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Role of Rock Saturation Condition on Rock−Mud Interaction: Sandstone Geomechanics Study

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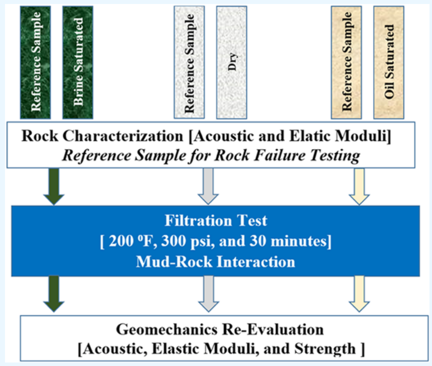
ABSTRACT: The rock saturation condition affects the rock elastic and strength characteristics due to the role of fluid−rock interaction. However, the role of this parameter has not been studied well for mud−rock exposure during drilling operations. Hence, this study targets to assess the role of different rock saturation conditions on the rock geomechanics changes during the rock exposure for the drilling fluids. During the drilling operation, the mud filtrate invades the drilled formation pore system and replaces the saturating fluid and consequent alterations occur for the rock elastic moduli and failure properties. The current study employed Berea Buff sandstone rock type with different saturation conditions (brine-saturated, dry, and oil-saturated) to interact with drilling mud (water-based) through the filtration test to mimic the downhole rock−mud exposure under pressure, temperature, and time conditions. Extensive laboratory analysis was accomplished that covered the scratching test to get the strength of rock samples, acoustic data determination, elastic moduli evaluation, and scanning electron microscopy to assess the internal alterations of the rock pore system. The obtained results showed that the oil-saturated sample showed the least filtration characteristics for the rock−mud exposure and the best condition to maintain the rock strength from deterioration compared to the dry and brine-saturated samples. The rock strength showed a weakening behavior for the brine-saturated and dry samples by 5 and 18% respectively, while the oil-saturated sample showed only a 2% strength reduction after the mud exposure. Poisson's ratio showed a 21% increase for the brine-saturated sample and the dry sample showed a small increase from 0.2 to 0.22, while the oil-saturated sample maintains a stable Poisson's ratio at 0.24. Young's modulus showed an increase for the dry and brine-saturated rock samples by 10 and 7%, respectively, while a 25% reduction for the oil-saturated. The spectrometry analysis results showed the internal changes in the rock samples' pore system for the brine-saturated and dry samples, while the oil-saturated sample showed no internal changes that maintain the rock structure and strength after the mud exposure.



1. INTRODUCTION

The drilling operation for any oil and gas well considers penetrating different formations till the designed total depth for the well plan is reached. There are specific petrophysical and geomechanical characteristics for these drilled formations that represent the drilled rock lithology, porosity, permeability, acoustic velocities, elastic, and strength properties.[1−3] Studying the formation characteristics is a very significant topic that has been studied in the literature, and new research still is required to cover the research gap for some specific technical problems. This research scope has a high interest due to the impact on the wellbore stability and the high expenditure cost associated with this during the well drilling, production, and development.[4−6]

The drilling mud is pumped during the drilling operation from the surface through the drill string and drill bit nozzles. Then, the drilling fluid starts to touch the drilled formation and do the required functions for drilling fluid as overbalancing the formation pressure of the drilled formation, formatting the filter cake for wellbore stability, lubricating and cooling the drill string, and carrying the drilled cuttings to the surface for hole cleaning purposes.[7,8] The drilling fluids can be classified based on the base fluid into water-based mud (WBM) or oil-based mud (OBM), and the chemical composition of the drilling fluid is mainly designed to provide efficient rheological and filtration characteristics and new additives are still introduced for such research and applications.[9−12] One of the main interests of such studies is to provide a non-damageable impact for the drilled formation.[13]

Each drilled formation has specific elastic moduli and failure characteristics.[14] The drilled rock show some kind of deformation under the downhole stresses and therefore determining the rock elastic moduli is so critical for modeling the reservoir geomechanics and designing the field develop-

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ment plans. Young's modulus and Poisson's ratio are considered the two most important elastic moduli, as they are commonly utilized as inputs for reservoir modeling and determining other geomechanical properties through existing correlations or prediction using artificial intelligence techniques.[15−17] Young's modulus represents the rock stiffness characteristics and Poisson's ratio represents the deformation behavior of the rock and drilled formations. On the other hand, rock failure characteristics show the maximum level of applied stresses before the rock failure occurs and are commonly represented in terms of the tensile strength (TS) and unconfined compression strength (UCS) values. The rock geomechanical parameters are extremely influenced by petrophysical characteristics of specific rock type in terms of pore structure, lithological texture, grain bonding, saturating fluid, and internal frame of rock grains.[18,19]

1.1. Rock−Mud Exposure. Once the drilled rock is exposed to the drilling mud, a chemical interaction may start and consequent changes occur for the drilled formation properties.[20] The rock characteristics are influenced by the chemical interactions between the drilling fluid and rock mineralogical composition that leads to severe alterations in the pore system that show different behavior either due to the plugging mechanism that is attributed to the precipitation process and/or the opening mechanism that is attributed to the dissolution process.[21−23] Consequently, there will be alterations in the rock petrophysical characteristics such as formation porosity, flow characteristic in porous media, interior topography for rock, pore structure, and rock geomechanics.[24−26]

Rock−mud exposure is a critical topic due to the rock sensitivity and fluid activity for chemical interaction and rock characteristic changes, and the topic is well covered for shale formation;[27,28] however, there is a research gap for sandstone formation.[25,29] The sandstone mineralogy has quartz and clay minerals with different categories and the content greatly affects the rock structure in addition to the frame of quartz and clay particles when exposed to drilling mud systems.[30] Consequent dissolution might occur for the rock minerals due to the pH value of the fluid and the temperature range of the downhole environment.[31] This dissolution behavior affects the cohesion bonds for the cementing minerals among the rock grains, the swelling rate of clay, and the consequential degree of the rock plasticity behavior.[32] The rock petrophysical characteristic in terms of rock fluid storage capacity (porosity) and fluid flow features are affected accordingly by the rock pore system structure changes.[33,34] In addition, the rock geomechanical properties show some extent of alterations for the rock's interior pore system and bonding strength for rock particles, formation strength behavior, and elastic moduli.[35,36] Recent studies provided the applications of nanomaterials for enhancing the rheological and filtration properties of the drilling fluid systems, which are considered successful technical solutions for the drilling operation to protect the reservoir zone from damage and improve the mud functionality that affects the operation performance and cost savings.[37−40]

Previous studies by the authors assessed the extent of the impact of different downhole parameters on the rock−mud exposure and concluded that extended exposure time during the exposure process greatly decreased the pore system flow characteristics with an associated decrease in strength.[3] The mud filtrate that commonly invaded the drilled formation was found to cause internal pore system alterations by different precipitation and dissolution mechanisms based on the rock clay content and type.[21,41] Experimental studies over an extended pressure range reported that the overbalanced pressure applied during the drilling operation greatly affected the rock petrophysical and geomechanical properties.[42,43] Even the weighting material in the drilling fluid system affected the pore system network, and the main cause was the particle size distribution of mud solids.[44]

1.2. Role of Saturation Condition on Rock Characteristics. The rock saturation condition is one of the main factors that have a great impact on rock strength weakening and dynamic behavior characteristics.[45] In addition, the hydromechanical characteristics behavior was found to be affected by the rock saturation, as the rock elastic properties showed alterations with strength reduction with the increasing degree of water saturation for Tournemire shale, and the results showed that the clay content was the main reason for such consequent alterations.[46] A geomechanical study for different rock types showed that sandstone is the most affected rock type (compared to tested marble and granite rock types) by the water content for the rock saturation condition as the rock elastic modulus and strength decreased from the dry state to the water-saturated state, and the results revealed that the rock porosity, mineral composition, and clay minerals type and content have a great impact on alterations in geomechanics.[47] The main reason for such sandstone strength weakening observed is mainly the quartz hydrolysis behavior and clay swelling activity that affect the rock geomechanics.[48−50] The rock strength (UCS and TS) were evaluated for 34 samples of sedimentary rocks [that have different sandstone and limestone] in dry and saturated conditions, and the results recorded that the saturated rock samples showed a severe reduction of 53% in average strength but a 16% increase in compressional and shear wave velocities.[51] The rock strength reduction is a common conclusion that can be observed for the rock water-saturation phase; in addition, the propagation of the acoustic wave is affected by the saturation condition and showed increased performance, and the rock porosity controls the degree of saturation impact on the rock physical−mechanical characteristics.[52] The interior pore system is very critical for propagating the acoustic waves, and studies through the literature reported that rock mineralogy significantly affects the shear wave, while the saturating fluid greatly affects the compressional wave type through the sonic data acquisition.[20,53,54] The effect of fluid saturation on rock geomechanics was studied for tight sandstone formation, and it was found that the strength reduction was higher for the brine-saturated samples than for the rock samples with oil saturation.[55]

As the rock saturation condition has an excessive influence on the rock features and due to the shortage to cover this research gap for the rock−mud interaction, this paper presents new contributions through experimental research to demonstrate the impact of saturation condition on the rock−mud exposure for the drilling operation. Different saturation conditions (dry, brine-saturated, and oil-saturated core samples) were studied for the Berea Buff sandstone rock type to determine the saturation condition on the exposure process for the drilling fluid and drilled formations. Water-based drilling fluid that was weighed using barite was utilized for the experimental work. Extensive laboratory work was achieved to assess the rock characteristics before and after the rock−mud exposure like rock mineralogy (X-ray diffractions), acoustic and elastic moduli determination, strength (scratch testing), and spectrometry of scanning electron microscope to study the internal rock topography changes. An adapted filter press cell was utilized to house the samples for exposure to the drilling fluid (WBM) during the filtration test. In addition, this study is considered one phase of a comprehensive research work accomplished to evaluate the rock−mud exposure impact on the rock pore system and geomechanics as different downhole conditions were tested and evaluated in previous studies that investigate the role of extended exposure time, mud filtrate, clay content and type, and overburden pressure as downhole conditions affecting the mud−rock exposure. Consequently, the impact of rock saturation conditions on the rock pores system and geomechanics was studied.

2. EXPERIMENTAL WORK AND MATERIALS

Sandstone rock samples (Berea Buff) were utilized for the current study to represent the drilled rock formation under three different saturation phases [brine-saturated (3 wt % potassium chloride), dry, and oil-saturated], and WBM formulated by barite as weighing material for mud−rock exposure.

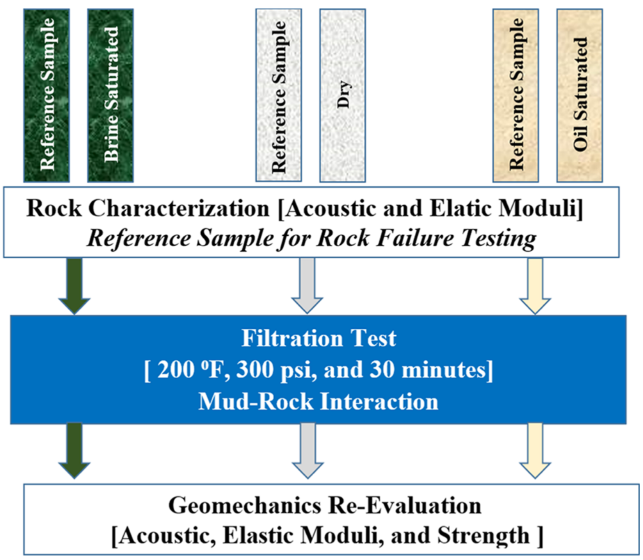

Figure 1. Experimental design layout.

2.1. Experimental Analysis.

The experimental work is designed as per Figure 1. The following procedures summarize the workflow for the experimental work:

1. The rock samples are prepared and cut into cylindrical shapes (2 in. in length by 1.5 in. in diameter).
2. Rock saturation phase: different saturation phases are applied for the rock samples, with one of them representing the dry condition, another sample representing saturation with 3 wt % KCl for clay stabilization,[56] and the third sample representing saturation with oil.
3. Rock geomechanics determination: a separate core sample (reference sample) from each saturation phase was left for the scratch testing, as it is partially destructive for the rock sample while the main core samples were characterized using acoustic data acquisition and elastic moduli determination to represent the premud interaction properties.
4. Filtration test: the rock samples were exposed to a filtration test that was executed for the main core samples through different experiments for each saturation phase using the same drilling formulation (WBM) and the same pressure, temperature, and time conditions. These parameters were designed to mimic the downhole conditions through the drilling operation as the temperature was designed to be 200 °F and 300 psi overbalance/differential pressure was applied. The experiment was extended to 30 min and the filtrate fluid was collected and recorded through the filtration test as per the standard procedures.[57]
5. Rock characteristics re-evaluation: the evaluation of rock properties was repeated after the filtration test to assess the saturation influence on the exposure process for the rock and drilling mud and consequent modifications to the rock structure, sonic wave propagation, elastic moduli, and strength.

The mineralogical composition (Figure 2) for the rock samples (sandstone type) was determined using X-ray

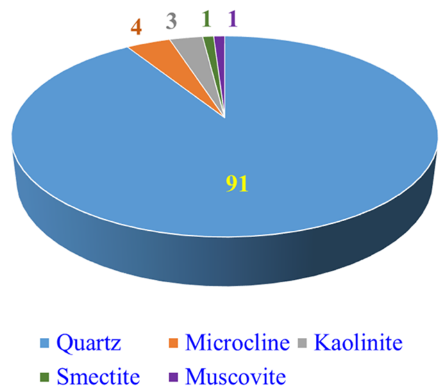

Figure 2. Mineralogical composition of Berea Buff samples.

diffraction, and the composition showed quartz as the main constituent (91 wt %), followed by microcline (4 wt %) and clay (5 wt %) (kaolinite, smectite, and muscovite in 3, 1, and 1 wt %, respectively).

The formulation of the drilling mud system contains water (base fluid) for the WBM mud system with a quantity of 290 g, XC- polymer type of 1.5 g with 4 g bentonite to control the viscosity, 6 g of starch as fluid loss control, 5 g of calcium carbonates (D_{50} of 50 μm) to provide a bridging agent, potassium chloride of 20 g for clay stabilization, 0.3 g of KOH to control the mud pH value, and 200 g of barite to adjust the designed weight for the drilling fluid. The drilling fluid rheology was evaluated at a temperature of 80 °F as commonly practiced in drilling operations, and the rheological properties reported 12.25 pounds per gallon (ppg) for the mud weight, 13 centi-Poises (cP) for the viscosity value, 63 lb/100 ft^2 for the mud yield point, and11, 21 lb/100 ft^2 for the initial and 10-min gel strength, respectively. In addition, a 9.5 fluid pH value that shows good filtration performance.[58]

2.2. Rock Geomechanics.

The scratching test provides the rock UCS profile along the core sample length using the scratching machine. The scratching machine is a new technique that is commonly used in research and industry for obtaining the rock strength characteristics through a cutter

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tool that scratches different cutting depths for the rock samples and measures the normal and shear forces that are correlated to an existing data bank of different rock types to finally provide UCS profile and average UCS value for the rock samples using the analysis software for the machine.[59,60]

Furthermore, the tensile strength of the rock samples was calculated through the UCS-TS correlations[61] and specifically used eq 1[62]

$$TS = 0.0963UCS^{0.932} \quad (1)$$

where UCS is the unconfined compressive strength and TS is the tensile strength (MPa).

The scratching machine uses sonic probes as an acoustic data acquisition system for sending and measuring the wave velocities for the compressional (Vp) and shear (Vs) waves. Consequent determination of the elastic moduli was achieved as per standards of the American Society for Testing and Materials.[63]

2.3. Rock Interior Pore System. The rock scanning was accomplished for the treated rock samples by a scanning electron microscope, and this approach helped to discover the interior alterations of the rock pore system after the rock−mud exposure process that reveals the changes and modifications for the interparticle cementing. Such an analysis represents the driving mechanism for precipitation and dissolution processes.[64,65]

3. RESULT ANALYSIS AND DISCUSSION

3.1. Filtration Test. The three rock samples with different saturation conditions were exposed to the drilling fluid through the filtration test (rock−mud exposure process) and the test results were recorded. The mud filtrate invaded the rock samples' pore system during the filtration process by the action of overbalance/differential pressure by displacing the existing saturation fluid from the rock pores.

The test values of the recorded filtrate volume and filter cake thickness are mainly the key factors that affect the invaded pore system of the drilled rock. The recorded filtration results for the collected mud filtrate volume and filter cake thickness are shown in Figure 3. The results revealed that the dry

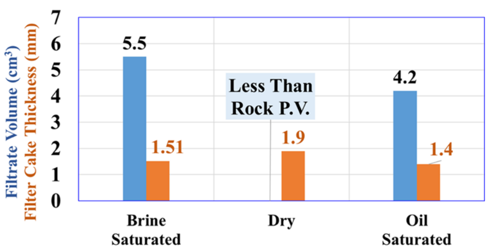

Figure 3. Filtration results for the three saturation conditions.

condition represents the largest filter cake thickness among the other saturation conditions, and the filtrate volume invaded the internal pores of the dry sample and filled some of the empty pore volume (P.V.), which is 12.29 cm^3; hence, the total filtrate volume is less than that of the rock sample P.V. The filter cake thicknesses recorded for the water- and oil-saturated samples were 1.51 and 1.4 cm^3, respectively. The filtrate volume was 5.5 cm^3 for the brine-saturated sample, which is higher than the filtrate volume for the oil-saturated sample (4.2 cm^3) and this might be attributed to the easy displacement of the mud filtrate with brine than oil as a saturation fluid inside the rock pores and the driving flow mechanism for more than one phase in the rock pore system.[66]

A general observation from the filtration properties for the rock−mud exposure is that the oil-saturated rock sample provides the least filter cake thickness and mud filtrate volume, while the filtration characteristics are higher than those of the brine-saturated rock sample and the dry sample has the highest filtration due to the easy fluid displacement performance for the mud filtrate during the rock−mud exposure.

3.2. Sonic Data Measurement. The compressional and shear wave velocities were determined for the three saturation conditions pre- and postmud exposure as shown in Figures 4

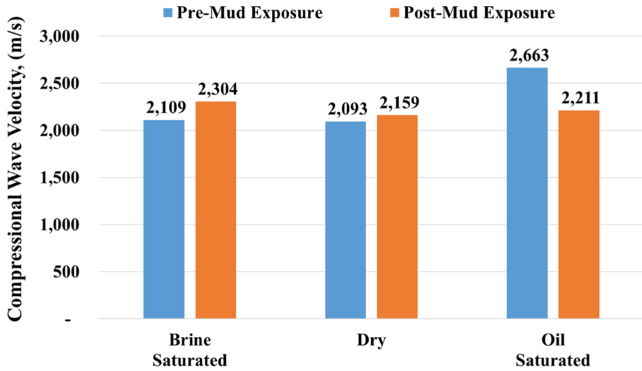

Figure 4. Compressional wave velocities for the three saturation conditions (pre- and postmud exposure).

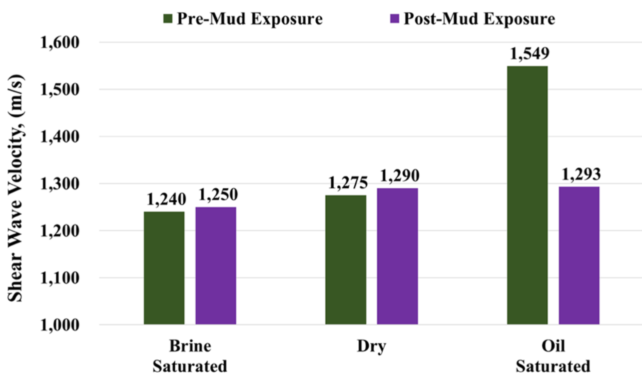

Figure 5. Shear wave velocities for the three saturation conditions (pre- and postmud exposure).

and 5, respectively. The result showed that the sonic wave velocities for the dry and brine-saturated rock samples generally increased after the mud exposure as the compressional wave velocities (Vp) increased by 3 and 9% for the dry and brine-saturated samples, respectively, while the shear wave velocities (Vs) showed a slight increase of around 1%. On the other hand, the oil-saturated sample showed a reduction in the sonic wave velocities after mud exposure as Vp and Vs decreased by 17 and 16.5%, respectively, and this observation was ascribed to the mud filtrate replacement for the oil fluid from the rock pores; and the high oil viscosity affected the wave velocities as the oil-saturated sample has high velocities due to the fast propagation for the sonic waves.[55]

The obtained sonic measurements through the mud exposure for the different rock saturated samples revealed that there is a role for the rock saturation condition on the

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rock−mud exposure process and the mud filtrate invasion for the rock pores and replacement of the pre-fluid saturation will affect the sonic wave propagation.

3.3. Rock Elastic Properties. The rock elastic moduli (Poisson's ratio and Young's modulus) were determined to assess the rock saturation condition on the mud exposure and the results showed that for the brine-saturated sample there is an increase in Poisson's ratio value from 0.24 before the mud exposure to be 0.29 after the mud exposure (21% increase), and there is a small increase in Poisson's ratio from 0.2 to 0.22 for the dry sample, while the oil-saturated sample maintains a stable Poisson's ratio at 0.24 as shown in Figure 6.

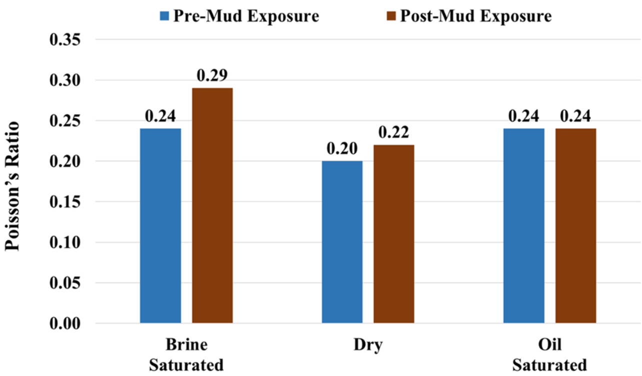

Figure 6. Poisson's ratio for the three saturation conditions (pre- and postmud exposure).

Young's modulus showed an increase for the dry and brine-saturated samples as shown in Figure 7, while the results

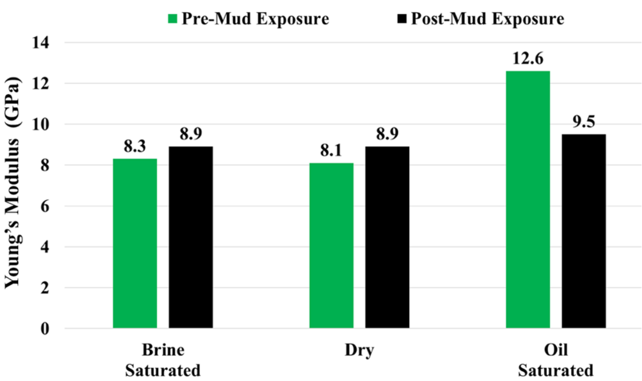

Figure 7. Young's modulus for the three saturation conditions (pre- and postmud exposure).

showed around a 25% reduction in Young's modulus value after the mud exposure for the oil-saturated sample. The results indicate the impact of the fluid saturation condition on the dynamic elastic moduli and the rock deformation characteristics for the rock−mud exposure and the driving mechanism for this behavior is the physicochemical interactions between rock and fluid based on the chemical activity of the saturation fluid and rock mineralogy.[67,68]

3.4. Rock Strength. The rock strength of the mud-processed rock samples showed changes in their strength profiles for the unconfined and tensile strength as shown in Figures 8 and 9. The dry samples had the maximum strength weakening impact among the other saturated sample as the dry condition showed a reduction of 18 and 17% strength

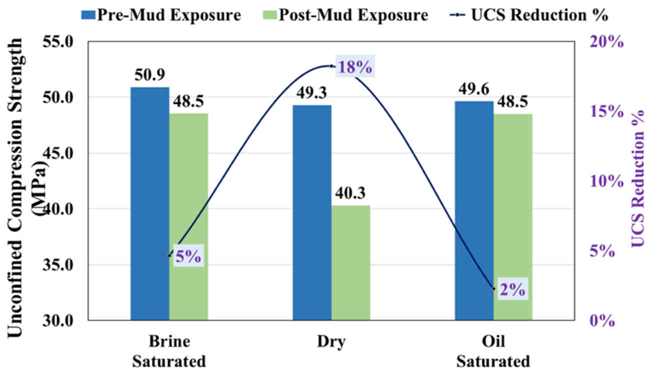

Figure 8. Unconfined compression strength for the three saturation conditions (pre- and postmud exposure).

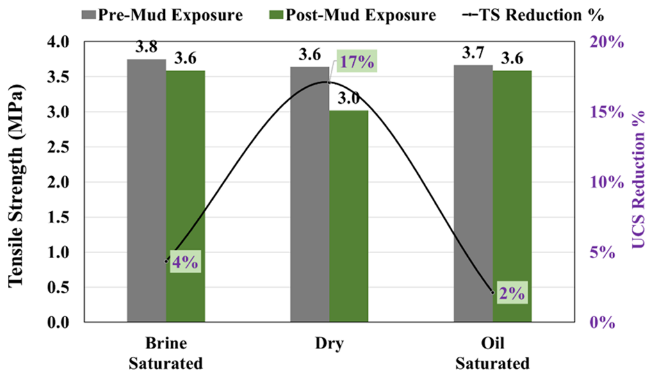

Figure 9. Tensile strength for the three saturation conditions (pre- and postmud exposure).

reduction for the unconfined compression strength and tensile strength, respectively, after the mud exposure process during the filtration test. This observation is mainly caused by the direct contact of the mud filtrate invasion with the clay content and type in the Berea Buff sandstone rock type, and it is found that the mud filtrate invasion causes a great impact on the sandstone strength reduction due to the sandstone-clay framework.[21,41] The brine-saturated samples showed a reduction of 5 and 4% strength, respectively, and it is found that the pre-exposure saturation preserved the rock's internal pore system from severe deterioration as recorded for the dry samples; this behavior is mainly attributed to the brine impact on the clay content stabilization.[69] The oil-saturated samples showed only a 2% reduction in the rock strengths after the mud exposure and this revealed that the oil saturation condition preserved the internal rock structure from the fluid−rock interactions that affect the rock structure and integrity. The oil base fluid was reported to preserve the rock characteristics from alterations during drilling than water-based fluid, and this fact was mainly attributed to the water chemical activity behavior, especially under the downhole conditions of pressure, temperature, and interaction time.[70]

The current study utilized Berea Buff sandstone type for the rock−mud exposure and this rock type has quartz by 91 wt % and microcline (4 wt %) with a clay content of 5 wt % that includes kaolinite (3 wt %), smectite (1 wt %), and muscovite (1 wt %). The frame of the quartz and clay minerals plays a critical role in the rock structure and integrity, and accordingly, the rock's elastic and strength characteristics.[30] The fluid saturation interactions and the invaded mud filtrate with the rock mineralogy affects the kinetic dissolution rate and

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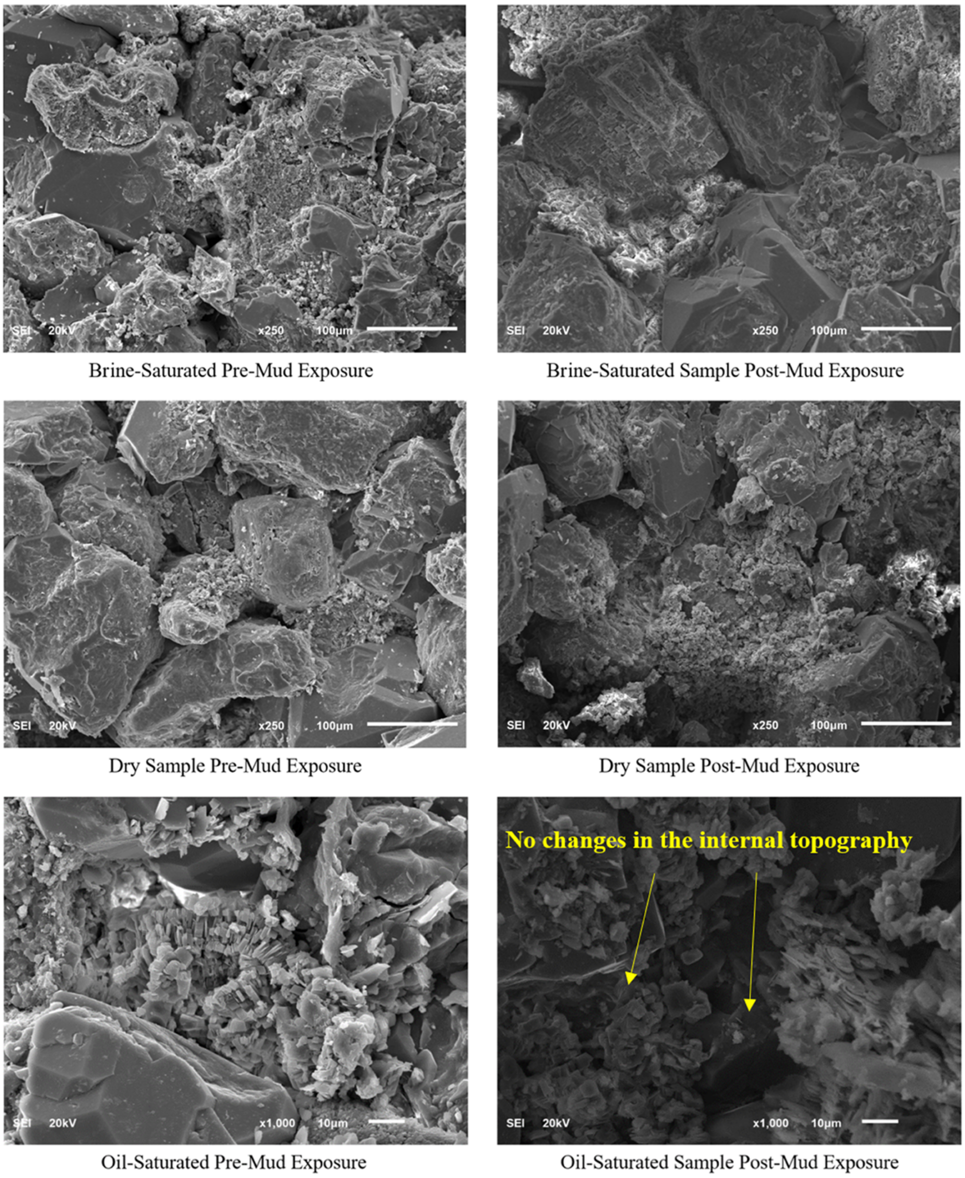

Figure 10. Spectrometry internal rock topography for the three saturation conditions (pre- and postmud exposure).

behavior of the mineralogical composition of the drilled saturated rock, especially for the microcline minerals and the new bonding of the hydrated quartz during the mud exposure process.[21,31,71]

The drilling operation design through different fluid-bearing formations is affected by these alterations for the rock elastic and strength characteristics; hence, the mud−rock exposure has to be clearly understood for the sandstone rock mineralogy and the drilling fluid chemical composition and activity.

3.5. Interior Pore System. Thin sections from the core samples were scanned using scanning electron microscopy (SEM) spectrometry, and the results are shown in Figure 10, which compares the pre and postmud exposure through different saturation conditions. Slight changes in the internal surface topography were observed for the brine-saturated rock sample after the mud exposure and these changes increased for the dry condition, and this observation was attributed to the clay minerals swelling and microcline deformation as the dry sample interacted directly with the mud filtrate from the water-based drilling fluid. The oil-saturated rock samples showed no changes in the rock's internal topography, confirming that the oil saturation preserves the rock structure and strength from deterioration.

4. CONCLUSIONS

The impact of saturating fluid in the rock−mud exposure process was studied through this research for the WBM and sandstone rock types under the downhole conditions during the drilling operation in terms of pressure, temperature, and exposure time. The following outcomes are drawn from the obtained results:

1. The filtration properties for the rock−mud exposure showed that the maximum filter cake thickness was recorded for the dry sample while the oil-saturated sample had the lowest values for the filter cake thickness and collected mud filtrate.
2. The sonic data in terms of Vp and Vs showed an increase for the dry and brine-saturated samples, while there is a decrease in the sonic waves for the oil-saturated sample after the mud exposure due to the rock

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pore filling with the mud filtrate and replacement of the saturation fluid that affect the wave propagation.
3. Poisson's ratio increased from 0.24 to record 0.29 after the mud exposure process for the brine-saturated sample with a 21% increase, and there is a small increase for the dry sample from 0.2 to 0.22, while the oil-saturated sample maintains a stable Poisson's ratio at 0.24.
4. Young's modulus showed an increase for the dry and brine-saturated samples by 10 and 7%, respectively, while Young's modulus showed around a 25% reduction after the mud exposure for the oil-saturated sample.
5. The rock strength showed a weakening behavior for the brine-saturated and dry samples by 5 and 18%, respectively, for the rock UCS, while the oil-saturated sample showed only a 2% strength reduction after the mud exposure.

The spectrometry analysis illustrated the internal pore structure changes for the brine-saturated and dry samples, while the oil-saturated sample has no changes in the rock internal topography that maintain the rock structure and strength after the mud exposure. The obtained conclusions from this research recommend implementing the methodology approach over different kinds of mud systems and rock types; especially carbonate, as it is a common reservoir source. In addition, implementing the finite element modeling to generalize and evaluate the mud−rock exposure influence over a wide domain.

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Author Contributions

The manuscript was written through the contributions of all authors [H.G. and S.E.]. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

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