Effect of the Filtrate Fluid of Water-Based Mud on Sandstone Rock Strength and Elastic Moduli

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ABSTRACT: During drilling operations, the filtrate fluid of the drilling mud invades the drilled rock. The invading filtrate fluid will interact with the rock and therefore alter the rock internal topography, pore system, elastic moduli, and rock strength. The objective of this study is to evaluate the effect of the mud filtrate of barite-weighted water-based mud on the geomechanical properties of four types of sandstone rocks (Berea Buff, Berea Spider, Bandera Brown, and Parker). The mud filtrate was collected to provide mud filtrate–rock exposure at a pressure of 300 psi and 200 °F temperature for 10 days. The study assessed the alteration in the rock geomechanics employing an integrated laboratory analysis of X-ray diffraction (XRD), scanning electron microscopy (SEM), nuclear magnetic resonance (NMR), and scratch testing. The ultrasonic results showed changes after exposure to the mud filtrate and an obvious reduction trend in the shear wave velocities due to the dissolution and mineralogical modifications in rock samples. The obtained results displayed a general strength reduction for the four sandstone types with different levels. The strength reduction ranged from 6% reduction for Berea Spider to a record 23% reduction for Parker. For all sandstone types, Young’s modulus showed a general reduction ranging from 11 to 40%, while Poisson’s ratio recorded an increase by 62–155% after the filtrate interaction. The study illustrated the role of pore-system alteration in controlling the rock strength and dynamic moduli.

INTRODUCTION

During drilling operations, the mud is pumped through the drill string down to the drill bit to control the formation pressure by the overbalanced pressure of the hydrostatic column of the mud. Water-based mud (WBM) has water as the base phase in addition to different additives as clays, polymers, brines, and weighting materials to provide the required mud rheological properties and density. Barite has wide applications in drilling fluids as a weighting material. The mud filtrate and fine mud solids will invade the permeable zones by the action of the mud pressure as shown in Figure 1. Then, the filter cake will be formed to support the wellbore stability and protect the formations from more damage; however, the mud filtrate invasion will depend on the formation permeability and porosity characteristics and mud filtration properties.

The invasion of the drilling fluids into the pore system of the drilled formation will affect its petrophysical properties (porosity, permeability, and pore system) and geomechanics in terms of strength and elastic moduli, especially for the long exposure time at the downhole conditions of pressure and temperature. The alterations in the rock petrophysical and geomechanical properties will affect the drilling and completion programs in addition to the reservoir and geomechanical earth modeling operations. The wellbore instability issues might be a result of such alterations in the rock properties, and...
consequently, many drilling problems might be encountered and require extra cost for solving such problems. Economically, the drilling cost increases 10–20% from the wellbore instability problems that are initiated during the drilling operations, and worldwide economic loss records annually 1–6 billion dollars in the petroleum industry for wellbore instability difficulties.12,13

In the petroleum industry, rock geomechanical characteristics are key parameters for the drilling operation design, earth geomechanical modeling, and reservoir simulation and stimulation.9,10 The rock geomechanics represents the rock failure and elastic properties that describe rock behavior.14 The elastic properties for the rock are commonly stated by Young’s modulus (E), Poisson’s ratio (ν), Lame’s parameter (λ), the rigidity or shear modulus (G), the bulk modulus (K), and uniaxial compaction modulus (H). Each modulus of the elastic moduli group shows specific rock behavior as Young’s modulus (E) characterizes the stiffness of the rock and it measures the rock resistance under uniaxial stress in a compression state, while Poisson’s ratio measures the rock deformation by determining the rock lateral expansion to the longitudinal contraction. Young’s modulus and Poisson’s ratio are considered the most important rock elastic properties among the other elastic moduli. The bulk modulus, which is the ratio of hydrostatic stress to the volumetric strain, provides the compressibility of the rock as the rock compressibility is the inverse of K. The uniaxial compaction modulus shows the compressional P wave. The rock shear modulus represents the resistance of the rock against shear deformation.14,15

Young’s modulus and Poisson’s ratio are commonly utilized to estimate the rock stresses,16 and the dynamic moduli for the rock are correlated to determine the rock static moduli.16,17 The rock failure behavior is characterized by the rock strength, which is the unconfined compressive strength (UCS) and the tensile strength (TS).18 The rock strength is a function of the rock properties such as the porosity, matrix packing, degree of cementing, and internal friction angle.15

**Drilling Fluid and Rock Interactions.** There are specific distinguished geomechanical and petrophysical properties for each formation type in terms of its chemical composition, particle size, structure, and fluid flow capabilities.19,20 The exposure of the drilled rock to the drilling fluids might cause a change in its properties to some degree based on the downhole conditions of pressure, temperature, and time. The alteration of the sandstone rock properties due to the interaction with drilling fluids required further studies to assess the level of changes and explore the mechanism of alteration.6,21

Sandstone formations usually contain different amounts of quartz, clays, feldspars, calcite, dolomite, and other minerals that are iron-based.22 The chemical activity is a critical property for the minerals and it differs from one group to another as ferritic, ferruginous, allitic, and kaolitic having low cation exchange activity while smectite, illitic, vermiculitic, and mixed families showing high cation exchange activity.23 Microcline and albite characterized the feldspar group, and their main composition is aluminum silicates that are bonded with each other by sharing of apical oxygen atoms.24 The phyllosilicate class contains several minerals as muscovite, illite, chlorites, kaolinite, and montmorillonite. Muscovite and illite are considered the most common mica minerals; they have different chemical compositions and structures, and as a result, they have different properties, and muscovite is the more resistant.25 Any chemical interactions for the rock–fluid will cause the dissolution of sandstone and a change in the rock properties.25,26

Knauss and Copenhaver27 showed that the dissolution kinetics of the silicate minerals is significantly controlled by the pH at temperature conditions. Ombaka28 also demonstrated that alterations of the clay minerals under chemical interaction processes will cause changes in the rock properties as grain cohesion, swelling rates, and rock plasticity. The content and type of the rock mineralogical composition were found to have a great impact on the rock characteristics,29–31 structure and integrity, acoustic properties, and elastic moduli.32–34

Yadav et al.35 studied the influence of water-based and oil-based drilling fluids on the geomechanics of Berea sandstone and shale rock samples. The study employed the triaxial test to determine the rock geomechanical properties (Young’s modulus, Poisson’s ratio, and rock strength). The results claimed that the oil-based mud (OBM) is better than the water-based mud (WBM) to preserve the strength. Xu et al.36 conducted a study to evaluate the effect of the drilling fluids (WBM and OBM) on the hardness of sandstone rock. The results showed that, after two hours of mud exposure, the rock hardness decreased by 22.9% with the water-based fluid, while a 10.1% hardness reduction was recorded with the OBM. The pressure and temperature were found to be controlling factors on the dynamic elastic moduli (E, K, and G) of the metamorphic rocks as quartz, mica, schist, and amphibolite. Using the sonic data, Motra and Stutz36 showed that the velocities of compressional and shear waves increase with increasing the pressure and decrease with increasing the temperature. The compressional wave has the motion of its particles in the direction of the wave propagation, and it is sensitive to the fluid saturating the pore system; on the other hand, the particles of the shear wave move perpendicularly to the wave propagation direction, and it is very sensitive to the rock lithology.37,38 The wave propagation will be affected by the media characteristics and the mineralogical modifications in the rock.39,40

Recently, Gamal et al.7,8 conducted a study to detect the effect of exposure time on the formation damage, strength reduction, and the elastic moduli alteration of Berea Buff sandstone rock due to exposure to barite WBM. The study results showed a decreasing logarithmic trend for porosity with time until reaching 41% reduction after five days of interaction with the WBM drilling fluid with observed changes in the internal surface topography. The study showed rock strength reduction after 5 days of 18 and 19% for TS and UCS, respectively. All the
The main objective of this study is to evaluate the effect of the WBM filtrate on the strength and geomechanical elastic moduli for four different sandstone formations (Berea Buff, Berea Spider, Bandera Brown, and Parker). The study simulated the real downhole environment for mud filtrate—rock exposure for 10 days at a pressure of 300 psi and 200 °F temperature. The novel contributions for this study are addressing the mud filtrate effect on the sandstone geomechanics at the real downhole drilling conditions and employing XRD, NMR, SEM, and rock scratching integrated laboratory analysis to detect the geomechanics alterations for the different types of sandstone rocks.

The next sections cover the materials and methods, results, discussion, and conclusions. The Materials and Methods section discusses in detail the description of the drilling fluid and rock properties and the experimental methodology that was employed in this study. The obtained results are represented in the Results section; however, the Discussion section had more discussion and the inference of results. The Conclusions part summarizes the main outputs of the study.

MATERIALS AND METHODS

Four types of sandstone rock were used in this study, and barite-weighted WBM was used to prepare the mud filtrate for rock—filtrate interactions. The mud filtrate was extracted using the filter press system and a ceramic disc. The disc was used to allow the mud filtrate to invade the disc only and prevent the mud solids from invading from outside. After that, the mud filtrate was used to interact with the sandstone samples at the designed pressure and temperature conditions for 10 days. Conditions of a pressure of 300 psi and 200 °F temperature were applied to simulate the downhole reservoir conditions at which the mud filtrate interacts with the drilled rock after the drilling operations as the mud solids and filtrate invade the drilled formations.

Rock compositional analysis was executed using X-ray diffraction (XRD) to determine the mineralogical composition of the sandstone samples and the different clay types and content. The rock porosity, permeability, and pore size distribution were determined by nuclear magnetic resonance (NMR). Scanning electron microscopy (SEM) was accomplished to detect the changes in the pore system at a macroscale. The rock strength UCS was obtained by utilizing rock scratch testing, and the ultrasonic data were acquired using the ultrasonic pulse velocity (UPV). Then, the dynamic elastic moduli were determined from the ultrasonic velocities. The experimental work procedures were performed as follows:

1. The core samples were cut into 1.5" diameter by 2" length each.
2. For each rock type, a reference core sample was selected for assessment.
3. Saturation was executed for the core samples by (3 wt % KCl) for clay anti-swelling.
4. The mud filtrate was prepared using the filter press system and WBM.
5. The rock samples were invaded by the mud filtrate.
6. The rock—filtrate interaction was achieved at 200 °F and 300 psi pressure for 10 days.
7. The rock geomechanics evaluation was performed before and after the rock—filtrate interaction.

The rock characterization and geomechanics evaluation were performed utilizing NMR, SEM, UPV, and scratch testing for the rock samples before and after interactions with the mud filtrate.

Core Samples’ Preparation and Characterization. The sandstone rock samples were cut into a size of 1.5” diameter and 2” length to be hosted in the modified aging cell of the filter press. After that, the samples were saturated with 3 wt % potassium chloride (KCl) for clay-swelling inhibition using the vacuum saturation method.

XRD was implemented to determine the rock mineralogy. Table 1 represents the results of the four types of sandstone samples as a component compositional fraction. XRD showed that quartz is the main constituent and its value ranged from 59 wt % in Bandera Brown to 91 wt % in Berea Buff. Bandera Brown is the only sandstone type that has a dolomite content of 15 wt %. Different contents of albite (Na-Feldspars) and microcline (K-Feldspars) exist in the composition. Many clay minerals such as kaolinite, illite, chlorite, smectite, and muscovite with different amounts are found in the composition as Berea Buff has 5 wt % total clay content and Bandera Brown has a maximum clay content of 14 wt %.

Preparation of Drilling Fluid and Mud Filtrate. The drilling fluid formula was used for water-based mud that was barite-weighted. The formula was prepared by water as a base fluid, and viscosity control materials such as xanthan gum polymer and bentonite were added. In addition, the formula contains starch as a fluid loss control additive, potassium chloride for clay stabilization, potassium hydroxide as a pH

Table 1. XRD of Sandstone Rock Samples

| Mineral   | Chemical Formula | Berea Buff | Berea Spider | Bandera Brown | Parker |
|-----------|------------------|------------|--------------|---------------|--------|
| Quartz    | SiO₂             | 91         | 82.2         | 59            | 87     |
| Albite    | Na(Al₂Si₃O₁₀)    | 0          | 1.4          | 12            | 5      |
| Microcline| K(Al₂Si₃O₁₀)     | 4          | 7            | 0             | 0      |
| Calcite   | CaCO₃            | 0          | 0.4          | 0             | 0      |
| Dolomite  | CaMg(CO₃)₂       | 0          | 0            | 15            | 0      |
| Pyrite    | FeS₂             | 0          | 0.5          | 0             | 0      |
| Barite    | BaSO₄            | 0          | 0.2          | 0             | 0      |
| Hematite  | Fe₂O₃            | 0          | 0.7          | 0             | 0      |
| Kaolinite | Al₂Si₂O₅(OH)₃    | 3          | 7            | 3             | 2      |
| Illite    | (K₁₋₃H)₀(AlMg₂Fe)₈(Si₃Al)O₁₀[(OH)₂(H₂O)] | 0 | 0 | 10 | 4 |
| Chlorite  | ClO₄⁻            | 0          | 0            | 1             | 0      |
| Smectite  | (NaCa)₀.₃₅(AlMg₂)(Si₃O₁₀)(OH)₂⋅nH₂O | 1 | 0.6 | 0 | 0 |
| Muscovite | KAl₃(Al₂Si₃O₁₀)(OH)₂ | 1 | 0 | 0 | 2 |
| Total Clay|                 | 5          | 7.6          | 14            | 8      |
controller, calcium carbonate of a size of 50 μm as a bridging material, and barite to provide the mud density. Table 2 shows the additives’ amounts and function of the composition.

Table 2. Drilling Fluid Formulation of WBM

| material       | amount (g) | function               |
|----------------|------------|------------------------|
| water          | 290        | base fluid             |
| defoamer       | 0.08       | anti-foam agent        |
| XC-polymer     | 1.5        | viscosity control      |
| bentonite      | 4          | viscosity control      |
| starch         | 6          | fluid loss control     |
| KCl            | 20         | clay stabilizer        |
| KOH            | 0.3        | pH control             |
| CaCO₃          | 5          | bridging material      |
| barite         | 200        | mud density            |

The density of the drilling fluid was 12.25 ppg, and the fluid had a 9.65 pH. The pH is a very critical fluid property for the drilling fluids as it affects the rheological and filtration properties. The filter press was utilized to collect the mud filtrate using a ceramic disc of size 10 microns that allows the mud filtrate to flow through the disc and prevent the mud solids that form the mud filter cake. The methodology simulates the real situation during the drilling operation as the mud solids accumulate on the rock surface to form the mud filter cake. The collected mud filtrate provided an 8.3 pH value.

The mud filtrate was collected with high care to be sure that there is no mud content to achieve the study objective. Minor spurt loss filtration was recorded, and it was not added to the collected mud filtrate. The mud solids’ impact was studied in previous studies, and it was found to cause pore plugging due to precipitation of the mud solid and as a result affect the sonic wave propagation and elastic moduli.

**Mud Filtrate–Rock Interaction.** The mud filtrate–rock interaction was performed by utilizing the filter press equipment as the mud filtrate was used to invade the pore system of the core sample that was hosted in the modified aging cell as shown in Figure 2. The invaded sandstone samples were hosted with the mud filtrate in an aging cell with a Teflon liner. The aging cell was pressurized with 300 psi pressure and kept in the oven at a temperature of 200 °F for 10 days.

**SEM and NMR Spectroscopy.** SEM with energy-dispersive spectroscopy (EDS) analysis was performed on rock sections from the sandstone samples before and after the mud filtrate exposure. SEM was used to determine the changes in the rock internal surface topography that indicates the rock integrity and the cementing degree. SEM was performed for thin sections from the core samples after the mud filtrate exposure and another section from a reference sample of each rock type to represent the filtrate impact before and after the exposure.

The evaluation of the rock pore system was performed by using NMR. NMR has been used in many research studies for evaluating the effect of the drilling fluids on the rock pore system. The transverse relaxation time measurement \( T_2 \) was measured for the saturated rock to illustrate the relaxation level of the hydrogen protons, and hence, relate the alteration in the internal pore system of the sandstone rock types. \( T_2 \) is reported in seconds, and it has a direct relationship to the rock pore throat radius \( \rho \).

Probability density function (PDF) and cumulative distribution function (CDF) profiles were plotted to indicate the alteration in the rock pore size distribution before and after the mud filtrate interaction. The CDF profile shows the summation of the different porosities in the pore system and stabilization at a value that is the total rock porosity.

**Ultrasonic Data and Dynamic Elastic Moduli.** The scratch machine (Figure 3) used for this study provides scratch testing by the machine cutter tool in addition to the ultrasonic data acquisition by the sonic probes. A sonic wave transmitter and receiver were used to determine the compressional and shear wave velocities \( (V_P \) and \( V_S \), respectively) through the two compressional and shear modes by two separate runs.

The ultrasonic wave velocities were determined for the rock samples before and after the mud filtrate exposure, and then, the dynamic elastic moduli were determined through the following correlations as per the American Society for Testing and Materials: 

\[
E_d = \rho V_S^2 (3V_P^2 - 4V_S^2) / V_P^2 - V_S^2 \quad (1)
\]

\[
\nu_d = (V_P^2 - 2V_S^2) / 2(V_P^2 - V_S^2) \quad (2)
\]

where \( E_d \) is the dynamic Young’s modulus (GPa), \( \rho \) is the rock density (g/cm³), \( V_S \) is the shear wave velocity (km/s), \( V_P \) is the compressional wave velocity (km/s), and \( \nu_d \) is the dynamic Poisson ratio.

The other dynamic moduli were determined using the following equations:

\[
K = E / 3(1 - \nu) \quad (3)
\]

\[
G = E / 2(1 + \nu) \quad (4)
\]

\[
\lambda = H - 2G \quad (5)
\]

\[
H = 3K(1 - \nu) / (1 + \nu) \quad (6)
\]

where \( K \) is the bulk modulus (GPa), \( G \) is the shear modulus (GPa), \( \lambda \) is Lamé’s parameter (GPa), and \( H \) is the uniaxial compaction modulus (GPa).
Scratch Testing. The rock unconfined compressive strength was evaluated for the core samples using the scratch testing machine. Figure 3 shows the scratch machine that was utilized in this study. Rock scratch testing is a practical technique for determining the rock strength profile using a sharp cutter that scratches the surface of the rock with a designed depth of cutting (Figure 3b). The machine records the applied shear and normal forces that have a proportional relationship with the specific energy of the rock. In addition, the rock specific energy is correlated to the unconfined compressive strength of the rock based on a built database for many different rock types. The scratch testing technique has been applied in many research studies related to the rock geomechanics.56,57 The test provides special features such as quick operation, inexpensive costs, no need for intensive core preparation, being partially destructive for the core samples, and providing a complete strength profile along the core sample length.53 The acquired strength profiles with the sonic data can be utilized for geomechanical facies identification.58

The tensile strength of the rock is a geomechanical feature that measures the rock resistance of failure under tension stresses, and this is a critical characteristic of the rock in rock fracturing in stimulation operations.55 The rock tensile strength can be acquired through two methods of laboratory testing, which are direct and indirect Brazilian methods.56,57 The rock strengths (unconfined compressive strength and tensile strength) are correlated in many research studies for different types of rocks to overcome the extensive cost and time for lab testing methods.55,58,59 Among the literature, Altindag and Guney58 utilized 143 core samples data for various types of rocks and determined the following strength correlation that has a correlation coefficient of 0.9

$$\text{TS} = 0.0963 \text{UCS}^{0.932}$$  \hspace{1cm} (7)

where UCS is the unconfined compressive strength and TS is the tensile strength; both are in MPa.

\section*{RESULTS}

Effect of the Mud Filtrate on Acoustic Characteristics. The ultrasonic data were determined for the different core samples, and the results of the wave velocities are presented in Figure 4. The results showed that changes for the compressional wave velocities ($V_p$) such as, for Berea Buff, a 13% reduction in $V_p$ from 2.72 to 2.36 km/s, minor changes for Berea Spider and Bandera Brown, and an 11% increase in $V_p$ for Parker samples from 3.92 to 4.36 km/s (Figure 4a). The shear wave velocity $V_s$ results (Figure 4b) showed that a general reduction trend was recorded for all the samples with different reduction percentages of 28, 19, 26, and 13% for Berea Buff, Berea Spider, Bandera Brown, and Parker samples, respectively.

The characteristics of the ultrasonic waves are different in terms of the propagation direction and the sensitivity to the lithology or fluid for the rock samples. The changes that occurred in the internal pore system of the core samples due to interactions with the WBM filtrate are the main cause for such alterations in the recorded ultrasonic measurements in terms of $V_p$ and $V_s$ as the wave propagation will be affected by the media characteristics. The obvious reduction trend in the shear wave velocities is referred to the dissolution and mineralogical modifications in the rock due to the interaction with the WBM filtrate at HPHT conditions.

Effect of the Mud Filtrate on Elastic Moduli. The dynamic elastic moduli were calculated using the ultrasonic measurements and rock density. The results are described in detail in the following subsections.

Effect on $E_d$ and $\nu_d$. The dynamic Young’s modulus ($E_d$) and dynamic Poisson’s ratio ($\nu_d$) were calculated using the aforementioned equations, eqs 1 and 2. The rock density for the rock types was 2.29 g/cm$^3$ for Buff and Spider types, 2.22 g/cm$^3$ for Bandera, and 2.38 g/cm$^3$ for Parker sandstone. The results of the dynamic Young’s modulus and dynamic Poisson’s ratio are represented in Figure 5 and showed overall $E_d$ reduction for the four types of sandstone after mud filtrate exposure (Figure 5a).
The observed reduction in Young’s modulus illustrated that the rock after mud filtrate exposure showed lower stiffness behavior than before exposure. The maximum reduction was for the Berea Buff type with 40% and Bandera Brown with 39%; however, Berea Spider showed 24% reduction and Parker only 11% reduction.

Figure 5b presents the new values for Poisson’s ratio ranging from 0.29 to 0.37, and the results illustrate an increasing trend for all sandstone types with different levels as Parker showed the highest increase followed by Buff, Spider, and Bandera samples. The increasing trend that was recorded for Poisson’s ratio showed that the rock became more deformable after exposure to the mud filtrate for the exposure time, pressure, and temperature conditions.

**Effect on Other Moduli.** The results of other dynamic elastic moduli, which are Lamé’s parameter ($\lambda$), the shear modulus ($G$), the bulk modulus ($K$), and the uniaxial compaction modulus ($H$) are presented in Figure 6. The results showed that there is increasing behavior for the values of the bulk modulus (Figure 6a) and Lamé’s parameter (Figure 6b). The shear modulus decreased for all sandstone types after the mud filtrate exposure (Figure 6c). Figure 6d represents the uniaxial compaction modulus values with a small reduction for the Berea Buff type and an increase for the Parker type and minor changes for Spider and Bandera types. Table 3 summarizes all the dynamic elastic moduli results.

**Effect of the Mud Filtrate on Rock Strength (UCS and TS).** The rock failure properties in terms of unconfined compressive strength and tensile strength were evaluated to detect the strength alteration due to the mud filtrate exposure at the HPHT downhole conditions. The scratch testing results showed rock strength reduction for the four types of sandstone samples and consequently same weakening behavior in the rock tensile strength as shown in Figure 7a,b. Parker had severe strength reduction as its UCS decreased from 66.5 to 51 MPa with 23% strength reduction followed by Berea Buff that showed 19% strength reduction, Bandera Brown had a 15% reduction percentage in its UCS value, and Berea Spider had the lowest strength reduction as its UCS decreased from 23.6 to 20.1 MPa with 6% reduction (Figure 7a). Figure 7b illustrates the general trend for the tensile strength reduction for the four sandstone rock types. Table 4 summarizes the results and statistical analysis for the strength evaluation.

**Alteration Mechanism SEM and NMR Analysis.** The alteration mechanism for the alteration that occurred in the rock strength and elastic moduli were studied with integrated SEM and NMR spectroscopy analysis for sections of the rock samples before and after the interaction with the WBM filtrate. The spectroscopy analysis assisted us to detect the changes in the rock integrity, pore system, and internal surface topography for the rock samples.

**SEM Analysis.** SEM analysis was performed in the study to capture the alteration that occurred in the topography of the internal pore system of the rock samples. Figures 8−11 represent the changes that occurred in the internal topography after the mud filtrate exposure at the pressure and temperature conditions for 10 days. The rock−mud filtrate interaction under these conditions is the main reason behind the decomposition, dissolution, and precipitation of the minerals of the different
types of sandstone rock. The rock samples have different types of clay minerals and feldspar classes that provided different responses with the mud filtrate exposure. A dominant dissolution effect was found clearly after the mud filtrate exposure for Barea Buff and Parker as shown in Figures 8b and 11b. Inconsiderable changes were found for the Bandera type (Figure 10b); however, the pore plugging effect was presented for Berea Spider as shown in Figure 9b.

**NMR Results.** The probability distribution function profiles were plotted for the four sandstone rock types before and after the mud filtrate exposure as shown in Figure 12. As the mud filtrate interacts with the sandstone rocks, two main dominant effects occurred, which are dissolution of the rock mineralogy and pore plugging due to clay swelling or precipitations of the dissolved minerals. The results present the obvious changes in

Table 3. Result Summary for the Dynamic Elastic Moduli

| geomechanical moduli | condition | Berea Buff | Berea Spider | Bandera Brown | Parker |
|----------------------|-----------|------------|--------------|---------------|--------|
| Young’s modulus (E) (GPa) | before | 16.28 | 16.87 | 12.82 | 35.26 |
| | after | 9.77 | 12.78 | 7.88 | 31.31 |
| alteration percentage, % | | −40 | −24 | −39 | −11 |
| Poisson’s ratio | before | 0.12 | 0.16 | 0.23 | 0.13 |
| | after | 0.29 | 0.33 | 0.37 | 0.32 |
| alteration percentage, % | | 134 | 107 | 62 | 155 |
| bulk modulus (K) (GPa) | before | 7.21 | 8.28 | 7.91 | 15.74 |
| | after | 7.73 | 12.72 | 10.23 | 29.42 |
| alteration percentage, % | | 7 | 54 | 29 | 87 |
| shear modulus (G) (GPa) | before | 7.25 | 7.27 | 5.21 | 15.65 |
| | after | 3.79 | 4.80 | 2.87 | 11.84 |
| alteration percentage, % | | −48 | −34 | −45 | −24 |
| uniaxial compaction modulus (H), GPa | before | 16.87 | 17.97 | 14.86 | 36.61 |
| | after | 12.78 | 19.12 | 14.06 | 45.21 |
| alteration percentage, % | | −24 | 6 | −5 | 23 |
| Lamé’s parameter (λ) (GPa) | before | 2.38 | 3.43 | 4.44 | 5.31 |
| | after | 5.20 | 9.52 | 8.32 | 21.53 |
| alteration percentage, % | | 119 | 177 | 87 | 306 |

Figure 7. Rock strength alteration after mud filtrate exposure. (a) UCS and (b) TS.

Table 4. Summary of the Strength Evaluation Results

| mechanical property | condition | Berea Buff | Berea Spider | Bandera Brown | Parker |
|---------------------|-----------|------------|--------------|---------------|--------|
| UCS (MPa) before    | 50.3      | 48.5       | 23.6         | 66.5          |
| after               | 40.5      | 45.4       | 20.1         | 51.0          |
| reduction percentage, % | 19 | 6 | 15 | 23 |
| TS (MPa) before     | 3.7       | 3.6        | 1.8          | 4.8           |
| after               | 3.0       | 3.4        | 1.6          | 3.8           |
| reduction percentage, % | 18 | 6 | 14 | 22 |
terms of dissolution and pore plugging that occurred for the two types of Berea; Buff (Figure 12a) and Spider (Figure 12b). The incremental porosity profile for Bandera brown is very small compared with other sandstone samples (Figure 12c). Parker showed two connected pore systems with different degrees of change in the pore-sized distribution (Figure 12d).

The results showed that the total porosity for Berea Buff changed from 21.6 to 20.4%, from 18.9 to 19.4% for Berea Spider, from 25.7 to 22.3% for Bandera Brown, and Parker porosity decreased from 17.1 to 16.5%. The results showed that the change in the total porosity is not extreme alteration, and the reason behind this is that the dissolution products did not come from the rock samples as the mud filtrate−rock interaction was at static conditions.

The different behaviors that occurred for the rock samples demonstrated different levels of action, and this is because of the different responses of the clay and silicate minerals that exist in different types and amounts in the sandstone samples.

■ DISCUSSION

The results obtained from the extensive laboratory work indicated that the sandstone rock types have complex mineralogical compositions. Different types and amounts of clay, silicate, and feldspar minerals exist in the four selected types for the study. Increasing the clay content does not always decrease the rock strength; however, the framework of the quartz−clay matrix plays a critical role in rock strength. The clay content was not only the main reason behind the obtained reduction in the rock strength for the sandstone types, but the
Figure 11. SEM photos of Parker. (a) Before mud filtrate exposure. (b) After exposure.

Figure 12. PDF $T_2$ profiles for the core samples before and after filtrate exposure. (a) Berea Buff, (b) Berea Spider, (c) Bandera Brown, and (d) Parker.

Figure 13. Rock strength vs the clay content.
type of clay mineral was found to have a great impact on the rock strength. Figure 13 shows that Parker and Berea Spider have the same clay content (7.6 and 8%, respectively); however, Parker had the maximum UCS reduction (23%). The Parker type has illite and muscovite clay minerals that do not exist in Berea Spider that had only 4% UCS reduction. The illite content (10%) in Bandera Brown in addition to chlorite caused the strength alteration with 15% reduction. The structure of the Berea Buff framework that has clay minerals (smectite and muscovite) and microcline is considered the reason for strength reduction. Therefore, the amount of each clay mineral in addition to its structure in the rock framework have a great impact on the rock strength alteration during the rock–filtrate interaction, not the total clay content, and this reason was mentioned in the literature.60

Additional statistical analysis as presented in Figure 14 showed that the strength reduction might be correlated to the kaolinite content with an inverse linear correlation that provides a high correlation coefficient of 0.95.

\[ UCS_r = -3.1 \times K_{\text{content}} + 27.57 \]  

(8)

where \( UCS_r \) is the reduction percentage of unconfined compressive strength in (%) and \( K_{\text{content}} \) is the kaolinite content in (%).

The content and type of mineralogical composition showed an impact on the rock properties, structure, and integrity, and hence, the rock geomechanical properties are affected. The exposure of the different sandstone samples with the WBM filtrate at the downhole temperature and pressure conditions for extended exposure time provided the chemical interaction environment between the different minerals with the mud filtrate. The complexity of the mineral compositions of the sandstone types caused these different alterations in the internal topography, porosity, and pore size distribution, rock strength, acoustic properties, and elastic moduli. The results highlighted in an experimental study the drilling problems that occurred because of the mud filtrate interaction with the rock during drilling operations that commonly affect the wellbore stability.

# CONCLUSIONS

This study presented the effect of the WBM filtrate on the rock strength and elastic moduli for different sandstone formations. The mud filtrate and rock sample interaction was performed in the drilling downhole conditions (300 psi pressure and 200 °F temperature for 10 days) to mimic the real alterations in the rock characteristics. The following conclusions are drawn based on the experimental results:

1. Ultrasonic measurements showed a general reduction trend in the shear wave velocities for all sandstone types, and this is attributed to the dissolution and mineralogical modifications in the rock after a mud filtrate interaction.
2. The dynamic elastic moduli showed a general reduction for \( E_d \) values (ranged from 11 to 40%); however, an increasing trend for \( E_d \) was recorded (ranged from 62 to 155%) after an interaction with the mud filtrate.
3. The alterations in the elastic moduli showed that the sandstone rocks became stiffer and have lower deformability performance after the mud filtrate exposure.
4. General strength reduction for the four sandstone samples is a result of alterations in rock integrity, bonding, and cementation, and pore size distribution. The clay type and quartz–clay framework were found to extremely affect the rock strength compared to the total clay content.
5. The strength reduction that was observed after the filtrate exposure was attributed to the dissolution effect that was clearly shown by NMR and SEM spectrometry.
6. Statistical analysis showed an inverse linear relationship between the strength reduction and the kaolinite content in sandstone rock samples with a high correlation coefficient of 0.95.

The limitations beyond this study are the pressure and temperature conditions (300 psi and 200 °F) for 10 days, the sandstone rock types (Berea Buff, Berea Spider, Bandera Brown, and Parker), and the mud type (barite-weighted water-based mud).

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ABBREVIATIONS
XRD, X-ray diffraction; SEM, scanning electron microscopy; NMR, nuclear magnetic resonance; WBM, water-based mud; OBW, oil-based mud; E, Young’s modulus; v, Poisson’s ratio; λ, Lamé’s parameters; G, rigidity or shear modulus; K, bulk modulus; H, uniaxial compaction or oedometer modulus; UCS, unconfined compressive strength; TS, tensile strength; V_p, compressional wave velocity; V_s, shear wave velocity; HPHT, high-pressure high-temperature; EDS, energy dispersive spectroscopy; T_res, transverse relaxation time; μ, pore throat radius (μm); PDF, probability distribution function; CDF, cumulative distribution function; UPV, ultrasonic pulse velocity

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