Investigating the Alteration of Sandstone Pore System and Rock Features by Role of Weighting Materials

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ABSTRACT: Drilled formations are commonly invaded by drilling fluids during the drilling operations, and as a result, the rock pore system will have alterations that consequently alter the rock properties. The objective of this study is to investigate the impact of the most commonly used weighting materials in water-based mud (WBM) on the Berea Buff sandstone pore system and rock characteristics. Rock—mud interaction was imposed by using a customized high-pressure high-temperature filtration test cell under 300 psi differential pressure and 200 °F temperature to simulate downhole conditions during drilling that affect the rock—mud interaction. Extensive lab analysis was accomplished to investigate the rock characteristic alterations in terms of rock porosity, permeability, pore size distribution, flow characteristics, resistivity, and acoustic properties. Ilmenite-WBM showed the maximum filtrate volume (8.3 cm³ filtrate volume and 7.6 mm cake thickness), while barite recorded the lowest filtrate volume (5.3 cm³) and thickness (3 mm). Nuclear magnetic resonance profiles illustrated the changes in the rock pore system due to the dominant precipitation or dissolution effects. A general porosity reduction was recorded with all mud types that ranged from 4.2 to 9.9% for ilmenite and Micromax, respectively. The rock permeability showed severe damage after mud exposure and a reduction in the pore throat radius. After mud invasion, the rock electrical resistivity showed alterations based on the mineralogical composition of the weighting materials that replaced the saturated brine from the rock pores. Compressional wave velocities ($V_p$) showed an increasing trend as $V_p$ of Micromax-WBM increased by 4.5%, while hematite- and ilmenite-WBMs recorded the minimum increase of 1.8%. A general reduction was found for shear wave velocities ($V_s$); Micromax-WBM showed the highest $V_s$ reduction by 6.6%, while ilmenite-WBM recorded the minimum reduction of 1.8%. The pore system alterations are the main reason behind $V_p$ increase, where the rock lithology alterations controlled the $V_s$ changes. The study findings will add more for the rock logging interpretation and rock properties alterations after the mud exposure.

1. INTRODUCTION

There are many functions for the drilling fluids, and among these functions, overbalancing the formation pressure, lifting the drilled cuttings from the downhole hole to the surface mud system, and formatting a thin and low-permeability filter cake for wellbore stability.¹ Barite, hematite, Micromax, and ilmenite are commonly used as weighting materials for the drilling fluids to maintain the required mud density and can be used individually or in a mixture.²,³ The formatted filter cake has to be removed after the drilling operations as its main function is to minimize the filtrate invasion during the well drilling. Filter cake removal is a required job to easily produce the reservoir hydrocarbons with good productivity, easily remove filter cake with low-cost operation.⁴,⁵

During the drilling operations, the pressure action of the overbalanced drilling causes the drilling fluid to invade the
permeable drilled zones. The invaded mud filtrate and solids will cause the rock–mud interaction, which is considered one of the main causes for formation damage. Productivity reduction is one of the consequences of formation damage.

The mud filtrate and fine mud solids (mostly the weighting materials particles) 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 invasion will depend on the formation permeability and porosity characteristics and the mud filtration properties. The mud invasion will cause an invaded section in the drilled formation that will be affected by the rock–mud interactions at the downhole pressure and temperature conditions. As a result, the rock characteristics will be affected by the role of mud invasion (mud filtrate and solids) into the pore system of the drilled sandstone. These alterations will affect the drilling operations and well logging interpretations, and hence, this problem is considered a technical issue in the oil and gas industry.

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, 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 it requires extra cost for solving such problems. Economically, the drilling cost increases 10–20% by 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.

Designing the drilling fluid is very critical and the inappropriate design will lead to many problems during the drilling or even after the formation damage and changing the rock properties. The changes in rock features include the petrophysical, elastic, strength properties. To avoid such problems, it is highly recommended to add specific additives to the drilling fluid composition to decrease the damaging effect and enhance the hole stability for the drilled zones. The design of the weighting material in the drilling fluids is controlled by many factors such as the environmental impact, technical issues with the drilling and logging operations, and the cost. Barite is considered the most widely utilized weighting material for the drilling fluid because of its good properties and low cost; on the other side, Micromax is an expensive additive as a weighting agent.

Among the literature, research was carried out to investigate the formation damage by the role of drilling fluids by different methodologies. X-ray diffraction (XRD) and X-ray fluorescence (XRF) were implemented and showed that the weighting materials represent at least 80% of the filter cake composition. Investigating the mud invasion depth was studied by using the computerized tomography (CT) scanning technique. A scanning electron microscope allows investigating the filter cake deposition at the nanoscale level. A recent application of nuclear magnetic resonance (NMR) in the oil and gas industry allowed to characterize formation damage in terms of reduced porosity of the rocks and pore size distribution.

The new research horizon in the drilling fluids is to find new additives that can act as rheology modifiers and support wellbore stability. Many additives were developed to minimize the plugging of pore throats and in turn, formation damage. Bentonite, perlite, bridging agents, polymers, and even nanoparticles are widely used in the industry to improve mud rheology and overall mud performance during the deposition of filter cake on the rock surface.

The existing work in the literature studied has much scope for the rock–mud interaction as the effect of weighting materials on the rock rheology, new additives as rheology modifiers, filter cake characterization, and formation damage due to drilling fluids, however, the current work deeply studies the impact on the rock pore system and characteristics of the role of different weighting materials. This paper presents an investigating study to assess the effect of four different weighting materials (barite, ilmenite, hematite, and Micromax) on the pore system of Barea Buff sandstone and the consequent alterations in the rock features. The novelty and contributions of this work study the rock–mud interaction impact of the pore system by extensive and integrative lab analysis in a deep manner. The conducted analysis includes XRF, XRD, particle size distribution (PSD), NMR, resistivity, and ultrasonic acquisition. The study utilized a customized filtration cell to impose mud–rock interaction under high-pressure high-temperature (HPHT) conditions and then evaluated alterations in rock properties after the mud exposure. The results covered the changes in the rock porosity, permeability, pore throats, pore size distribution, rock resistivity, and acoustic characteristics. The findings from this study will add more to the logging interpretations and understanding of the alterations for the sandstone formation by the role of weighting materials.

The next sections in the paper structure will discuss the Material and Methods followed in this study, then, Results and Discussion section, and finally, the Summary and Conclusions section.

2. MATERIALS AND METHODS

The study utilized Barea Buff sandstone rock to evaluate the rock properties after exposure to water-based drilling fluids with different weighting materials. Four types of the most common weighting materials in the drilling fluids industrial applications...
were utilized in this study (barite, hematite, Micromax, and ilmenite).

Figure 2 illustrates the methodology layout for this study, starting from the rock sample preparation, saturation, and characterization [resistivity, porosity (Φ), permeability (k), pore size distribution, flow characteristics, and acoustic properties]. The weighting materials were characterized in terms of PSD, then, the drilling fluids were prepared, and the rheology was determined. HPHT filtration test was performed for rock–mud interaction under the pressure and temperature conditions, and the filtration properties (filter cake thickness and filtrate volume) were evaluated. The rock properties were re-evaluated after the mud exposure to assess the impact of weighting materials. Finally, results were analyzed for presenting the study conclusions.

2.1. Core Sample Preparation and Characterization. Berea Buff sandstone outcrop rock samples were cut into a cylindrical shape with a size of 1.5″ diam and 2″ length to be used in the customized aging cell of the filter press test and the end facing for surface smoothing. The core samples were saturated with 3 wt. % potassium chloride to prevent clay swelling, and then, rock characterization was performed for the saturated samples. XRD for Berea Buff sandstone (Table 1) shows that quartz represents 91% of the mineralogical composition, microcline with 4%, and 5% of total clay content that includes kaolinite (3%), smectite (1%), and muscovite (1%). Each clay type has different properties as smectite shows high cation exchange activity, kaolinite is considered as the common clay mineral in the phyllosilicate group and it has the lowest charge among the clay minerals, while muscovite is considered the most common mica mineral. The clay minerals have different chemical compositions and structures, and as a result, they have different properties. The clay minerals can decompose if exposed to water and this will affect the rock features.

2.2. Drilling Fluid Mixing and Rheology Measurements. The drilling fluid formula was used for water-based mud (WBM) that was weighted individually by barite, Micromax, ilmenite, and hematite. The weighting material properties were evaluated in terms of the PSD and XRF spectroscopy for elemental composition analysis. The weighting materials PSD showed that Micromax had the smallest size followed by ilmenite, while barite had the largest size among the weighting materials, as shown in Table 2. Micromax had the sizes of 0.73, 1.65, and 3.87 μm, while barite showed 3.89, 17.47, and 53.76 μm for $D_{10}$, $D_{50}$ and $D_{90}$ respectively. Figure 3 clearly shows the comparison of PSD between the four used weighting materials in this study.

Table 2. PSD of the Weighting Materials

| mineral     | barite | hematite | Micromax | ilmenite |
|-------------|--------|----------|----------|----------|
| quartz SiO₂ | 3.89   | 2.47     | 0.73     | 1.46     |
| microcline K(AlSi₃O₈) | 17.47 | 15.22 | 1.65 | 5.17 |
| kaolinite Al₂Si₃O₈(OH)₄ | 53.76 | 47.28 | 3.87 | 12.82 |
| smectite (Na₄Ca)₀.₃₃(Al,Mg)₀.₃₃(Si₄O₁₀₇) (OH)₂·nH₂O | 2.00 | 0.89 | 0.76 | 1.23 |
| muscovite KAl₃(AlSi₃O₁₀) (OH)₂ | 1.99 | 0.88 | 0.76 | 1.23 |
| total clay | 1.99 | 0.88 | 0.76 | 1.23 |

Table 3 shows the XRF analysis of the weighting materials. The results illustrated that barite (barium sulfate) is mainly composed of barium (69.36%) and sulfur (15.84%), while iron (Fe) is the main component for hematite (iron oxide) weighting material (95.84%), and Micromax (manganese tetraoxide) has manganese with a high percent of 97.6%, while ilmenite (titanium–iron oxide) mainly has iron (55.86%) and titanium (37.04%).

Each specified weighting material was mixed with the drilling formula as per Table 4. Water was utilized as the base fluid with 290 mL, the fluid viscosity control materials as Xanthan gum biopolymer (XC polymer) and bentonite were added to adjust the required viscosity for the drilling fluid; 6 g of starch was added for fluid loss control, 5 g of calcium carbonate as a bridging agent, and 300 g of the weighting material. Evaluating mud rheology is significant as it affects the mud functions and filtration properties. The drilling fluid rheological properties and density were evaluated at 80 °F and are listed in Table 5 for the four types of WBM.

2.3. Mud–Rock Interaction. The drilling fluid was prepared, and then, the customized aging cell (Figure 4) was utilized for rock–mud interaction to host the rock sample at the pressure and temperature conditions (300 psi differential pressure and 200 °F) to simulate the reservoir rock exposure to the drilling fluids during the drilling operation. The filtrate fluid was continuously recorded during the 30 min of filtration test as per API standards for the filtration property evaluation.

2.4. NMR Spectrometry. The evaluation of the rock pore system was performed by using NMR. The transverse relaxation time measurement ($T₂$) 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. $T_2$ has a direct relation with the rock pore size.\textsuperscript{59} Probability density function (PDF) and cumulative distribution function (CDF) profiles were plotted before and after the
mud filtrate interaction as these profiles can indicate the alteration in the rock pore size distribution. The CDF profile shows the summation of the different porosity in the pore system and stabilizes at a value, which is the total rock porosity.

In addition, the relaxation time from NMR measurements can be correlated to calculate the rock permeability by a derived equation by Kenyon et al. Many studies were conducted to modify this correlation based on the formation type as sandstone and carbonates. Morriss et al. correlated the NMR data for 110 core samples from three reservoirs to provide the following permeability equation

$$k = C T_{\text{LM}}^2 \Phi^4$$

where \( k \) is the permeability (in mD), \( T_{\text{LM}} \) is the logarithmic mean \( T_2 \) (in ms), and \( \Phi \) is the total porosity (in %). \( C \) is a statistical model parameter, and its value can be derived from lab NMR experimental data of core samples.

The pore throat is a key rock petrophysical parameter that controls the flow characteristics of the rock. The Winland equation was used to calculate the change in the pore throat radius before and after the rock–mud filtrate exposure as per eq

$$\log r_{35} = 0.732 + 0.588 \log k - 0.864 \log \Phi$$

where \( r_{35} \) is the calculated pore throat radius corresponding to 35% mercury saturation from a mercury-injection capillary pressure test (in \( \mu m \)), \( k \) is the permeability (in mD), and \( \Phi \) is the total porosity (in %).

The type of the petrophysical flow units based on the \( r_{35} \) can be categorized into four scales as mega-porous for \( r_{35} \) value greater than 10 \( \mu m \), macroporous for the value between 2 and 10 \( \mu m \), mesoporous for the range between 0.5 and 2 \( \mu m \), and microporous for \( r_{35} \) value less than 0.5 \( \mu m \).

2.5. Rock Resistivity Evaluation. The resistivity evaluation reflects the high impact of the weighting material on the logging operation. Resistivity log is commonly used in the petroleum industry for many purposes such as reservoir fluid distribution and fluid in place. Shallow and deep resistivity logs can also determine the depth of mud invasion and formation damaged. The electrical properties system was employed to measure the electrical resistance for the rock samples for the saturated phase after mud exposure. The rock sample was loaded between the electrode plates, and a plastic cover core holder isolated the core sample to preserve the saturation profile from the outside environment.

2.6. Ultrasonic Measurements. The compressional and shear waves’ velocities are considered important acoustic properties and have a direct relationship with the dynamic elastic moduli of the rock. Ultrasonic data acquisition was performed by 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.

3. RESULTS AND DISCUSSION

This section presents the obtained results through the experimental work in detail that provides a clear understanding of the effect of the WBM weighting materials on the pore system and the rock properties of Berea Buff sandstone core samples.

3.1. Filtration Properties. The filtration properties of the drilling fluids are extremely critical during the drilling operation and are commonly reported in total filtrate volume and filter cake thickness. During the filtration test, the filtrate volume was collected and recorded with time, and the results are shown in Figure 5.

Table 6 summarizes the comparison of the filtration properties for the four types of WBM, and it is clear that ilmenite-WBM had the maximum filtrate volume and filter cake thickness (8.3 cm³ and 7.6 mm), while barite-WBM showed the minimum filtrate volume was 5.3 cm³ and filter cake thickness was 3.0 mm. Hematite-WBM recorded a filtrate volume of 6.3 cm³ and 4.1 mm thickness for the filter cake, and Micromax-WBM showed 7.1 cm³ of collected filtrate volume with 5.8 mm filter cake thickness.
3.2. Porosity and Pore Size Distribution Alterations. There are two main controlling mechanisms for the rock–mud interactions, which are dissolution and precipitation. The rock and/or clay minerals are suspected for dissolution because of the effect of mud filtrate under the pressure and temperature conditions; on the other hand, the rock pores could be plugged because of the mud solid precipitation and/or clay swelling. In addition, the two mechanisms might occur; however, one of them will be the dominant controlling mechanism. The rock storage and flow capacities will be affected by these alterations for the rock pore system.

Figure 6 shows the PDF $T_2$ profiles for the core samples before and after exposure to the four drilling fluids for barite-WBM (Figure 6a), hematite-WBM (Figure 6b), Micromax-WBM (Figure 6c), and ilmenite-WBM (Figure 6d). The PDF profiles show that a dominant plugging effect for all drilling fluid types but with different intensities because of the degree of solid precipitations for each drilling fluid type. The obvious impact for the pore opening effect was shown by barite- and ilmenite-WBMs, as shown clearly in Figure 6a,d. Table 7 clearly shows that the plugging effect was dominated with high $T_2$ values (large pore throat radius), while the pore opening impact was dominant with small $T_2$ values (small pore throat radius).

Figure 7 illustrates the cumulative profiles for the core samples with a general porosity reduction. However, the barite-WBM profile showed that the new CDF has an incremental porosity at lower $T_2$ values (Figure 7a), and the dominant porosity reduction was recorded at $T_2$ higher than 800 and 600 ms for hematite- and ilmenite-WBM, respectively. Table 8 shows the porosity values and the porosity reduction percentage for each drilling fluid. The results showed that a slight similar porosity reduction was recorded; Micromax-WBM showed the maximum porosity reduction with 9.9%, while the minimum reduction for the rock porosity was found for the ilmenite weighting material by 4.2%.

3.3. Rock Permeability Alterations. The permeability evaluation showed the impact of the weighting materials on the rock formation damage. The permeability showed severe damage after the rock exposure to the drilling fluids. Table 9 shows that the permeability reduction was slightly close for the four weighting materials. In addition, the area index which represents the calculated area under the PDF $T_2$ profiles was calculated for more analysis to compare the alterations that happened in both $T_2$ and incremental porosity values for the PDF plots.

The following equation represents a direct linear relationship that correlates the permeability reduction percentage with the calculated area under the PDF $T_2$ profile.

$$K_r = 0.7132A_{index} + 39.071$$ (3)

$$\Phi = 0.3489A_{index} + 0.3457$$ (4)
where $K_r$ is the permeability reduction percentage (%), $A_{\text{index}}$ is the calculated area under the PDF $T_2$ profile, and $\Phi_r$ is the porosity reduction percentage (%).

Figure 8 shows that the area index reduction provides a good direct linear relationship with the permeability and porosity reduction with a correlation coefficient ($R$) of 0.8.

3.4. Pore Characteristic Alterations. The pore system characteristics show how the weighting material precipitation and the fluid filtrate affect the internal pore system. All weighting materials impact caused the overall pore throat reduction and hence, significantly affected the flow characteristics; Figure 9 illustrates that the pore system caused reduction in the pore throat radius with all the drilling fluid formulations, however, still being in the macroporous zone.

3.5. Rock Resistivity Alterations. A reference sample was used to evaluate the base resistivity for the saturated condition, which is 2.67 Ω·m, and the results are shown in Figure 10. It is noted from the results that there is an alteration in the resistivity log before and after the mud exposure as barite weighting material caused the maximum increase for the core resistivity value by 2.96 Ω·m, followed by ilmenite (2.73 Ω·m) and Micromax (2.71 Ω·m), and hematite showed the minimum resistivity value (2.66 Ω·m), and this is because hematite is mainly composed of 95.84 mass percent of iron mineral (Fe) that has a good conductivity feature. It is clear that during the filtration test, the drilling fluid and the solids of weighting materials replaced the brine, and hence, the rock resistivity increased and the extent of resistivity changes is controlled by the weighting material only as it is the only different component within the drilling fluid formulations.

3.6. Acoustic Wave Alterations. The ultrasonic data were evaluated for the core samples before and after the exposure to different weighting material formulations, and the results of the wave velocities are presented in Figure 11. The changes that occurred in the internal pore system of the core samples are the

Table 8. Porosity Determination before and After the Mud Exposure to Sandstone Samples

| sample# | drilling fluid | $\Phi$ before mud invasion (%) | $\Phi$ of rock after the invasion (%) | $\Phi$ reduction of rock (%) |
|---------|----------------|-------------------------------|-------------------------------------|-----------------------------|
| 1       | barite-WBM     | 20.8                          | 19.3                                | 7.2                         |
| 2       | hematite-WBM   | 21.3                          | 19.6                                | 7.8                         |
| 3       | Micromax-WBM   | 20.9                          | 18.9                                | 9.9                         |
| 4       | ilmenite-WBM   | 21.3                          | 20.4                                | 4.2                         |

Table 9. Permeability and Area Index Evaluation

| drilling fluid  | $K$ (mD) before | $K$ (mD) after | reduction % | area index before | area index after | reduction % |
|-----------------|-----------------|----------------|-------------|-------------------|------------------|-------------|
| barite-WBM      | 168             | 79             | 53          | 589               | 454              | 23          |
| hematite-WBM    | 185             | 84             | 55          | 604               | 503              | 17          |
| Micromax-WBM    | 172             | 72             | 58          | 601               | 451              | 25          |
| ilmenite-WBM    | 185             | 98             | 47          | 604               | 517              | 14          |
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 results showed a dominant increasing trend for the compressional wave velocities ($V_p$) as, for barite-WBM, $V_p$ increased from 2.45 (reference sample) to 2.54 km/s by an increasing percentage of 3.7, while the maximum increase was recorded for Micromax-WBM as 2.56 km/s by an increasing ratio of 4.5% (Figure 11a). The observable increasing trend in the compressional wave velocities is referred to the different impacts of the weighting materials that were precipitated in the rock pore system as $V_p$ is sensitive to the fluid saturating the rock pores.

The shear wave velocity $V_s$ results (Figure 11b) showed a decreasing behavior from the base/reference sample. Hematite showed a reduction in the $V_s$ value by 1.8% from 1.31 to 1.29 km/s, while Micromax showed the highest $V_s$ reduction by 6.6% from 1.31 to 1.22 km/s. The alterations that occurred in the sandstone pore system are the main reason behind the changes in $V_s$ as $V_s$ mainly detects the rock lithology alterations.

4. SUMMARY AND CONCLUSIONS

Based on the experimental work performed on the selected types of weighting materials and Berea Buff sandstone rock type, the following conclusions can be drawn:

- The filtration properties showed that barite-WBM had the lowest filtrate volume and filter cake thickness (5.3 cm$^3$ and 3.0 mm, respectively); however, ilmenite-WBM had the maximum values for filtrate volume and filter cake thickness (8.3 cm$^3$ and 7.6 mm, respectively).
- The dominant pore plugging effect was recorded for all WBM formulations with a porosity reduction percentage ranging from 4.2% for ilmenite-WBM to 9.9% for Micromax-WBM.
Statistical analysis showed a linear relationship between the permeability/porosity reduction after mud exposure and the area index for PDF $T_2$ profiles with a correlation coefficient of 0.8.

All WBM formulations affected the core flow characteristics as it caused a reduction in the pore throats to a different extent.

The weighting materials affected the rock resistivity, while hematite WBM recorded the lowest rock resistivity value, and this is because of the good conductivity of iron.

A dominant increasing trend for the compressional wave velocities ($V_p$) was recorded and Micromax-WBM had the maximum increase as $V_p$ increased from 2.45 to 2.56 km/s with an increasing ratio of 4.5%, while ilmenite- and hematite-WBMs had the minimum increase of 1.8%.

General $V_p$ reduction was observed; Micromax-WBM showed the highest reduction as the measurements indicated a 6.6% reduction ratio, while ilmenite-WBM had the minimum reduction of 1.8%.

The limitations beyond the current study are represented by the sandstone rock Berea Buff type, water-based drilling fluids, weighting materials of (barite, hematite, Micromax, and ilmenite), and operating conditions of 300 psi differential pressure and 200 °F temperature. Further recommendation is to study the impact of mud–rock interaction on the pore system and rock characteristics by employing oil-based mud and other field operating conditions.

Figure 11. Ultrasonic measurements. (a) Compressional wave velocity $V_p$. (b) Shear wave velocity $V_s$.

- $V_p$ reduction was observed; Micromax-WBM showed the highest reduction as the measurements indicated a 6.6% reduction ratio, while ilmenite-WBM had the minimum reduction of 1.8%.

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The manuscript was written through the contributions of all authors [H.G., S.E., S.P., and B.S.B.]. All authors have approved the final version of the manuscript.

Notes
The authors declare no competing financial interest.

ACKNOWLEDGMENTS
The authors wish to acknowledge the King Fahd University of Petroleum and Minerals for giving permission to publish this work in memorial for Dr. Hisham Nasr-El-Din, Ph.D. advisor for S.E.

NOMENCLATURES
WBM water-based mud
HPHT high-pressure high-temperature
XRD X-ray diffraction
XRF X-ray fluorescence
CT computerized tomography
SEM scanning electron microscopy
NMR nuclear magnetic resonance
PSD particle size distribution
$D_{10}$ portion of particles with diameters smaller than this value is 10%.
$D_{50}$ portions of particles with diameters smaller and larger than this value are 50%.
$D_{90}$ portion of particles with diameters below this value is 90%.
PV plastic viscosity
YP yield point
PDF probability density function
CDF cumulative distribution function
$T_2$ transverse relaxation time
$k$ permeability
$\Phi$ porosity
$r_{55}$ pore throat radius corresponding to 35% mercury saturation
$R$ correlation coefficient
$V_p$ compressional wave velocity
$V_s$ shear wave velocity
$K_r$ permeability reduction percentage
$\Phi_r$ porosity reduction percentage
$A_{nf}$ calculated area under the PDF $T_2$ profile
$\mu$ micrometer
mD milli-Darcy

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