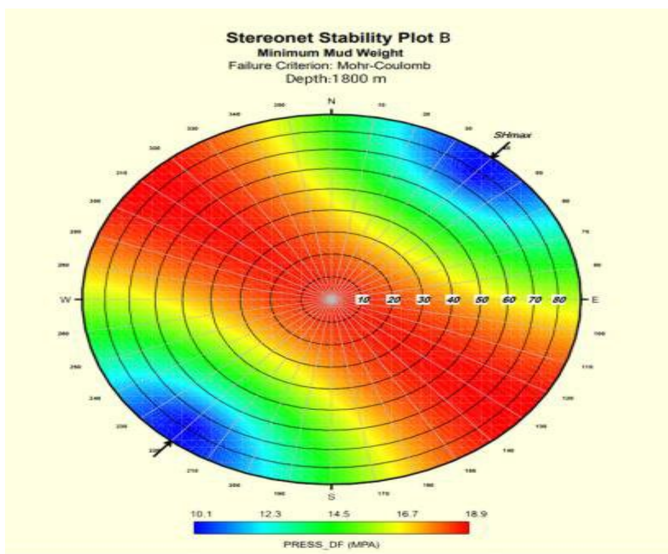

Fig. 21
Minimum mud pressure in the field in depth 1800 m.

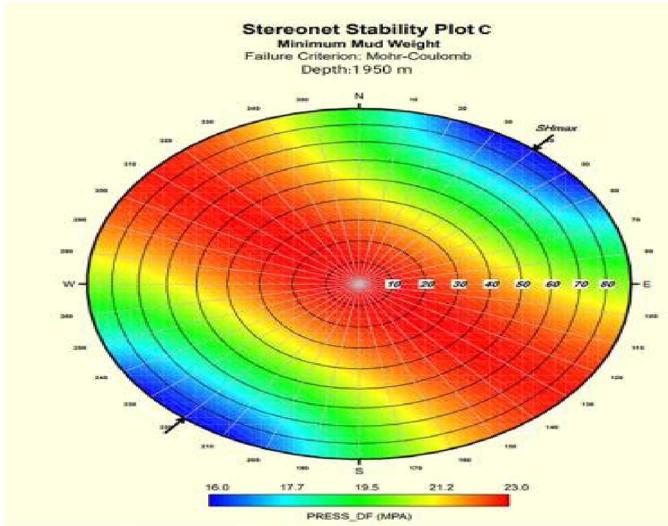

Fig. 22
Minimum mud pressure in the field in depth 1950 m.

8 COCLUSIONS

Mohr-Coulomb and Mogi-Coulomb failure criteria and caliper logs were employed to determine the safe mud window. The research results are summarized as follows:
1) The formations located at the north wing of the studied oil field are more stable than the other zones. Among the investigated zones, Zone 5 is the most stable and Zone 6 is the least stable zone in terms of shear stability.
2) The Mohr-Coulomb failure criterion is more competent in predicting the stability of the wells compared to the Mogi-Coulomb failure criterion. The Mogi-Columb failure criterion generates more optimistic results compared to the Mohr-Columb criterion. This means that a broader safe mud window is predicted by the Mogi-Columb failure. Application of this wider-than-practical safe mud window in the wellbore while drilling can result in wellbore collapse (significant wellbore instability) or unplanned hydraulic fracturing (leading to severe drilling mud loss/lost circulation and even possibly wellbore blowout).
3) The least mud window is in the middle zone in Well 3, and the safe mud window is about 15 Mpa in other parts of the field.
4) A 40-degree azimuth should be selected as the safe drilling route to decrease the instability of wells during drilling operations in this field.
To improve the quality of numerical modeling carried out in this study, the following suggestions are presented:
i) Using more data and wells to reduce modeling error.
ii) Using other failure criteria (such as the Hoek-Brown failure criterion) and comparison of the results obtained through different criteria.
iii) Using artificial intelligence to predict and evaluate modeling results.

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