University of Baghdad
College of Engineering
JOURNAL OF ENGINEERING

Journal of Engineering
journal homepage: www.jcoeng.edu.iq

Volume 31 Number 9 September 2025

From Rock to Practice: Philosophy of Oilfield Challenges Through Geomechanical Insights

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ABSTRACT

It is well known that drilling challenges, in addition to fluctuating oil prices and increasing competition for production, can contribute to unscheduled field expenditures exceeding one billion U.S. dollars annually. This study emphasizes the importance of integrating geomechanical principles into petroleum engineering, which includes reservoir, drilling, and production operations. A case study was conducted on one well in Rumaila oilfield, located in southern Iraq, to determine the geomechanical properties of carbonate, sandstone, and shale formations. Stress regimes, elastic, and rock strength properties were analyzed. The results showed the stress regime is a strike-slip regime from the Sadi to Zubair formations. The Tanuma formation exhibits low elasticity and strength properties, indicating optimized mud rheological properties for effective lifting capacity. The MishCR1 reservoir, as a producible formation with high rock mechanical stability, can resist compaction and fault reactivation. Other oil-producible reservoirs (MishMA, MishMB2, MishMB1, Zu1, and Zu2) have moderate geomechanical properties, requiring tailored production rates, pressure management, and enhanced recovery methods to mitigate deformation risks. For sandstone reservoirs (Zu1 and Zu2), gravel packing or chemical stabilization is recommended to sustain reservoir performance and enhance oil recovery. This study presents the need for geo-mechanical insights to optimize petroleum operations and mitigate production risks.

Keywords: Geomechanics, Reservoir operations, Drilling operations, Production operations, Mechanical rock properties.

1. INTRODUCTION

Geomechanics has a vital role in both pre-exploitation planning and post-production stages of reservoir development **(Bazyrov et al., 2017; Mohamadian et al., 2021; Mohammed et al., 2022; Rajabi et al., 2022; Ayal et al., 2024)**. Geomechanics is an integration of geophysical, geological, and engineering principles. Complex reservoirs, especially those with heterogeneous rock properties, high pore pressure, and non-uniform stress states, call

*Corresponding author
Peer review under the responsibility of University of Baghdad.
https://doi.org/10.31026/j.eng.2025.09.04
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Article received: 12/03/2025
Article revised: 02/05/2025
Article accepted: 26/05/2025
Article published: 01/09/2025

for integrating geomechanical knowledge into operations to mitigate risks and improve decision-making **(Zoback, 2010)**. Geomechanical parameters encompass the mechanical properties of the rock, pore pressure, and in-situ stresses. Mechanical Properties regulate how the rocks respond to the applied external stresses and influence wellbore stability as well as reservoir performance. The strength and elastic properties constitute two subdivisions. Elastic properties, including Young's modulus (E), Poisson's ratio (ν), Bulk modulus (K), and Shear modulus (G), indicate the ability of the rock to deform when subjected to stress under a load without sustaining any permanent loss. Strength parameters such as Unconfined Compressive Strength (UCS), Tensile Strength (Ts), Cohesion (C_0), and Friction Angle (ϕ or FANG) indicate the ability of the rock to resist failure. In-situ stresses, i.e., vertical stress (Sv), maximum horizontal stress (Shmax), and minimum horizontal stress (Shmin), control the mechanical behavior of the subsurface. They control rock deformation, fault slip, and wellbore stability under various regimes of stress.
The petroleum industry loses around $1 billion annually due to wellbore instability **(Al-Ajmi and Zimmerman, 2006; Zeynali, 2012)**. Drilling incorporates mechanical, physicochemical, and stress redistribution issues that impact wellbore stability and the efficiency of the drilling operation. Stress redistribution occurs in the area near the wellbore due to drilling operations, leading to instability risks such as wellbore collapse, lost circulation, and differential sticking **(Maleki et al., 2014; Haider et al., 2020; Edan and Abdulhussein, 2023)**. In addition, issues such as bit wear, torque and drag, transmission of cuttings, reactive formations, and vibrations of drill string also complicate drilling operations. Geomechanics plays a significant role in minimizing these risks by optimizing mud weight, wellbore trajectory, drilling fluid properties, casing design, and breakout zone prediction **(Quosay and Knez, 2016; Knez and Rajaoalison, 2021)** to ensure safe and efficient drilling performance.
Production operations are confronted with several challenges that affect reservoir longevity and production efficiency. Some of the key challenges include formation stimulation, orientation and selection of perforation zones, sand production zones, fault reactivation, fluid migration, and surface subsidence. All these contribute directly to hydrocarbon recovery efficiency, and therefore, a comprehensive geomechanical understanding is required to minimize risks and maximize production **(Liu et al., 2021; Wang and Tang, 2024)**.
This study aims to provide a comprehensive understanding of reservoir, drilling, and production operations and their challenges through geomechanical insights and considerations. Furthermore, seeking to predict, interpret, and treat the potential challenges that might be faced in the oilfields. The elastic and strength rock properties have been done in this study for carbonate, sandstone, and shale formations in directional well X within the Rumaila oil field in the south of Iraq. Also, determining the petrophysical properties and in-situ stresses of the well to establish a 1D mechanical rock properties model and to analyze the reservoir, drilling, and production challenges with the geomechanical insights.

2. MATERIALS AND METHODS

2.1 Rock Mechanical Properties

Assessing rock mechanical properties is a vital step for constructing a mechanical earth model (MEM). These properties involve linear elastic deformation characteristics and rock strength parameters, which can be determined either directly by laboratory and field testing (static methods), which involves applying direct pressure to rock samples in controlled conditions, or indirectly by using empirical correlations (dynamic methods) in which correlations for calculating the shear and compressional wave velocities from well logs are normally used **(Abbas et al., 2019; John et al., 2020)**.

2.1.1 Elastic Properties

Elasticity indicates the material's ability to resist deformation in volume or shape under external forces and return to its original form once the forces are removed. The simplest elastic response occurs where there is a direct relationship between the exterior forces (applied stress) and the resultant deformation (strain). The most important elastic features are Young's modulus, Shear modulus, and Poisson's ratio. Elasticity is considered the basis for all rock Geomechanics aspects.

2.1.1.1 Shear Modulus (Modulus of Rigidity)

Shear modulus (G) quantifies the material's resistance to deformation under applied shear stress. Unlike solids, the shear modulus vanishes for fluids **(Fjaer et al., 2008)**. **Table 1** summarizes the relevant equations of rock elastic properties with their units, including the shear modulus equation. Based on **(Moos et al., 2003; Fjaer et al., 2008; Zoback, 2010) Table 2** presents a comprehensive overview of the effects of high and low magnitudes of the rock elastic properties on different parameters and properties, including the rocks, fracture propagation, wellbore stability, and rock drill ability.

2.1.1.2 Bulk Modulus

Bulk modulus (K) is the material's resistance to uniform volumetric compression. It represents the ratio of the applied stress (σ) to the volumetric strain **(Tables 1 and 2)**.

Table 1. Elastic rock properties' equations and units **(Dakhiel and Hadi, 2021)**.

Rock Mechanical Property	Theoretical Equation	Used Equation	Units	Eq. (#)
Shear Modulus	$G = \frac{\tau}{\gamma}$	$G_{dyn} = 13474.45 \times \frac{\rho_b}{(\Delta t_{shear})^2}$	G= MPsi τ= MPsi γ= Unitless ρ_b = g/cm³ Δt_{shear} = μs/ft	(1)
Bulk Modulus	$K = \frac{\sigma}{(\Delta V/V)}$	$K_{dyn} = 13474.45 \times \left[\frac{\rho_b}{(\Delta t_{comp})^2}\right] - \frac{4}{3} \times G_{dyn}$	K_{dyn} = Mpsi Δt_{comp}= μs/ft	(2)
Young's Modulus	$E = \frac{\sigma_x}{\varepsilon_x}$	$E_{dyn} = \frac{9 \times G_{dyn} \times K_{dyn}}{G_{dyn} + 3K_{dyn}}$ $E_{sta} = 0.032 \times E_{dyn}^{1.632}$	E= MPsi	(3) (4)
Poisson's Ratio	$\upsilon = \frac{\epsilon_h}{\epsilon_v}$	$\upsilon_{dyn} = \frac{3K_{dyn} - 2G_{dyn}}{6K_{dyn} + 2G_{dyn}}$ $\upsilon_{sta} = \upsilon_{dyn} \times PR_{mult}$	υ= Unitless PR_{mult}= Unitless	(5) (6)

Table 2. A comparison between high and low values of rock elastic properties and their effects on other parameters and drilling problems **(Moos et al., 2003; Fjaer et al., 2008; Zoback, 2010)**.

Elastic Property	Value	Rocks	Fracture propagation	Wellbore stability	Rock drill ability
Shear Modulus	High	Hard; resist shear stress deformation.	controlled fracturing.	Stable and resists shear stresses.	Harder to drill.
	Low	Soft, deformable with plastic behavior.	Less Suitable for controlled fracturing.	Risk of wellbore collapse and washout.	Easier to be drilled.
Bulk Modulus	High	Compacted rocks resist volumetric deformation.	Controlled fracturing.	Highly stable; resists volumetric deformation and has no risk of washouts.	Harder to drill.
	Low	Compressible rocks like shale and clay.	Uncontrolled fracture growth.	Unstable; collapse and washout risks.	Easier to be drilled; Soft.
Young's Modulus	High	Rigid rocks; directional deformation.	No induced fractures that enable targeted fracturing.	Stable; supports high mud weights.	Harder to drill.
	Low	Ductile deformable rocks.	Not Suitable for controlled fracturing.	Unstable; collapse risks.	Easier to be drilled.
Poisson's Ratio	High	Ductile rocks with lateral expansion and compaction.	Resists fracture propagation at low pressures.	Unstable; collapse and washout risks.	Easier to be drilled; less resistance.
	Low	Brittle rocks without lateral expansion and compaction.	Controlled fracturing.	Stable; handles high mud weights effectively.	Harder to drill; Strong rocks.

2.1.1.3 Young Modulus (Hook's Law)

Young's modulus quantifies the material's ability to resist deformation along a single direction when subjected to uniaxial stress, either in compression or tension. Mathematically, it is the lengthwise stress change divided by longitudinal strain change according to Hooke's law of elasticity, which expresses how much a material will deform under a given load **(Tables 1 and 2)**.

2.1.1.4 Poisson's Ratio (v)

Poisson's ratio measures the extent to which a rock expands when subjected to axial compression. It is the ratio of horizontal to vertical strain **(Zoback, 2010)**. Poisson's ratio reflects the tendency of the rocks to undergo lateral expansion or contraction. High mud weight density is necessary for drilling a rock with a high Poisson's ratio that exerts inward pressure on the wellbore, which leads to potential well collapse **(Mitchell, 2001; Dakhiel and Hadi, 2021)**. Another inherent issue is that a careful balance of mud weight and pressure control is required when rocks with low Poisson ratios are drilled to avoid fracturing the brittle formation. This means that low mud weights are more appropriate than high mud weights, but careful monitoring of wellbore conditions is essential to keep it away from both underbalance (which might lead to wellbore collapse) and overbalance (which might lead to induced fractures) **(Tables 1 and 2)**.

2.1.2 Rock Strength Properties

The strength of a material is defined as the rock strength that withstands the applied load before failure (i.e., permanent deformation). The relationship between the applied external loads of material and the resulting deformation or the change in the material's dimensions is directly influenced by the rock's strength properties. These properties are crucial in reservoir geomechanics because they govern the formation's behavior when subject to operational conditions **(Aadnoy and Looyeh, 2011)**.

2.1.2.1 Unconfined Compressive Strength (UCS)

Unconfined compressive strength is an indicator of a rock's ability to withstand compression before failure occurs. When the compressive shear strength exceeds the rock strength, the rock will fail. This failure can cause deformation and fracturing in the wellbore due to compression, probably leading to mechanical instability in the wellbore. **Table 3** summarizes the relevant equations of rock strength properties with their units.

Table 3. Strength rock properties' equations and units **(Dakhiel and Hadi, 2021)**.

Rock Mechanical Property	Used Equation	Units	Eq. (#)
Unconfined Compressive Strength	$UCS = 330.7 + 0.0041 \times E_{sta}$	UCS= Psi E_{sta}= MPsi	(7)
Friction Angle	For shaly sedimentary rocks: $\emptyset = 70 - 0.417 \times GR$ For shaly rocks: $\emptyset = tan^{-1}(\frac{78 - 0.4 \times GR}{60})$ For sandstone rocks: $\emptyset = 57.8 - 105 \times GR$	$\emptyset$= degree	(8) (9) (10)
Cohesive Strength	$C_o = \frac{UCS}{2[\sqrt{1 + (tan\,\emptyset)^2} + tan\,\emptyset]}$	C_o= Psi	(11)
Tensile Strength	$T_s = UCS \times k$	T_s= Psi	(12)
Shear Strength	$\tau = C_o + \sigma_n \times tan\,\emptyset$	τ= Psi σ_n= Psi	(13)

Based on **(Moos et al., 2003; Fjaer et al., 2008; Zoback, 2010)**. **Table 4** shows the effects of high and low magnitudes of each property on different parameters and properties, including the rocks, the fracture propagation, wellbore stability, and rock drillability.

2.1.2.2 Internal Friction Angle (FANG Or $\emptyset$)

Internal friction angle is the shear resistance due to the intergranular friction between particles within the rock **(Alidaryan et al., 2023)**. According to the Mohr circle model, the angle between the normal and resulting stresses at failure due to the shear stress is the internal friction angle (**Tables 3 and 4**).

2.1.2.3 Cohesive Strength (Cohesion S_0 or C_0)

Cohesion, or cohesive strength, is the ability of rocks' parts to stay united with each other and resist separation. In essence, the shear strength of a rock is the cohesion when there is no applied normal stress acting on it. For the deformation that occurs in a rock, there should be a movement between the individual grains relative to one another. This movement is resisted by the cementation and friction between the grains, which provides the rock with its strength. Several factors influence this internal friction, including grains' shape and size, the magnitude of compressive forces across the grains, grains' orientation, and the amount of lubricating fluids in pore spaces **(Fjaer et al., 2008; Zoback, 2010; Aadnoy and Looyeh, 2019) (Tables 3** and **4)**.

Table 4. A comparison between high and low values of rock elastic properties and their effects on other parameters and drilling problems **(Moos et al., 2003; Fjaer et al., 2008; Zoback, 2010)**.

Strength Property	Value	Rocks	Fracture propagation	Wellbore stability	Rock drill ability
UCS	High	Hard, withstands compression.	Harder to fracture with control.	Stable; handles high mud weights effectively.	Harder to drill due to high strength.
	Low	Low-strength rocks.	Easy fracturing with limited control.	Unstable; collapse and washout risks.	Easier to be drilled due to lower strength.
Friction Angle	High	Strong intergranular friction rocks.	High resistance to fracture.	Stable; handles high mud weights.	Harder to be drilled.
	Low	Soft and fine-grained rocks.	Easy fracture initiation at lower pressures.	Unstable; collapse and washout risks.	Easier to be drilled.
Cohesive Strength	High	Grains are strongly bonded.	Harder to fracture.	Stable; resists collapse	Harder to be drilled.
	Low	Weakly bonded rocks.	Easily uncontrolled fractures.	Unstable; collapse and washout risks.	Easier to be drilled.
Tensile Strength	High	Resilient rocks; resist separation under tension.	Ideal for fracturing; withstand tensile stress.	Stable; resist tensile failure	Harder to be drilled.
	Low	Brittle, less dense rocks; separate easily under tensile stress.	Easily uncontrolled fractures.	Susceptible to tensile cracking and failure.	Easier to be drilled.
Shear Strength	High	Strong inter-grain cohesion rocks.	Harder to fracture with control.	Stable even under high deviatoric stresses.	Harder to be drilled.
	Low	Loosely bound or highly porous rocks.	Easily uncontrolled fracture propagation.	Risks of shear failure, collapse, and washout.	Easier to be drilled.

2.1.2.4 Tensile Strength Ts

Tensile strength is the maximum stress a rock can withstand under tension before failure. It is a critical limit; if exceeded by a tensile effective stress, rocks will experience tensile failure, leading to a fracture that splits the sample, predominantly originating from pre-existing microcracks within the rock structure, typically propagating along planes perpendicular to the direction of applied tensile stress. Substantially, tensile strength is highly sensitive to the pre-existing flaws in the rock substance that make tensile strength very small and may even approach zero when the cracks occur normally to the tensile load **(Fjaer et al., 2008; Aadnoy and Looyeh, 2011; Yang et al., 2022) (Tables 3 and 4)**.

2.1.2.5 Shear Strength (Compressive Strength T)

It is the ability to resist forces (shear force) that causes the material's internal slippage along failure planes within its structure. In other words, it is the maximum shear force a material can withstand before failure. This property evaluates how a material responds to shear force deformation when subject to high compressive loads **(Tables 3 and 4)**.

2.2. Oilfield Challenges Through Geomechanical Insights

The understanding of field challenges through a geomechanics point of view is crucial for optimizing drilling and production operations in hydrocarbon reservoirs. Geomechanics provides a framework to comprehensively evaluate how rocks behave and respond under applied stresses, pressures, and fluid interactions **(Zoback, 2010; Aadnoy and Looyeh, 2019; Albattat and Hoteit, 2021; Khankishiyev and Salehi, 2024)**.

2.2.1 Geomechanical Insights in Reservoir Challenges

Reservoir characteristics are influenced by geo-mechanical processes that can increase or decrease porosity and permeability. Pores act as rock weaknesses by concentrating stress, reducing mechanical strength, and increasing failure potential under applied loads **(Atapour and Mortazavi, 2018; Alomari et al., 2023).** Rigid rocks (denser rocks) that have high E and UCS show less pore volume compared to soft rocks with lower density. Permeability is related to interconnected pore networks (pathways) that might also indicate the planes of weakness **(Fjaer et al., 2008; Jaeger et al., 2009; Zoback, 2010)**. The reservoir depletion alters the field stresses that reduce pore spaces and fluid flow pathways. This directly impacts hydrocarbon recovery and might cause compaction or subsidence. Furthermore, these changes may create new fractures or close existing ones, hence affecting the reservoir's connectivity and fluid flow properties **(Wong and Baud, 2012; Mahdi and Farman, 2023b)**.

Compressibility is the rock's (reservoir) ability to compact under stress. It determines how rocks respond to pressure changes. High compressibility is linked with low bulk modulus, which increases compaction and subsidence risks. In contrast, low compressibility (high bulk modulus) increases the rock’s structural solidity.

In saturated formations, fluids decrease friction among grains because the fluids are lubricants, thereby causing a reduction in cohesion and friction angle **(Alomari et al., 2023)**. The fluid's existence also affects effective stress by creating pore pressure, which opposes the applied stress and causes a decrease in the effective stress, as indicated in Eq. (14). This decreased effective stress preserves pore volumes and preserves fracture conductivity, a condition that is favorable for maintaining reservoir characteristics. Conversely, in fluid-free formations, the effective stress is approximately equal to the total applied stress, thereby subjecting the rock to its maximum potential effective stress. Such a scenario promotes grain interlocking, mechanical strength, and potential brittleness, which favors stable drilling.

$$\sigma` = \sigma_{total} - \alpha P_P \quad (14)$$

2.2.2 Geomechanical Insights in Drilling Challenges

Numerous geo-mechanical challenges affect drilling operations, such as wellbore instability, stuck pipe, loss of circulation, torque and drag, and lifting capacity. One of these challenges is the wellbore stress regime that includes tangential (hoop), radial, and axial stresses around the wellbore (Kirsch…). Tangential stress can cause wellbore collapse if it is higher than the rock's compressive strength **(Fjaer et al., 2008)**; the radial and axial stresses represent the interaction between drilling fluids and the formation stresses **(Jaeger et al., 2009)**. Radial Stress is related to the hydrostatic pressure of the drilling fluid inside the wellbore, where the used mud weight is insufficient, which may cause wellbore collapse (shear failure), while excessive mud weight can cause tensile rock fracturing **(Fjaer et al., 2008)**.

Some challenges may arise when we do not consider the in-situ stress regimes. There are three fault stress regimes: normal, strike-slip, and reverse. In normal faulting regimes (Sv > Shmax > Shmin), it is crucial to balance the mud weight with pore pressure to avoid fracturing. when the Sv is the greatest and the minimum horizontal stress is the smallest, making the rock prone to fracture in the horizontal direction, If the mud weight (hydrostatic pressure) is higher than the fracture gradient of the formation (typically tied to Shmin it can induce fractures in the wellbore wall. So, collapse should be prevented by maintaining the hydrostatic pressure between the pore and fracture gradient pressure. For strike-slip regimes (Shmax > Sv > Shmin), needs to avoid high-angled wellbores to minimize shear failure chances by reducing the impact of Shmax and avoiding the regions with high stress concentration. In reverse faulting regimes (Shmax > Shmin > Sv), the horizontal stresses are the greatest, the rocks surrounding the wellbore is subjected to high horizontal compressive stresses, which require to be faced by higher mud weights to prevent collapse **(Jaeger et al., 2009, Zoback, 2010)**. The borehole trajectory should be aligned with the principal (highest) stress directions to avoid the high stress concentration **(Zoback, 2010)**. Where Sv, Shmax, and Shmin can be calculated by Eqs. (15 to 17).

$$S_v = \int_0^z \rho \, z \, g \, dz \quad (15)$$

$$\sigma_h = \frac{v}{1-v} \times \sigma_v - \frac{v}{1-v} \times \alpha p_p + \alpha p_p + \frac{E_s}{1-v} \times \varepsilon_h + \frac{v \times E_s}{1-v^2} \times \varepsilon_H \quad (16)$$

$$\sigma_H = \frac{v}{1-v} \times \sigma_v - \frac{v}{1-v} \times \alpha p_p + \alpha p_p + \frac{E_s}{1-v} \times \varepsilon_H + \frac{v \times E_s}{1-v^2} \times \varepsilon_h \quad (17)$$

Where, ρ: bulk density in g/cm3, g: is a gravity acceleration, v: static Poisson's ratio, E: static Young's modulus, α is Biot's coefficient, and ε_h and ε_H are tectonic strains, they determined by equations. εh and εH are tectonic strains, and estimations from Eqs. (18 and 19).

$$\varepsilon_h = \frac{\sigma_v \times v}{E} \times (1 - \frac{v^2}{1-v}) \quad (18)$$

$$\varepsilon_H = \frac{\sigma_v \times \upsilon}{E} \times (\frac{\upsilon^2}{1-\upsilon} - 1) \quad (19)$$

Chemical reactions between drilling fluids and the formation rocks also complicate the drilling operations **(Zoback, 2010)**. Reactive shales, for instance, may swell or weaken when they contact with water-based mud **(Jaeger et al., 2009)**. Carbonate formations may react with acidic drilling fluids that dissolve calcite or dolomite, hence reducing the strength of the contacted rocks. Similarly, in sandstone formations, acidic or incompatible fluids can dissolve cementing minerals, subsequently weakening the grain structure (decreasing Co) and increasing the risk of sand production **(Fjaer et al., 2008; Mahdi and Farman, 2023a)**. The mechanical properties of drilled rocks influence the size and shape of cuttings. Strong and stiff rocks (high values of E, G, K, and UCS) tend to create coarse, large, angular cuttings, which require higher annular velocities than small cuttings, along with an optimized drilling fluid property, such as higher density and customized rheology to keep the lifting capacity effective and prevent cuttings from settling **(Chang et al., 2024)**. Conversely, soft and ductile rocks (low values of E, G, K, and UCS) tend to produce smaller cuttings. These finer cuttings can be carried more easily by the drilling fluid with less energy for removing the cuttings **(Zoback, 2010)**. However, high deformation is normally produced from drilling the soft and ductile rocks, which requires more attention to the rheological mu properties to maintain an optimum lifting capacity by controlling the ratio of yield point to plastic viscosity of drilling mud.

2.2.3 Geomechanical Insights in Production Challenges

Geomechanics analysis guides production management and completion strategies for the assurance of long-term well integrity and efficient hydrocarbon recovery **(Zoback, 2010; Aadnoy and Looyeh, 2011; Albattat and Hoteit, 2021; Khankishiyev and Salehi, 2024)**. Production and completion operations have various challenges needing geomechanical expertise. When the reservoir pressure declines results in high effective stress that induces compaction, subsidence, or rock failure. To prevent these issues, robust casing designs and improved cementing jobs are necessary.

Formation stimulation, whether through hydraulic fracturing or through an injection process that modifies fluid or rock properties physically or chemically **(Lake et al., 1989; Zoback, 2010)**. These processes need geomechanical analysis to implement these strategies effectively without undesirable reservoir damage. For example, selecting the candidate zones for implementing the hydraulic fracturing techniques is entirely related to the zones that have high values of Young's modulus (i.e., low deformation).

Selecting the perforation zones with the perforation orientation is another example related to the construction of mechanical earth modeling for the production zone, for achieving efficient reservoir drainage. The zones that should be targeted for the perforation operation should have high elastic and strength rock properties to satisfy stability conditions. Furthermore, the orientation of the perforations should be aligned with the dominant in-situ stress field to minimize risks of instability or poor stimulation. Reservoir conditions may force the operator to perforate in low elastic or strength rock properties and/or not in a direction parallel to the dominant in-situ stress, which requires other solutions such as perforating through a cased hole.

Another key example is related to sandstone reservoirs in which sand production zones require special sand-control treatment, such as gravel packs or specialized screens, to maintain productivity and minimize sand production. Drawdown pressure management is important to control sand production in hydrocarbon reservoirs. Drawdown pressure is the pressure difference between the reservoir and the wellbore during production operations. If the drawdown pressure is too high, it can destabilize the formation by increasing stress on the rock, making sand grains break loose. This high drawdown pressure increases the speed of fluid flow around the wellbore and then creates strong forces which is enough to carry sand grains and even widen or create induced fractures. Keeping the drawdown pressures at moderate values helps reduce these problems, thus stabilizing the wellbore and minimizing the chances of collapse and sand production **(Nemati et al., 2024)**.

Sand production can be estimated by utilizing the Combined Modulus method ($E_{c-Index}$) Sand cannot be produced when $E_{c-Index}$ value is 2.88x10^6 psi or greater, if $E_{c-Index}$value is ranged between (2.16x10^6 psi - 2.88x10^6) psi, the sand is lightly producible, but if $E_{c-Index}$ is below 2.16x10^6 psi, the sand will be severely **(Hong'en et al., 2005)**. $E_{c-Index}$ is determined through Eq. (20).

$$E_{c-\text{Index}} = \frac{9.94*10^8\,\rho}{DTC^2} \tag{20}$$

Fault reactivation happens as a consequence of stress redistribution during reservoir production because the depletion of pore pressure increases effective stress, which leads to shear failure, fault slip, and stress heterogeneity. It is responsible for creating overpressure zones, permeability destruction, or even fracture reactivation **(Fjaer et al., 2008; Zoback, 2010)**. These changes may form fault-related leak pathways that damage the sealing of the reservoir **(Zoback, 2010)** and increase the likelihood of water encroachment or hydrocarbon migration into undesired zones **(Jaeger et al., 2009)**. Avoiding fault reactivation issues by maintaining reservoir pressure with water or gas injection to reduce effective stress changes **(Dake, 1983)** and employing advanced geomechanical modeling to manage reservoir compartmentalization and optimize production rates, reducing non-uniform pressure drawdowns and stress concentrations around faults **(Jaeger et al., 2009; Albattat and Hoteit, 2021)**.

2.3 Field Case Study

Rumaila oilfield is one of the most important Iraqi oilfields and one of the largest petroleum fields in the world. The field is divided into south and north domes, separated by an anticline structure (saddle), and extends along 80 Km north to south and 20 Km west to east. The stratigraphy of the Rumaila oilfield extends from the Upper Jurassic to recent geological times and primarily consists of a thick carbonate succession with minor shale and sandstone formations, as shown in **Fig. 1a (Aqrawi et al., 1998; Sharland et al., 2001)**. The selected well (Well X) is a directional oil producer well, located in the northern dome of the Rumaila oilfield, drilled as an S-shaped directional well as illustrated in **Fig. 1** to enhance the reservoir's" behavior" through drilling operations, completion management, and production strategies of the field, geomechanical analysis is of great importance for identifying the elastic and strength rock properties, as well as the far-field stresses and stress distribution around the wellbore.

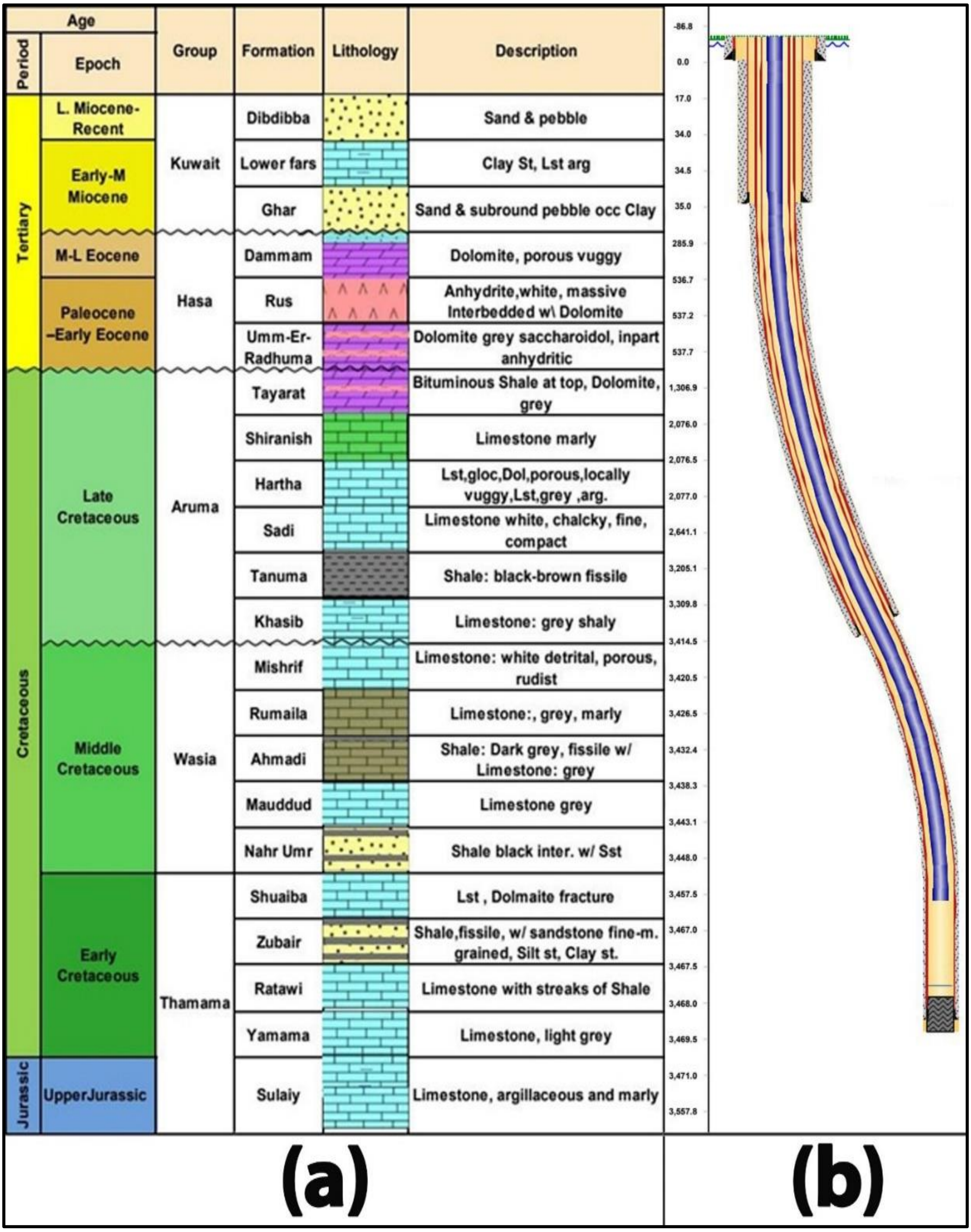

Figure 1. (a) The stratigraphic column of the Rumaila oilfield, modified from **(Aqrawi et al., 1998; Sharland et al., 2001)**; (b) Drilling trajectory of well X.

3. RESULTS AND DISCUSSION

3.1 1D Mechanical Rock Properties

The 1D rock mechanical properties model is a decision-making framework that integrates elastic and strength properties with in-situ stresses for further applications related to reservoir geomechanics. The 1D rock mechanical properties model was determined based on the illustrated equations in **Tables 1 and 2**. The in-situ stresses are determined through Eqs. (14 to 18). The sand production prediction was established using Eq. (19). **Fig. 1a** demonstrates the lithology of the formations under study, where Sadi, Khasib, Mishrif (MishCR1, MishMA, MishMB1, and MishMB2), Rumaila, Ahmadi, Mauddud, and Shuaiba are carbonates, while Nahr Umr and Zubair (Zu1 and Zu2) formations are sandstone formations, and Tanuma formation is a shaly formation. **Figs. 2** to **6** show the volume of shale (Vsh) included with depth track, caliper and ROP logs records to indicate the wellbore's problems and challenges, elastic properties (E, G, K, and Vstatic) track, strength properties (UCS, Co, FANG, and Ts) track, in-situ stresses (Shmax, Shmin, and Sv) logs track, WOB, mud weigh and RPM profiles track to show the driller jobs, and porosity and permeability logs. **Figs. 5 and 6** for sandstone formations, which required the Ec_Index (Eq. 19) log to estimate zones that are prone to sand production.

Table 5 shows that the Sadi to Zubair formations are subjected to a strike-slip fault regime. This requires avoiding high-angled drilling because it tends to increase shear failure risks and stress concentrations. The Tanuma formation, as a shale formation, is the least stable formation among the studied formations because it has the lowest E and UCS. These properties make the formation highly ductile and mechanically weak, hence high instability as shown in **Fig. 2,** where it collapsed along the formation. Low Co is an indication of weak grain cementation, hence high compaction and deformation tendency under stress. These factors make Tanuma prone to instability, subsequently requiring the use of advanced drilling fluids, improved cementing techniques, and real-time stress monitoring to ensure safe operational jobs.

The MishCR1 formation is highly stable with higher E and Ts among other formations under study. These properties indicate strong stress resistance, low compressibility, and high mechanical properties. The formation's stability reduces the likelihood of subsidence risk, reactivation of faults, and closure of pore throat, thus maintaining permeability and petrophysical characteristics. Therefore, MishCR1 is an appropriate reservoir for long-term hydrocarbon production at low structural risks, even under high production rates.

The MishMA, MishMB1, MishMB2, Zu1, and Zu2 formations are hydrocarbon-producible zones. Their geomechanical properties are intermediate with relatively low values of G, K, Co, and Ts than MishCR1. These formations have a higher likelihood of stress deformation and compaction and, subsequently, a higher probability of subsidence and reduced permeability. To avoid these problems, it is recommended to adopt strategies that encompass controlled production rates, effective pressure management, and optimized drilling trajectories. In addition, more recovery methods like gravel packing or chemical stabilization can help maintain reservoir performance if such risks are encountered. The Rumaila, Maudud, and Shuaiba have high elastic and strength properties, which are highly stable through drilling operations.

Table 5. Average mechanical rock properties and vertical and horizontal stresses for well X.

Formation	Es	G	K	v	UCS	Co	FANG	Ts	Sv	σ_H	σ_h	Fault Regime
	Gpa	Gpa	Gpa		Mpa	Mpa	Deg.	Mpa	Mpa	Mpa	Mpa	
Sadi	30	12	36	0.31	64.0	15.5	38°	0.9	41.3	43.5	41.0	Strike Slip
Tanuma	14	6	17	0.31	43.4	12.6	29.5°	0.6	44.7	46.6	44.0	
Khasib	34	14	39	0.3	68.9	16.4	38.9°	1.0	45.5	47.5	44.7	
MishCR1	45	18	56	0.32	92.9	20.2	42.1°	1.3	46.6	48.4	45.6	
MishMA	38	15	43	0.3	75.3	17.4	40.1°	1.1	47.6	49.4	46.6	
MishMB1	33	13	37	0.3	67.1	16.0	38.6°	1.0	48.5	50.3	47.4	
MishMB2	30	12	34	0.3	62.3	15.2	38°	0.9	49.4	51.1	48.1	
Rumaila	44	17	52	0.31	87.2	19.5	41.8°	1.3	50.9	52.6	49.5	
Ahmadi	28	11	37	0.32	66.9	16.3	37.4°	1.0	53.8	55.2	52.0	
Maudud	41	17	50	0.31	82.7	18.6	41.3°	1.2	56.9	58.1	54.7	
Nahr Umr	30	12	31	0.29	62.3	15.4	36.8°	0.9	61.3	62.4	58.7	
Shuaiba	45	18	54	0.31	87.0	19.2	42.3°	1.3	65.3	66.1	62.2	
Zu1	28	12	30	0.3	65.0	16.3	36.3°	0.9	67.4	68.1	64.1	
Zu2	33	14	30	0.27	63.5	15.7	37.2°	0.9	68.8	69.3	65.3	

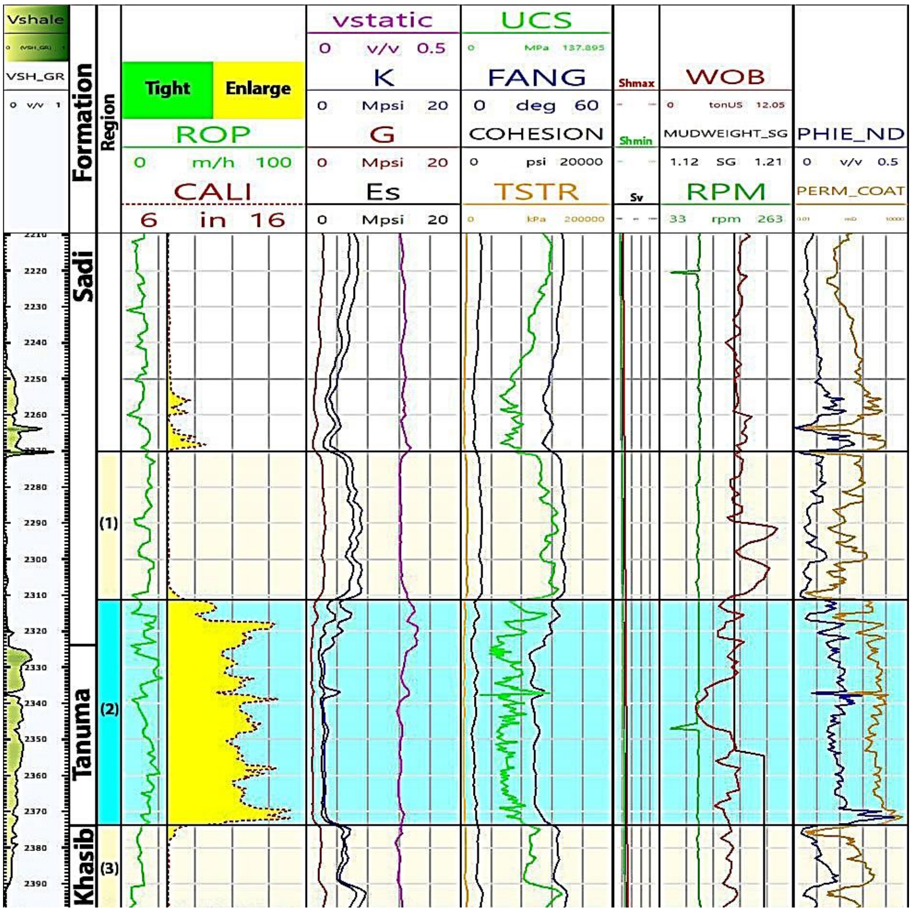

Figure 2. Geomechanical, petrophysical, and drilling parameters profiles for Sadi, Tanuma, and Khasib formations.

3.2 Reservoir Challenges Through Rock Mechanical Insights

Fig. 2 (region 2) and **Fig. 4** (regions 2, 4, and 6) present high-porosity rocks, which are normally characterized by low E and UCS, which makes them softer, more deformable, and more likely to collapse under stress. Conversely, low-porosity rocks are normally characterized by higher E and UCS, making them more rigid and resistant to deformation, such as in region 1 in **Fig. 2** and region 3 in **Fig. 3** .

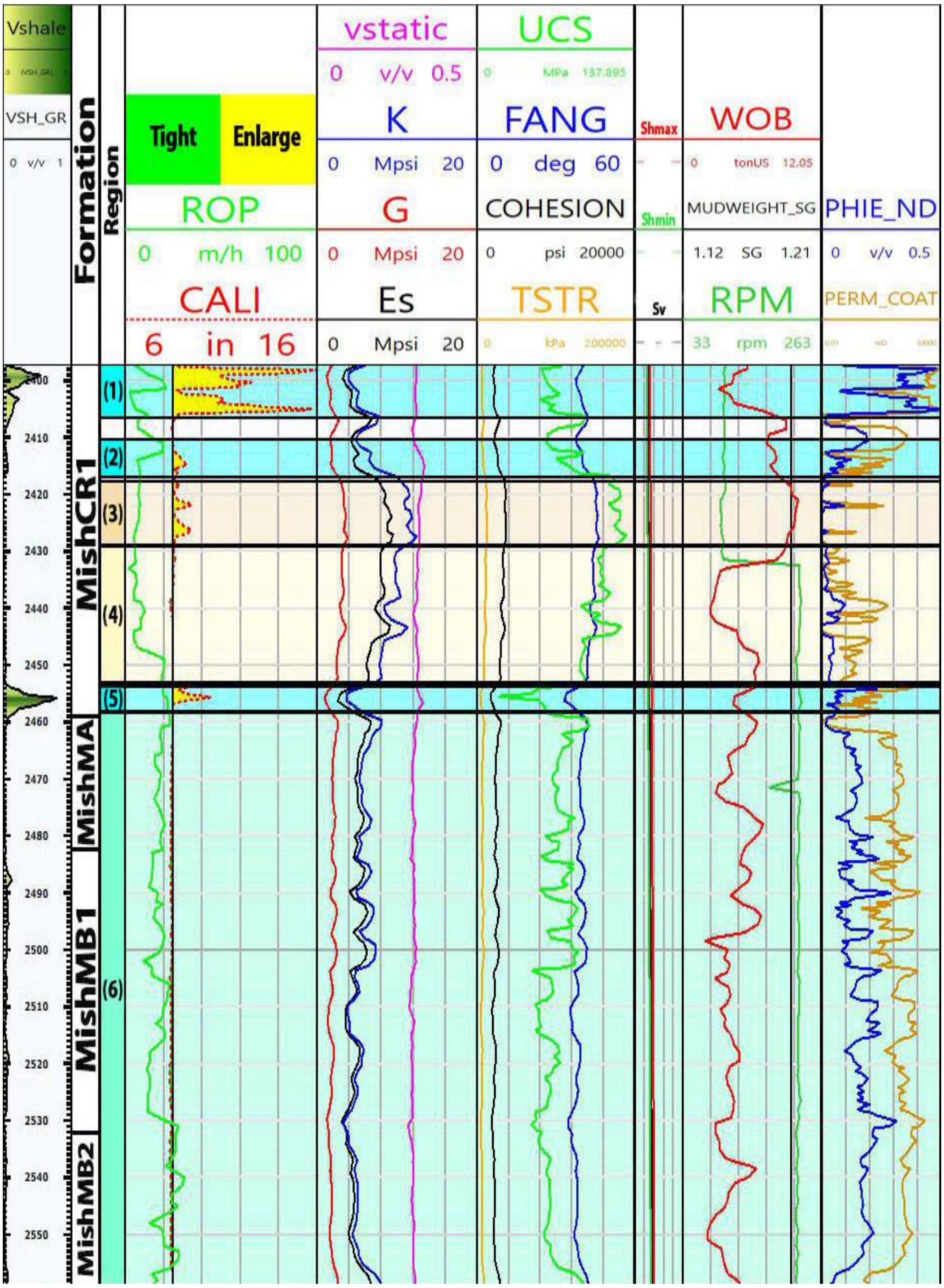

Figure 3. Geomechanical, petrophysical, and drilling parameters profiles for Mishrif formation.

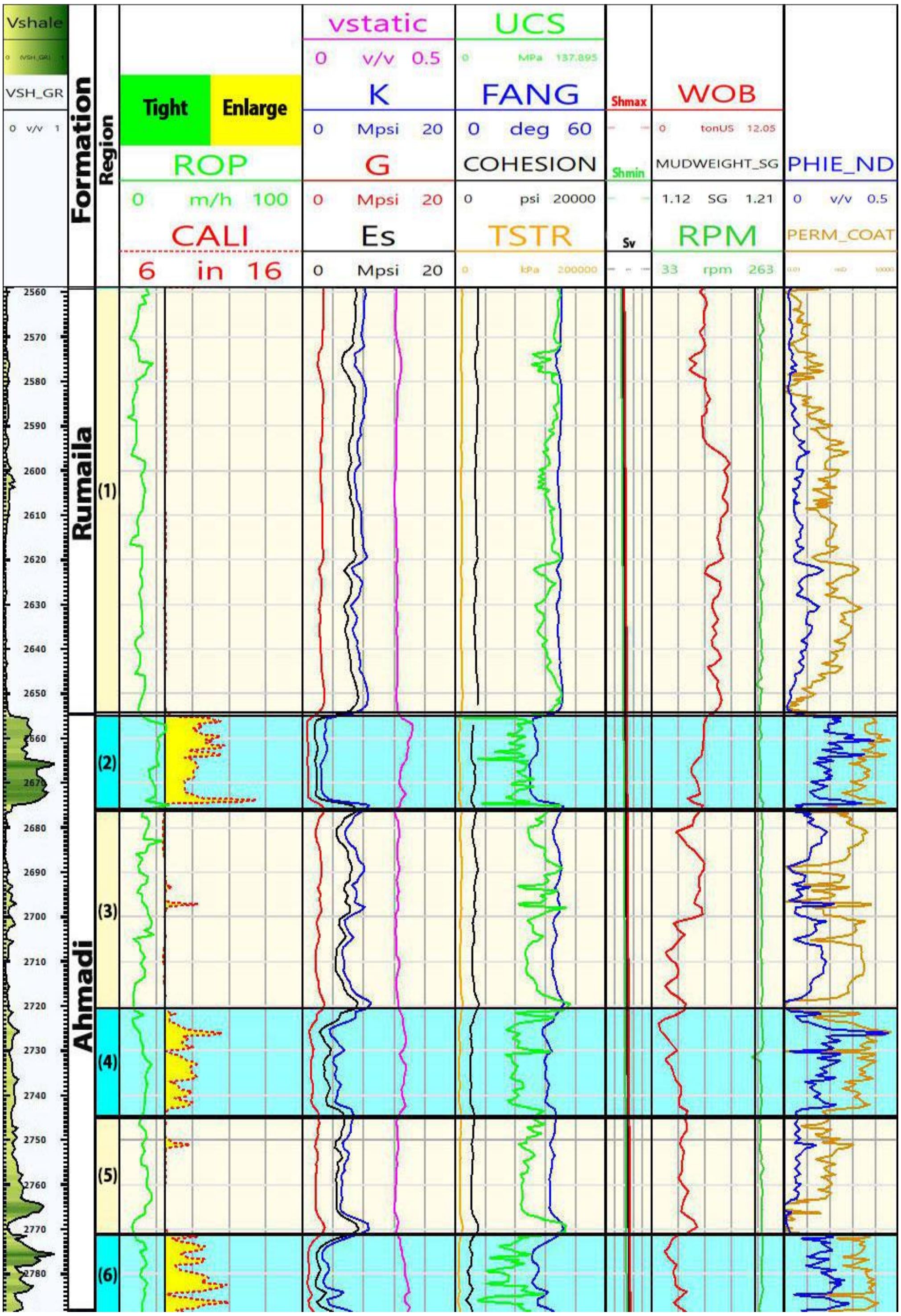

Figure 4. Geomechanical, petrophysical, and drilling parameters profiles for Rumaila and Ahmadi formations.

High-permeability rocks are normally characterized by low E, UCS, and Ts that indicate a weak rock structure under stress, subsequently reduced shear and compressive strength as presented in **Fig. 2** (region 2), and **Fig. 4** (regions 2, 4, and 6). In contrast, low-permeability rocks are normally characterized by higher E, UCS, and Ts, which have fewer interconnected

pores. These rocks correlate with stronger and more stable rocks, as in **Fig. 2** (region 1), and **Fig. 3** (region 3). Brittleness remains a concern under high-stress conditions.
High compressible rocks are normally associated with low bulk modulus, it indicates that rocks cannot sustain their volume under stress such as regions (1,2, and 5) in **Fig. 3**, and regions (1 and 7) in **Fig. 5**.

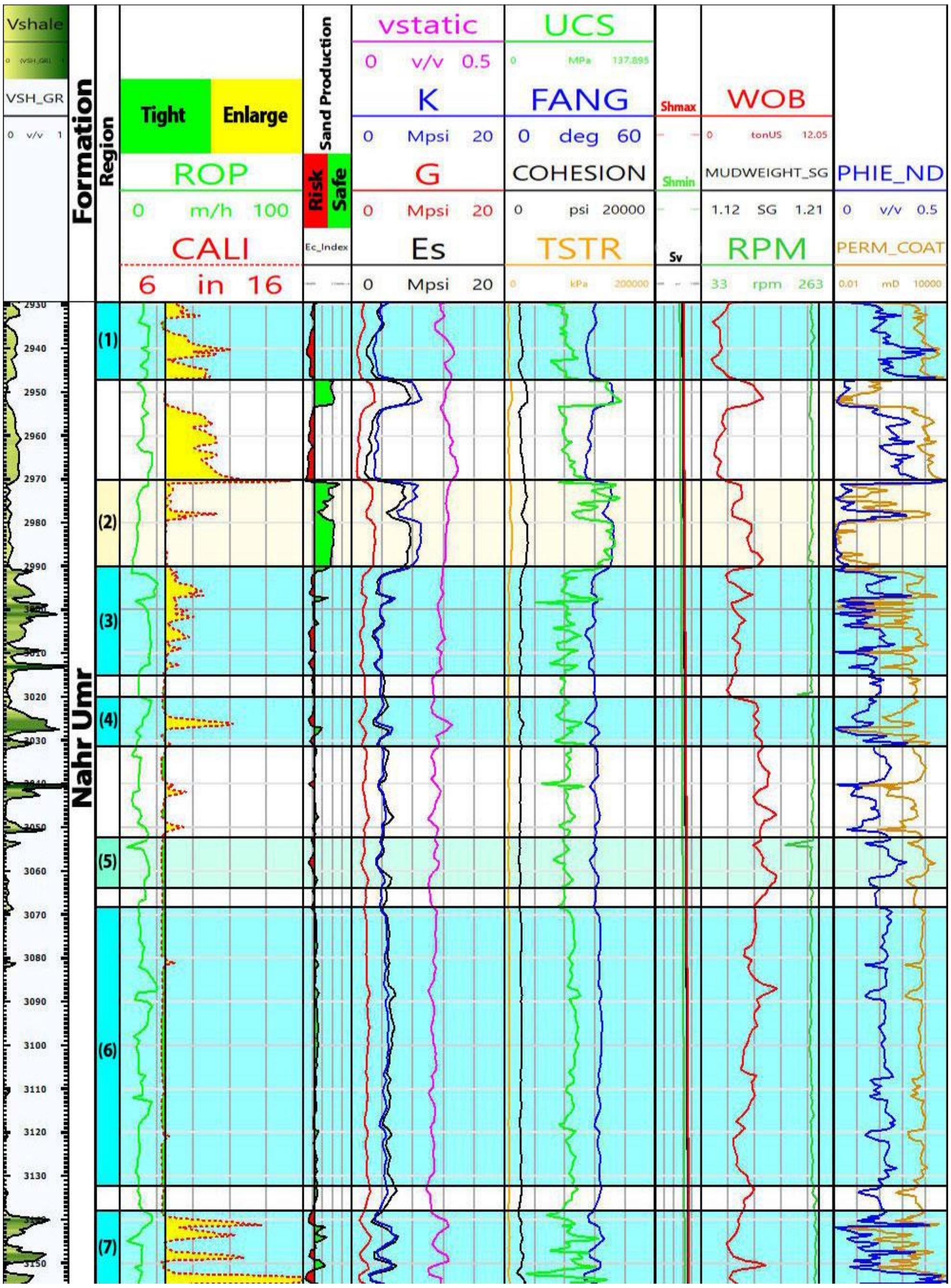

Figure 5. Geomechanical, petrophysical, and drilling parameters profiles for the Nahr Umr formation.

These rocks are normally resilient and prone to compaction or collapse during high stress or pressure depletion; hence decreasing both the porosity and the permeability (closing pore throats). Reservoir compaction ability represents a compaction drive mechanism that, in some cases, enhances the driving of the hydrocarbons out of the rock's matrix **(Dake, 1983; Zoback, 2010; Wong and Baud, 2012)**. In contrast, low compressibility is associated with a high K that indicates the rocks that resist changes in volume under stress, therefore reducing the risk of compaction, hence supporting reservoir permeability, such as in **Fig. 3** (region 3), and **Fig. 5** (region 2). Usually, production from these reservoirs depends on fluid expansion or water and gas injection for sustained production rather than compaction drive **(Dake, 1983; Lake et al., 1989)**. The brittleness of these reservoirs can make them susceptible to fracturing (or fault reactivation), which could lead to unintended fracturing that may cause issues like water breakthrough or unwanted communication between reservoir zones **(Lake et al., 1989; Zoback, 2010)**. In these reservoirs, maintaining reservoir pressure depending on secondary recovery techniques is very important to avoid those fractures. In the regions in the central areas and those distant from water, the creation of fractures can be advantageous for increasing production rates **(Sun and Pollitt, 2021)**.

Maintaining reservoir characteristics based on geomechanical insights remains vital even after producing all recoverable hydrocarbons. Most enhanced oil recovery strategies convert producing areas into injection units for sustaining continued reservoir utility and the long-term viability of the operations.

3.3 Drilling Challenges Through Rock Mechanical Insights

Geomechanical insights play an important role in addressing drilling challenges involving the interactions of mechanical stresses, elastic and strength rock properties, and chemical effects on these parameters. Drilling operations strongly depend on geomechanical factors, including in-situ stress orientation, rock mechanical properties, and wellbore stress redistribution. From **Figs. 2** to **6**, the caliper and ROP profiles closely reflect the trend of elastic and strength properties; any change in these properties reflects a behavior in the caliper and ROP readings.

Regions with high E and UCS that can handle high mud weights and WOB, such as in **Fig.2** (regions 1 and 3), **Fig. 3** (region 4), and **Fig. 4** (regions 1, 3, and 5), are stable. Conversely, areas with low E and UCS, such as in **Fig. 2** (region 2) and **Fig. 4** (regions 2, 4, and 6), are collapsed due to ductility and susceptible to deformation under stress. These zones require careful evaluation of mud rheology to suspend cuttings and minimize stress concentrations. The used mud weight is not sufficient to maintain the wellbore stability. To overcome this challenge, increasing the mud weight is one of the suggested recommendations to prevent the wellbore from collapsing. The orientation of the wellbore should be in the direction of minimum. Another inherent issue is that the wellbore collapse can be due to a chemical reaction between the drilling fluid and the formation's rock.

Collapses seen in high or moderate Young's modulus and UCS zones, such as in **Fig. 3** (region 3) signify the requirement of stress analysis to determine optimal azimuth and inclination. Well trajectory alignment with stress fields (e.g., perpendicular to Shmax), minimizes stress concentration and increases stability. Stress redistribution of tangential, radial, and axial stresses during drilling is another factor contributing to instability in such zones. Besides, there are chemical interactions between drilling fluids and rock formations. These effects are very different for sandstone, carbonate, and shale formations due to their different mineralogical composition and geomechanical behavior.

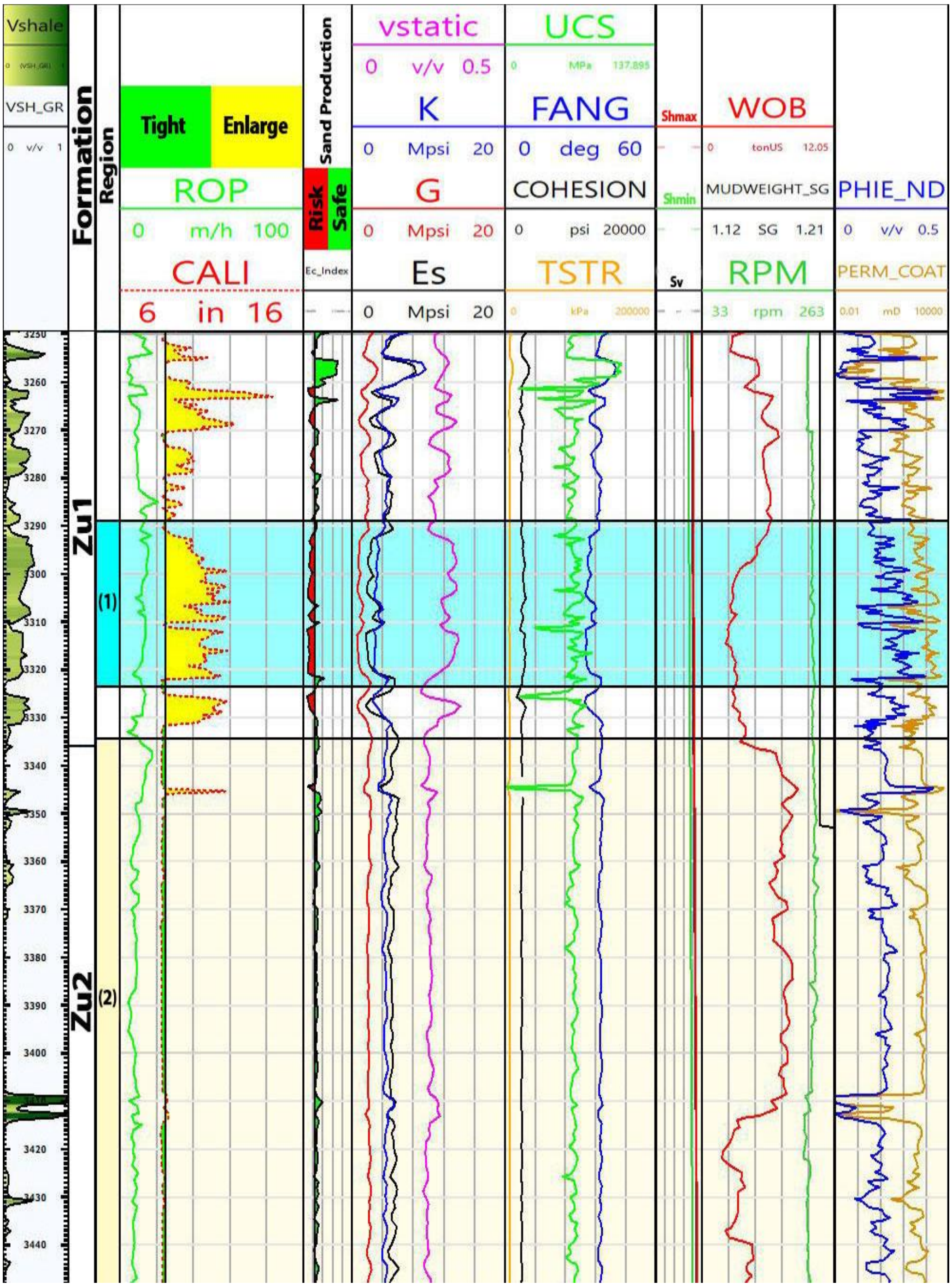

Figure 6. Geomechanical, petrophysical, and drilling parameters profiles for Zubair formation.

The ROP profile shows a strong correlation with E and UCS. Variations in these mechanical properties have a clear effect on the ROP trend since both parameters are related to the rock's resistance and rock deformation. Generally, harder and more resistant rocks have higher E and UCS values; therefore, (regions 3, 4, and 5) in **Fig. 3** and (region 2) in **Fig. 5** present a reduction in ROP. However, deviations from this behavior may be attributed to changes in operating parameters like WOB, RPM, or some other drilling conditions that may be exposed. For instance, an increase in WOB and/or RPM to drill high-strength formations would lead to an apparent increase in ROP despite the high mechanical properties of the rocks. Conversely, a decrease in these parameters in low-strength formations may further increase the ROP, such as in **Fig. 4** (region 2), and **Fig. 5** (region 3).

Well deviation is preferred to be in high E, UCS, and Ts areas oriented perpendicular to Shmax to minimize tensile stress and breakout risks (e.g., **Fig. 2** (regions 1 and 3), **Fig. 3** (region 4), and **Fig.4** (regions 1, 3, and 5)). Understanding the complex interplay of geomechanical and chemical factors is critical for controlling wellbore stability. Adequate mud systems optimized well trajectories, and real-time stress management are important to decrease drilling challenges and ensure operational efficiency in complex geological settings.

3.4 Production Challenges Through Rock Mechanical Insights

The caliper log, when analyzed alongside elastic and strength properties, is indicative of zones that have potential wellbore instability. Regions with low strength or low elastic modulus generally form tight or enlarged borehole sections. These require thicker casings or special cementing techniques for stability. For instance, regions (1, 2, and 5) in **Fig. 3**, regions (2, 4, and 6) in **Fig. 4**, and regions (1 and 7) in **Fig. 5** as indicated by the strength profiles, with high-stress gradients in some sections, thus requiring strong casing designs. These designs must be able to bear variations in stress without deforming to maintain structural integrity throughout the lifetime of the well.

Sand production presents a major problem in unconsolidated formations; it potentially destabilizes the wellbore and/or reduces productivity. The Ec_index profile in **Figs. 5** and **6** indicates the regions that might suffer from sand production or not. For instance, region (2) in **Fig. 5** shows a safe sand production index, primarily due to higher E, G, UCS, Ts, and low Vstatic. This stability correlates with the given (Final well report) FWR, WOB, and Caliper data that reflect consistent mechanical properties with a low likelihood of sand production. Region (1) in **Figs. 5 and 6** has a high probability of sand production index due to low E, G, UCS, Ts, and high Vstatic as mentioned in an internal FWR of well X. The caliper and ROP profiles in these zones have shown considerable deformation and high drilling-induced stresses. To address such risks, gravel packing, sand screens, chemical consolidation, and controlled drawdown pressures are required to stabilize these formations and reduce excessive sand production. The formulation of mud cake due to the highly permeable zone in the region (5) in **Fig. 5** has prevented the risk of sand production as indicated by the Ec Index profile. The hydraulic fracturing strategy is important to enhance the performance of a reservoir by creating conductive pathways for hydrocarbon flow.

For instance, regions (3 and 4) in **Fig. 3** of the hydrocarbon-producible MishCR1 formation show preferred conditions for hydraulic fracturing due to high elastic and strength rock properties. The profiles correlate with stable caliper readings, suggesting controlled fracture propagation. By considering these zones in conjunction with other conditions of reservoir production, excellent potential can be realized for effective fracturing treatments.

Region (1) in **Fig. 6** of the hydrocarbon-producible Zubair formation is not suitable for hydraulic fracturing because of low E, UCS, and high Vstatic. The fracture propagation in this zone is uncontrolled, as indicated by irregular caliper readings. This zone may require stimulation if the production rates of the reservoir are low, and the hydraulic fracturing operation can be replaced with chemical stimulation to enhance productivity and reduce risks.

Perforation zones should be selected based on stress and mechanical property profiles to enhance stability and productivity. Aligning perforations with the dominant in-situ stress direction, and high E, G, K, UCS, and Ts, such as in region (2) in **Fig. 5,** which was perforated in the depths recorded in **Table 6** to reduce collapse risks and enhance flow efficiency. In zones that cannot support open-hole perforation, characterized by low elastic and strength values, perforating through the casing is necessary for stability and to maintain productivity. Since perforation decisions should be based on the conditions of the reservoir, for example, it is essential to perforate far from water zones to avoid problems such as water breakthrough and water coming. Perforating through the casing in these cases is preferred for long-term wellbore stability.

Table 6. Perforation details for well X.

Interval (m)		**Thickness (m)**
Top	**Bottom**	
3370.5	3371.5	1
3362	3367	5
3359	3360.5	1.5
3350	3355	5

4. CONCLUSIONS

The integration of geomechanical principles with field operations allows the development of a predictive framework for drilling and production challenges, optimization of hydraulic fracturing, and design of perforation strategies. Besides, this approach underlines the maintenance of reservoir characteristics and operational sustainability, even after primary recovery by deploying enhanced recovery techniques and injection strategies.

This study presents the petroleum challenges through drilling operations, reservoir management, and production strategies based on the geomechanical point of view. The results of this study can be summarized as follows:

1- The geomechanical insights play a vital role in effectively addressing the field challenges encountered during drilling, reservoir management, and production strategies. Integrating geomechanics into field practices enhances operational efficiency, minimizes risks, and ensures sustainable hydrocarbon recovery.

2- The strike-slip fault regime exists through the Sadi to Zubair formation, which is an indicator of the necessity of optimizing the wellbore trajectory for mitigating the stress concentration and the wellbore and thus mitigating the rock failure. MishCR1 reservoir is a highly mechanically stable zone, it is characterized by high values of rock stiffness and strength. It has a minimum likelihood of subsidence risk, reactivation of faults, and closure of pore throat, thus maintaining permeability and petrophysical characteristics.

3- Reservoirs such as MishMA, MishCR2, MishMB1, Zu1, and Zu2 have intermediate mechanical rock, which are more susceptible to stress-induced deformation and subsidence. To maintain reservoir integrity, it is recommended to adopt strategies that encompass controlled production rates, effective pressure management, and sand control measures such as gravel packing or chemical stabilization.

4- More attention is required for selecting the optimum mud weight and rheological mud properties against the Tanuma shaly formation since it is a mechanically weak formation.

Mitigating the chemical reaction between this formation and drilling mud is also recommended.

5- Despite the general trends of the rock mechanical properties profiles are sufficient to achieve the study objective, direct core measurements are recommended for further geomechanical applications.
6- While log-derived mechanical properties sufficiently meet the study's objectives, direct field measurements (LOT, XLOT, or mini-fracture tests) are recommended to enhance the reliability of geomechanical interpretations and for accurately predicting the drilling challenges, reservoir management, and production strategies.
7- Sanding risk is identified in sandstone formations (Zu1 and Zu2). This requires proactive sand control strategies. Additionally, intervals with high elastic and strength properties are candidates for implementing hydraulic fracturing to ensure controlled fracture propagation and enhanced hydrocarbon recovery.
8- Comprehensive geomechanical understanding facilitates a roadmap toward sustainable and efficient field development methodologies within each unique reservoir formation challenge, including perforation design, well stimulation, and secondary recovery, thus maximizing the reservoir performance and minimizing the field expenditures.
9- Rumaila, Maudud, and Shuaiba are highly stable through drilling operations.

Credit Authorship Contribution Statement

Hussein A. Ayyed: Writing –original draft and Methodology. Farqad A. Hadi: Review, Validation, and proofreading

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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بين التحليل الصخري والممارسة العملية: فلسفة تحديات الحقول النفطية من خلال وجهة نظر جيوميكانيكية

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

الخلاصة

تُساهم تحديات الحفر بخسائر تتجاوز المليار دولار سنوياً بجانب تقلبات أسعار النفط والمنافسة المتزايدة على إنتاجه، لذلك تؤكد هذه الدراسة أهمية الأخذ بمبادئ ميكانيكا الارض بنظر الاعتبار في كل عمليات الحقول النفطية ابتداءً من المكامن والحفر حتى الإنتاج. تم إجراء دراسة على بئر اتجاهي في حقل الرميلة النفطي الواقع جنوب العراق لحساب الخواص الجيوميكانيكية في تكوينات الكربونات والحجر الرملي والصخر الزيتي؛ وعند تحليل الإجهادات السائدة وخصائص مقاومة الصخرة ومرونتها أظهرت النتائج ان الانزلاق الضربي (Strike Slip) هو الإجهاد السائد خلال التكوينات من السعدي الى الزبير؛ وأنّ خصائص مقاومة تكوين التنومة ومرونته المنخفضتان يشيران إلى خواص إنسيابية طينية مثالية لقدرة رفع فعّالة؛ ويُظهر مكمن (MishCR1) القابل للإنتاج ثباتاً ميكانيكياً عالياً مقاوماً للانضغاط ولإعادة تنشيط الصدع او بنائه، أما بالنسبة للمكامن (MishMA وMishMB2 وMishMB1 وZu1 وZu2 وNahrUmr) المنتجة للبترول فهي ذات خواص جيوميكانيكية متوسطة تجعلها تتطلب تصميماً خاصاً لإدارة الضغط ومعدلات الإنتاج، علاوةً على الحاجة الى توظيف طرق تحسين استخلاص البترول لتفادي مخاطر تشوه المكامن او تهدمها، وتنفرد مكامن الحجر الرملي المتمثلة بتكويني الزبير (Zu1 وZu2) ونهر عمر بضرورة استعمال اما مصفاة رمل (Gravel Pack) خاصة او مواد كيميائية تُحقن لتعزيز تصلب حبيبات الرمل وتماسكها وذلك للحفاظ على أداء المكمن عند الانتاج. أكدت الدراسة حاجة عمليات الحقول البترولية كافة إلى تضمين الرؤى الجيوميكانيكية لمنع او تقليل المخاطر التي قد تطرأ على المكامن او تحدث خلال الحفر والانتاج.

الكلمات المفتاحية: الجيوميكانيك، عمليات المكامن، عمليات الحفر، عمليات الإنتاج، خواص الصخور الميكانيكية.