



# An integrated one-dimensional geomechanical model to identify the optimal mud weight and the well trajectory for the Zubair formation

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## Abstract

The Zubair formation is a significant producing reservoir in southern Iraqi oil fields. During the drilling of this formation, many wellbore instability issues were encountered, including shale caving, tight hole, lost circulation, and pipe sticking. These challenges significantly lead to an increase in non-productive time (NPT). The drilling data analysis indicated that the wellbore shear failure was the principal cause of these issues. The main objective of this study is to build a one-dimensional geomechanical model using core and well logging data from offset wells. Thus, the safe mud weight necessary to prevent the initiation of the shear and tensile failures against the Zubair formation was determined by employing the Mogi-Coulomb failure criterion. The results revealed that the horizontal and strongly deviated wells are less secure and stable than vertical and slightly deviated wells (less than 30°). This is based on a sensitivity analysis of the wellbore at a specific depth. The recommended mud weight for drilling wells having angles of inclination that vary from 0 to 30° is 11.9 to 12.3 ppg. A 140° NW-SE azimuth is the optimum azimuth to drill the deviated and horizontal wells which is analogous to the orientation of the minimal horizontal stress. The research's findings can be applied to planning upcoming wells in the study region's vicinity.

**Keywords** Wellbore stability · Mechanical earth model · Sensitivity analysis · In situ stresses

## Introduction

Wellbore instability is the most significant drilling issue in oil and gas wells, which can lead to delays in drilling operations, i.e., increased non-productive time (NPT) and profit losses (Adil Issa et al. 2022). Prior to the excavation, the solid rocks were nearly in equiponderant with little or no motion. Once the borehole is drilled, the static state of the

stress will change, leading to a redistribution of the concentration of the stresses surrounding the wellbore. These stresses may surpass the capability of the rocks; subsequently, borehole failure is expected to occur. It is possible to use the induced stresses to investigate borehole issues such as fracture, collapse, sand production, and lost circulation. These issues can be diminished by planning the optimum trajectory and mud weight of the wellbore (Aadnoy and Looyeh 2019; Zhang 2019; Zhu et al. 2022; Zoback 2007).

In spite of the attentiveness of the petroleum industry, the instability of the wellbore is still responsible for the more challenges through the drilling and production activities which can annually cost the petroleum industry billions of dollars (Adegbamigbe et al. 2020; Issa and Hadi 2021). Consequently, drilling new wells requires a wellbore stability analysis because, without it, the field development plan, optimizing the well trajectories, and safe mud weight design are very difficult to achieve (Chen et al. 2003; Kiran and Salehi 2017). Moreover, to ensure a secure wellbore, it is essential to take into account two additional parameters: (a) manageable factors, such as the wellbore's trajectory and

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drilling fluid density, and (b) uncontrollably factors, such as overburden stress, rock mechanical characteristics, pore pressure, and the direction and magnitude of the far-field horizontal stresses (Alam et al. 2019; Mohiuddin et al. 2007).

The employed drilling mud must be in the proper range to ensure the wellbore is stable. In other words, when the drilling fluid is lower than the formation pressure, washouts of the wellbore occur, and in the case of shear and compressive failures, the wellbore will break out if the gradient of shear failure is greater than the mud weight. The tensile fracture occurs during the drilling when mud weight exceeds the fracture gradient, causing drilling fluid losses and circulation issues (Li et al. 2012; Peng et al. 2007; Ranjbar et al. 2017).

In general, the mechanical earth model (MEM) must be generated to achieve the purpose of the wellbore stability, which is to develop a suitable path and a safe mud window for the wellbore (Al-Mansory and Alrazzaq 2021). All available data, such as far-field stresses, mechanical and petrophysical rock parameters, and pore pressure, are essential to building a one-dimensional MEM. Consequently, these properties are integrated with appropriate failure criteria to prophesy the minimum mud density that is required to fulfill the safe drilling condition (Gholami et al. 2015). A particular and compatible failure criterion should be applied to understand more of a failure phenomenon. However, many empirical failure criteria were developed to predict wellbore failure due to the stress concentration around the wellbore exceeding the rock strength. In this regard, several of these criteria neglect the influence of the intermediate principal stress and are uneasy mathematically (Fjar et al. 2008; Mansourizadeh et al. 2016; Zoback 2007). Thence, Al-Ajmi and Zimmerman (2006) proposed using a new failure criterion named the Mogi-Coulomb criterion that incorporates the influence of the intermediate principal stress. It is simple to relate this criterion to strength characteristics that include cohesion strength and internal friction angle, and it can provide the best fit, thus giving reasonable results.

The Zubair formation is one of the critical prolific reservoirs located in the south of Iraq. Many problems with instabilities have been encountered through drilling in the Zubair formation. Therefore, Zubair reservoir was conducted in this study to analyze the wellbore instability and to identify the minimal mud weight that was required to avoid wellbore failure. To accomplish the aforementioned objective, a 1-D MEM was developed relying on the relevant well logging data from offset wells. Subsequently, mechanical rock properties, directions and magnitudes of the in situ stresses, and pore pressure were determined. Then, the resultant profiles of the characteristics of the 1-D MEM along with the Zubair formation were validated utilizing field and lab data (i.e., consolidated drained triaxial, multistage triaxial, mini-frac, and repeated formation tests).

## Materials and methods

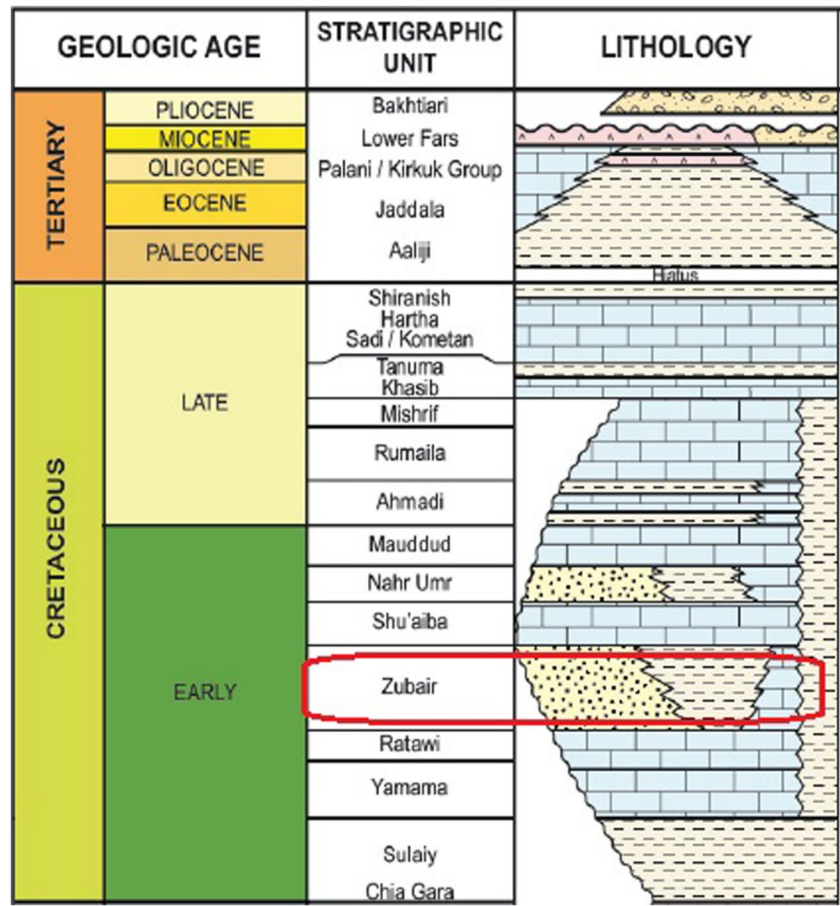
### Area of study

A field study in the south of Iraq was performed to investigate the more secure mud density necessary for mitigating shear and tensile rock failures. The lower cretaceous Zubair formation, which is a crucial prolific reservoir within this oilfield of interest, has been adopted in this study. The stratigraphic column of most Iraqi oil fields is mainly extended from the tertiary ages to the upper Jurassic. A thick carbonate-based rock succession incorporating clastic stone may be employed to characterize it. The Zubair formation is a clastic reservoir that contains approximately 30% of Iraq's oil and gas reserves. The Shuaiba formation (dolomite and limestone) surrounds the Zubair formation at the top, while the Ratawi formation (limestone and shale interbed) surrounds the Zubair formation at the bottom (Fig. 1). The Zubair stratum has a gross vertical thickness of around 450m. It mostly comprises shale scattered with sandstone and a few siltstones and limestone. As per the shale/sand ratio, the Zubair formation is divided into the following members: upper shale, upper sand, middle shale, lower sand, and lower shale. (Jassim and Goff 2006).

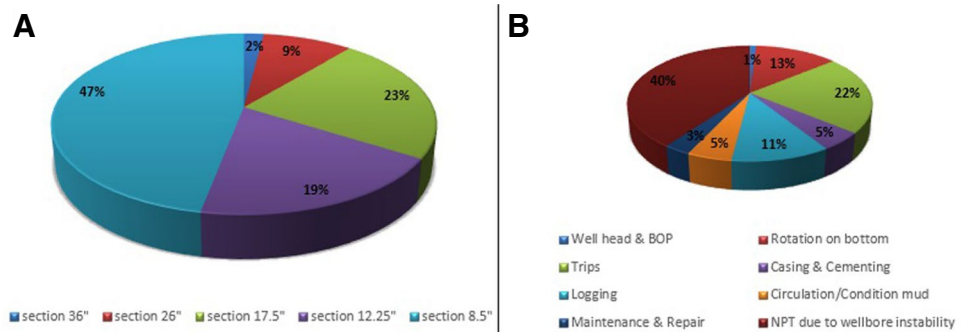
### Statement of the problem

The Zubair formation is the area of interest within 8 ½" section (production section). The instability of the wellbore is responsible for more than 80% of the borehole difficulties while drilling the Zubair formation. Final well reports, master logs, daily mud reports, and daily drilling reports for the deviated and vertical wells were thoroughly examined in this study to quantify the effect of the wellbore instability on the drilling performance. According to the time breakdown analysis (Fig. 2a), the Zubair formation consumes the most days (47%) of the total time spent on drilling these wells compared to other sections. To investigate how NPT influenced the drilling operation, the entire time breakdown for section 8 ½" was then evaluated independently. Consequently, the non-productive time related to borehole instability issues accounted for around 40% of the total time spent in drilling this section (Fig. 2b). Furthermore, the majority of unstable challenges identified throughout the analyzed span were stuck pipes, wireline logging tool sticking, shale caving, and tight hole, all of which resulted in fishing and sidetracking in the worst-case scenario. According to drilling data, these difficulties are largely attributable to the wellbore failure, which lengthened circulation and reaming periods, thereby increasing the NPT.

**Fig. 1** The stratigraphic unit and lithology of the Southern Iraqi Oilfield



**Fig. 2** Total time consuming of one well drilled in SE Iraq: (A) total drilling time and (B) the entire time breakdown for section 8 1/2"



Drilling the Zubair formation using mud weight of 1.2 g/cc (10 ppg) without considering the principles of geomechanics can be considered the main reasons for motivating this study in order to minimize the risk of instability and increase the commercial production income by minimizing the NPT of drilled wells.

**Methodology**

The study aims to identify the optimal mud weight and well trajectory for the Zubair formation. A 1-D MEM, single-depth sensitivity analysis, and development plan

were implemented using Schlumberger Techlog software to fulfill the target of this research. The following steps can outline the methodology of the present study:

- Gather and examine the necessary data for the area of study. This data includes open-hole logging measurements, field test data, and core mechanical laboratory tests.
- Determine the most problematic wellbore section using the time breakdown analysis and evaluate the influence of the instability on drilling performance.

- Construct a 1-D MEM to evaluate the instability hazards of the Zubair formation. To create this model, the pertinent well logging data and core specimens from offset wells were combined.
- Use the formation imager and caliper logs, formation pressure data points, mechanical rock data points, and any extra pertinent data from the final well report and daily drilling report to validate the precision of the created 1-D MEM.
- Conduct a single-depth sensitivity analysis to identify the optimum mud weight window, inclination, and azimuth for drilling future wells in adjacent locations.
- Implement the development plan for future wells at different trajectories to identify the most appropriate mud weight to drill the Zubair intervals with less tensile and shear failures.

### Determination of geomechanical parameters

The MEM is a deterministic analytical technique that is widely utilized for applications involving reservoir geomechanics in oil and gas wells. The MEM incorporates the in situ stresses, rock mechanical characteristics, and formation pore pressure, all of which are linked to the model of the rock failure. After developing a MEM, the probability of sanding and the issues of the instability of the wellbore in an individual wellbore and possibly field development can be predicted. To provide a reliable workflow and outcomes, gathering and verifying pertinent data for the study area are necessary. In this work, data from different wells was utilized to build the 1-D MEM along with the Zubair

formation. This data includes field tests such as mini-frac tests as well as well logs data, which involves gamma-ray log, formation imager and caliper logs, and porosity logs (i.e., density, sonic, and neutron logs). Additionally, the profiles of the geomechanical parameters were validated using laboratory data. Figure 3 presents the steps of constructing a 1-D MEM. The model starts with data collection and auditing; then, it ends with the model calibration.

### Mechanical stratigraphy (shale flag)

Stratigraphy is an examination of the progression and time-associated construction of rock formations. lithostratigraphy, or mechanical stratigraphy, which categorizes the types of sedimentary rock according to its appearance, composition, and structure (Shaban and Hadi 2020). Consequently, ranking the rocks relies on their lithostratigraphy, and the suitable correlations can be specified for various formations of lithology to better determine their rock mechanical parameters. The Zubair reservoir consists principally of sandstone and shale. The segregation between them was fulfilled by setting a threshold for gamma-ray logs (75 API). According to the fourth track in Fig. 4, the established lithostratigraphy (mechanical stratigraphy) agrees well with master mud logging reports and data points derived from pore pressure measurements in permeable formations.

### Overburden stress

Far-field stresses or in situ stresses (i.e., vertical stress, maximum and minimum horizontal stresses) data is crucial in constructing different stages of well life, including planning, excavations, completion, and production. This means that it is

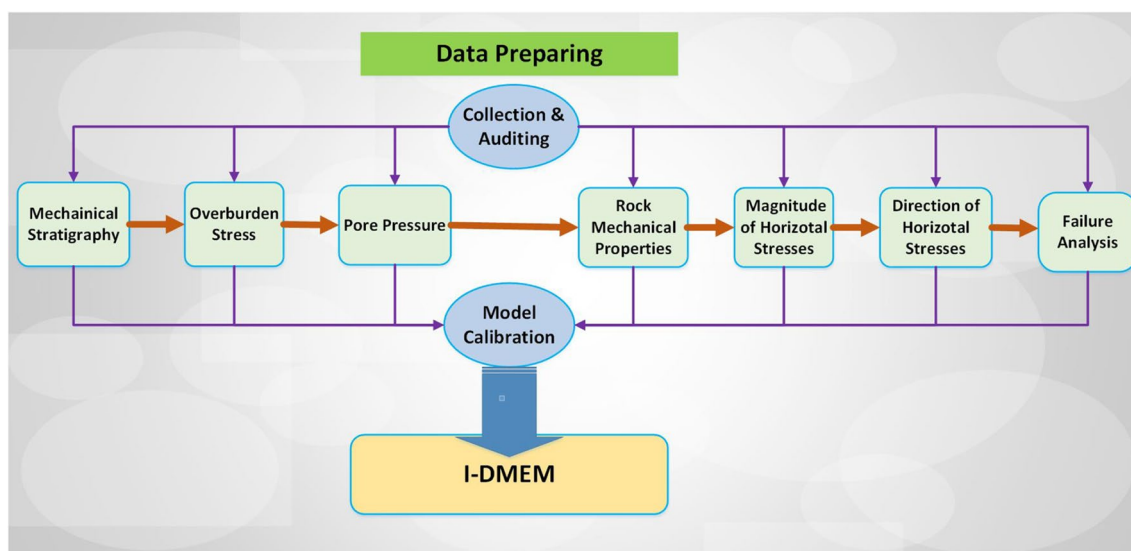


Fig. 3 The steps of constructing 1-D MEM



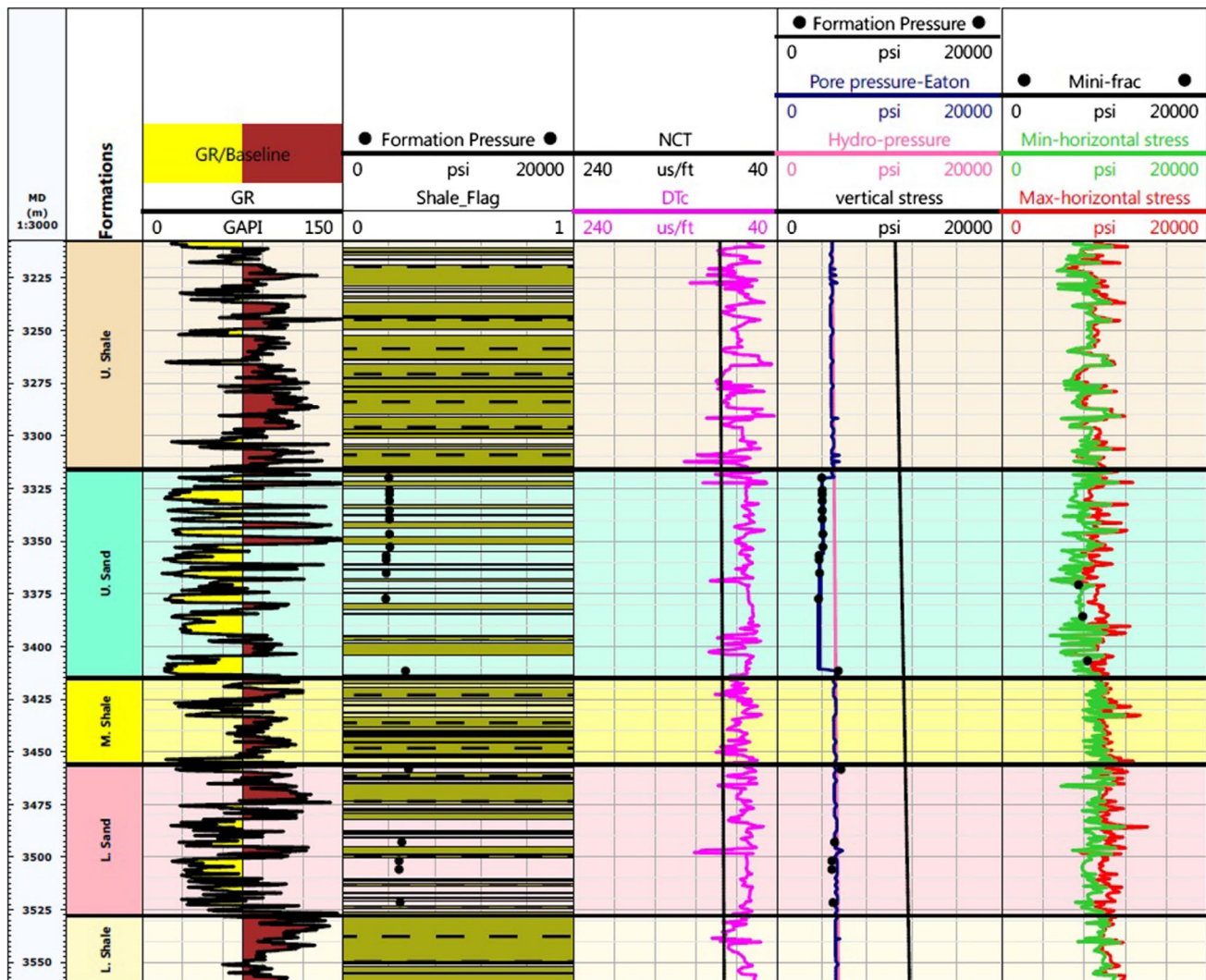


Fig. 4 Profiles of the shale flag, pore pressure, and far-field stresses along with the Zubair formation

essential to know the in situ stresses before execution of any rock failure investigation or stress analysis through the life of a field (Aadnoy and Kaarstad 2010).

Overburden stress or vertical stress ( $\sigma_v$ ) is an essential input parameter of the mechanical earth model (MEM). The weight from the above strata contributes to overburden stress. The bulk densities of formation at the point of interest can be integrated to calculate it using Eq. 1 (Ma et al. 2022), where  $\rho_b(z)$  is the rock density, which may be obtained from the measurement of the density log coupled with the depth;  $g$  is the gravitational constant.

$$\sigma_v = \int_0^z \rho_b(z)gdz \tag{1}$$

### Formation pore pressure

The fluid pressure inside the pores of porous stone is known as pore pressure ( $P_p$ ); it is an important parameter in geomechanical modeling procedures, drilling management, and production optimization. It is primarily utilized to estimate effective stress and in situ stresses, and design a safe mud window (Najibi et al. 2017).

It is possible to determine the pore pressure either directly or indirectly. While the direct methods (e.g., repeated formation test (RFT)) are highly accurate, they are restricted for reasons of cost- and time-saving (Hadi et al. 2019). In contrast, the indirect techniques are frequently employed depending on the mechanical compaction of rocks with respect to depth (e.g., Eaton 1975). In this study, the profile of the hydrostatic pressure (normal pore pressure) along the Zubair formation was computed using Eq. 2 (Bjorlykke

2010). Because the repeated formation test (RFT) data along with the Zubair formation are limited for certain depths, the pore pressure magnitudes were calculated utilizing the modified Eaton (Eq. 3) (Eaton 1975). This equation was derived based on a sonic wireline log. Notably, the mud pressure employed to drill the Zubair intervals is higher than the formation pressure, so the formation pore pressure profile was adjusted and verified based on the actual mud weight and data points extracted from the repeated formation test (RFT).

$$P_h = \int_0^z \rho_w g dz \tag{2}$$

where  $\rho_w$  is formation water density (g/cc);  $g$  is gravitational constant; and  $dz$  is the depth (m).

$$P_{pg} = OBG - (OBG - P_{ng}) \left( \frac{NCT}{\Delta T} \right)^3 \tag{3}$$

where  $P_{pg}$  is the pore pressure gradient;  $P_{ng}$  is the hydrostatic or normal pressure gradient;  $OBG$  represents the overburden gradient;  $\Delta T$  represents a compressional sonic wave (sonic transit time); and  $NCT$  indicates a normal compaction trend that fits observations of compressional waves.

The relationship between the formation pore pressure gradient and the compaction is the normal compaction trend line (NCTL). In Eaton’s original equation, the normal sonic transit time ( $\Delta t_n$ ), also called NCT, cannot be easily calculated in the condition of normal pore pressure. The easiest way is to consider the normal transit time as a constant. In contrast, it often varies depending on the burial depth rather than being a constant. Therefore, a normal compaction trend line must be established to forecast pore pressure. The NCT profile (fifth track of Fig. 4) was established utilizing Eq. 4 (Zhang 2011), where  $\Delta t_m$  is the compressional sonic wave in the shale matrix (normally=70  $\mu$ s/ft);  $\Delta t_{ml}$  is the mudline transit time (normally=200  $\mu$ s/ft);  $c$  is the compaction constant (equal to 0.0003 for sandstone and 0.0005 for shale); and  $Z$  is the true vertical depth below the mudline.

$$NCT(\mu\text{s}/\text{ft}) = \Delta t_m + (\Delta t_{ml} - \Delta t_m) e^{-c Z} \tag{4}$$

The sixth track of Fig. 4 illustrates the profiles of formation pore pressure, hydrostatic pressure, and vertical stress along with the Zubair formation.

### Mechanical rock properties

Knowing the mechanical rock parameters of the subsurface strata is essential in connection with subsidence problems, including wellbore stability issues, sand production assessment, and fracturing operations. Tensile strength (TSTR), strength properties such as internal friction angle (FANG), and uniaxial or unconfined compressive strength (UCS), in

addition to rock elastic parameters including Young’s modulus ( $E$ ) and Poisson’s ratio ( $\nu$ ), are the main mechanical rock properties (Issa et al. 2023). Several ways are utilized to determine these properties, such as laboratory tests (static properties) and correlations using petrophysical and well logging data (dynamic properties). In most cases, cores and rock testing are not available along the interested area. The result is a lack of MEM modeling in addition to that the MEM modeling carried out a range of uncertainty as a result of the ambiguity of the geomechanical characteristics (Hadi et al. 2017). To remedy these difficulties, several empirical correlations depending on petrophysical properties may be utilized to estimate the mechanical rock parameters (Chang et al. 2006). This work employed measurements of the acoustic log data and the bulk density to estimate the dynamic Young’s modulus ( $E_{dyn}$ ) and dynamic Poisson’s ratio ( $\nu_{dyn}$ ) (Eqs. 5 and 6, respectively), where  $\rho_b$  refers to the bulk density (g/cc) and  $V_p$  and  $V_s$  are compressional and shear wave velocities respectively (km/s) (Fjar et al. 2008; Missagia et al. 2019; Najibi et al. 2017; Słota-Valim 2015; Zhang 2019).

$$E_{dyn} = \frac{\rho_b V_s^2 (3V_p^2 - 4V_s^2)}{(V_p^2 - V_s^2)} \tag{5}$$

$$\nu_{dyn} = \frac{(V_p^2 - 2V_s^2)}{2(V_p^2 - V_s^2)} \tag{6}$$

In this study, the static Young’s modulus profile was calculated as a function of the  $E_{dyn}$  using Eq. 7 (Bradford et al. 1998), as shown in Fig. 5 ( third track). It is generally considered that both the static and dynamic Poisson ratios are identical (Archer and Rasouli 2012). As a result, Eq. 6 is used to determine the static Poisson’s ratio profile, which is seen in the second track of Fig. 5. Concerning the strength rock properties, the profile of the uniaxial compressive strength (fifth track of Fig. 5) was established depending on the static Young’s modulus using Eq. 8 (Plumb 1994). The tensile strength profile (fourth track of Fig. 5) was computed as an index of the rock strength (0.1 multiplied by uniaxial compressive strength) (Aadnoy and Looyeh 2019). The profile of the internal friction angle (sixth track of Fig. 5) was constructed depending on the clay volume ( $V_{clay}$ ) and effective porosity ( $\emptyset$ ) using Eq. 9 (Plumb 1994).

$$E_{sta} = 0.0018(E_{dyn})^{2.7} \tag{7}$$

$$UCS = 14.86(E_{sta})^{0.464} \tag{8}$$

$$FANG \text{ (deg)} = 26.5 - 37.4 (1 - \emptyset - V_{clay}) + 62.1 (1 - \emptyset - V_{clay})^2 \tag{9}$$

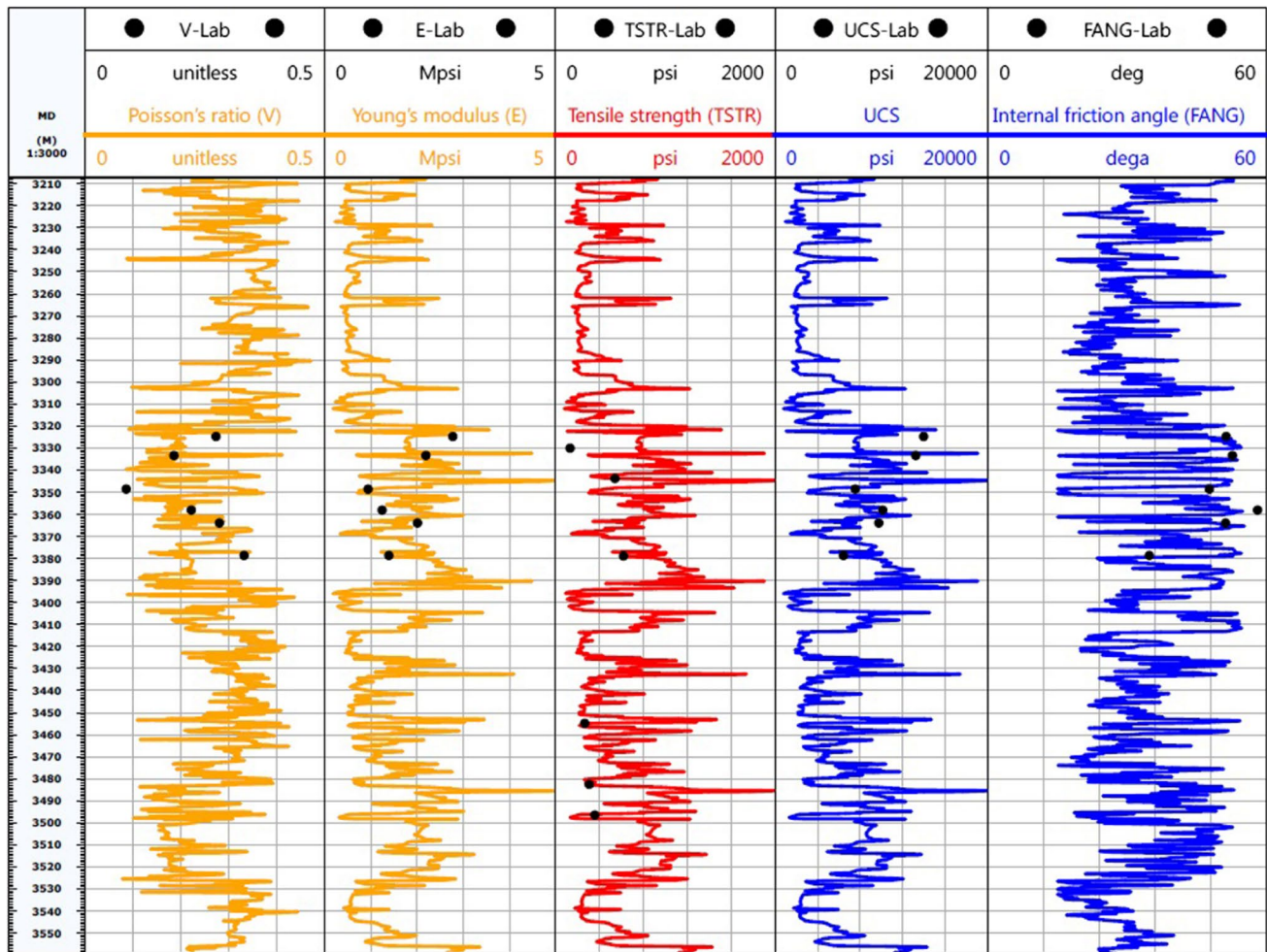


Fig. 5 Profiles of the strength and elastic rock properties along with the Zubair formation

### Horizontal stresses

It is critical to determine the magnitude and orientation of the in situ horizontal stresses for the field of interest so that the stress regime, well planning, wellbore instability issues, and casing set points can be understood and recognized (Zoback et al. 2003). The vertical stress tries to shift the underlying rocks in horizontal lateral directions, and this motion affects horizontal lateral stresses, which are known as minimum and maximum horizontal stresses ( $\sigma_h$  and  $\sigma_H$ ) (Aadnoy and Looyeh 2019). It is possible to estimate the value of the  $\sigma_h$  in oil and gas wells directly through using techniques like the extended leak-off test (XLOT), mini-frac test, and leak-off test (LOT). While the magnitude of the  $\sigma_H$  is difficult to measure because there is no simple direct technique for determining this in situ. A diagnostic fracture injection test (DFIT) or multi-cycle extended leak-off test (XLOT) may be utilized to evaluate the  $\sigma_H$  (Karthikeyan et al. 2020).

The seventh track of Fig. 4 displays the maximum and minimum in situ horizontal stresses profiles along the Zubair formation using the poro-elastic horizontal strain models (Eqs. 10 and 11), respectively. These models are more reliable models to determine the magnitudes of the  $\sigma_H$  and  $\sigma_h$  (Zhang 2019; Thiercelin and Plumb 1994). In this study, the mini-frac data points were employed to validate the profile of the  $\sigma_h$ .

$$\sigma_h = \frac{\nu}{1 - \nu} (\sigma_v - \alpha p_p) + \alpha p_p + \frac{E}{1 - \nu^2} (\epsilon_h + \nu \epsilon_H) \quad (10)$$

$$\sigma_H = \frac{\nu}{1 - \nu} (\sigma_v - \alpha p_p) + \alpha p_p + \frac{E}{1 - \nu^2} (\epsilon_H + \nu \epsilon_h) \quad (11)$$

where  $E$  is Young's modulus;  $\nu$  is Poisson's ratio;  $p_p$  is the formation pore pressure;  $\alpha$  is Biot's constant (generally  $\alpha = 1$ ); and  $\epsilon_H$  and  $\epsilon_h$  are the tectonic strains in direction of the maximum and minimal horizontal stress, respectively.



These two constant strains may be expressed using Eqs. 12 and 13, respectively (Kidambi and Kumar 2016).

$$\varepsilon_H = \frac{\sigma_v \nu}{E} \left( 1 - \frac{\nu^2}{1 - \nu} \right) \quad (12)$$

$$\varepsilon_h = \frac{\sigma_v \nu}{E} \left( \frac{1}{1 - \nu} - 1 \right) \quad (13)$$

### Orientation of the in situ horizontal stresses

Any geomechanical model must consider the horizontal stress orientation; it has a crucial role in hydraulic fracture design and optimizing the well trajectory (Dohmen et al. 2017). The principal stress direction can be identified from analyzing the failures of the borehole including breakout failure and tensile fracturing failure. The orientation of the  $\sigma_H$  is orthogonal to the direction of the breakouts in a nearly vertical or vertical wellbore while it is aligned to the direction of induced tensile fractures. In contrast, the orientation of  $\sigma_h$  is in the direction of breakout failure (Thorsen 2011; Zoback 2007; Zhang et al. 2003). Moreover, the multi-arms caliper log, formation imager log, and the word stress map may all be utilized to estimate the orientations of the horizontal stresses. It is essential to note that combining borehole failure with an imager and caliper logs is a proper technique to estimate the orientation of the far-field horizontal stresses, which is commonly utilized in the oil industry (Kingdon et al. 2016; Fjar et al. 2008). In this investigation, data from the formation micro imager (FMI) log were processed and evaluated to identify the direction of the far-field horizontal stresses. According to the interpretation results, the Zubair formation has a direction of around (140°) NW-SE, as shown in Fig. 6. The maximum horizontal stress is oriented 50° NE-SW, meaning that it is perpendicular to the direction of the  $\sigma_h$ .

### Wellbore stability model

Wellbore stability has become a crucial component of drilling, planning, and execution since unstable wellbores are risky, expensive, and time-consuming in the petroleum industry. Thus, the absence of accuracy in the wellbore stability analysis can lead to several problems, such as borehole breakouts, washouts, losses of the borehole, and stuck drill string. Therefore, identifying the principal far-field stresses for rock formation is necessary to determine the concentration of the stresses around the wellbore (Shi et al. 2023).

For a cylindrical coordinate system, the concentration of the stress around the wellbore is addressed through three principal stresses (i.e., tangential or hoop, radial, and longitudinal

stress). Kirsch (1898) proposed several relationships to compute the induced stress around a vertical wellbore drilled analogous to the principal longitudinal stress (overburden stress) in homogeneous, an isotropic, and elastic medium. Kirsch's (1898) equations may be stated as follows (Javani et al. 2017; Zoback 2007):

$$\sigma_r = P_w \quad (14)$$

$$\sigma_\theta = (\sigma_H + \sigma_h) - 2(\sigma_H - \sigma_h) \cos 2\theta - P_w \quad (15)$$

$$\sigma_z = \sigma_v - 2\nu(\sigma_H - \sigma_h) \cos 2\theta \quad (16)$$

where  $\sigma_r$  is the radial stress;  $\sigma_\theta$  is the hoop stress;  $\sigma_z$  is the longitudinal stress;  $P_w$  is the mud pressure (wellbore pressure);  $\sigma_h$  is the minimum horizontal stress;  $\sigma_H$  is the maximum horizontal stress;  $\sigma_v$  is the vertical stress;  $\nu$  is the Poisson's ratio; and  $\theta$  is the measured angle derived clockwise from the orientation of the  $\sigma_H$ .

A particular and compatible failure criterion should be applied to understand more of a failure phenomenon. However, several failure criteria in the literature are used to contrast the stresses to the formation rocks to assess whether formation rocks fail or not. Mogi-Coulomb and Mohr-Coulomb are two rock failure criteria frequently applied in the petroleum sector. Because the Mohr-Coulomb criterion disregards the intermediate principal stress ( $\sigma_2$ ), the expected strength of rocks is underestimated (Ma et al. 2015).

Mogi (1971) proved experimentally by using an actual triaxial compression test; the brittle fracture happens always along a plane striking, analogous to the orientation of the intermediate principal stress ( $\sigma_2$ ). Consequently, Mogi presented a new criterion as follows (Al-Ajmi and Zimmerman 2006):

$$\tau_{oct} = f(\sigma_{m,2}) \quad (17)$$

where  $\tau_{oct}$  is the octahedral shear stress;  $f$  is the Mogi function; and  $\sigma_{m,2}$  is mean normal stress.

Mogi-Coulomb failure criterion can provide a better fit, and the linear relation of this criterion can be expressed as follows:

$$\tau_{oct} = a + b \sigma_{m,2} \quad (18)$$

where the strength parameters ( $a$  and  $b$ ) from the Mogi-Coulomb criterion are expressed as the following:

$$a = \frac{2\sqrt{2}}{3} c \cos \varphi \quad (19)$$

$$b = \frac{2\sqrt{2}}{3} \sin \varphi \quad (20)$$



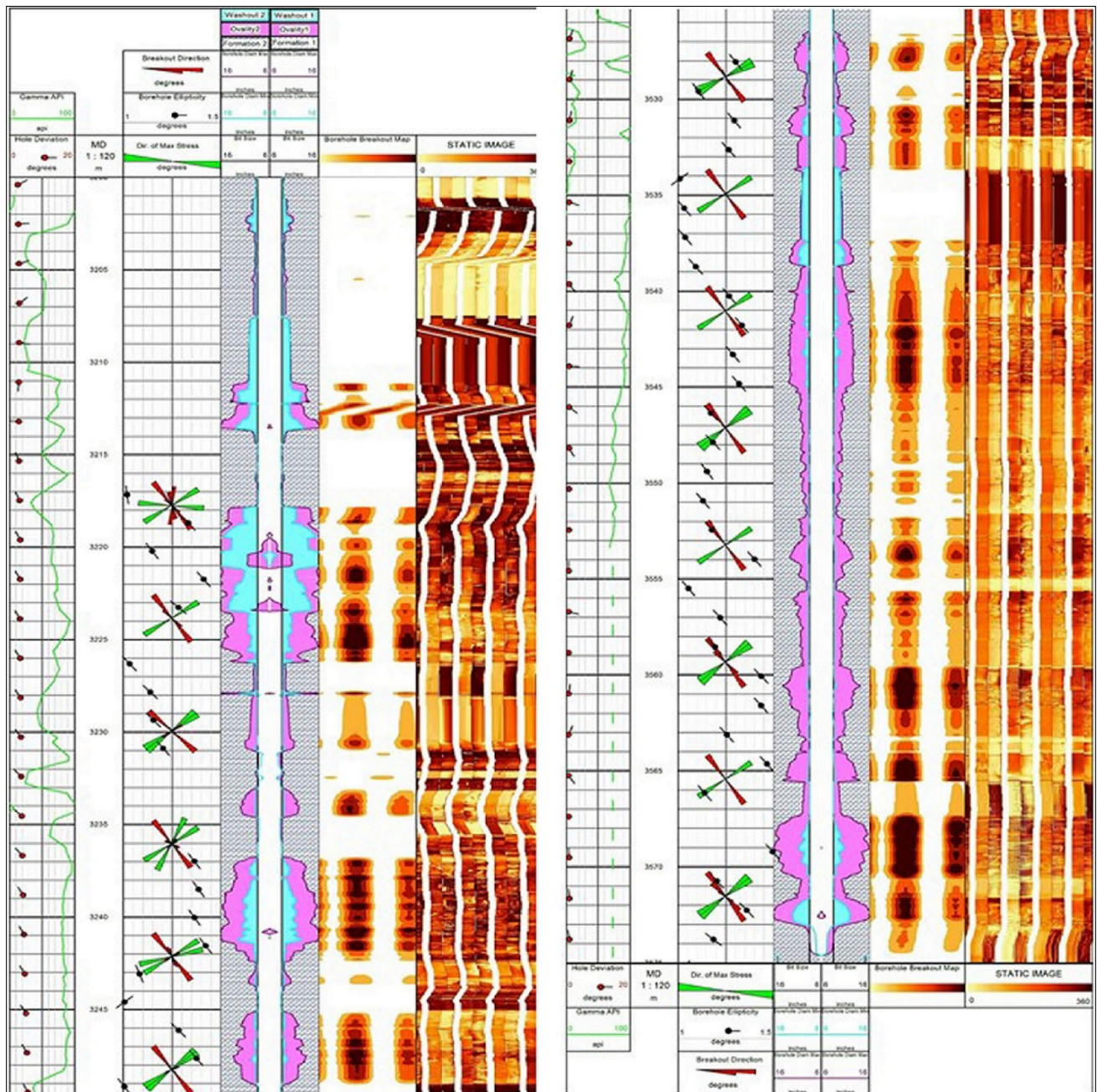


Fig. 6 Interpreted FMI log for the starting and the ending of the Zubair formation

$$\tau_{oct} = \frac{1}{3} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2} \quad (21)$$

$$\sigma_{m,2} = \frac{\sigma_1 + \sigma_3}{2} \quad (22)$$

By applying the Mogi-Coulomb criterion, the influence of the  $\sigma_2$  and the notion of effective stress are taken into consideration.

$$\sqrt{I_1^2 - 3I_2} = a' + b' (I_1 - \sigma'_2) \quad (23)$$

where  $a' = 2c \cos \varphi$  and  $b' = \sin \varphi$ .

$$I_1 = \sigma'_1 + \sigma'_2 + \sigma'_3 \quad (24)$$

$$I_2 = \sigma'_1 \sigma'_2 + \sigma'_3 \sigma'_2 + \sigma'_1 \sigma'_3 \quad (25)$$

where:  $I_1$  and  $I_2$  are the first and second stress constants and  $\sigma'_2$  is the mean effective stress.

According to Al-Ajmi and Zimmerman (2006), Tables 1 and 2 display the equations that are utilized to predict the shear failure (breakout) pressure ( $P_{wb}$ ) and tensile failure (breakdown) pressure ( $P_{wf}$ ), respectively.

## Results and discussions

### Mechanical earth model construction and validation

The one-dimensional mechanical earth model (1-D MEM) construction has been complemented using borehole azimuth and inclination, strength and elastic rock characteristics, overburden stress, pore pressure, and orientation and magnitude of the in situ horizontal stresses. Model validation aims to minimize the uncertainty induced by data limitations and accessibility. Based on the depth and the stratigraphic column, the resulting model depicts the anticipated rock failure, pore pressure, the magnitude of the far-field stresses, and rock mechanical characteristics.

Additionally, the appropriate failure criterion was chosen and a constitutive model was applied. Consequently, a safe mud-weight window will be selected. Typically, rock failure criteria establish a boundary of failure that separates unsafe and safe zones. To select the most appropriate

criterion, the expected failure was examined using drilling incidents, caliper log, and FMI log. The outcomes of this study demonstrated that the Mohr-Coulomb criterion underestimated the anticipated strength of the rock because it neglected the effect of the  $\sigma_2$ , as illustrated in the fifth track of Fig. 7. Because the effects of the  $\sigma_2$  and the notion of effective stress have been considered, the Mogi-Coulomb failure criterion, a more precise and suitable criterion for evaluating the stability of the wellbore, was employed for the study region (sixth track of Fig. 7).

Borehole collapses were expected according to the mud density (10 ppg) used to drill the well (fourth track of Fig. 7). Dark blue shows the tensile fracture zone, whereas yellow indicates the shear failure zone. The results indicated that the expected borehole failures with the Zubair formation ranged from shallow knockouts, which are green in color ( $\sigma_z > \sigma_\theta > \sigma_r$ ), to extensive breakouts, which are red in color ( $\sigma_\theta > \sigma_z > \sigma_r$ ), where  $\sigma_\theta$ ,  $\sigma_z$ , and  $\sigma_r$  are hoop or tangential, axial, and radial stresses, respectively.

The seventh track of Fig. 7 demonstrates the borehole caliper log for comparing the anticipated failures of rock with the realistic issues associated with drilling once 10 ppg weight of mud had been employed to drill the well to verify the established one-dimensional MEM and the selected failure criterion are reliable. Since the caliper log substantially correlates between anticipated and actual borehole failures, it may be considered a validation reliability index.

**Table 1** Breakout pressure in a vertical wellbore according to the Mogi-Coulomb criterion

Case	$\sigma_1 \geq \sigma_2 \geq \sigma_3$	Shear failure equations
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	$\sigma_\theta \geq \sigma_r \geq \sigma_z$	$P_{wb3} = \frac{1}{6-2b^2} \left[ (3A + 2b'G) - \sqrt{H + 12(G^2 + b'AG)} \right]$

Where:

$$A = 3\sigma_H - \sigma_h; B = \sigma_v + 2\nu(\sigma_H - \sigma_h); H = A^2(4b^2 - 3) + (B^2 - AB)(4b^2 - 12); K = a' + b'(B - 2P_o); G = K + b'A$$

**Table 2** Breakdown pressure in a vertical wellbore according to the Mogi-Coulomb criterion

Case	$\sigma_1 \geq \sigma_2 \geq \sigma_3$	Tensile failure equations
1	$\sigma_r \geq \sigma_\theta \geq \sigma_z$	$P_{wf1} = \frac{1}{6-2b^2} \left[ (3D + 2b'N) + \sqrt{J + 12(N^2 + b'DN)} \right]$
2	$\sigma_r \geq \sigma_z \geq \sigma_\theta$	$P_{wf2} = \frac{1}{2}D + \frac{1}{6} \sqrt{12 [a' + b'(D - 2P_o)]^2 - 3(D - 2E)^2}$
3	$\sigma_z \geq \sigma_r \geq \sigma_\theta$	$P_{wf3} = \frac{1}{6-2b^2} \left[ (3D + 2b'M) + \sqrt{J + 12(M^2 + b'DM)} \right]$

Where:

$$D = 3\sigma_h - \sigma_H; E = \sigma_v + 2\nu(\sigma_H - \sigma_h); J = D^2(4b^2 - 3) + (E^2 - DE)(4b^2 - 12) N = a' + b'(E - 2P_o); M = N + b'D$$



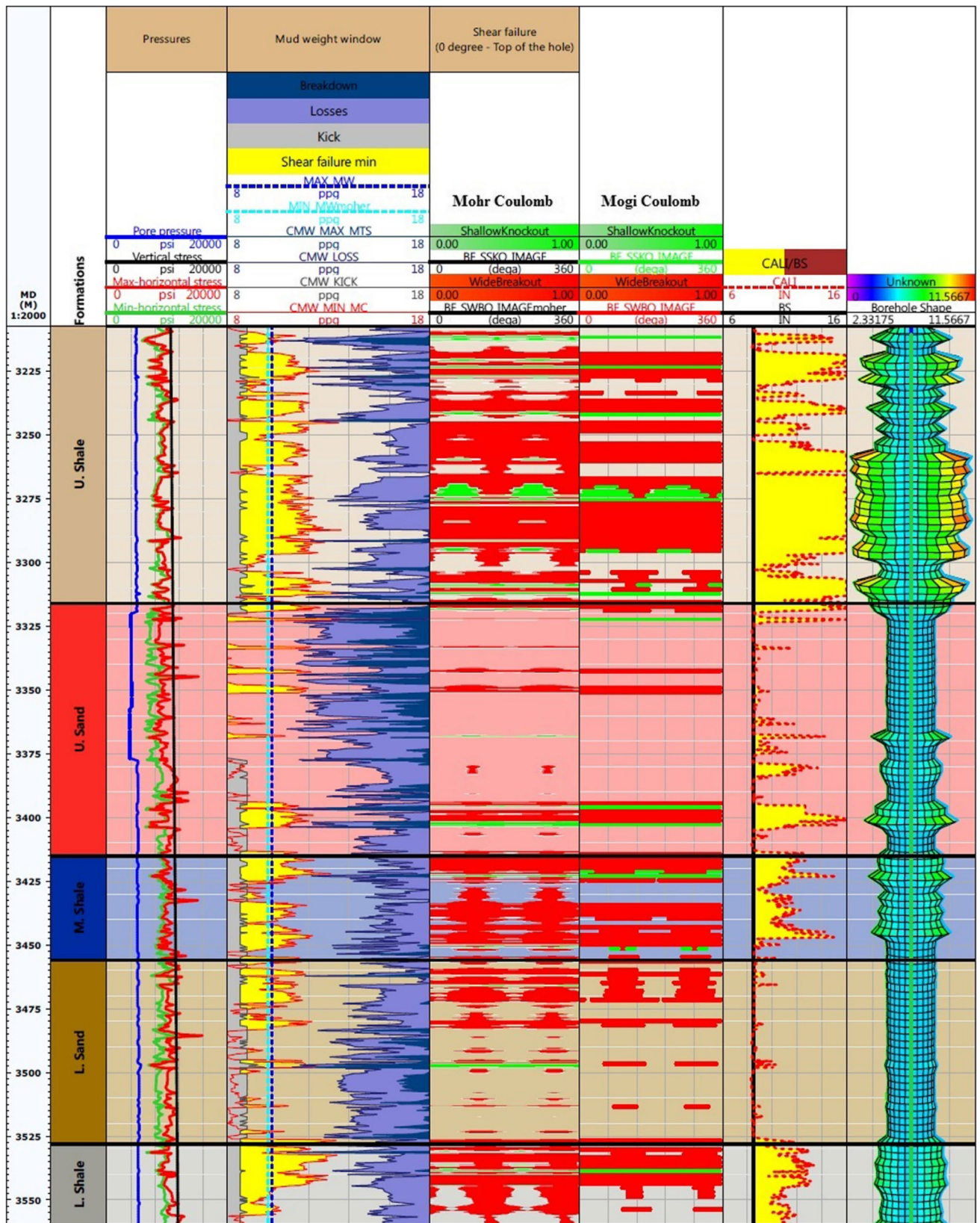


Fig. 7 1D MEM of a well in the Zubair formation demonstrating rock collapse

### Single-depth sensitivity analysis

The required mud weights with different orientations (azimuth and inclination) of the wellbore at a particular depth are determined in this section using sensitivity analysis. The result is a hemisphere plot, which is a common plot for presenting the sensitivity analysis of wellbore stability at different well trajectories. The sensitivity analysis was carried out at critical depths over the hazardous sections of the Zubair formation utilizing Mogi-Coulomb criterion and the developed 1D-MEM.

Figure 8a presents the influence of the orientation and azimuth of the wellbore on the rock breakout failure; it illustrates the limit of the minimal mud weight that is needed to keep the wellbore from shear failure conditions. The results of Fig. 8a showed that more significant mud weights are needed to drill the deviated wells with an inclination greater than 40° at all wellbore azimuths. In contrast, the deviated wells that ranged between 0 and 40° are more stable and

require a minimal mud weight to maintain the wellbore breakout, particularly in the orientation of the  $\sigma_h$ .

Figure 8b depicts the relationship between the wellbore breakdown and the well orientation. The result is a maximum permissible mud weight that should not be exceeded to avoid any wellbore breakout. The outcomes of Fig. 8b revealed that higher mud weights are expected to be required in the orientation of the  $\sigma_h$ . This means that fracture initiation is unlikely to arise with a wellbore oriented to the  $\sigma_h$  when the inclination angle is less than 50°. In contrast, the horizontal or the significantly deviated wells that are oriented in the orientation of the  $\sigma_H$  demonstrated the lowest limit of the breakdown mud weight.

Regarding the mud pressure (mud-weight window) versus wellbore azimuth and inclination (Fig. 8c and d), the safe mud pressure should be constructed to avoid borehole problems, including but not limited to wellbore collapse, washouts, mud loss, and pipe sticking. The following parameters, i.e., the breakdown pressure, shear failure pressure,

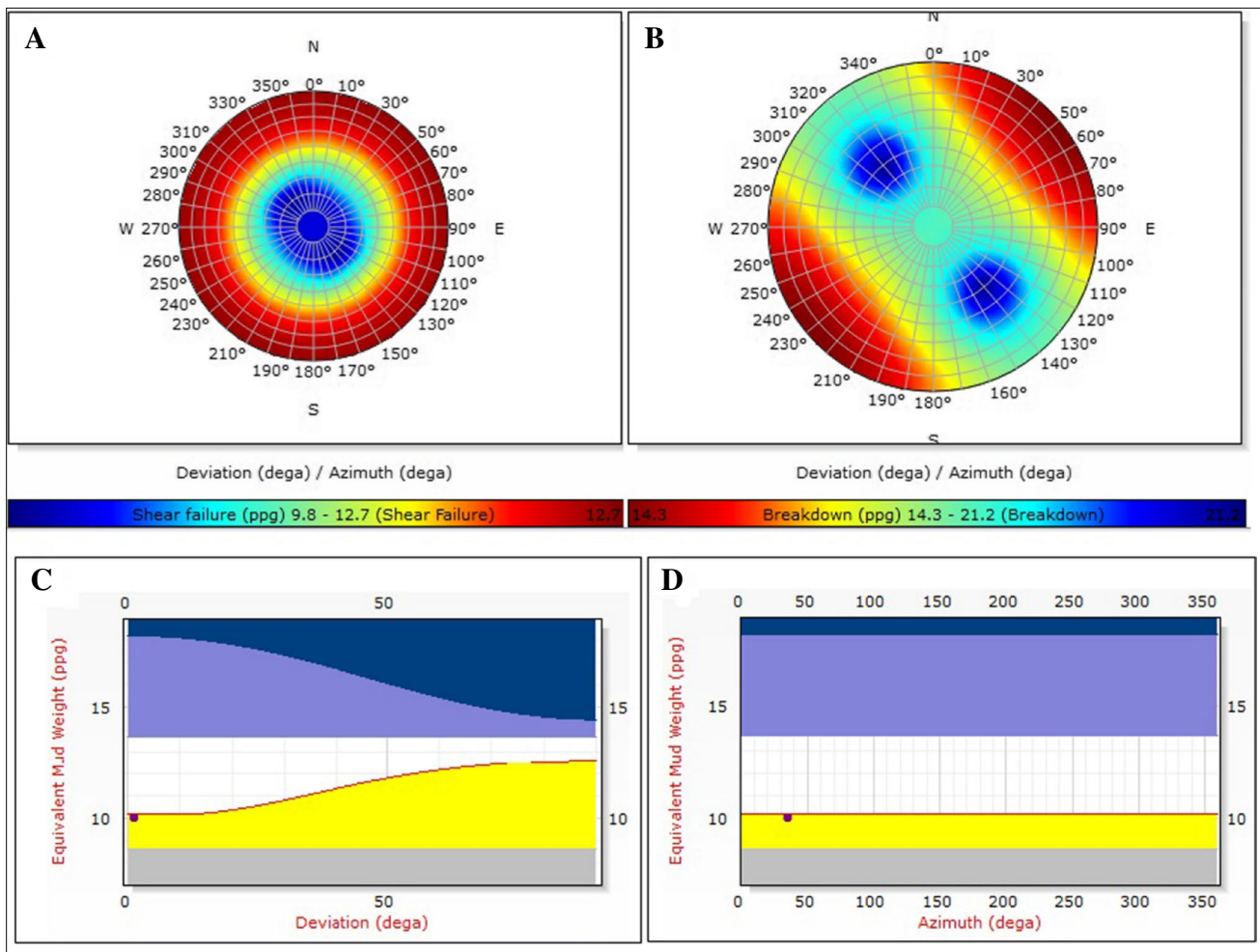


Fig. 8 Single-depth sensitivity analysis for the Zubair formation (at 3445 m)



formation pore pressure, and minimal horizontal stress, constrain the mud weight window. Thus, the optimal mud weight (mud pressure) must be sufficiently high to assure the stability of the borehole while low sufficiently to prevent formation fracturing. Consequently, as the wellbore's inclination or azimuth varies, the shear failure and breakdown pressures will also alter since they are trajectory-dependent. Figure 8c and d depict the impacts of the inclination and azimuth of the wellbore on the mud-weight window for single depths to improve the trajectory of the wellbore utilizing the Mogi-Coulomb criterion. The blue and dark blue profiles in this mud-weight window demonstrate the mud weight relating to mud loss and formation fracturing, respectively. In contrast, the shear failure and kick will happen if the drilling mud density is below the yellow and gray profiles, respectively. The results showed that the secure operational mud-weight window for drilling into the Zubair formation is represented by the white region in the center, and it tends to shrink when the deviation angle is greater than  $40^\circ$ . For more stable conditions, the wells should be drilled with an inclination angle less than this angle. Furthermore, it is conceivable to drill horizontal and deviated wells in the orientation of the  $\sigma_h$ , but more attention is required when designing the breakout and breakdown mud weights. Notably, at this depth and present inclination, the azimuth has no influence on mud weight, as depicted in Fig. 8d.

### Wellbore instability forecast (development plan)

A sensitivity analysis at a single depth can specify the most stable wellbore azimuth and inclination. This approach, however, cannot forecast the severity of the tensile and shear failures along a specific trajectory. This is because of the naturalistic diversity of rock characteristics within a formation.

In this research, a wellbore stability forecast (development plan) was executed for several wellbore trajectories that ranged from vertical to highly deviated borehole ( $0^\circ$ ,  $30^\circ$ ,  $45^\circ$ , and  $60^\circ$ ) along with the azimuth that is equivalent to the orientation of the  $\sigma_h$  ( $140^\circ$ ) to assess possible drilling hazards and evaluate the potential mud-weight window to reduce the issues of the borehole instability along the path of the Zubair formation. The technique was performed using the Mogi-Coulomb criterion with the integrated 1-D MEM.

Figure 9 illustrates the planned wellbore at  $30^\circ$  inclination and  $140^\circ$  azimuth. In this figure, the shear failure of the wellbore was examined for all layers of the Zubair formation (section 8  $\frac{1}{2}$ "') utilizing the Mogi-Coulomb criterion. Considering the expectation for wellbore instability and the mud-weight window. 12.3 ppg was assigned as the safe operational mud weight to drill the Zubair formation along the mentioned trajectory. Bearing in mind the selected mud weight was developed to avoid the tensile fracture and

mitigate the shear failure as presented in the fifth and sixth tracks of Fig. 9.

According to the wellbore stability prediction, some breakout across small intervals of weak shale zones is anticipated at the selected mud weight (e.g., between 3270 and 3295, 3310 and 3315, and 3530 t and o 3550 m MD), as shown in Fig. 9. Consequently, the effective drilling techniques (i.e., select the optimum borehole cleaning, adequate mud condition, specified the appropriate equivalent circulation density (ECD), observing tripping speed, regulating the penetration rate, etc.) should be applied from the drilling crew to be aware of these particular intervals in which wellbore collapse may occur when drilling through these intervals. These techniques will aid in managing the lack of stability and preventing significant drilling issues. Also, the outcomes revealed that vertical and slightly deviated wellbores (less than or equal to  $30^\circ$ ) tend to be more secure, and the proposed drilling mud weight is 11.9 to 12.3 ppg. While the other trajectories ( $45^\circ$  and  $60^\circ$ ) with an azimuth of  $140^\circ$ , the designed mud weights are 12.4 and 12.6 ppg, respectively. Eventually, the development plan findings are utilized to improve the wellbore planning for future wells that are anticipated in the vicinity of the examined well.

### Conclusions

The following statements can summarize the conclusions:

- A 1D MEM has been constructed for the area of interest, and it has been verified utilizing caliper log and drilling data from an offset well.
- The profile of the pore pressure was calculated employing the Eaton equation. It was lower in the upper sand unit than in the lower sand unit; this is due to more wells producing from the upper sand unit for many years.
- Far-field horizontal stresses were evaluated utilizing the poro-elastic strain model, and the continuous profiles from this model were compatible with mini-frac test data.
- According to the axis of breakouts indicated by the caliper and FMI logs, the  $\sigma_h$  direction for the Zubair strata was ( $140^\circ$ ) NW-SE.
- Depending on the magnitudes of far-field stresses, the Zubair formation was dominated by a normal faulting stress regime ( $\sigma_v > \sigma_H > \sigma_h$ ).
- The Mogi-Coulomb failure criterion, which provided an acceptable fit with FMI and caliper logs, is deemed a more precise and appropriate criterion for the Zubair stratum.
- To avert the instability issues of the Zubair formation, the mud weight should be increased from 10 to 12.3 ppg to drill the slightly vertical wells, whereas 12.6 ppg for the strongly deviated wells.

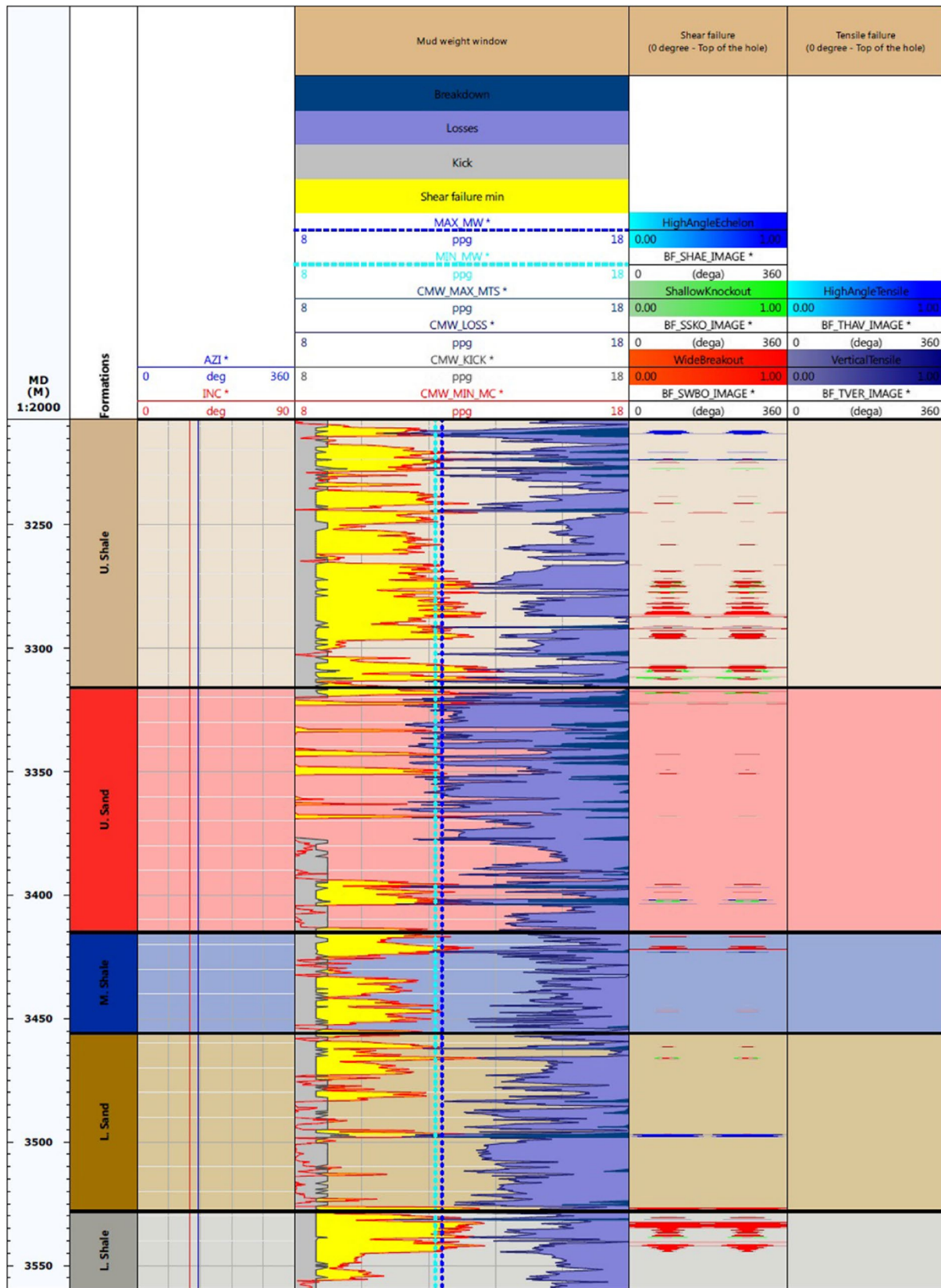


Fig. 9 Shear and tensile failures at 30° inclination and 140° azimuth

- Based on a single-depth sensitivity analysis, when the well inclination is more than 40°, in this case, the required mud weight should be raised to avoid the breakout failure.

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## Declarations

**Conflict of interest** The authors declare no competing interests.

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