JP&M Engineering
Journal of Petroleum and Mining Engineering

A Review of the Effect of Drilling Technique and Fluid Type on Borehole Stability

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Article Info

Received 2 Jun. 2025
Revised 20 Jun. 2025
Accepted 2 Jul. 2025

Keywords

Drilling fluid; Wellbore stability; Mixed metal oxide mud; Managed pressure drilling; Underbalance drilling

Abstract

Oil and gas exploration employs various drilling fluids throughout the drilling operation. Furthermore, the drilling fluid serves the purpose of maintaining the stability of the borehole and preventing any damage to the wells. As the complexity of wells continues to rise, a wide variety of drilling techniques are currently being utilized. This article reviews the influence that the characteristics and type of drilling fluid have on the stability of the wellbore. In addition to this, it reviews the influence that innovative drilling technologies have on the stability of wellbores. This review supports the ways in which the choice of particular drilling fluids can strengthen the efficiency of these cutting-edge techniques, which will ultimately result in increased operational efficiency and a reduction in risks that are encountered during drilling. Through reviewing various studies, our objective is to offer insights into the most effective methods for maximizing wellbore stability in more complicated drilling environments.

1. Introduction

The wellbore stability is crucial in well design and drilling operations because it impacts both the safety of drilling and production as well as the economic viability of oilfield development. Borehole collapse, fracturing, or loss of circulation can occur when the stress exerted by the borehole wall exceeds the stability limit [1]. The borehole stability limit is influenced by rock mechanical properties, in-situ stress, and operational conditions. Conventional methods for predicting this stability limit have primarily concentrated on these factors. However, environmental conditions during the drilling process, including thermal, hydraulic, and chemical factors, may also impact the borehole stability limit. Drilling fluids play a critical role in drilling operations, as different types or properties of mud can disrupt wellbore stability [2].

Water-, oil-, and synthetic-based drilling fluids are the main types. We typically used oil-based mud for difficult drilling due to its wellbore stability. Synthetic mud has replaced oil-based mud over the past decade to reduce environmental impact. Environmental concerns have made water-based mud more appealing because it has the least environmental impact and lowers drilling costs [3]. The selection of drilling fluid, whether water-based or oil-based, and the specific additives employed are critical for maintaining borehole stability and mitigating drilling-related issues.

The complex interactions between shale formations and water-based drilling fluids make wellbore instabilities difficult to prevent. Excavated material rests on the surrounding rock when drilling. Stress concentration can cause borehole failure. Rock is supported by drilling mud to prevent failures and mud loss. Shale around a borehole absorbs water from water-based drilling mud, causing hydration swelling and deterioration. Hydration swelling weakens shale, increases tensile stress, and increases wellbore instability [4].

So, it is important to study the effect of the drilling fluid type and properties on borehole stability. In addition, in this review paper we presented the effect of different drilling techniques, including underbalanced and managed pressure drilling, on the wellbore stability.

2. Mechanics of Borehole Stability

Wellbore stability is essential for drilling operations. The sediment and rock surrounding the wellbore cavity must endure the stresses that arise around it to ensure the stability of the open hole. The surrounding rock must endure various stresses until the casing is installed, or for an indeterminate duration if left uncased. The stability of the wellbore is influenced by two categories of variables:

one that is beyond our control and another that is within our control [5].

1. There exist in-situ variables that exceed our capacity for control, including far-field stresses, pore pressure, and rock properties.
2. Controllable variables encompass hydraulic pressure, including bottom hole pressures, the type and composition of the drilling mud, and the orientation of the wellbore, specifically azimuth and deviation in the designated direction.

2.1. Hole problems Associated with the Borehole instability

Wellbore instability refers to a situation in which the drilled wellbore fails to maintain stability, potentially resulting in various impacts on drilling operations. These effects can unintentionally and markedly negatively impact drilling progress, leading to unsafe drilling operations [6]. The primary consequences of wellbore instability include stuck pipe incidents, wellbore collapse, and the necessity for remedial interventions on the well. Such actions can cause an increase in non-productive time (NPT) during which no drilling takes place, resulting in operating hour losses. The extended exposure of a well to drilling or other activities increases the likelihood of issues arising from wellbore instability. Consequently, effective management of wellbore stability is essential to prevent such complications [7].

The wellbore stability issue can be characterized as a balance between the forces that stabilize the wellbore and those that contribute to its failure. Stability of the wellbore is maintained when stabilizing forces exceed failure forces. Increased failure forces may lead to wellbore instability and subsequent failure [1]. Wellbore failure can occur either during the construction of a wellbore or after it has been completed. Different drilling techniques and technologies influence wellbore stability. Poor drilling techniques, such as drilling a large diameter at the surface with insufficient hole cleaning, can result in wellbore instability. The stability of the wellbore may be influenced by various types of drilling equipment. For instance, experts recommend avoiding stabilizers when drilling through shales. Wells drilled using oil-based mud exhibit greater resistance to wellbore collapse compared to those using water-based mud systems, indicating that the type of fluid significantly influences wellbore stability. The temperature, type, and chemistry of drilling fluids can additionally impact the wellbore stability [8].

Wellbore instability causes several significant drilling issues, including but not limited to:

1. Delay in Drilling Operations: Addressing instability issues can cause significant delays in the drilling schedule, impacting overall project timelines and increasing the non-productive time (NPT).
2. Borehole Collapse: The walls of the wellbore can collapse, resulting in loss of the hole and necessitating side-tracking or re-drilling efforts.
3. Wellbore Breakouts: Elevated pressure can cause wellbore breakouts, where certain sections expand, complicating the maintenance of the drilling trajectory.
4. Loss of Circulation: Instability may lead to fluid loss into the surrounding formation, impeding the ability to maintain appropriate drilling fluid levels.
5. Increment of the torque and drag: Instability can elevate friction between the drill string and the wellbore, resulting in increased torque and drag, which adversely affects drilling efficiency.
6. Stuck pipe: Wellbore instability can lead to differential sticking, where the drill string becomes stuck due to pressure differences between the wellbore and the formation.
7. Formation damage: Disturbances in the wellbore can inflict damage on the surrounding formation, negatively impacting future production capabilities.
8. Equipment Wear and Tear: Increased instability can lead to accelerated wear on drilling equipment, resulting in higher maintenance costs.
9. Reduction in the rate of penetration (ROP): Instability can lead to slower drilling progress, increasing overall drilling time and costs.

These issues highlight the importance of managing wellbore stability during drilling operations to ensure both efficiency and safety [9]. This paper reviews the effect of drilling fluid types and properties on borehole stability; in addition, it reviews the effect of other drilling techniques.

3. Drilling fluid technology in drilling operations

The presence of an extensive range of drilling fluid types in the petroleum industry reflects the multiplicity of functions the drilling fluid must perform. Oil and gas drilling programs and the choice and use of drilling fluids are influenced by various economic and technical factors. A suitable drilling fluid should be able to provide several functions, the most important of them being stabilizing formations, hole cleaning, and bit cooling. This is, however, in conjunction with several other engineering functions, such as providing hydrostatic heads to prevent blowouts, preventing shale hydration, and reducing torque and drag on pipes. Control, maintenance, and safeguarding of the reservoir formations are of utmost importance in the introduction of drilling fluid in the wellbore. A loss of pressure in the well can lead to water or drilling fluid flowing into the well, and if the well is not shut in, oil or gas can flow into the wellbore with the water or drilling fluid, causing the drilling equipment to break. The loss of a well severely impacts the investment and operation of the drilling party, and the leaking well can lead to serious environmental pollution [10].

3.1. Types of Drilling Fluids

Currently, two conventional types of drilling fluids are used in the oil and gas industry, which are either water-based mud (WBM) or oil-based mud (OBM). WBM can be either freshwater mud or seawater mud. OBM can be high oil content mud (HOCM) or low oil content mud (LOCM).

In addition to these conventional types, pneumatic drilling has been used with aerated fluids for the past decades (**Error! Reference source not found.**) [11].

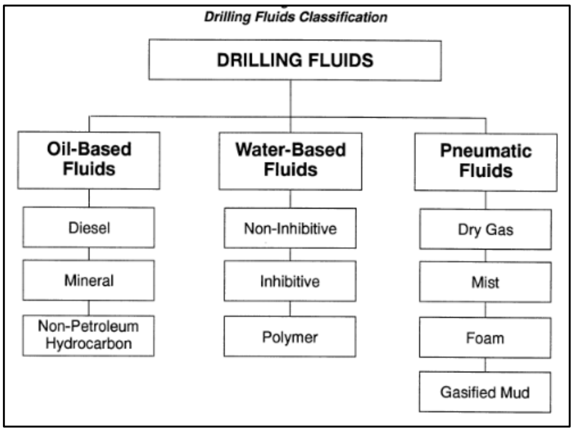

Figure 1 Drilling Fluid Classification [11]

Water-based muds (WBMs) are composed of water and a variety of minerals and additives. WBM are the most extensively used drilling fluids. They are generally easy to build, inexpensive to maintain, and can be formulated to overcome most drilling problems. In order to better understand the broad spectrum of water-based fluids, they are divided into three major subclassifications: inhibitive, non-inhibitive, and polymer fluid. Inhibitive mud is a type of drilling fluid specifically designed to prevent or minimize the interaction between the drilling fluid and the geological formations being drilled. Its primary purpose is to stabilize the borehole and reduce issues associated with the instability of rock formations, particularly in shales or other sensitive formations that can swell, shrink, or otherwise degrade when in contact with water-based fluids. Non-inhibitive mud is a type of drilling fluid that does not contain specific additives designed to prevent or minimize the interaction between the drilling fluid and the geological formations being drilled. The non-inhibitive muds are typically more straightforward and may not provide the same level of protection against formation damage. Polymer mud is a type of drilling fluid that incorporates polymer additives to enhance its properties and performance during the drilling process. These polymers improve various characteristics of the mud, such as viscosity, filtration control, and stability, making it suitable for a wide range of drilling applications, particularly in challenging conditions. The water used to build the WBM could be freshwater or saltwater. Most water-based mud systems are designed using different additives, such as barite, caustic soda, or soda ash. In general, WBMs are more stable than oil-based mud, require less environmental consideration, and have lower costs than oil-based and gas-based mud. But it will hydrate clay and has poor lubricity [11, 12].

Oil-based muds (OBMs) consist mainly of crude oil and water. The principal application of oil-based fluids is for drilling problematic shales and enhancing borehole stability. They are also suitable for drilling highly deviated holes due to their superior lubricity and capacity to inhibit clay hydration. They are also chosen for specific applications, including high-temperature/high-pressure wells, minimizing formation damage, and native-state coring. A further explanation for selecting oil-based fluids is their resistance to contaminants, including anhydrites, salt, and acidic gases such as CO_2 and H_2S. Cost is one important consideration when choosing oil-based muds. The initial cost per barrel of an oil-based mud is significantly higher than that of a conventional water-based mud system. Nevertheless, due to the reconditioning ability and reusability of oil muds, the expenses associated with a multi-well program may be comparable to those spent when utilizing water-based fluids. Furthermore, buy-back policies for used oil-based muds can make them an attractive option in scenarios where the utilization of water-based muds prevents the effective drilling and/or completion of the well. Currently, due to increasing environmental concerns, the utilization of oil-based muds is either restricted or significantly limited in numerous regions. In certain regions, the use of oil-based drilling fluids requires the safe storage and transportation of mud and cuttings to a sanctioned disposal location. The expenses associated with isolation, transportation, and disposal can significantly raise the costs of utilizing oil-based fluids. Oil-based fluids are divided into three major subclassifications: diesel, mineral, and non-petroleum hydrocarbon. Diesel drilling oil-based mud (OBM) is a type of drilling fluid that uses diesel oil as its primary base fluid. This oil-based mud is formulated with various additives to enhance its performance during the drilling process. Diesel OBM is particularly effective in challenging drilling environments, such as those involving high temperatures, high pressures, and unconsolidated formations. The mineral-based drilling fluid is a type of drilling fluid that primarily consists of naturally occurring minerals, typically clays and other materials. These minerals help to provide essential properties required for effective drilling operations. Mineral drilling muds are commonly used in various drilling applications, including oil and gas exploration, water well drilling, and geothermal drilling. Non-petroleum hydrocarbon drilling mud is a type of drilling fluid that utilizes hydrocarbon components derived from non-petroleum sources. These fluids aim to provide effective drilling performance while reducing environmental impact, making them increasingly popular in the drilling industry, especially in environmentally sensitive applications. Oil-based muds (OBMs) typically comprise 90% weight oil-based fluids, 3% weight surfactants, 7% weight water, and 6 to 12% emulsifier, which is a surfactant that maintains water in suspension. OBMs can be categorized into three classifications based on toxicity: (1) low toxicity, (2) medium toxicity, and (3) high toxicity. At the extreme end of the toxicity spectrum, OBMs can influence fish behavior, survival, biomass abundance, and reproduction. Most OBMs: (1) exhibit thermal and chemical stability; (2) inhibit clay swelling; (3) obstruct formation water intrusion; and (4) avert the formation of sticky cuttings, which may result in borehole collapse [11, 13].

Pneumatic (air/gas-based) fluids are utilized for drilling depleted zones or zones with abnormally low formation pressures. An advantage of pneumatic fluids compared to liquid mud systems is the enhancement of penetration rates. The significant pressure differential accelerates the ejection of cuttings from the cutting surface in front of the bit. The high differential pressure enables the entering of formation fluids from permeable zones into the wellbore. Air- or gas-based fluids are insufficient in regions with a significant amount of formation fluids. A significant influx of formation fluids requires the conversion of the pneumatic fluid to a liquid-based system. Consequently, the risk of losing circulation or harming a productive area is significantly greater. Another factor to consider when choosing pneumatic fluids is the depth of the well. They are not advisable for wells deeper than approximately 10,000 ft, as the air volume necessary to elevate cuttings from the bottom of the borehole may exceed the capacity of the surface equipment [11].

As drilling operations advance and more complex wells are developed, research on drilling fluids has been conducted, leading to the introduction of new technologies, such as nanoparticles, to enhance the efficiency of these fluids. Mixed metal oxide (MMO) fluids are formulated to incorporate MMO particles into water-based mud (WBM) and oil-based mud (OBM) to enhance borehole stability in high-temperature, high-pressure, and deepwater drilling environments. Preliminary testing of the MMO drilling fluids indicated the viability of borehole stabilization when employing conventional fluids, which are ineffective [14].

4. Effect of Drilling Fluid Type on borehole stability

Drilling muds are categorized into three primary types based on their fundamental structures and properties: water-based muds, oil-based muds, and synthetic-based muds. Although all categories of drilling fluids perform the same objective, their interactions with various geological formations encountered downhole differ, resulting in varying degrees of control in the surrounding area. Consequently, the wellbore diameter varies due to the breaking down of the ground formations by the drilling operations, which increases the pressure on the layer between the drill bit and the borehole walls. Despite its predominant use in horizontal directional drilling, this idea holds significant importance in the oil and gas drilling industries [12].

The nature of drilling fluid strongly impacts borehole stability, especially in water-sensitive shales. The following describes how various drilling fluid characteristics affect stability [15, 16].

4.1. Water-Based vs. Oil-Based Fluids:

Water-based fluids may lack the inhibitive properties of oil-based muds, resulting in increased interactions with the pore fluid and charged surfaces of clays. This can generate large swelling pressures, contributing to wellbore instability. The water-sensitive shales pose significant challenges; thus, selecting the right drilling fluid is vital for maintaining borehole stability [2].

Oil-based fluids tend to provide better stability in certain formations by reducing the interaction with water-sensitive clays. They also provide better lubrication, which can help reduce friction and improve overall drilling efficiency. Oil-based drilling fluids can significantly enhance borehole stability in high-temperature environments due to their superior rheological properties compared to water-based fluids [17]

4.2. Synthetic-Based Fluids:

Synthetic-based fluids can provide the benefits of oil-based fluids while being more environmentally friendly. They typically offer better thermal stability and lower toxicity. The synthetic-based drilling fluid containing NSF prevents swelling damage to the reservoir, reduces drilling fluid costs by mitigating environmental and field issues arising from interactions with the reservoir, and significantly enhances the rate of penetration by minimizing drill pipe sticking [18, 19].

4.3. Additives:

The addition of salt or polymers to drilling fluids can enhance wellbore stability by reducing hydration swelling. This improvement helps maintain the mechanical integrity of the borehole [20, 21].

Modified additives, such as organoclays or synthetic polymers, can improve the rheological properties of drilling fluids, enhancing their performance and potentially mitigating issues related to sag and fluid loss [22].

It can be concluded from this research that mud type can significantly affect wellbore stability by altering the in-place stresses. This effect is in addition to other known effects on wellbore stability. A change in mud type can cause a change in different stresses in the borehole [23].

5. Effect of drilling fluid properties in borehole stability

5.1. Rheological Properties

The yield point of a drilling fluid determines the force required to initiate flow. A higher yield point can help suspend cuttings and prevent them from settling in the borehole, which is essential for maintaining borehole stability.

Plastic viscosity affects the fluid's ability to carry cuttings to the surface. If the plastic viscosity is too low, the fluid may not effectively transport cuttings, leading to potential blockages and instability in the borehole [24].

The gel strength of a drilling fluid indicates its ability to resist flow when at rest. A higher gel strength can help maintain borehole integrity when circulation is stopped, preventing the collapse of the borehole walls [25].

5.2. Fluid Density

The density of drilling fluid creates hydrostatic pressure that counteracts formation pressures. This pressure is gravity head adjusted by the mud density, which is called mud pressure. Hydrostatic pressure and excess mud pressure are comparable. It controls the loss. Thus, initiation of any potential fracture is controlled by the mud pressure. The mud pressure can have a positive effect for the formation that has a pore pressure below hydrostatic [26].

If the fluid density is too low, it may not provide sufficient pressure to prevent the borehole from collapsing, especially in unstable formations. Field experience shows that mud pressure makes the borehole stable on the overburden layer of a rock formation with a weak and brittle stress state (Figure 2) [27].

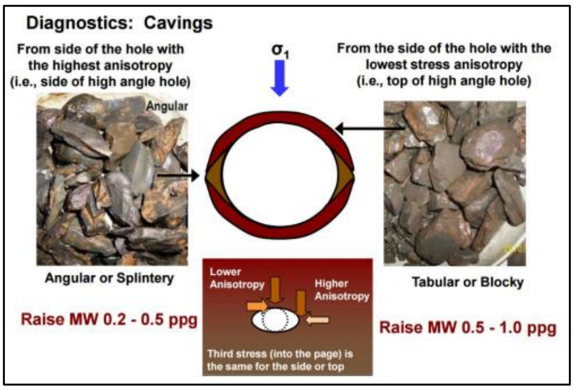

Figure 2 showing the effect of the MW on shape caving and wellbore stability [26]

In most cases, increased mud pressure significantly increases borehole stability [28]. However, it is not always the case. In overbalanced drilling, the fluid density is higher than the formation pressure, which helps stabilize the borehole. Conversely, underbalanced drilling can lead to wellbore instability if not managed carefully. Maintaining the right pressure is crucial to prevent borehole collapse or fracture. Too low a pressure can lead to collapse, while too high a pressure can fracture the wellbore.

There's a specific range of drilling fluid pressures—a "safety window"—that allows for stable drilling. This window needs to be determined for each well to avoid breaking the formation (Figure 3).

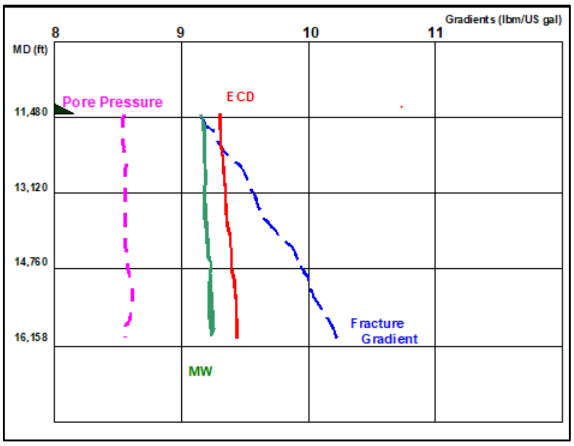

Figure 3 Example of drilling pressure winodw, presenting possibilty of fracture the formation during circulation due to the higher ECD

There are different factors affecting the pressure requirements. Formation type plays an important role in determining the required pressure. The stability of drilling fluid pressures must be carefully calibrated to account for the fact that different types of rock have different strengths and pore pressures. The in-situ stress state of the rock formation also influences the required drilling fluid pressure (Figure 4).

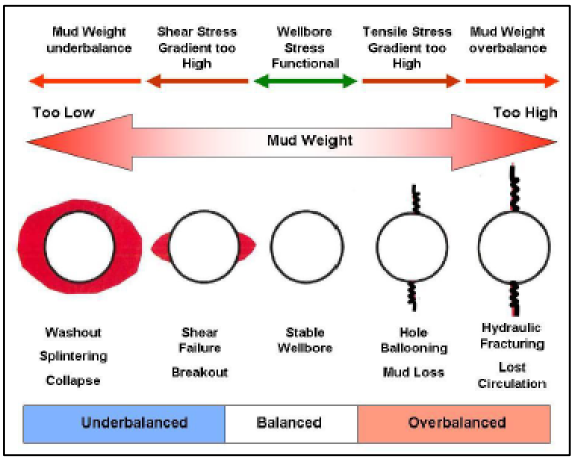

Figure 4 Formation pressures on the wellbore are kept in check with mud weight. Because the formation pressures are different at different depths, the average density of the mud may cause problems at some depths[29]

5.3. Chemical Composition

More than 75% of all drilled formations are thought to be shales, which also cause more than 90% of all wellbore instability problems. Problems with unstable boreholes cost the industry more than $1 billion a year. At its core, wellbore stability depends on how a drilled rock unit reacts to the mechanical stresses in the area of a well. When the stress is higher than the rock's strength, the rock breaks. The chemical and thermal interactions between the shale and the mud have a big effect on the stress level in the rock. You can solve this issue with oil-based muds or KCL polymer mud [28].

Water-based fluids can react with clay formations, leading to swelling and instability. Oil-based fluids, while more expensive, tend to be less reactive and can provide better stability in certain formations.

Wellbore instability generally causes substantial shale fragments (approximately 100 cm^3) to detach from the wellbore wall, descend to the bottom of the hole, or adhere to the drill pipe. This leads to drilling delays that may incur additional expenses amounting to several hundred thousand dollars [4]. (Figure 5) presents laboratory findings for a wellbore that underwent shale failure following 53 hours of exposure to drilling fluid. Examination of the defective shale fragments indicated that failure was likely due to ion intrusion. The primary focus of this is the ionic flow and water flow [28].

Various additives (e.g., polymers, surfactants) can enhance fluid properties, improve lubrication, and reduce friction, which can contribute to better borehole stability. For example, adding bentonite can help form a stable mudcake that protects the borehole walls [30].

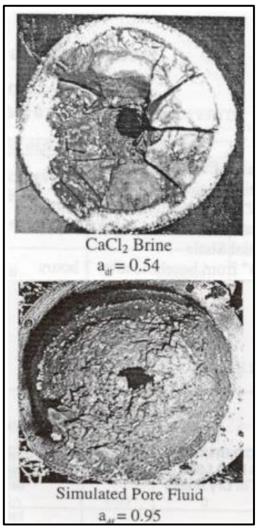

Figure 5 Shale samples from the Gulf of Mexico subjected different drilling fluids under conditions of zero hydraulic differential pressure [4]

5.4. Temperature Effects

The performance of drilling fluids can degrade at high temperatures, leading to changes in viscosity and fluid loss. High temperatures can cause evaporation of water-based fluids, increasing their density and potentially leading to instability.

As temperature increases, the viscosity of drilling fluids typically decreases. This reduction can affect the fluid's ability to carry cuttings and maintain stability in the borehole.

The fracture pressure exhibits greater sensitivity to temperature. Temperature influences collapse pressures differently based on lithological characteristics; however, fracture pressure variation is independent of lithology [31].

The required collapse and breakdown mud weights go up when the formation is heated, but the effect on the collapse mud weights is smaller than the effect on the breakdown mud weights. Also, the flow of cooler mud can move the thermal neutral point higher, which is good because it helps the lower parts of the borehole. The shallow formations above the thermal neutral point, on the other hand, get hot and may become unstable (Figure 6, Figure 7, and Figure 8) [28].

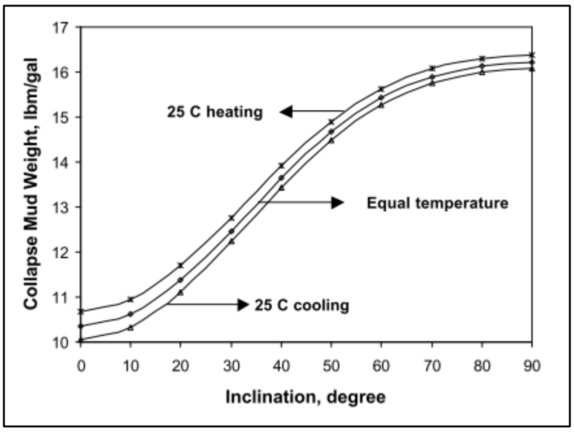

Figure 6 Thermal impacts on collapse mud densities for inclined boreholes [27]

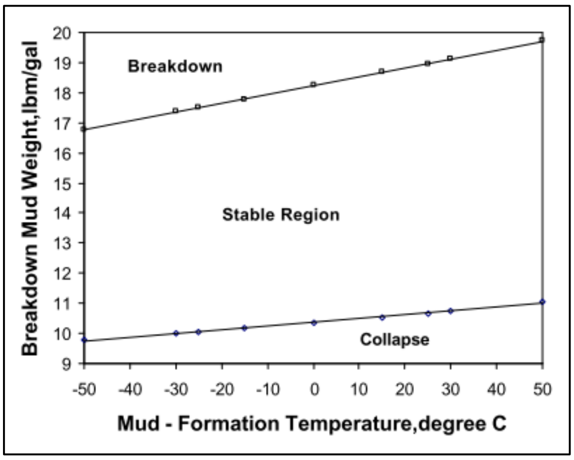

Figure 7 Impact of temperature variations on essential mud weights for vertical boreholes [27]

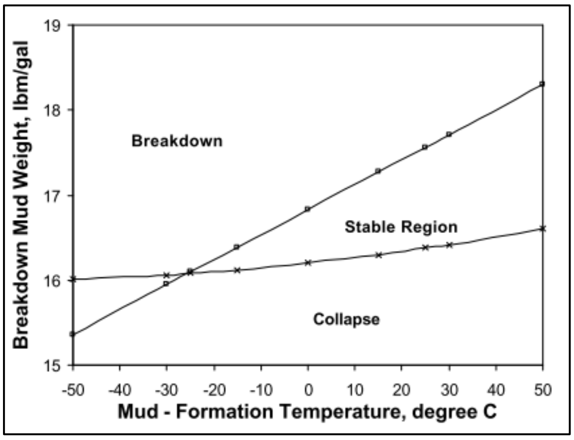

Figure 8 Impact of temperature variations on essential mud weights for horizontal wellbores [27]

When the temperature difference between the rock in the borehole and the drilling fluid stays the same, and the fluid filtration improves, the pressure in the rock increases. This leads to a rise in collapse pressure, a drop in breakdown pressure, a smaller safe range for drilling fluid density, and worse stability of the borehole. If the drilling fluid raises the wall rock temperature and the temperature difference grows, both collapse pressure and breakdown pressure increase, the safe range for drilling fluid density widens, and the borehole wall becomes more stable, making drilling safer. If drilling fluid makes wall rock temperature increase, with the temperature difference increasing, both the collapse pressure and breakdown pressure increasing, the safe drilling fluid density window becoming larger, and the borehole wall tending to stabilize, it is conducive to drilling safely (Figure 9) [32].

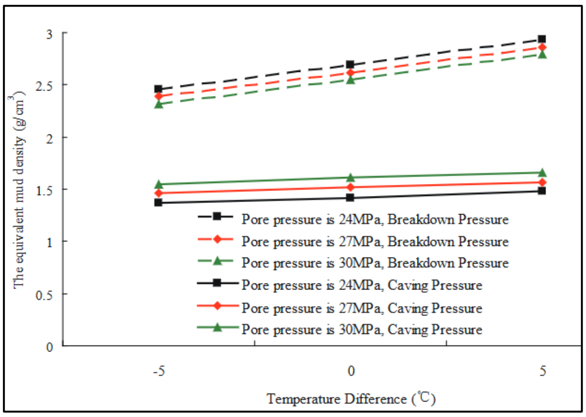

Figure 9 The Impact of Temperature Variation on the Safety Mud Density Window in Relation to Varying Borehole Rock Pore Pressure [31]

5.5. Filtration and Fluid Loss

Mudcake Formation: The ability of a drilling fluid to form a mudcake on the borehole wall is critical for stability. A well-formed mudcake minimizes fluid loss into the formation and helps maintain pressure balance.

Excessive fluid loss can lead to formation damage and instability. Using fluid loss control additives can help maintain the integrity of the borehole by minimizing the amount of fluid that penetrates the formation (Figure 10). The accumulation of mud cake mitigates the rise in pore pressure and expands the safe mud weight range by enhancing the effective compressive stress [33].

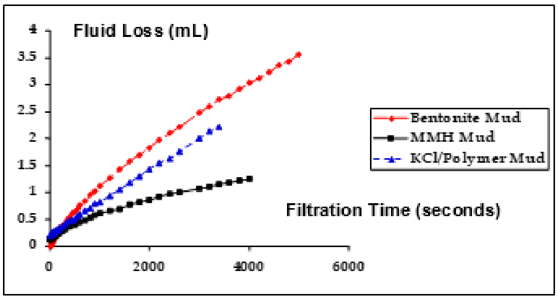

Figure 10 Fluid loss variation based on mud type

5.6. Environmental Conditions

Formation Characteristics: The geological characteristics of the formation (e.g., rock type, porosity, permeability) influence how drilling fluids interact with the borehole. Understanding these characteristics is essential for selecting the appropriate drilling fluid [34].

Pressure and Stress Conditions: Variations in subsurface pressure and stress can affect borehole stability. The drilling fluid must be capable of compensating for these variations to maintain stability.

When a borehole is drilled in stressed rock, the stresses are redistributed as the rock formation attempts to push the hole closed. Balancing this redistribution can be complicated. Not only do increased stress concentrations arise at the borehole wall, but the stress orientations can also be perturbed. Even if a wellbore is planned to be drilled overbalanced, local overpressure can render a borehole underbalanced, causing fracture caging effects [26].

6. Advancements in Drilling Techniques and Drilling fluid Technology affects wellbores stability

The increasing complexity of wells has led to the introduction of various mud types in the oilfield to enhance drilling, including unconventional options such as mixed metal oxide mud. Alongside advancements in mud chemicals, various unconventional drilling techniques are presently employed in the oil industry, such as Managed Pressure Drilling (MPD) and Underbalanced Drilling (UBD) (Figure 11). Consequently, examining the impact of drilling fluid is essential for wellbore stability and drilling performance.

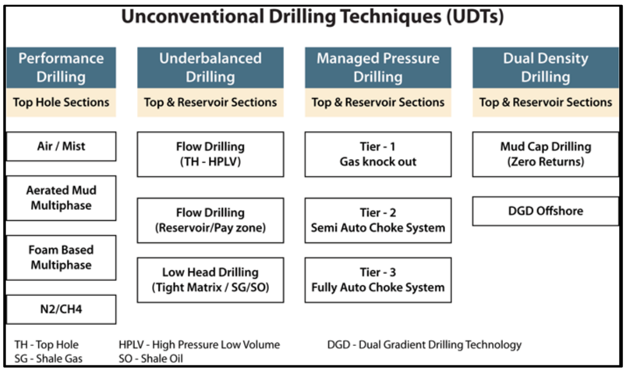

Figure 11 Presents different types of unconventional drilling techniques (UDTs) exist [35]

MMO mud is a drilling fluid that integrates various metal oxides to improve its characteristics and efficacy in drilling operations. The mixed-metal fluids exhibited sensitivity to anionic additives and necessitated prolonged mixing periods to attain optimal performance [36].

The mixed metal oxide mud exhibits unique rheological properties that facilitate plug flow, thereby enhancing the removal of suspended solids from the borehole. Optimal drilling of coarse sands, gravel, and cobblestones utilizing MMO mud. It alleviates issues associated with high-solids drilling fluids. No other drilling fluid suspends large cuttings either. It eliminates borehole cuttings comparable to the size of golf balls. It functions at reduced pumping rates, enabling even minor rigs to produce sufficient flow for optimal drilling velocities. The risk of hydraulic fracturing is mitigated by reduced downhole pressure. Robust borehole support is derived from the fluid that permeates wall fissures and rapidly solidifies upon gelling. Ultimately, MMO fluids are ideal for recycling. This will not obstruct screens for shale shakers. It traverses screens fluidly, akin to water [37].

The mixed metal oxides effectively reduced fluid loss in drilling applications. This reduction in filtration not only improves wellbore stability but also minimizes environmental impacts associated with excessive fluid loss during drilling operations (Figure 10) [38].

Managed Pressure Drilling (MPD) techniques significantly influence wellbore stability by allowing for more precise control over downhole pressure conditions. MPD allows for the maintenance of a constant bottom hole pressure regardless of the depth, preventing pressure fluctuations that could lead to wellbore instability. This control helps to avoid formation fracturing as well as collapse due to insufficient pressure, specially with small drilling window (Figure 12) [39].

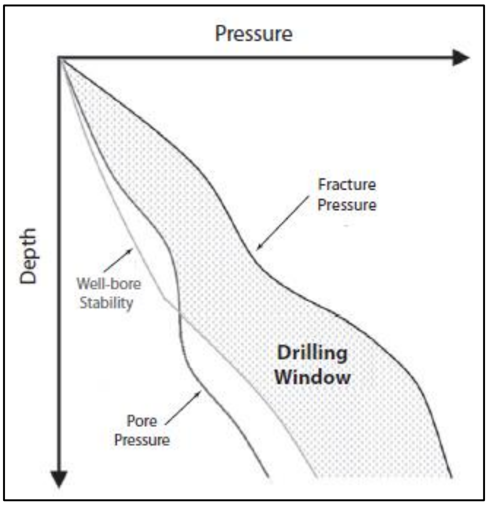

Figure 12 MPD good choice for narrow drilling window to avoid fracture formation and wellbore instability [40]

MPD minimizes fluid invasion. By optimizing the pressure at which the drilling fluid is circulated, MPD techniques can minimize fluid invasion into the formation. This reduction in fluid loss helps maintain the mechanical integrity of the borehole wall and mitigates the risk of destabilization caused by fluid-sensitive formations [40].

MPD can help to manage the filtration rates of drilling fluids, reducing the damage caused by fluid loss and maintaining a stable wellbore environment. The ability to monitor and adjust drilling parameters in real-time enhances the adaptability of the drilling operation (Figure 13). If signs of instability arise, adjustments can be made immediately to pressure and mud properties, thereby preserving wellbore stability.In zones with unconsolidated or weak formations, MPD techniques can provide the necessary pressure support to keep the wellbore stable and prevent collapse [41].

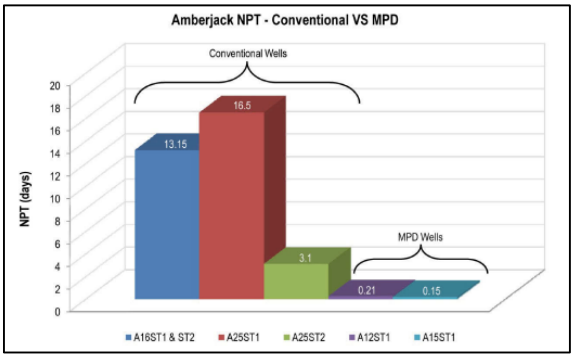

Figure 13 Less non-productive time (NPT) for MPD compared to conventional drilling [42]

Underbalacnced drilling (UBD) technique involves maintaining the wellbore pressure below the formation pressure. UBD often uses lightweight drilling fluids, which can help control fluid loss and minimize damage to the formation. This is particularly useful in sensitive formations such as shales, which can react adversely to water-based fluids. In some cases, UBD can enhance the stability of porous and permeable formations. The lower pressure can prevent fluid invasion from the borehole into the formation, maintaining the integrity of the formation and reducing the risk of swelling clays or other instability triggers so, increase the overall drilling performace (Figure 14) [43].

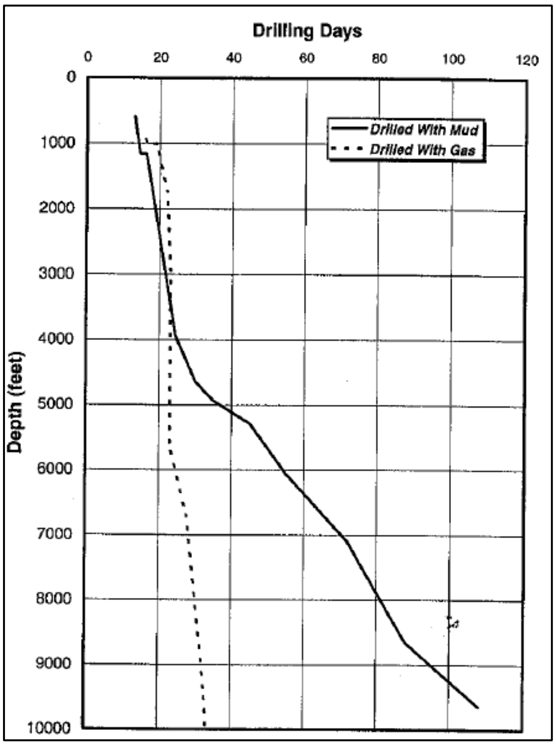

Figure 14 UBD can improve drilling rate of penetration (ROP) and total days of drilling [44]

However, If UBD is not properly managed, it can lead to wellbore instability, particularly in formations that are not strong enough to withstand the lower pressure (Figure 15). This can result in the collapse of the borehole, especially if the formation's integrity is compromised [45, 46].

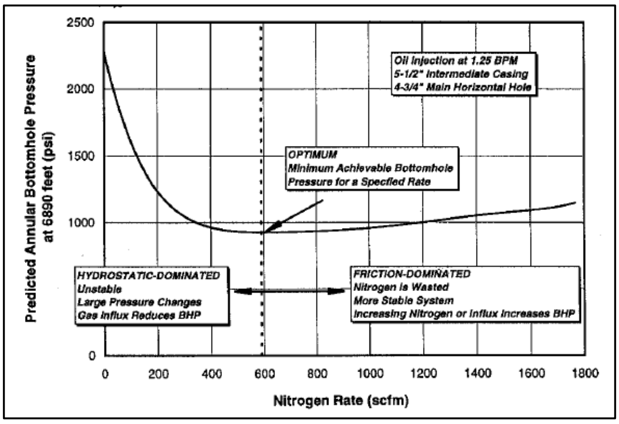

Figure 15 There is optimum nitrogen rate to control the bottom hole pressure and the wellbore stability [44]

7. Conclusions

In the well-planning phase, it is important to select the drilling technique and drilling fluid type to maintain the wellbore stability.

The type and properties of drilling fluids play a crucial role in ensuring borehole stability. By optimizing these properties—such as rheology, density, chemical composition, and filtration characteristics—engineers can mitigate risks associated with borehole instability, leading to safer and more efficient drilling operations. Understanding the interplay between these factors is vital for successful drilling in various geological environments.

Oil-based fluids tend to provide better wellbore stability than water-based fluids; however, synthetic fluids can provide the benefits of oil-based fluids while being more environmentally friendly.

The mixed metal oxides effectively reduced fluid loss in drilling applications. This reduction in filtration not only improves wellbore stability but also minimizes environmental impacts associated with excessive fluid loss during drilling operations.

Managed Pressure Drilling techniques greatly enhance wellbore stability by providing precise control over downhole pressure conditions, reducing formation damage, improving drilling efficiency, and allowing for real-time adaptability. These advantages make MPD a valuable approach for drilling in challenging formations, where traditional methods may face significant risks of instability. By optimizing drilling conditions, MPD contributes to safer and more efficient drilling operations.

Underbalanced drilling techniques can provide significant benefits for wellbore stability, including enhanced formation integrity, improved cuttings removal, and minimized influx. However, they also present challenges, particularly the risk of borehole collapse and hydraulic fracturing if not carefully managed. Successful UBD operations depend on accurate monitoring and the ability to adapt to dynamic downhole conditions to maintain stability and ensure effective drilling performance.

Funding Sources

This research received no external funding.

Conflicts of Interest

There are no conflicts to declare.

Abbreviations

The following abbreviations are used in this manuscript:

NPT	Non-productive time
OBM	Oil-based mud
WBM	Water-based mud
HOCM	High oil content mud
LOCM	Low oil content mud
MMO	Mixed metal oxide mud
MPD	Managed pressure drilling
UBD	Underbalanced drilling

References

[1]. Ali, A., & Alsubaih, S. (2016). *Shale instability of deviated wellbores in southern Iraqi fields*. Retrieved from https://scholarsmine.mst.edu/masters_theseshttps://scholarsmine.mst.edu/masters_theses/7545

[2]. Tao, Q. (2006). *Wellbore stability in water-sensitive shales*. Retrieved from https://core.ac.uk/download/235056519.pdf

[3]. Hamoodi, A., Rahimy, A. A., & Khalid, A. W. (2018). The Effect of Proper Selection of Drilling Fluid on Drilling Operation in Janbour Field. *American Scientific Research Journal for Engineering*, *39, No 1*, 224–234. Retrieved from http://asrjetsjournal.org/

[4]. Simpson, J. P., & Dearing, H. L. (2000). Diffusion Osmosis-An Unrecognized Cause of Shale Instability. In IADC/SPE Drilling Conference. SPE. https://doi.org/10.2118/59190-MS

[5]. Nicolas Espinoza. (2023). Introduction to Energy Geomechanics.

[6]. Alsubaih, A. A. S. (2016). *Shale instability of deviated wellbores in southern Iraqi fields* (Master Thesis). Missouri University of Science and Technology. Retrieved from https://core.ac.uk/download/229038849.pdf

[7]. Chudyk, I. I., Femiak, Ya. M., Orynchak, M. I., Sudakov, A. K., & Riznychuk, A. I. (2021). NEW METHODS FOR PREVENTING CRUMBLING AND COLLAPSE OF THE BOREHOLE WALLS. *Scientific Bulletin of the National Mining University*. Retrieved from http://nvngu.in.ua/jdownloads/pdf/2021/4/04_2021_Chudyk.pdf

[8]. Fan, X., Zhang, M., Zhang, Q., Zhao, P., Yao, B., & Lv, D. (2020). Wellbore stability and failure regions analysis of shale formation accounting for weak bedding planes in Ordos basin. *Journal of Natural Gas Science and Engineering*, *77, p.103258*. Retrieved from https://www.sciencedirect.com/science/article/am/pii/S1875510020301128

[9]. Thomas, N. C. (2017, August). *Visualizing Wellbore Instability and Fracture Direction by Application of Principal Stress Trajectory Analysis* (Master Thesis). Texas A&M University. Retrieved from https://core.ac.uk/download/154406099.pdf

[10]. Al-Shargabi, M., Davoodi, S., Wood, D. A., Al-Musai, A., Rukavishnikov, V. S., & Minaev, K. M. (2022). Nanoparticle applications as beneficial oil and gas drilling fluid additives: A review. *Journal of Molecular Liquids*, *352*, 118725. https://doi.org/10.1016/J.MOLLIQ.2022.118725

[11]. Amoco Production Company. (1994). *Drilling Fluids Manual* (Rev. 6.). Amoco Corporation.

[12]. Fakhari, N. (2022, June). *A mud design to improve water-based drilling in clay rich* (PhD Thesis). Curtin University. Retrieved from https://espace.curtin.edu.au/bitstream/handle/20.500.11937/92323/Fakhari N 2022 Public.pdf?sequence=1

[13]. Arbad, N. (2020). *EXPERIMENTAL INVESTIGATIONS OF THE EFFECT OF OIL BASED MUD (OBM) CONTAMINATION ON LONG-TERM INTEGRITY OF API CEMENTS* (Master Thesis). University of Oklhoma. Retrieved from https://shareok.org/bitstreams/c433b379-88d6-46e5-85fb-51d43bec2079/download

[14]. Hale, A., Americas, A., Amer, A., Hallmark, P., & Newpark Fluids Systems. (2022). An In-Depth Analysis of Mixed Metal Oxide Fluids and Their Suitability for Lost Circulation. In the American Association of Drilling Engineers (Ed.), (pp. 1–4). Texas: Fluids Technical Conference and Exhibition. Retrieved from https://www.newpark.com/assets/pdfs/AADE-22-FTCE-045_-_Hale_et_al.pdf

[15]. Ai, E., Li, Q., Liu, Z., Zhang, B., Wang, L., & Ma, C. (2024). Advanced Trends in Shale Mechanical Inhibitors for Enhanced Wellbore Stability in Water-Based Drilling Fluids. *Minerals*, *14*(12), 1197. https://doi.org/10.3390/min14121197

[16]. Razali, S. Z., Yunus, R., Abdul Rashid, S., Lim, H. N., & Mohamed Jan, B. (2018). Review of biodegradable synthetic-based drilling fluid: Progression, performance and future prospect. *Renewable and Sustainable Energy Reviews*, *90*, 171–186. https://doi.org/10.1016/j.rser.2018.03.014

[17]. Murtaza, M., Alarifi, S. A., Kamal, M. S., Onaizi, S. A., Al-Ajmi, M., & Mahmoud, M. (2021). Experimental Investigation of the Rheological Behavior of an Oil-Based Drilling Fluid with Rheology Modifier and Oil Wetter Additives. *Molecules*, *26*(16), 4877. https://doi.org/10.3390/molecules26164877

[18]. Sun, Y., Zhu, X., Zhao, J., & Sui, D. (2020). Study on a New Environmentally Friendly Synthetic Fluid for Preparing Synthetic-Based Drilling Fluid. *Frontiers in Chemistry*, *8*. https://doi.org/10.3389/fchem.2020.539690

[19]. Park, S., Cullum, D., & McLean, A. D. (1993). The Success of Synthetic-Based Drilling Fluids Offshore Gulf of Mexico: A Field Comparison to Conventional Systems. In *SPE Annual Technical Conference and Exhibition*. SPE. https://doi.org/10.2118/26354-MS

[20]. Abdullah, A. H., Ridha, S., Mohshim, D. F., Yusuf, M., Kamyab, H., Krishna, S., & Maoinser, M. A. (2022). A comprehensive review of nanoparticles: Effect on water-based drilling fluids and wellbore stability. *Chemosphere*, *308*, 136274. https://doi.org/10.1016/J.CHEMOSPHERE.2022.136274

[21]. Retnanto, A., Yrac, R., Shaat, A., Retnanto, A., Abughaush, L., Al Sulaiti, M., & Badar, N. (2023). Evaluation of the viability of nanoparticles in drilling fluids as additive for fluid loss and wellbore stability. *Petroleum*, *9*(3), 342–351. https://doi.org/10.1016/j.petlm.2023.02.005

[22]. Davoodi, S., Al-Shargabi, M., Wood, D. A., Rukavishnikov, V. S., & Minaev, K. M. (2024). Synthetic polymers: A review of applications in drilling fluids. *Petroleum Science*, *21*(1), 475–518. https://doi.org/10.1016/J.PETSCI.2023.08.015

[23]. El Sherbeny, W., Baghdady, A., Farag, A., & Vossen, J. (2023). Managing Wellbore Stability Challenges for an Optimum Well Delivery; Case Study, Balsam Field, Nile Delta, Egypt. In *Middle East Oil, Gas and Geosciences Show*. SPE. https://doi.org/10.2118/213734-MS

[24]. Chilingarian, G. V., Alp, E., Caenn, R., Al-Salem, M., Uslu, S., Gonzales, S., … Yen, T. F. (1986). Drilling Fluid Evaluation Using Yield Point-Plastic Viscosity Correlation. *Energy Sources*, *8*(2–3), 233–244. https://doi.org/10.1080/00908318608946052

[25]. Zhai, C., Xiang, X., Zou, Q., Yu, X., & Xu, Y. (2016). Influence factors analysis of a flexible gel sealing material for coal-bed methane drainage boreholes. *Environmental Earth Sciences*, *75*(5), 385. https://doi.org/10.1007/s12665-016-5286-1

[26]. Thomas, N. C. (2017, August). *Visualizing Wellbore Instability and Planes of Failure in Boreholes by Application of Principal Stress Trajectory Analysis*. Retrieved from chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://core.ac.uk/download/154406099.pdf

[27]. Radwan, A. E. (2022). Drilling in Complex Pore Pressure Regimes: Analysis of Wellbore Stability Applying the Depth of Failure Approach. *Energies*, *15*(21), 7872. https://doi.org/10.3390/en15217872

[28]. Yu, M. (2002, August). *CHEMICAL AND THERMAL EFFECTS ON WELLBORE STABILITY OF SHALE FORMATION* (Thesis).

[29]. Li, S., George, J., & Purdy, C. (2012). Pore-Pressure and Wellbore-Stability Prediction To Increase Drilling Efficiency. *Journal of Petroleum Technology*, *64*(02), 98–101. https://doi.org/10.2118/144717-JPT

[30]. SINGH, P. K., & SHARMA, V. P. (1991). Effect of Additives and Aging on the Rheological Properties of Water-Based Drilling Fluid. *Energy Sources*, *13*(3), 369–387. https://doi.org/10.1080/00908319108908995

[31]. Yan, C., Deng, J., Yu, B., Li, W., Chen, Z., Hu, L., & Li, Y. (2014). Borehole Stability in High-Temperature Formations. *Rock Mechanics and Rock Engineering*, *47*(6), 2199–2209. https://doi.org/10.1007/s00603-013-0496-2

[32]. Chi, A., Yuwei, L., & Yu, L. (2013). The Effects of Pore Pressure and Temperature Difference Variation on Borehole Stability, *6, No. 1*, 22–26. https://doi.org/DOI:10.3968/j.aped.1925543820130601.1546

[33]. Li, J., Qiu, Z., Zhong, H., Zhao, X., Liu, Z., & Huang, W. (2022). Effects of water-based drilling fluid on properties of mud cake and wellbore stability. *Journal of Petroleum Science and Engineering*, *208*, 109704. https://doi.org/10.1016/J.PETROL.2021.109704

[34]. Diaz, A., & Norman, P. (2004). *CHEMOPOROELASTIC SOLUTION OF TRANSVERSELY ISOTROPIC SATURATED POROUS MEDIA*. Retrieved from https://core.ac.uk/download/215216373.pdf

[35]. Malik, H., Aljubran, M. J., & Saudi Aramco. (2018, March 12). MPD vs underbalanced drilling: 10 ways

they differ in operational strategy and implementation. Retrieved March 20, 2024, from https://drillingcontractor.org/mpd-vs-underbalanced-drilling-10-ways-they-differ-in-operational-strategy-and-implementation-45943

[36]. Greg Plutko. (2020). The Basics of a Mixed-Metal Fluid System for Drilling Jobs. Retrieved April 21, 2025, from https://www.thedriller.com/articles/91758-the-basics-of-a-mixed-metal-fluid-system-for-drilling-jobs

[37]. Michael Kleespies. (2021). Using Mixed-Metal Oxide with Small to Medium HDD Rigs. Retrieved January 21, 2025, from https://www.thedriller.com/articles/92354-using-mixed-metal-oxide-with-small-to-medium-hdd-rigs

[38]. Javay, A., ElBatran, A., Sharma, S., M. Franco, N., Corona, M., & A. Alismail, A. (2022). Use of Mixed-Metal Oxide Water-Based Drilling Fluid System Increased Drilling Performance and Eliminated Mud Losses. In *Day 2 Tue, February 22, 2022*. IPTC. https://doi.org/10.2523/IPTC-21961-MS

[39]. Cai, X., Guo, Q., & Jiang, H. (2021). Utilizing Managed Pressure Drilling Technique to Prevent Rock Failure and Maintain Wellbore Stability. *IOP Conference Series: Earth and Environmental Science*, *861*(6), 062055. https://doi.org/10.1088/1755-1315/861/6/062055

[40]. Fossli, B., Sangesland, S., Rasmussen, O. S., & Skalle, P. (2006). Managed-Pressure Drilling; Techniques and Options for Improving Efficiency, Operability, and Well Safety in Subsea TTRD. In *Offshore Technology Conference*. OTC. https://doi.org/10.4043/17798-MS

[41]. Vieira, P., Arnone, M., Russel, B., Cook, I., Moyse, K., Torres, F., … Qing, C. (2008). Constant Bottomhole Pressure: Managed-Pressure Drilling Technique Applied in an Exploratory Well in Saudi Arabia. In *SPE/IADC Managed Pressure Drilling and Underbalanced Operations Conference and Exhibition*. SPE. https://doi.org/10.2118/113679-MS

[42]. Demirdal, Barkim. (2011). *Managed Pressure Drilling*. Texas: Society of Petroleum Engineers.

[43]. Islam, Md. A., Skalle, P., & Evgenity, T. (2009). Underbalanced Drilling in Shales- Perspective of Mechanical Borehole Instability. In *All Days*. IPTC. https://doi.org/10.2523/IPTC-13826-MS

[44]. McLennan, J., Carden, R. S., Curry, D., Stone, C. R., & Wyman, R. E. (97AD). *Underbalanced Drilling Manual*. Chicago, lllinois: Gas Research Institute.

[45]. Oyeneyin, M. B. (2003). Challenges of Underbalanced Drilling for West Africa. In *Nigeria Annual International Conference and Exhibition*. SPE. https://doi.org/10.2118/85662-MS

[46]. Zhang, W., Dang, W., Zhang, W., Sun, X., & Zhu, Z. (2020). Underbalanced Drilling Optimum Methodology. *E3S Web of Conferences*, *198*, 03004. https://doi.org/10.1051/e3sconf/202019803004