Hindawi
Geofluids
Volume 2022, Article ID 1748605, 20 pages
https://doi.org/10.1155/2022/1748605

Review Article

Review of the Generation of Fractures and Change of Permeability due to Water-Shale Interaction in Shales

Kerui Liu,[1] Dangliang Wang ,[1] James J. Sheng ,[2] and Jianfeng Li[3]

[1]*China University of Mining & Technology (Xuzhou), School of Resources and Geosciences, China*
[2]*Texas Tech University, Lubbock, USA*
[3]*Xuzhou Coal Mining Group Corporation, China*

Correspondence should be addressed to Dangliang Wang; wangdangliang@cumt.edu.cn and James J. Sheng; james.sheng@ttu.edu

Received 7 March 2022; Accepted 11 May 2022; Published 13 June 2022

Academic Editor: Tao Chen

In shale development, water-based liquids are injected into the formations. In this process, water can interact with shales, especially with clay content. The interaction can lead to some phenomena, including clay swelling, reduction of mechanical properties of shales and fractures, generation and propagation of fractures, particle detachment, and permeability change. All the phenomena can impact productivity during the development, thereby impacting our investment and return on investment (ROI). So far, many researchers have put their time and efforts into this topic, and many articles have been published. However, some discrepancies still exist in shale reservoirs regarding the role of the interaction between water and shale, especially the impact of clay swelling. Some believe that clay swelling causes formation damage, mainly impairing shale permeability. Others state that fractures can be induced because of clay swelling, leading to the enhancement of shale permeability. So far, few articles have reviewed the various views on this interaction. Additionally, the relationship between each phenomenon is not discussed. In this paper, we try to draw a clear picture of water-shale interaction by reviewing the published studies, mainly focusing on experimental methodology and experimental results. Based on the review, we summarized the influencing factors as well as the mechanisms about the formation of fractures and change of permeability due to water-shale interaction. In water-shale interaction, the induced fractures are generated by the combined effects from clay swelling, reduction of mechanical properties of shales and fractures, and stress anisotropy. Shale permeability can be enhanced if the generated fractures can form an effective flow channel. However, if the generated fractures cannot serve as an effective flow channel, shale permeability will be impaired by clay swelling, water blocking, stress-sensitive, etc.

1. Introduction

The unconventional resource is becoming more and more important in the USA. The unconventional oil from tight oil reservoirs is estimated to exceed 12 million barrels per day [1]. Shale is an important resource in unconventional plays. Lots of companies have great interests and invest plenty of resources into developing shale. Shale is low permeable; hydraulic fracturing is the key to improve shale productivity [2]. Water is the major component of the fracturing fluid [3], and less than 10% of fracturing fluids are recovered [4]. Besides, aqueous solutions, working as EOR methods, are injected into shale plays to enhance oil recovery [5] Once aqueous solutions are injected into shales, water can interact with shale, which cause clay swelling, changing of mechanical properties of shales, and changing of petrophysical properties, thereby impacting oil productivity and oil recovery.

Clay swelling commonly occurs in water-shale interaction. It is widely accepted that clay swelling causes the impairment of formation permeability in conventional reservoirs [6–8]. However, many experimental results show that clay swelling can induce fractures in shales [9–15]. The generated fractures may result in permeability enhancement. No articles thoroughly explain the role of water-shale interaction in the development of shales so far. This paper was aimed at filling this research gap by summarizing the research results and analyzing the impacting factors.

Changing of mechanical properties of shales and fractures is another result of water-shale interaction. Due to water imbibition, the strength of shale can be weakened [16–18]; thus, fractures can be induced more easily. Besides, water-shale interaction can weaken the mechanical properties of fractures [19–23]. Studies show that stress intensity factor, crack extension force, and subcritical fracture growth index (SCI) can be impacted by clay swelling and water-shale interaction [19, 20]. The change in the mechanical properties of fractures is beneficial for fracture generation, as well. However, no articles have summarized those changes and discussed the effect of those changes in water-rock interaction.

Water-shale interaction can alter the permeability dramatically by the generation of fractures [12, 24, 25], particle detachment [11, 12], plugging of flow channels [26], and pore spaces [6], as well as water blocking [24]. We review previous works on the effect of water-shale interaction on permeability change in this paper. The experimental methodologies that were used in the published articles are discussed. The advantages and disadvantages of those experimental methodologies are analyzed. Besides, the relationship between the generated fractures, particle detachment, and permeability change is stated. The factors that could influence particle detachment and permeability change are summarized.

The rest of this paper is extended in four parts: Part 2 briefly introduces the characteristics of shales, clay minerals, and clay swelling. Part 3 discusses the role of water-shale interaction in fracture generation and the possible mechanisms. Part 4 discusses the role of water-shale interaction in permeability change and the possible mechanisms. Part 5 concludes this paper and provides a further experimental approach.

2. Characteristics of Shale, Clay Minerals, and Clay Swelling

2.1. Characteristics of Shales. Shale belongs to sedimentary rock and is most abundant on earth [27]. Shale is characterized as layered, fissile fine-grained, heterogeneous, and anisotropic. Shale's mineralogical composition controls the lithological properties of shale [28]. The typical minerals that are usually found in shales include clay minerals, quartz, feldspars, and carbonates [29, 30]. Organic matter is also a common component for shales [31, 32]. Clay minerals form the load-bearing framework in shales [33, 34]. Clay minerals are the key factor in the water-shale interaction and will be detailed discussed in Subsection 2.2. Shale has a low permeability, ranging from nano-Darcy to micro-Darcy [35, 36]. To accurately evaluate the permeability of shales is difficult. Many factors can impact permeability, like porosity, fluid viscosity, grain size and shape, and tortuosity [37]. Natural fractures and beddings largely exist in shales [38–40]. Therefore, laboratory-measured permeability underestimates the reservoir permeability in shales [41]. How to accurately measure the permeability of shales is an interesting topic and worthy to put efforts on. In this review paper, we will only focus on the change of permeability due to water-shale interaction.

2.2. Clay Minerals in Shales and Clay Swelling. Clay is a layered silicate mineral called phyllosilicate. Typically, clays are fine crystalline particles with two-dimensional arrays of silicon/oxygen tetrahedra or aluminum (or magnesium)/oxyhydroxy octahedra. There are five sorts of clays: illite, montmorillonite, chlorite, kaolinite, and attapulgite [42]. Most often, based on properties, crystal structure, and capacity to accommodate water within clay structure, clay minerals are divided into three main groups: smectite, illites, and kaolinite [43]. Montmorillonite is included in the smectite family [44]. Based on the swelling potential, smectite, illite, and kaolinite are marked as high, moderate, and low swelling potential clays [43]. The swelling potential is the potential volume change for clay minerals. Clay mineralogy plays the most important role in volume change, even in small fractions [45]. Clay can expand up to 20 times its original volume [46].

The process by which clay minerals in shale absorb water is called clay hydration [47]. For most studies, clay hydration is clay swelling. Simply put, clay swelling is the result of increased space between the layered structure of clay minerals and the adsorbed cations [48, 49]. Clay swelling consists of two stages: intracrystalline swelling and osmotic swelling [49]. The hydration of exchangeable cations in the interlayer space leads to internal crystallization, resulting in enhanced space between the clay layers (as shown in Figure 1). Concentration differences between ions in solution and ions in the space between clay layers cause osmotic swelling (shown in Figure 2).

Clay swelling can be affected by initial water content, adsorbed water, clay fraction, and confining pressure. Swelling occurs only when the water balance inside the shale is disturbed when it is in contact with the fluid. Studies show that dry shales are more reactive to water than water-saturated shales [50, 51]. The initial water content in shales can influence swelling rate as well as swelling potential. A study by Chenevert [52] showed that the swelling rate decreased sharply with increasing water absorption time. The highest expansion rates were recorded in the first few hours. Studies conducted by Al-Mhaidib and Al-Shamrani [53] and Sabtan [54] showed that swelling volume and swelling ratio decreased with increasing initial water content. Gomez-Gutierrez et al. [55] stated that the more water adsorbed, the larger the swelling volume, which was supported by Bryson et al. [56]. For here, the samples were not confined. Sabtan [54] measured the free swelling potential for 30 clay shale samples with different clay fraction. In his study, swelling volume increased as the clay fraction increased. A similar trend was achieved by Gomez-Gutierrez et al. [55] and Bryson et al. [56]. Confining pressure could negatively influence the swelling volume of clay minerals [57]. To combine those influencing factors, Lyu et al. [58] developed an MLR model to predict clay swelling. The relationship between swelling potential (S), water content (W), clay fraction (C), and confining pressure (P) can be expressed as $S = 30.0247 - 0.274W + 0.0455C - 9.1778 \log(P)$.

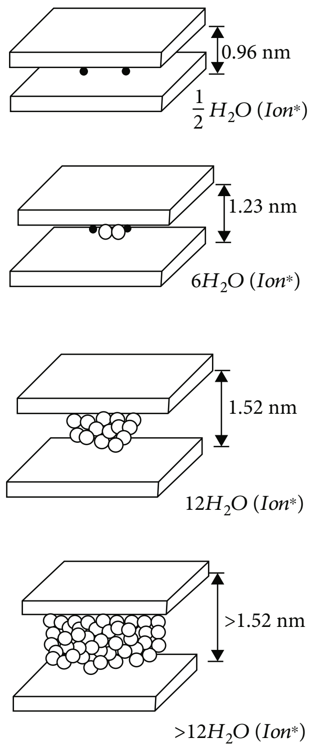


Figure 1: Schematic illustration of intracrystalline expansion of sodium montmorillonite: the interlayer space is expanding due to the hydration of exchangeable cations in the presence of water [49].

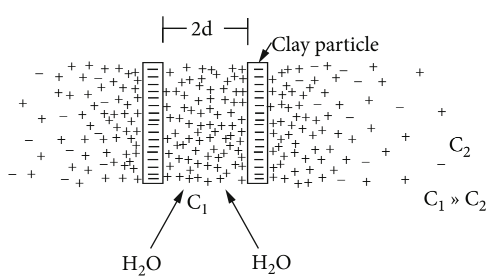


Figure 2: Illustration of osmotic swelling of the clay particle [49].

The temperature could influence clay swelling, as well. Wang et al. [59] and Huang et al. [60] employed a temperature range from −10°C to 23°C to investigate the swelling of shales. Their results showed that when the temperature is lower than 10°C, the expansion potential of shale decreases with the increase of temperature. The temperature could positively influence the swelling volume of shales when the temperature was higher than 10°C. Li et al. [61] studied the effect of temperature change on fracture generation in water-shale interaction. They compared the CT images for the tests under 80°C with those under 20°C. They found that fractures were more likely to develop in the tests using 80°C. The combined effects from high temperature and water-shale interaction led to the propagation of fractures. Additionally, as cool water is injected into hot formations, the water-cooling effect can induce fractures by the increase in pore pressures and the shrinkage of formations [62, 63]. The thermal effect is beneficial to the generation of fractures in water-shale interaction. However, so far, no experiments have been conducted to support this statement when samples are under stress anisotropy.

The types and concentrations of salts in water-based liquids also have an impact on clay swelling. The ions of Na^+, K^+ can influence the clay swelling. KCl is a commonly used swelling inhibitor [64, 65]. Wong [18] used water and brine (1% NaCl solution) to test the swelling potential of La Biche shale samples. He found that clay swelled more in the water when compared with brine.

3. The Influence of Water-Shale Interaction on Fracture Formation and Propagation

This section introduces the experimental methodologies and results related to fracture formation and propagation due to water-shale interaction. The interaction-induced fractures and the testing conditions are discussed. Based on those experimental results, the mechanisms about the role of water-shale interaction in fracture formation and propagation are discussed.

3.1. Induced Fractures in Experimental Studies. To study the interaction between water and shale, spontaneous imbibition tests were carried out. Figure 3 shows the imbibition tests performed by Morsy and Sheng [66]. Other researchers conducted the similar tests [9, 66–75]. From their results, the imbibition process was controlled by capillary actions, osmotic fluid flow, and clay minerals. To represent the imbibed water, the weight difference was used in most tests. Dehghanpour et al. [9] conducted imbibition tests for samples from five different shale formations. In their tests, they compared the imbibition profiles of oil and brines. The brine intake of all samples was significantly higher than the oil intake of the same samples. Besides, they found that excess water intake was due to water adsorption by clay minerals by comparing the inhalation profiles of oil and brine with oil intake. The water-shale interaction-induced microfractures even disintegration were observed in their tests. Samples from Fort Simpson had the highest clay content; therefore, disintegration was observed; samples from Otter Park had the least clay content, and only microfractures were observed. Figure 4 shows the generated fractures in the tests which were conducted by Morsy et al. [71] and Morsy and Sheng [66]. From their results, clay swelling can induce fractures. The above results indicate the following: (1) clay content is the main reason for the water uptake in the tests; (2) clay swelling can generate fractures in the imbibition tests; and (3) whether or not disintegration can occur is related to the amount of clay content in the samples. However, those tests were conducted without any restrains, and the mechanisms behind the generation of fractures were not discussed in these studies.

To examine the role of confining pressure in fracture generation because of clay swelling, several researchers introduced confining pressure into their tests [11, 25, 76–79]. In their tests, a core holder capable of holding the core sample and a pump for applying confining pressure are required. Figure 5 shows a schematic diagram of the

Figure 3: Imbibition tests from Morsy and Sheng [66].

device used by Bin et al. [76] and Wang et al. [25]. In their tests, the sample can imbibe water from the open ends of the core holder.

To observe the generated fractures, a CT scanner was employed by Bin et al. [76] and Wang et al. [25]. The general test procedure is that (1) the core samples are scanned before the tests; (2) the sample is placed in the core holder and exposed to confining pressure for imbibition tests; and (3) after imbibition tests, pressures are released, and the samples are scanned again to observe the generated fractures. For this experimental methodology, elastic strain energy is stored inside the samples as long as the confining pressure is applied. The release of confining pressure can result in a sudden release of strain energy, thereby causing the generation of fractures or even the failure of samples [80–82]. In their tests, it is hard to tell whether the fractures are generated by water-shale interaction or the sudden release of strain energy. It is better to monitor the process of the generation and propagation of fractures when the water imbibition tests are running under confining pressures. Two methods were employed: (1) first is monitoring the pressure change in the tests [11]. In their tests, A shale sample is exposed to a designed upstream pressure of water under confining pressure. Downstream pressure is maintained at atmospheric pressure. The upstream pressure is recorded. A pressure drop can be achieved if the fractures are generated. (2) Second is using an X-ray core holder system [77–79]. Figure 6 shows the schematic of the apparatus in their tests. CT images are achieved without releasing the confining pressure. In these ways, the effect of the sudden release of strain energy on fracture generation can be eliminated.

Bin et al. [76] and Wang et al.'s [25] results show that fractures were induced and developed (shown in Figure 7). In Bin et al.'s [76] results, fractures grow and connect to form complex fracture networks (shown in Figure 7(a)). In Wang et al.'s [25] tests, both isolated and connected fractures were observed on the CT images. In both studies, the reason for the generated fractures was clay swelling due to water-shale interaction. However, based on the description of their experimental procedures, both studies dried the cores and scanned the samples to get the CT images. Once the confining pressure is released, the CT scanning cannot accurately show the welling induced fractures. The effect of the sudden release of confining pressure, which caused the sudden release of strain energy inside the samples, cannot be differentiated from the effect of clay swelling. Therefore, it is difficult to identify whether the generated fractures were caused by clay swelling or by the sudden release of confining pressure. In Bin et al.'s [76] study, another set of tests was performed to characterize the distribution of pore-fracture structures in the samples during imbibition testing. The distribution of T_2 spectra was analyzed. The longer the transversal relaxation time, the larger the size of the pore-fracture structure should be. From Figure 8, the peak value of the transversal relaxation time increased in their tests, which means the size of the pore-fracture structure increased due to water-shale interaction. Combined with the results from CT images and those from the T_2 spectra, it is found that under the action of confining pressure, the expansion of clay can produce fractures.

Roshan et al. [11] explored the underlying mechanism of water uptake by using partially saturated samples to conduct tests. Free and confined water imbibition tests were done. For the confined test, a shale sample was placed under confining pressure of 1000 psi. The sample was exposed to distilled water by upstream pressure of 500 psi for 40 h. Figure 9 shows the induced fracture in the test. The fracture was formed by taking a longer time under confining pressure when compared with the tests without restrain. They stated that the formation of fractures under confining pressure is due to the decrease in the mechanical strength of the rock and the swelling of the clay. Besides, they indicated that this fracture was formed along with weak structures (beddings and laminations).

By comparing the results from Bin et al. [76], Wang et al. [25], and Roshan et al. [11], we can see that fractures can be generated due to the effect of water-shale reaction in shales under confining pressure. However, the formation of such fractures may take a longer time. The main factor that can contribute to the generation of such fractures is clay swelling. Other factors, like the degradation of the mechanical strength of shale, can also be beneficial for fracture generation in water-shale interaction.

Zhang and Sheng [77, 78] and Zhang et al. [79] employed CT images to observe fractures. Isotropic confining pressure was applied in their tests. Samples from Mancos shale formation were used. The constant pore pressure (0.03 MPa) was used for all the tests, and confining pressure (0.1 MPa, 2.0 MPa, and 20.0 MPa) was applied for the tests. Figure 10 shows the CT images from Zhang and Sheng [78]. They observed that at lower confining pressures, the samples developed more fractures. The generated fractures under confining pressures could close and reopen, which means the generation of the fractures was largely impacted by water-shale interaction and the applied confining pressure. Besides, Zhang and Sheng [78] found that swelling strain decreased due to confining pressure. The larger the confining pressure, the more the swelling strain was reduced. Ewy and Stankovic [83] reached similar results: increasing confining pressure leads to a decrease in swelling. Sufficient confining pressure could prevent clay swelling from occurring. A threshold confining pressure exists. Above this threshold, swelling decreases with the increasing confining

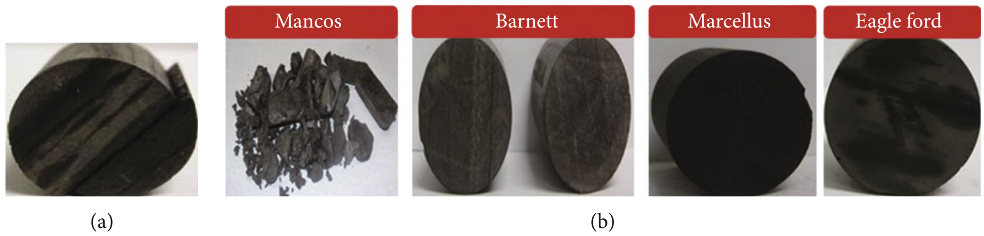


Figure 4: (a) Barnett shale sample after one week of spontaneous imbibition in distilled water [71]. (b) Imbibition testing results from Morsy and Sheng [66].

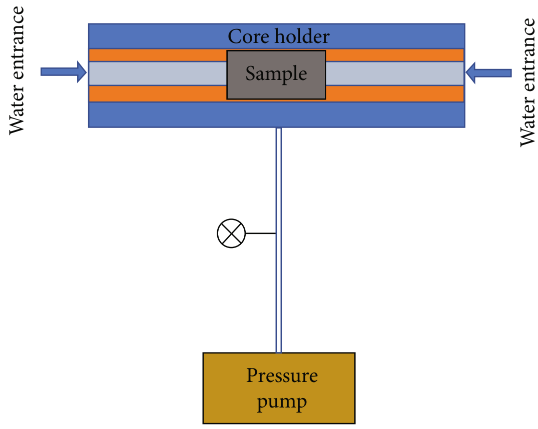


Figure 5: The schematic of the apparatus that was used by Bin et al. [76] and Wang et al. [25] to conduct imbibition tests with confining pressure.

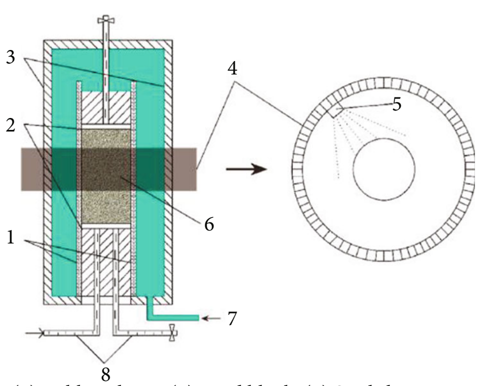


Figure 6: The CT scanner and X-ray core holder that were used by Zhang and Sheng [77, 78] and Zhang et al. [79].

pressure or is prevented by confining pressure completely. The threshold for confining pressure changes from shale to shale. In conclusion, in water-shale interaction, confining pressure has a negative impact on fracture formation.

In fracture formation, stress anisotropy plays a positive role. Liu and Sheng [10], Liu and Sheng [12], and Liu et al. [13] investigated the role of clay swelling in fracture formation in shales with stress anisotropy. In their tests, stress anisotropy is applied using anisotropic core support. The schematic of the test system is shown in Figure 11. The results indicate that clay swelling and stress anisotropy can facilitate the fracture initiation and development when shales meet water. More fractures can be formed with larger stress anisotropy (shown in Figure 12).

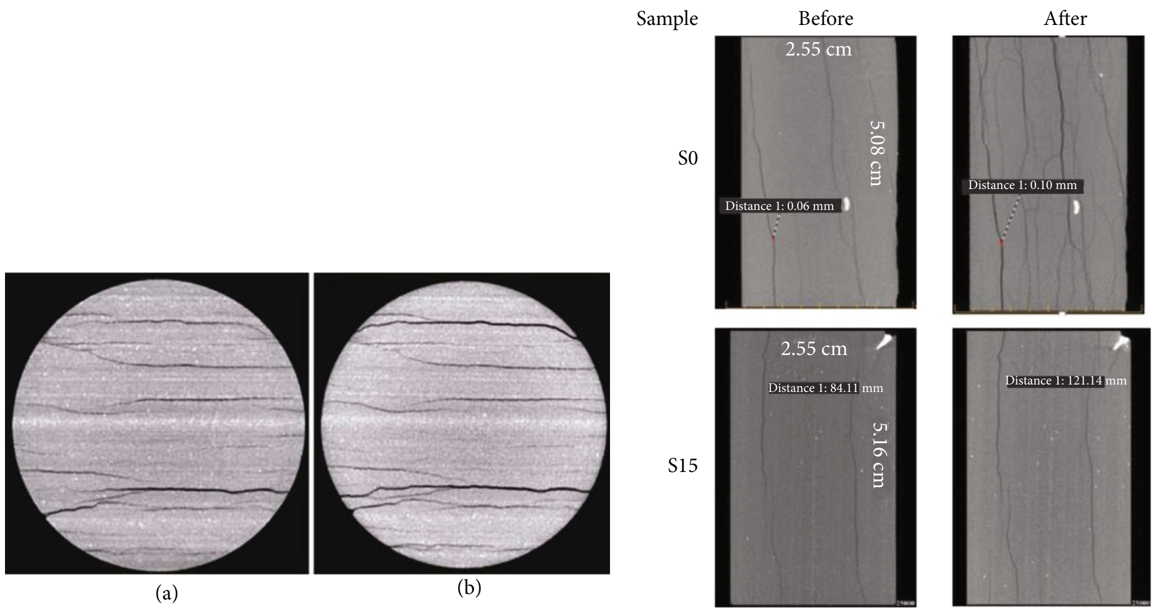
Liu and Sheng [10] also observed the dynamic changes of the generated fractures in water-shale interaction under stress anisotropy. They and Zhang and Sheng [78] reached the same conclusions: (1) water-shale interaction does have a positive effect on fracture formation for samples; (2) fractures can be induced much easier in water-shale interaction when samples are under stress anisotropy.

3.2. The Influencing Factors for the Generation of Fractures in Shales. Wang et al. [84] found that clay mineral types and fractions are critical for water-shale interaction. Shale reacts with water stronger with more clay minerals. Clay swelling can change the stress distribution, leading to a stress concentration around fracture tips, thus causing the fractures to grow. This statement is supported by the simulation work done by Liu et al. [13]. Clay swelling can cause the redistribution of the stress in the models. Stress concentration was observed around the generated fractures to cause the generation and propagation of the fractures.

Natural fractures are everywhere in shales [39, 40, 85]. Natural fractures are suspected as a factor in productions in shales. Additionally, natural fractures serve as the sites for fracture creation and propagation in shales [10, 39, 86, 87]. The locations of natural fracture also can impact the fracture formation and distribution [86]. Natural fractures can facilitate the formation and growth of new fractures in water-shale interaction (shown in Figure 13).

Bedding and lamination are ubiquitous in shales [40]. Roshan et al. [11] observed that the induced fracture was formed along with the bedding (shown in Figure 9). Moradian et al. [88] also observed that if the bedding directions are 60° and 90°, fractures with bedding directions were dominant. This result is same as the results from Liu and Sheng [10] and Makhanov et al. [68]. Water absorption parallel to the lamination is higher than perpendicular to the same lamination [89]. The enhancement of the imbibition rate was caused by the generation of fractures. This observation indicated that lamination was beneficial for the generation of fractures in water-shale interaction. By those results, bedding and lamination is another positive factor to influence the generation and propagation of fractures in water-shale interaction.

Organic matter is a common component in shales [32, 90]. Xue et al. [91] conducted water imbibition tests under



(a) (b)

Figure 7: (a) Fracture generated and propagated in Bin et al.'s [76] tests. (b) Fracture generated and propagated in Wang et al.'s [25] tests.

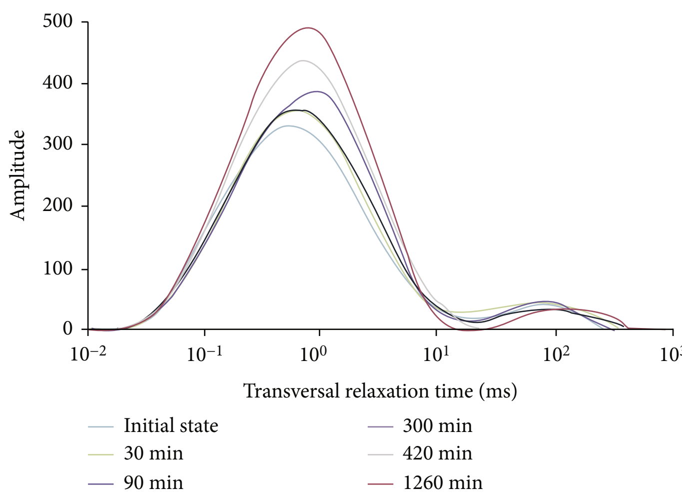
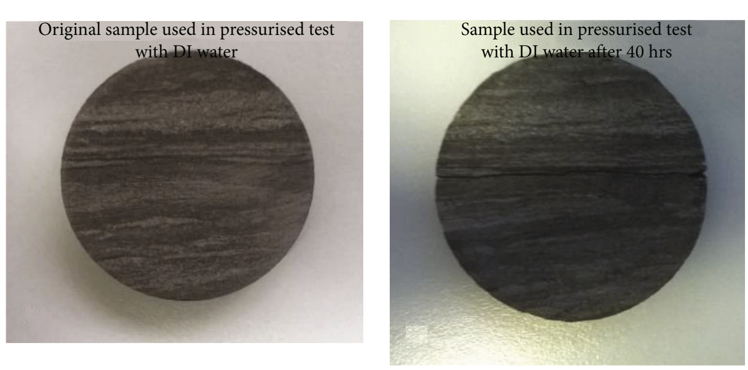


Figure 8: T_2 spectra of one sample during water-shale interaction in Bin et al.'s [76] tests.



(a) (b)

Figure 9: Testing results from [11].

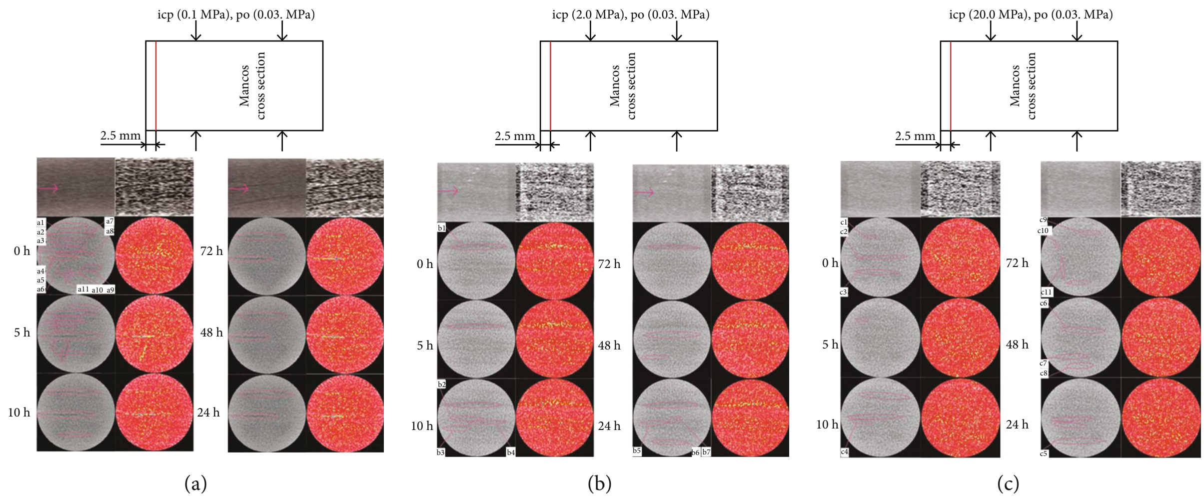


FIGURE 10: CT images of Mancos shale samples at different confining pressures. ICP means confining pressure. PO means injected fluid pressure or pore pressure [78].

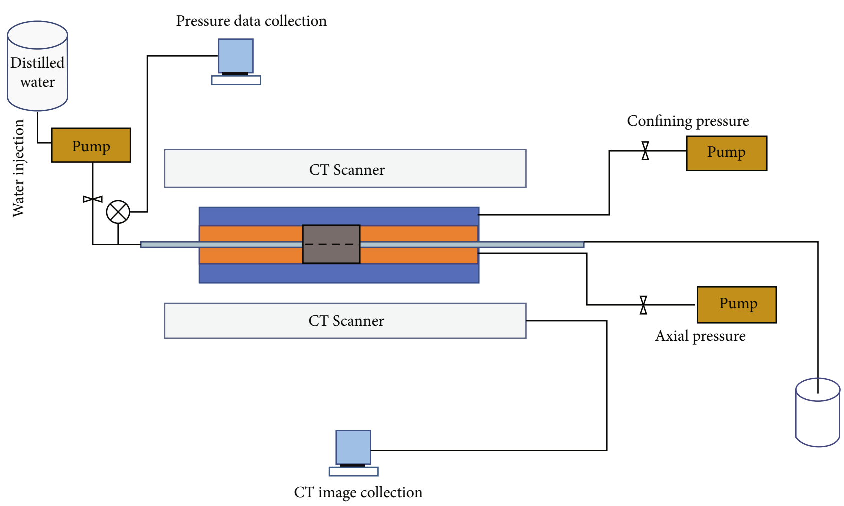


FIGURE 11: The schematic of the test system (Liu and Sheng [10] and Liu and Sheng [12].

atmospheric conditions. They found that the generation of fractures mainly occurred in the areas between organic matter and inorganic minerals. The cohesion between the mineral particles could be weakened after the water-shale interaction. The nonclay mineral particles are exfoliated to form inorganic pores, which gradually develop into microfractures between the nonclay mineral particles and the clay mineral particles.

Li et al. [92] observed that microfractures were generated along with the interfaces between organic and inorganic matter as well as between different components. Similar results were observed by Wang et al. [84]. Organic matter can provide space for fracture development caused by clay swelling and capillary pressure [93]. Organic matter is another positive factor for the generation and propagation of fractures in water-shale interaction.

3.3. Change of Shale's Mechanical Properties due to Water-Shale Interaction. The mechanical properties of shales and fractures are changed because of water-shale interaction. The elasticity, hardness, and strength of shales are deteriorated, which is termed as "shale softening." The properties of fractures, like fracture conductivity, stress intensity factor (K_c), crack extension force (G_c), and subcritical fracture growth index (SCI), are reduced.

Shale's mechanical strength can be weakened under the effect of water-shale interaction [16–18]. Cheng et al. [16] compared the shale strength of dry and water-saturated samples. The results indicated that the compressive strength, Young's modulus, and the anisotropy of the water-saturated samples were reduced compared to the results of the dry samples (as shown in Figure 14). The average compressive strength of water-saturated samples was 28.9% lower than that of the dry samples, with a maximum decrease of 54% for water-saturated samples. Likewise, the mean and maximum reductions in Young's modulus of the water-saturated samples were 26.1% and 62%, respectively. Two reasons why we need to compare Young's modulus are as follows: (1) the brittleness of shales can be used to determine the ability to be fractured of the shales [94], and brittleness is

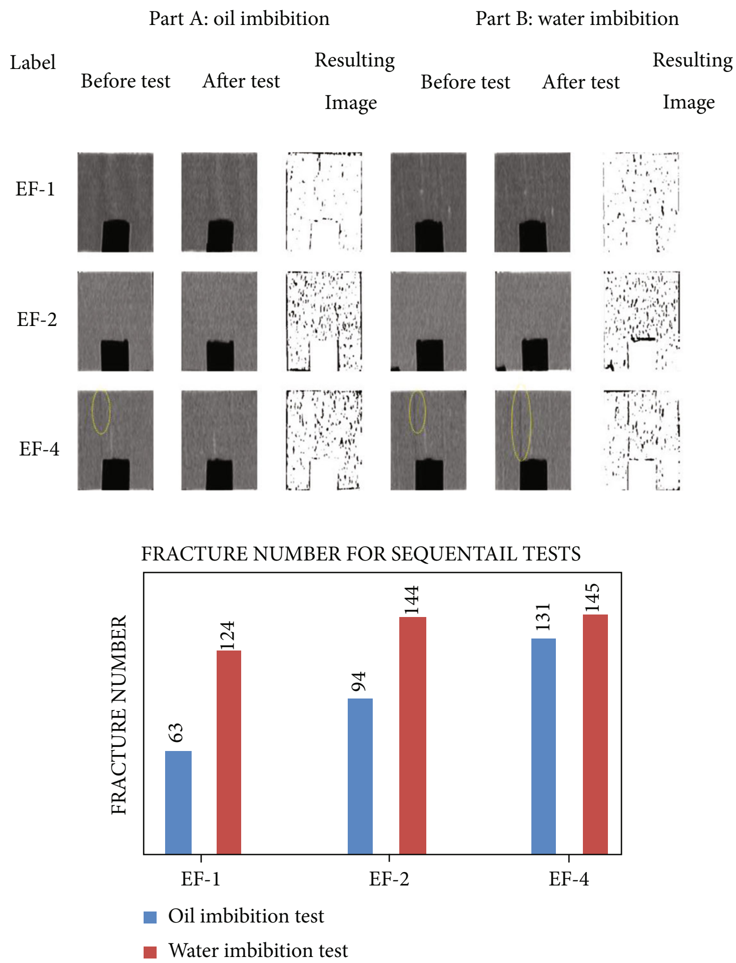


Figure 12: Results from Liu and Sheng [10].

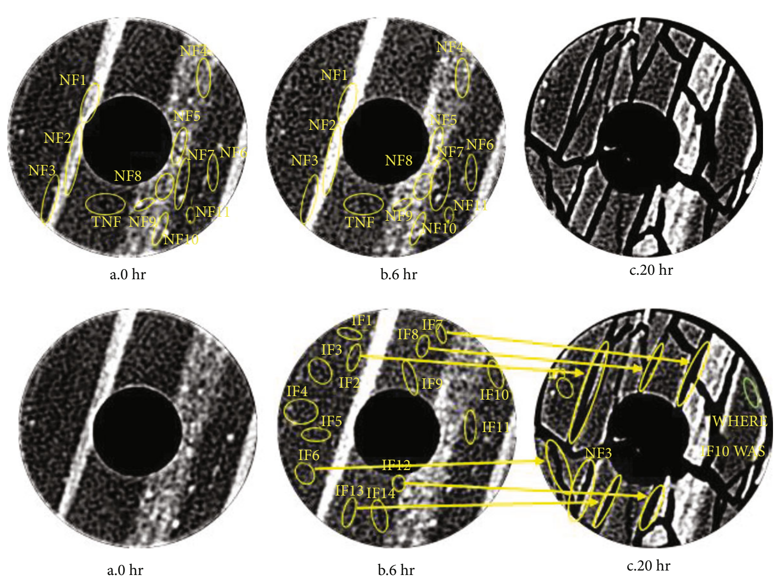
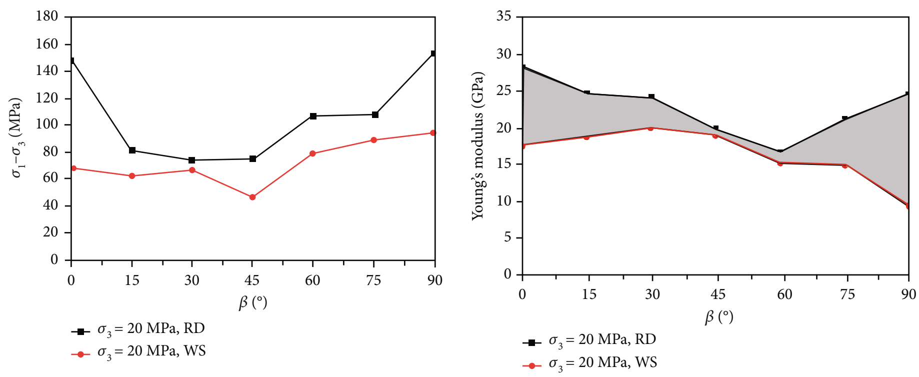


Figure 13: Results for EF-6. The testing condition was 1350 psi axial and 500 psi confining pressure [10].

a function of Young's modulus. The shale is more brittle with a higher Young's modulus. Brittle shale has a higher potential for fracture initiation and propagation and the formation of a complex fracture network than ductile shale. (2) Decreased Young's modulus leads to deterioration of fracture conductivity [95]. Once the compressive strength of



(a) (b)

FIGURE 14: (a) Comparison of the compressive strength of the dry (RD) and water-saturated (WS) samples from Cheng et al. [16]. (b) Comparison of Young's modulus of the dry (RD) and water-saturated (WS) samples from Cheng et al. [16].

the shales is weakened by water-shale interaction, it is easier to meet the failure criterion and fractures could develop in shales. The results from Wong [18] indicated that Young's modulus decreased with increasing swelling. Besides, the behavior of shale under larger swelling was like a ductile material. Similar results were achieved by Yang et al. [96]. Talal [17] compared the effect of Na^+, K^+, Ca^{2+} on the compressive strength of shales. The results indicated that K^+ had a strengthening effect on shale strength, while Na^+ and Ca^{2+} ions had a weakening effect on shale strength. Akrad et al. [95] measured Young's modulus of shales before and after exposure to 2% KCl slickwater and freshwater. The results showed that potassium ion (K^+) caused the reduction of Young's modulus of shales, no matter it was "soft" mineral with Young's modulus below 30 GPa or "hard" mineral with Young's modulus above 30 GPa. The highest reduction occurred in Eagle Ford shale (70%), which resulted in a 39% loss in fracture conductivity. 52% of the reduction was observed for Bakken shale, causing a 14% loss in fracture conductivity. For these two shales, high calcite (77%) and low clay content (8% for Eagle Ford and 4% for Bakken) were measured. For the clay-rich samples, like Lower Bakken (clay content of 47%) and Haynesville (clay content of 57%), a lesser decrease was observed in Young's modulus (22% for Lower Bakken and 6% for Haynesville), resulting in a lesser reduction in fracture conductivity (5% for Lower Bakken and 1% for Haynesville). These results indicated that clay swelling might not cause permeability impairment as bad as assumed. The reduction of fracture conductivity was also reported by Pedlow and Sharma [97] and Jansen et al. [98]. Li et al. [92] examined the effect of water-shale interaction on the tensile strength of shales. Tensile strength is critical for predicting fracture initiation and growth. The smaller the tensile strength, the easier the fractures can be generations. As shown in Figure 15, as the water content increases from 4.45% to 11.7%, the water-shale interaction reduces the tensile strength by 4.4% to 51.7%, which means that fractures are more likely to develop due to the decrease in tensile strength. In conclusion, the change of the mechanical properties of shales due to water-shale interaction can facilitate fracture generation in shales.

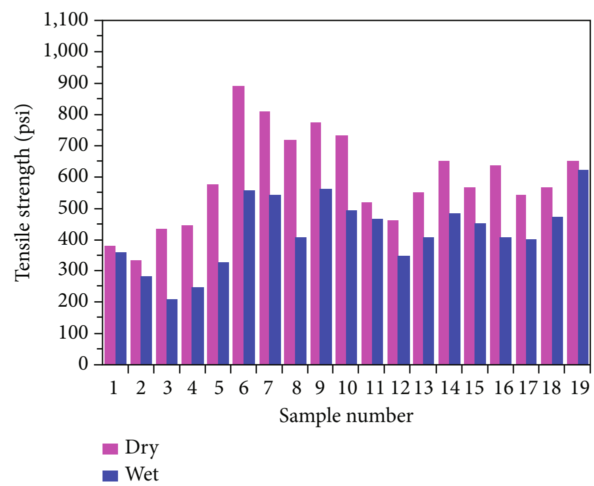


FIGURE 15: Comparison of the tensile strength of dry and wet Eagle Ford samples from Li et al. [92].

The properties of fractures are affected by water-shale interaction. Based on the equilibrium law, stress intensity factor (K_c) or crack extension force (G_c) has a critical value. Once those values are reached or exceeded, the fracture can propagate [99]. As stress corrosion occurs, fracture can develop when the K or G is far below the critical values, which is known as subcritical fracture growth [99]. Stress corrosion means that the strained Si-O bonds at crack tips are more reactive to environmental agents than the unstrained bonds of crystalline silicates because of the reduced strain-induced overlap of atomic orbitals [99]. A weakened state is produced due to strained bond-environmental agent reaction, resulting in that the bonds can be broken at a lower stress than the unstrained bonds. A general expression to represent the weakening effect of silicate and quartz in water is proposed as the following [100–104]:

$$H-O-H+[-Si-O-Si-] \rightleftarrows [-Si-OH\cdot HO-Si-] \quad (1)$$

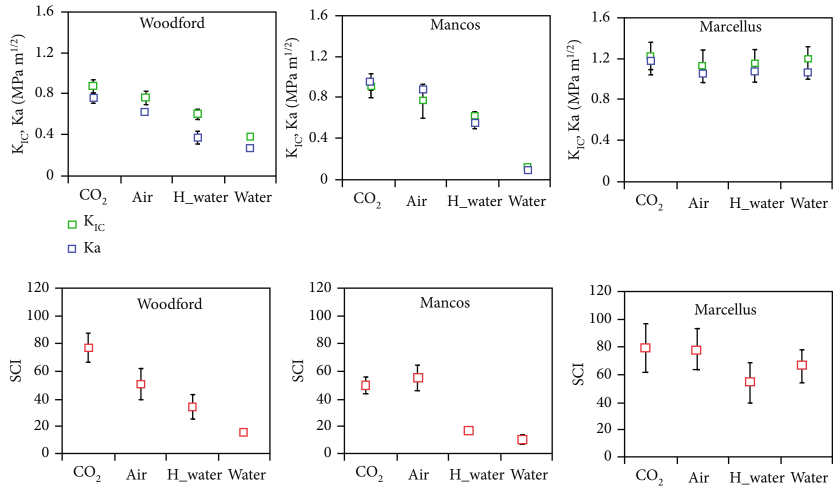
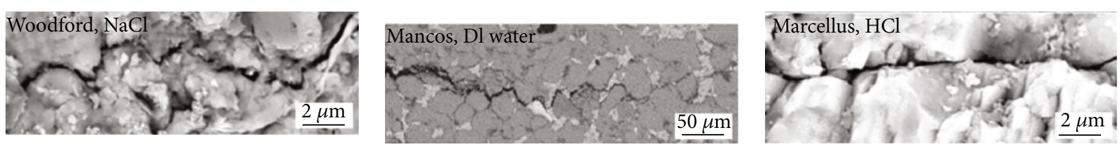


Figure 16: Testing results from Chen et al. [19].



(a) (b) (c)

Figure 17: Fracture traces by SEM in Chen et al. [20].

It is first-order chemical reaction when strong Si – O bonds hydrolyze to weaker hydrogen-bonded hydroxyl groups attached to silicon atoms. Thus, water-shale interaction can result in stress corrosion.

Chen et al. [19] investigated the change of fracture mechanical properties in clay-rich shales under water-shale interaction. Their results (shown in Figure 16) indicated that even at low smectite content, clay-rich shales had a strong water-weakening effect, resulting in a 54% reduction in fracture toughness and 77% reduction in subcritical fracture growth index for water-saturated samples. The carbonate-rich shale barely had water-weakening effects. Besides, K_{IC} for wet samples was reduced by more than 50% compared to dry samples for clay-rich shales. For samples without clay minerals [105], K_{IC} dropped less than 20% with increasing water saturation. The reduction in subcritical fracture growth index in clay-rich samples could reach 77%, while the reduction in subcritical fracture growth index for samples without clay minerals was negligible or less than 50% [21–23].

Their findings suggest that water-shale interactions lead to the weakening of the subcritical fracture properties of clay-rich shale, which may lead to subcritical fracture growth and failure more prone to clay-rich shale than clay-poor shale.

Chen et al. [20] conducted comparison work for Woodford shale, Mancos shale, and Marcellus Shale with different temperatures, pH, and varying fluid salinities. The generated fractures were traced by scanning electron microscopy (SEM) (shown in Figure 17). The clay fabrics and grain boundaries are shown in Figure 18.

It can be seen from Figure 17 that intergranular fractures are generated in the clay-rich shale, forming zigzag traces at the grain scale. As can be seen in Figure 18, clay fabrics and grain boundaries and pits are observed on the fracture surfaces of the Woodford and Mancos Shales (red arrows in Figures 18(b) and 18(d)). The fracture trace observations were compared with the clay structure and grain boundaries, and the fractures were formed by clay swelling.

According to Chen et al. [19], Chen et al. [20], Nara et al. [21, 22], and Waza et al. [23], two points are reached: (1) clay swelling is primarily responsible for the generation of the fractures in water-shale interaction; (2) the reduction in stress intensity factor (K_c), crack extension force (G_c), and subcritical fracture growth index (SCI) can facilitate the generation and propagation of fractures in water-shale interaction. However, those tests were conducted without restrains.

Through the comparison, the degradation of mechanical properties of shales and fractures due to water-shale interaction has a positive effect on the generation of fractures in shales.

3.4. Mechanisms about the Generation and Development of Fractures in Water-Shale Interaction. The initiation of swelling-induced fractures is due to swelling pressure [106], which is the difference in the hydrostatic pressure of the water inside and outside of the clay membrane. Once the swelling pressure is large enough, it can break the natural cementation of shale and allow the generation of swelling-induced fractures. A similar explanation is stated by Steiger [107] which suggests that interactions between water and

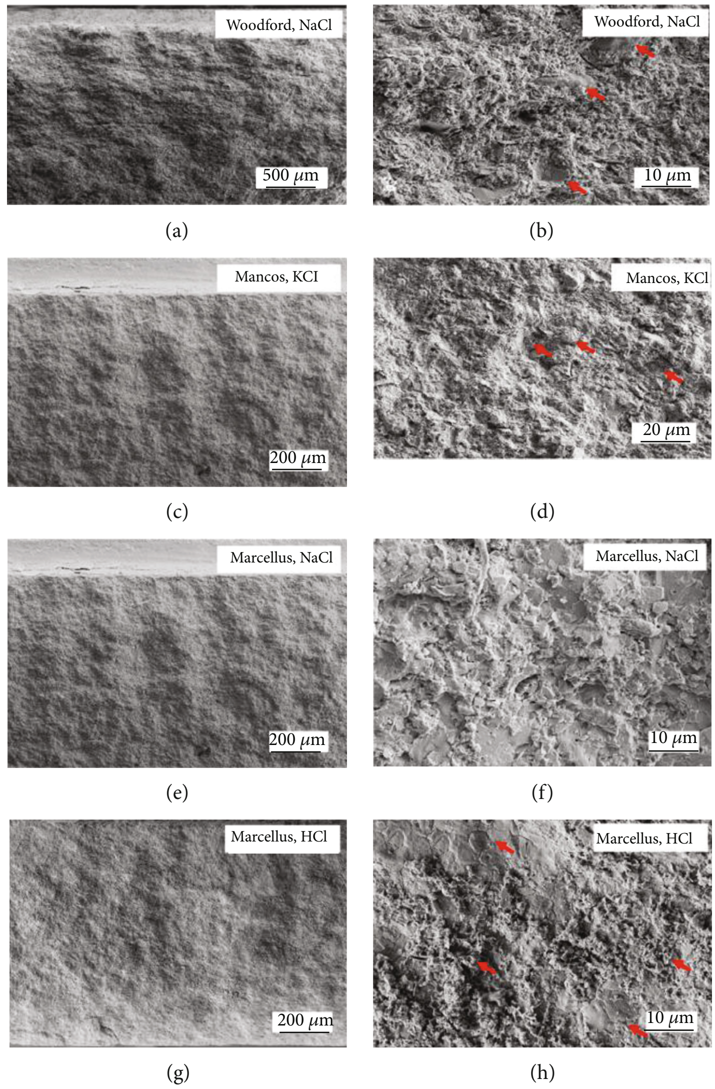


Figure 18: Fracture surfaces in the tests conducted by Chen et al. [20].

silicate surfaces or cations provide the driving force, causing water adsorption and swelling until separation between crystallites occurs, leading to the disintegration of unconfined shale. However, it is still controversial that if the own effect of swelling stress is large enough to initiate fractures under confined conditions. Xu et al. [108] measured the swelling stress under confining conditions. The measured stress was less than 100 psi (0.69 MPa). However, the measurements from Nuesch et al. [109] showed that swelling stress could reach 682 psi (4.7 MPa). No studies have evidence to show that fractures can be directly induced by the only effect of clay swelling under confined conditions. More efforts are needed to answer this question.

The fractures induced by the water-shale interaction under stress conditions are more likely caused by the combined effects from clay swelling, reduction of mechanical properties of shales and fractures, and stress conditions. The initiation of fractures can be triggered by clay swelling through the formation of new pores and microfractures. Meanwhile, clay swelling can induce nonuniform stress, resulting in the local stress concentration around fractures. The reduction of mechanical properties of shales and fractures can facilitate the generation of fractures by lowering the fracture mechanical properties. Fractures can propagate under the combined effect of clay swelling, stress anisotropy, shale, and reduced mechanical properties of fractures. The characteristics of shale natural fractures, bedding, and organic and inorganic matter interface can be used as the place for the generation of induced fractures. In this process, clay swelling, redistribution of stress, and the reduction of mechanical properties of shales and fractures are caused by water-shale interaction. Therefore, water-shale interaction is critical in the formation of fractures under stress conditions. However, new experimental methodology or even new apparatus is needed to quantitatively reflect the contribution of water-shale interaction in the generation of fractures in shales.

Another mechanism that may induce fractures in water-shale interaction is mechanical failure. The mechanical failure is caused by increased pore pressure caused by the imbibition of fluids. Makhanov et al. [110] found that although oil had no affinity for absorption in clays, some microfractures still were created with oil adsorption. This result revealed that the pore pressure due to fluid imbibition reduced the effective stress and thus created fractures. This kind of fractures is generated by mechanical failure of samples. A similar conclusion was reached by Santos et al. [51]. However, it is difficult to tell the amount and importance of the fractures caused by mechanical failure due to fluid imbibition. Besides, it is hard for us to separately study the effect of mechanical failure due to fluid imbibition in water-shale interaction. The reason is that once the fluid is imbibed into samples, the fractures caused by fluid-shale interaction and fractures caused by the mechanical failure may occur at the same time, and we cannot tell whether the fractures are caused by the interaction or mechanical failure.

4. The Change of Permeability due to Water-Shale Interaction

In this part, the permeability change due to water-shale interaction in the experiments is summarized. Based on those experimental results, the mechanisms about the change of permeability due to water-shale interaction are analyzed.

4.1. Experimental Methodologies That Were Used and the Experimental Results. Most researchers believe that water-shale interaction causes formation damage, mainly permeability impairment in shales; however, many studies showed that induced fractures were formed in water-shale interaction. Unlike conventional reservoirs, enhancing oil productivity in shales mainly relies on the conductivity of fractures, even though the conductivity of such induced fractures is lower than that of propped fractures in hydraulic fracturing [98, 111]. The matrix permeability and conductivity of natural fractures can be damaged due to the interaction between water and shale, especially clay swelling [47, 112]; however, shale permeability can be enhanced by the induced fractures [9, 11, 24]. What is the final effect on permeability change is an interesting question.

Based on the methodology, the permeability tests can be divided into two types: gas permeability measurement during water imbibition and pressure monitor during water imbibition. The gas permeability measurement during water imbibition was popularly used by lots of researchers [6, 24, 25, 75, 77]. The general testing procedure is the following: the sample is exposed to water-based fluid initially. After a certain period, the sample is removed from the fluid and the gas permeability is measured. Then, the sample is resumed to the fluid to continue the imbibition test. For this method, this procedure may be repeated several times to achieve the gas permeability for different time spots in the fluid imbibition tests. In the studies from Aksu et al. [6], Shen et al. [24], and Zhou et al. [75], they did not mention clean the samples before measuring permeability. In Wang et al. [25], they dried the core samples before measuring permeability. In Zhang and Sheng [77], they vacuumed the sample before measuring the permeability. This methodology can quantitatively reflect the effective gas permeability change in the tests. However, gas permeability cannot truly represent absolute permeability in shales. Besides, different methodologies are employed to measure shale permeability [113]. Pressure monitor during water imbibition was not as widely used as gas permeability measurements [11, 12]. For this methodology, the upstream pressure or pressure difference is monitored in the tests. The increase of pressure can reflect the enhancement of shale permeability; otherwise, the impairment of shale permeability can be shown by the decrease of pressure. This methodology can indirectly and qualitatively reflect the change of shale permeability. However, it is still unsolved to quantitatively reflect the change of shale permeability in the tests. Permeability is a function of multiple factors, like stress, pore throat, pore size, and liquid viscosity. This research gap needs to be filled.

Shen et al. [24] measured the permeability change in water imbibition tests for sandstones and shales. The pulse-decay permeability methodology was used to measure samples' permeability. Before they conducted imbibition tests, permeability for dry samples was measured. Then, the imbibition tests were conducted. After a certain period of imbibition tests, the imbibition cells were removed from the imbibition liquid, and permeability tests were conducted as soon as the cells were removed. Figure 19 shows the permeability change vs. the increased water content in their tests. In the early stage, the decrease of shale permeability (Y1, Y2, and Y3) was due to the reduction of effective flow channel caused by water blocking and stress sensitivity. It means that the applied stress conditions have an impact on the permeability change [24]. At the middle stage, samples' permeability (Y1, Y2, and Y3) increased due to the generation and propagation of new induced fractures caused by clay swelling. Shale permeability (Y1, Y2, and Y3) decreased, at the last stage, which is due to water blocking and stress sensitivity. A failure occurred in the sample Y4, resulting in a permanent increase in the sample's permeability. The failure was caused by clay swelling. They stated that the three critical factors to control shale permeability are clay swelling, stress sensitivity, and water blocking. Whether the permeability can be increased depends on the comparison of these three factors.

Shales' wettability, hydration stress, and permeability change in slickwater treatment are studied by Yuan et al. [114]. The testing methodology is similar to Shen et al.'s [24]. The permeability was damaged by the narrowed flowing channels due to clay swelling at the beginning of the test. Under the effect of swelling stress and capillary pressure, fractures were induced. However, the fractures are not interconnected to form effective flow channels. Therefore, the contribution from these fractures to permeability was negative. As water-shale interaction continues, fractures propagated and interconnected because of the increased hydration stress and wettability change. Thus, shale permeability was recovered and even higher than the original value. A pressure build-up method was used by Zhou et al. [75] to measure the samples' gas permeability. They stated that matrix permeability and fracture permeability were

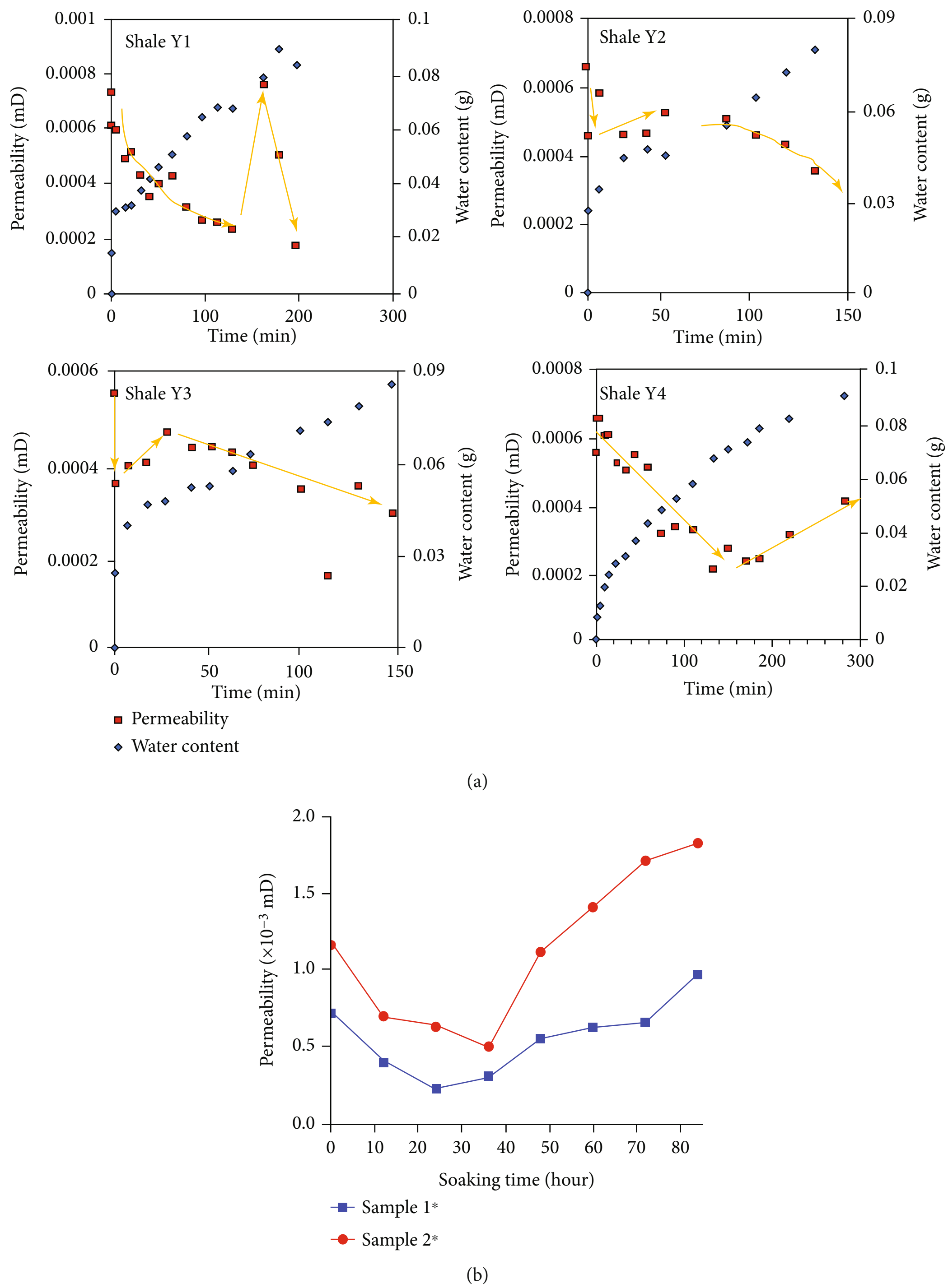


Figure 19: (a) Change of shales' permeability in water imbibition tests [24]. (b) Change of shales' permeability in water imbibition tests [114].

decreased due to clay swelling and water blocking. Besides, they observed that the samples' permeability could be increased due to the generation of microfractures. In the pictures provided by them, the generated microfractures propagated through the core samples and formed an effective flow channel, thereby increasing the sample's permeability. All the above three studies used effective gas permeability to represent the change of shale permeability. However, it is widely accepted that gas permeability is higher than liquid permeability [115–117]. Moreover, no accurate formula was proposed to represent the gas and liquid permeability correlations for various shales. The measured gas permeability cannot correctly represent the permeability change in water-shale interaction.

Roshan et al. [11] conducted a test under confining pressure (1000 psi). In the test, the injection pressure is 500 psi

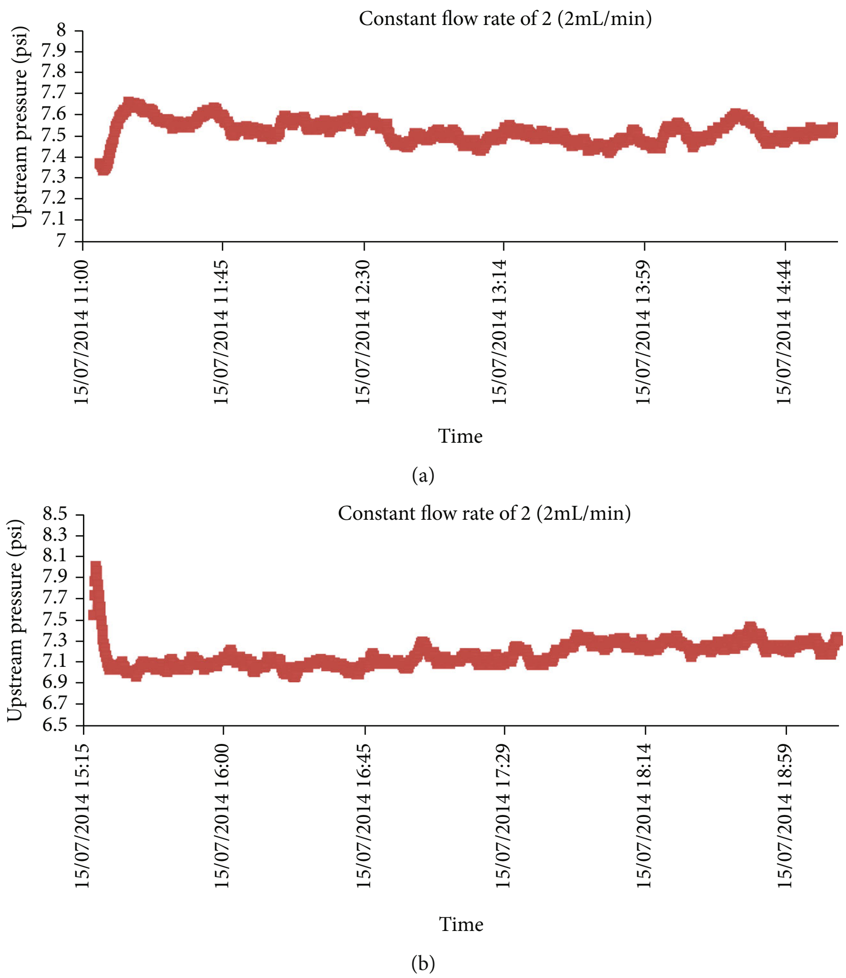


Figure 20: Upstream pressure curve from Roshan et al. [11].

and the injected fluid is DI water. The upstream pressure was recorded. No pressure change was observed until a fracture was generated (shown in Figure 9). Similarly, in their permeability test, they recorded the change of the upstream pressure in the imbibition test with the downstream pressure at atmospheric conditions. Figure 20 shows the pressure curve from their test. In the test using 10 wt.% NaCl solution, the upstream pressure was almost constant, whereas, in the test using DI water, the pressure changed from 8 psi to 7 psi. After close observation of the tested sample, they found that particle detachment by clay swelling occurred and caused this pressure drop.

To study permeability change due to water-shale interaction, one set of experiments was performed by Liu and Sheng [12]. In their tests, the upstream pressure was monitored to represent the change of permeability. Figures 21 and 22 show the experimental results.

From Figure 22, pressure data decreased once fractures were generated or propagated. Multiple fractures were generated and interconnected to form flow channels and cause the failure of the sample, resulting in the permanent recovery of shale permeability. In another test, an isolated fracture was generated and did not form an effective flow channel for DI water; thereby, the pressure increased in the test. The results indicated that if the fractures are isolated and could not form an effective flow channel, the fractures did not contribute to the recovery of shale permeability. However, once the fractures form effective flow channels, shale permeability can be recovered. It is seen from Figure 22 that particle detachment occurred on the artificial fracture surface. The detached particles were washed away by the DI water, enhancing the shale permeability.

4.2. Mechanisms about Permeability Change due to Water-Shale Interaction. From those studies, shale permeability can be enhanced if the generated fractures can form an effective flow channel. However, if the generated fractures cannot serve as an effective flow channel, shale permeability will be impaired by clay swelling, water blocking, stress-sensitive, etc. Gas permeability cannot be used to represent the permeability change in water-shale interaction. Pressure monitor cannot quantitatively show the permeability change in water-shale interaction. It is unsolved to quantitatively reflect permeability change by water-shale interaction. More efforts are needed.

Particle detachment affects permeability changes. The permeability of the shale can be increased when the separated particles can be washed away from the shale. Grain

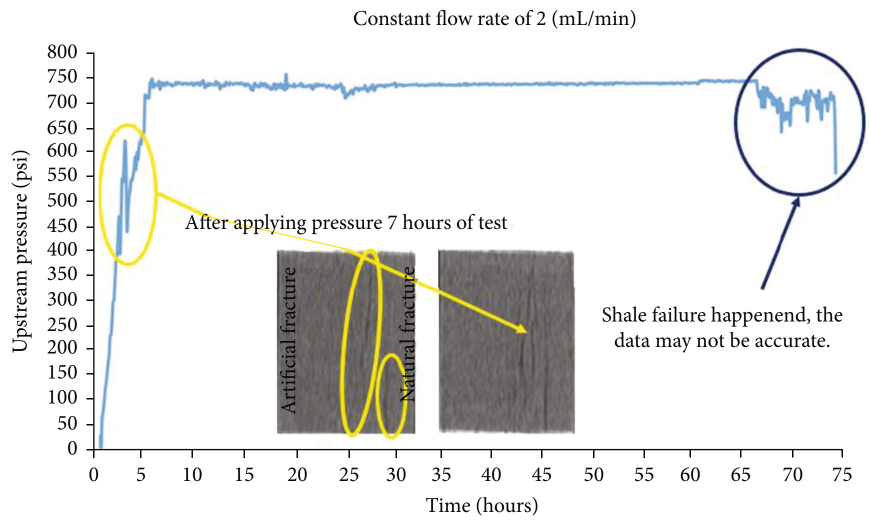


Figure 21: One testing result from Liu and Sheng [12].

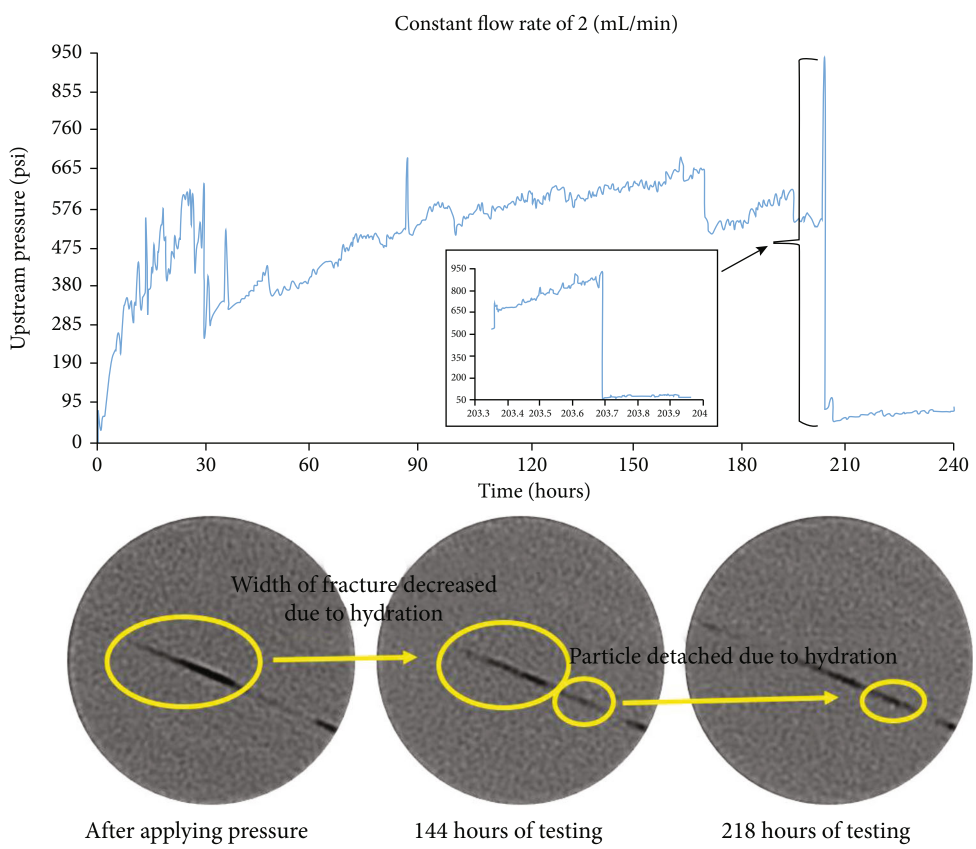


Figure 22: Another testing result from Liu and Sheng [12].

detachment can lead to pore or pore-throat plugging problems, thereby impairing shale permeability. Mohan et al. [118] found that kaolinite and muscovite are more easily detached from the shale surface when swelling occurs. The effects of pH, ion exchange, and brine salt concentration can affect particle separation. Higher pH, lower ionic strength, and low salinity can facilitate separations [119–123]. Whether particle detachment is beneficial to shale permeability depends on whether the detached particles can be transported from the shale.

5. Concluding Remarks

Water-shale interaction is a complex phenomenon. This reaction can cause clay swelling, reduction of mechanical properties of shales, generation and propagation of fractures,

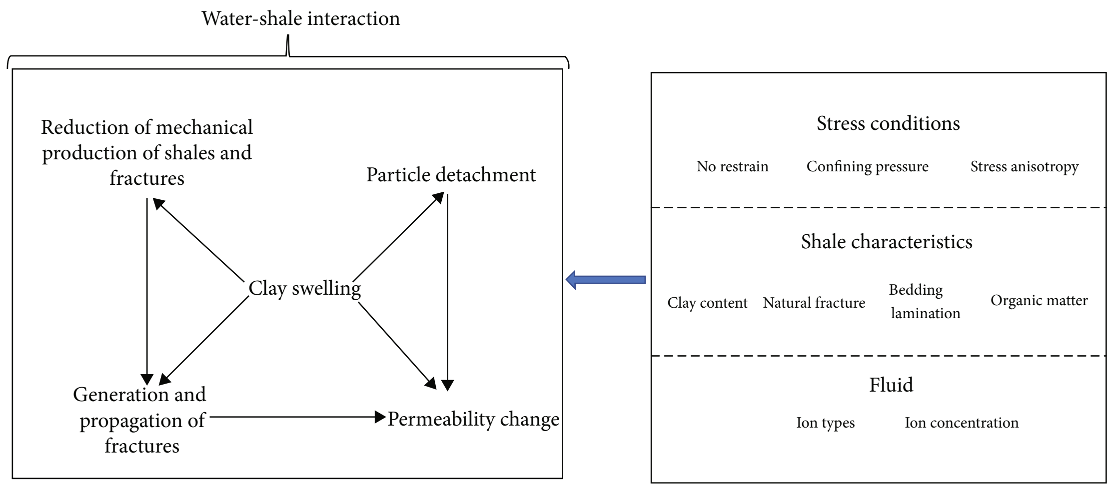


Figure 23: Phenomena appearing in water-shale interaction, the impact between these processes, and the other influencing factors.

particle detachment, permeability change, etc. Other conditions, like stress condition, shale characteristics, and reacting fluid, could influence the reaction. Figure 23 summarizes these phenomena and the relationship between each other.

Clay swelling is the key phenomenon occurring in water-shale interaction. Clay swelling can trigger the generation of fractures, cause the detachment of particles, influence the magnitude of the reduction of mechanical properties of shales and fractures, and impact permeability change. Experiments showed that fracture can be generated in water-shale interaction. The most likely mechanism for the generation of fractures in water-shale interaction is that the induced fractures are generated by the combined effects from clay swelling, reduction of mechanical properties of shales and fractures, and stress anisotropy. However, other mechanisms can induce fractures as well, like the swelling pressure, the mechanical failure caused by the imbibition of water. Whether clay swelling can directly induce fractures under stress conditions is still questionable. To answer this question, a new experimental methodology and apparatus are needed. Ideally, the process of the generation of clay swelling inducing fractures under stress conditions should be monitored and captured in the reaction between water and shale. The effect of clay swelling and stress conditions should be separated. Measuring gas permeability cannot accurately reflect the permeability change by water-shale interaction. Using liquid to measure the liquid permeability is difficult because of the injectivity issue in low permeable shales. Pressure monitoring can qualitatively reflect permeability change in shales. However, it is better to quantitatively reflect the permeability change in water-shale interaction under stress anisotropy. More efforts are needed.

Data Availability

Data are available by contacting the authors.

Additional Points

Highlight. (i) Water-shale interaction can cause clay swelling, change of mechanical properties of shales, generation of fractures, and permeability change. (ii) Fractures are generated by the combined effects from clay swelling, reduction of mechanical properties of shales and fractures, and stress anisotropy. (iii) Both the induced fractures and particle detachment can impact shale permeability. (iv) Stress condition, shale characteristics, and the reacting fluid could influence water-shale interaction.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work is supported by the National Key Research and Development Program of China (No. 2019YFC1805400) and the Fundamental Research Funds for the Central Universities (No. 2020ZDPY0201).

References

[1] F. Aloulou and T. Cook, “Tight oil expected to make up most of U.S. oil production increase through 2040,” 2017, https://www.eia.gov/todayinenergy/detail.php?id=29932.

[2] J. B. Curtis, “Fractured shale-gas systems,” *AAPG Bulletin*, vol. 86, no. 11, pp. 1921–1938, 2002.

[3] J. D. Arthur, B. Bohm, and M. Layne, *Hydraulic fracturing considerations for natural gas wells of the Marcellus shale*, ALL Consulting, LLC, Tulsa, Oklahoma, 2009.

[4] M. E. Mantell, “Recycling and reuse of produced water to reduce freshwater use in hydraulic fracturing operations,” in *Summary of the technical workshop on water acquisition modeling: Assessing impacts through modeling and other means*, U.S. Environmental Protection Agency, Washington, D.C., 2013.

[5] J. J. Sheng, *Enhanced Oil Recovery Field Case Studies*, Gulf Professional Publishing, 2013.

[6] I. Aksu, E. Bazilevskaya, and Z. T. Karpyn, "Swelling of clay minerals in unconsolidated porous media and its impact on permeability," *GeoResJ*, vol. 7, pp. 1–13, 2015.

[7] D. H. Gkay and R. W. Rex, "Formation damage in sandstones caused by clay dispersion and migration," in *Clays and Clay Minerals*, pp. 355–366, Berkeley, California, 1966.

[8] M. J. Wilson, L. Wilson, and I. Patey, "The influence of individual clay minerals on formation damage of reservoir sandstones: a critical review with some new insights," *Clay Minerals*, vol. 49, no. 2, pp. 147–164, 2014.

[9] H. Dehghanpour, Q. Lan, Y. Saeed, H. Fei, and Z. Qi, "Spontaneous imbibition of brine and oil in gas shales: effect of water adsorption and resulting microfractures," *Energy & Fuels*, vol. 27, no. 6, pp. 3039–3049, 2013.

[10] K. Liu and J. J. Sheng, "Experimental study of the effect of stress anisotropy on fracture propagation in Eagle Ford shale under water imbibition," *Engineering Geology*, vol. 249, pp. 13–22, 2019.

[11] H. Roshan, S. Ehsani, C. E. Marjo, M. S. Andersen, and R. I. Acworth, "Mechanisms of water adsorption into partially saturated fractured shales: an experimental study," *Fuel*, vol. 159, pp. 628–637, 2015.

[12] K. Liu and J. J. Sheng, "A new experimental methodology to investigate water adsorption into shale under stress anisotropy conditions," in *SPE Liquids-Rich Basins Conference-North America*, Society of Petroleum Engineers, 2019.

[13] K. Liu, J. J. Sheng, and Z. Zhang, "A simulation study of the effect of clay swelling on fracture generation and porosity change in shales under stress anisotropy," *Engineering Geology*, vol. 278, p. 105829, 2020.

[14] K. Liu and J. J. Sheng, "Experimental study of the effect of temperature change in water-shale interaction on fracture generation and permeability change in shales under stress anisotropy," in *55th US Rock Mechanics/Geomechanics Symposium*, One Petro, 2021.

[15] K. Liu and J. J. Sheng, "Experimental study of the effect of water-shale interaction on fracture generation and permeability change in shales under stress anisotropy," *Journal of Natural Gas Science and Engineering*, vol. 100, article 104474, 2022.

[16] J. Cheng, Z. Wan, Y. Zhang, W. Li, S. S. Peng, and P. Zhang, "Experimental study on anisotropic strength and deformation behavior of a coal measure shale under room dried and water saturated conditions," *Shock and Vibration*, vol. 2015, Article ID 290293, 13 pages, 2015.

[17] A. B. Talal, "A novel experimental technique to monitor the time-dependent water and ions uptake when shale interacts with aqueous solutions," *Rock Mechanics and Rock Engineering*, vol. 46, no. 5, pp. 1145–1156, 2013.

[18] R. C. K. Wong, "Swelling and softening behaviour of La Biche shale," *Canadian Geotechnical Journal*, vol. 35, no. 2, pp. 206–221, 1998.

[19] X. Chen, P. Eichhubl, J. E. Olson, and T. A. Dewers, "Effect of water on fracture mechanical properties of shales," *Journal of Geophysical Research: Solid Earth*, vol. 124, no. 3, pp. 2428–2444, 2019.

[20] X. Chen, P. Eichhubl, J. E. Olson, and T. A. Dewers, "Salinity, pH, and temperature controls on fracture mechanical properties of three shales and their implications for fracture growth in chemically reactive fluid environments," *Geomechanics for Energy and the Environment*, vol. 21, article 100140, 2020.

[21] Y. Nara, K. Morimoto, T. Yoneda, N. Hiroyoshi, and K. Kaneko, "Effects of humidity and temperature on subcritical crack growth in sandstone," *International Journal of Solids and Structures*, vol. 48, no. 7-8, pp. 1130–1140, 2011.

[22] Y. Nara, H. Yamanaka, Y. Oe, and K. Kaneko, "Influence of temperature and water on subcritical crack growth parameters and longterm strength for igneous rocks," *Geophysics Journal International*, vol. 193, no. 1, pp. 47–60, 2013.

[23] T. Waza, K. Kurita, and H. Mizutani, "The effect of water on the subcritical crack growth in silicate rocks," *Tectonophysics*, vol. 67, no. 1-2, pp. 25–34, 1980.

[24] Y. Shen, H. Ge, M. Meng, Z. Jiang, and X. Yang, "Effect of water imbibition on shale permeability and its influence on gas production," *Energy & Fuels*, vol. 31, no. 5, pp. 4973–4980, 2017.

[25] Q. Wang, C. Lyu, and D. R. Cole, "Effects of hydration on fractures and shale permeability under different confining pressures: an experimental study," *Journal of Petroleum Science and Engineering*, vol. 176, pp. 745–753, 2019.

[26] S. Tangparitkul, A. Saul, C. Leelasukseree, M. Yusuf, and A. Kalantariasl, "Fines migration and permeability decline during reservoir depletion coupled with clay swelling due to low-salinity water injection: an analytical study," *Journal of Petroleum Science and Engineering*, vol. 194, article 107448, 2020.

[27] F. T. Mackenzie and R. M. Garrels, *Evolution of Sedimentary Rocks*, Norton, New York, 1971.

[28] F. R. Sattler and D. A. Barnes, "Geological characterization and assessment of confining layer potential of the Upper Ordovician Utica shale, Michigan Basin, USA," in *Paleozoic Stratigraphy and Resources of the Michigan Basin*, G. M. Grammar, W. B. Harrison, and D. A. Barnes, Eds., vol. 531, pp. 35–54, Geological Society of America, USA, 2018.

[29] D. M. Wang, Y. M. Xu, D. M. He, J. Guan, and O. M. Zhang, "Investigation of mineral composition of oil shale," *Asia-Pacific Journal of Chemical Engineering*, vol. 4, no. 5, pp. 691–697, 2009.

[30] D. H. Yaaton, "Mineral composition of the average shale," *Clay Minerals Bulletin*, vol. 5, no. 27, pp. 31–36, 1962.

[31] J. W. De Leeuw and C. Largeau, "A review of macromolecular organic compounds that comprise living organisms and their role in kerogen, coal, and petroleum formation," in *Organic Geochemistry*, M. H. Engel and S. A. Macko, Eds., vol. 11 of Topics in Geobiology, pp. 23–72, Springer, Boston, MA, 1993.

[32] A. C. Hutton, A. J. Kantsler, A. C. Cook, and D. M. McKirdy, "Organic matter in oil shales," *The APPEA Journal*, vol. 20, no. 1, pp. 44–67, 1980.

[33] M. H. Bhuiyan, M. I. Kolstø, and R. M. Holt, "Effects of stress and strain on wave velocities in compacted sand-kaolinite and kaolinite-smectite," in *73rd EAGE Conference and Exhibition incorporating SPE EUROPEC 2011*, p. 238, European Association of Geoscientists & Engineers, 2011.

[34] E. Fjar, R. M. Holt, A. M. Raaen, and P. Horsrud, *Petroleum Related Rock Mechanics*, Elsevier, 2008.

[35] M. E. Best and T. J. Katsube, "Shale permeability and its significance in hydrocarbon exploration," *The Leading Edge*, vol. 14, no. 3, pp. 165–170, 1995.

[36] A. Salama, M. F. E. Amin, K. Kumar, and S. Sun, "Flow and transport in tight and shale formations: a review," *Geofluids*, vol. 2017, Article ID 4251209, 21 pages, 2017.

[37] J. Cui, Q. Sang, Y. Li, C. Yin, Y. Li, and M. Dong, "Liquid permeability of organic nanopores in shale: calculation and analysis," *Fuel*, vol. 202, pp. 426–434, 2017.

[38] J. F. Gale and J. Holder, "Natural fractures in some US shales and their importance for gas production," *Geological Society, London, Petroleum Geology Conference Series*, vol. 7, no. 1, pp. 1131–1140, 2010.

[39] J. F. Gale, S. E. Laubach, J. E. Olson, P. Eichhubl, and A. Fall, "Natural fractures in shale: a review and new observations," *AAPG Bulletin*, vol. 98, no. 11, pp. 2165–2216, 2014.

[40] M. Mokhtari, B. T. Bui, and A. N. Tutuncu, "Tensile failure of shales: impacts of layering and natural fractures," in *SPE Western North American and Rocky Mountain Joint Meeting*, Society of Petroleum Engineers, 2014.

[41] C. M. Bethke, "Modeling subsurface flow in sedimentary basins," *Geologische Rundschau*, vol. 78, no. 1, pp. 129–154, 1989.

[42] H. van Olphen, *Clay Colloid Chemistry*, John Wiley & Sons Inc, New York City, 2nd edition, 1977.

[43] P. C. Kariuki, T. Woldai, and F. Van Der Meer, "Effectiveness of spectroscopy in identification of swelling indicator clay minerals," *International Journal of Remote Sensing*, vol. 25, no. 2, pp. 455–469, 2004.

[44] H. H. Murray, "Traditional and new applications for kaolin, smectite, and palygorskite: a general overview," *Applied Clay Science*, vol. 17, no. 5-6, pp. 207–221, 2000.

[45] K. H. Head, *Manual of Soil Laboratory Testing*, Pentech Press, London, 1992.

[46] J. H. Park, H. J. Shin, M. H. Kim et al., "Application of montmorillonite in bentonite as a pharmaceutical excipient in drug delivery systems," *Journal of Pharmaceutical Investigation*, vol. 46, no. 4, pp. 363–375, 2016.

[47] H. Singh, "A critical review of water uptake by shales," *Journal of Natural Gas Science and Engineering*, vol. 34, pp. 751–766, 2016.

[48] E. J. Hensen and B. Smit, "Why clays swell," *The Journal of Physical Chemistry B*, vol. 106, no. 49, pp. 12664–12667, 2002.

[49] F. T. Madsen and M. Müller-Vonmoos, "The swelling behaviour of clays," *Applied Clay Science*, vol. 4, no. 2, pp. 143–156, 1989.

[50] H. Santos and S. A. B. da Fontoura, "Concepts and misconceptions of mud selection criteria: how to minimize borehole stability problems?," in *SPE Annual Technical Conference and Exhibition*, Society of Petroleum Engineers, 1997.

[51] H. Santos, S. A. B. da Fontoura, A. Gupta, and J. C. Roegiers, "Laboratory tests for wellbore stability in deepwater, Brazil," in *Latin American and Caribbean Petroleum Engineering Conference*, Society of Petroleum Engineers, 1997.

[52] M. E. Chenevert, "Shale alteration by water adsorption," *Journal of Petroleum Technology*, vol. 22, no. 9, pp. 1141–1148, 1970.

[53] A. I. Al-Mhaidib and M. A. Al-Shamrani, "Influence of swell on shear strength of expansive soils," in *Advances in Unsaturated Soil, Seepage, and Environmental Geotechnics*, pp. 160–165, Melbourne, Australia, 2006.

[54] A. A. Sabtan, "Geotechnical properties of expansive clay shale in Tabuk, Saudi Arabia," *Journal of Asian Earth Sciences*, vol. 25, no. 5, pp. 747–757, 2005.

[55] I. C. Gomez-Gutierrez, L. S. Bryson, and T. C. Hopkins, "Correlations between geotechnical properties and the swell behavior of compacted shales," in *Geo-Frontiers 2011: Advances in Geotechnical Engineering*, pp. 4119–4128, Dallas, Texas, United States, 2011.

[56] L. S. Bryson, I. C. Gomez-Gutierrez, and T. C. Hopkins, "Development of a new durability index for compacted shale," *Engineering Geology*, vol. 139-140, pp. 66–75, 2012.

[57] M. A. Al-Shamrani and A. W. Dhowian, "Experimental study of lateral restraint effects on the potential heave of expansive soils," *Engineering Geology*, vol. 69, no. 1-2, pp. 63–81, 2003.

[58] Q. Lyu, P. G. Ranjith, X. Long, Y. Kang, and M. Huang, "A review of shale swelling by water adsorption," *Journal of Natural Gas Science and Engineering*, vol. 27, pp. 1421–1431, 2015.

[59] Z. W. Wang, S. L. Huang, and R. C. Speck, "Swelling behavior of shales in cold regions," *Journal of Cold Regions Engineering*, vol. 8, no. 1, pp. 21–34, 1994.

[60] S. L. Huang, R. C. Speck, and Z. Wang, "The temperature effect on swelling of shales under cyclic wetting and drying," *Pergamon*, vol. 32, no. 3, pp. 227–236, 1995.

[61] Z. Li, Y. Duan, Y. Peng, M. Wei, and R. Wang, "A laboratory study of microcracks variations in shale induced by temperature change," *Fuel*, vol. 280, article 118636, 2020.

[62] P. Fakcharoenphol, S. Charoenwongsa, H. Kazemi, and Y. S. Wu, "The effect of water-induced stress to enhance hydrocarbon recovery in shale reservoirs," *SPE Journal*, vol. 18, no. 5, pp. 897–909, 2013.

[63] P. A. Siratovich, I. Sass, S. Homuth, and A. Bjornsson, "Thermal stimulation of geothermal reservoirs and laboratory investigation of thermally-induced fractures," *GRC Transactions*, vol. 35, pp. 1529–1535, 2011.

[64] C. L. G. Amorim, R. T. Lopes, R. C. Barroso et al., "Effect of clay-water interactions on clay swelling by X-ray diffraction," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 580, no. 1, pp. 768–770, 2007.

[65] O. F. Joel, U. J. Durueke, and C. U. Nwokoye, "Effect of KCL on rheological properties of shale contaminated water-based MUD (WBM)," *Global Journals Inc.(USA)*, vol. 12, no. 1, 2012.

[66] S. Morsy and J. J. Sheng, "Imbibition characteristics of the Barnett shale formation," in *SPE Unconventional Resources Conference*, Society of Petroleum Engineers, 2014.

[67] F. Liang, J. Zhang, H. H. Liu, and K. M. Bartko, "Multiscale experimental studies on interactions between aqueous-based fracturing fluids and tight organic-rich carbonate source rocks," in *SPE Kingdom of Saudi Arabia Annual Technical Symposium and Exhibition*, Society of Petroleum Engineers, 2018.

[68] K. Makhanov, H. Dehghanpour, and E. Kuru, "An experimental study of spontaneous imbibition in Horn river shales," in *SPE Canadian unconventional resources conference*, Society of Petroleum Engineers, 2012.

[69] S. S. Morsy, J. J. Sheng, and M. Y. Soliman, "Improving hydraulic fracturing of shale formations by acidizing," in *SPE Eastern Regional Meeting*, Society of Petroleum Engineers, 2013.

[70] S. Morsy and J. J. Sheng, "Effect of water salinity on shale reservoir productivity," *Advances in Petroleum Exploration and Development*, vol. 8, no. 1, pp. 9–14, 2014.

[71] S. Morsy, A. Gomaa, and J. J. Sheng, "Imbibition characteristics of Marcellus shale formation," in *SPE Improved Oil Recovery Symposium*, Society of Petroleum Engineers, 2014.

[72] S. Morsy, A. Gomaa, and J. J. Sheng, "Improvement of eagle ford shale formations water imbibition by mineral dissolution and wettability alteration," in *SPE Unconventional Resources Conference*, Society of Petroleum Engineers, 2014.

[73] S. Morsy, J. J. Sheng, A. M. Gomaa, and M. Y. Soliman, "Potential of improved waterflooding in acid-hydraulically-fractured shale formations," in *SPE Annual Technical Conference and Exhibition*, Society of Petroleum Engineers, 2013.

[74] L. L. Wang, G. Q. Zhang, S. Hallais, A. Tanguy, and D. S. Yang, "Swelling of shales: a multiscale experimental investigation," *Energy & Fuels*, vol. 31, no. 10, pp. 10442–10451, 2017.

[75] Z. Zhou, H. Abass, X. Li, and T. Teklu, "Experimental investigation of the effect of imbibition on shale permeability during hydraulic fracturing," *Journal of Natural Gas Science and Engineering*, vol. 29, pp. 413–430, 2016.

[76] Q. I. A. N. Bin, Z. H. U. Juhui, Y. A. N. G. Hai et al., "Experiments on shale reservoirs plugs hydration," *Petroleum Exploration and Development*, vol. 44, no. 4, pp. 652–658, 2017.

[77] S. Zhang and J. J. Sheng, "Effects of salinity and confining pressure on hydration-induced fracture propagation and permeability of Mancos shale," *Rock Mechanics and Rock Engineering*, vol. 50, no. 11, pp. 2955–2972, 2017.

[78] S. Zhang and J. J. Sheng, "Effect of water imbibition on fracture generation in Mancos shale under isotropic and anisotropic stress conditions," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 144, no. 2, 2018.

[79] S. Zhang, J. J. Sheng, and Z. Shen, "Effect of hydration on fractures and permeabilities in Mancos, Eagleford, Barnette and Marcellus shale cores under compressive stress conditions," *Journal of Petroleum Science and Engineering*, vol. 156, pp. 917–926, 2017.

[80] Z. Liu, J. Shao, W. Xu, and Y. Meng, "Prediction of rock burst classification using the technique of cloud models with attribution weight," *Natural Hazards*, vol. 68, no. 2, pp. 549–568, 2013.

[81] S. P. Singh, "Burst energy release index," *Rock Mechanics and Rock Engineering*, vol. 21, no. 2, pp. 149–155, 1988.

[82] J. Zhou, X. Li, and H. S. Mitri, "Evaluation method of rockburst: state-of-the-art literature review," *Tunnelling and Underground Space Technology*, vol. 81, pp. 632–659, 2018.

[83] R. T. Ewy and R. J. Stankovic, "Shale swelling, osmosis, and acoustic changes measured under simulated downhole condition," *SPE Drilling & Completion*, vol. 25, no. 2, pp. 177–186, 2010.

[84] Y. Wang, X. Liu, L. Liang, and J. Xiong, "Experimental study on the damage of organic-rich shale during water-shale interaction," *Journal of Natural Gas Science and Engineering*, vol. 74, article 103103, 2020.

[85] A. Ougier-Simonin, F. Renard, C. Boehm, and S. Vidal-Gilbert, "Microfracturing and microporosity in shales," *Earth-Science Reviews*, vol. 162, pp. 198–226, 2016.

[86] Q. Lei, J. P. Latham, J. Xiang, and C. F. Tsang, "Role of natural fractures in damage evolution around tunnel excavation in fractured rocks," *Engineering Geology*, vol. 231, pp. 100–113, 2017.

[87] W. Wang, J. E. Olson, M. Prodanović, and R. A. Schultz, "Interaction between cemented natural fractures and hydraulic fractures assessed by experiments and numerical simulations," *Journal of Petroleum Science and Engineering*, vol. 167, pp. 506–516, 2018.

[88] Z. Moradian, A. Seiphoori, and B. Evans, "The role of bedding planes on fracture behavior and acoustic emission response of shale under unconfined compression," in *51st US Rock Mechanics/Geomechanics Symposium*, American Rock Mechanics Association, 2017.

[89] E. Ghanbari and H. Dehghanpour, "Impact of rock fabric on water imbibition and salt diffusion in gas shales," *International Journal of Coal Geology*, vol. 138, pp. 55–67, 2015.

[90] M. F. Romero-Sarmiento, J. N. Rouzaud, S. Bernard, D. Deldicque, M. Thomas, and R. Littke, "Evolution of Barnett shale organic carbon structure and nanostructure with increasing maturation," *Organic Geochemistry*, vol. 71, pp. 7–16, 2014.

[91] H. Xue, S. Zhou, Y. Jiang, F. Zhang, Z. Dong, and W. Guo, "Effects of hydration on the microstructure and physical properties of shale," *Petroleum Exploration and Development*, vol. 45, no. 6, pp. 1146–1153, 2018.

[92] H. Li, B. Lai, H. H. Liu, J. Zhang, and D. Georgi, "Experimental investigation on Brazilian tensile strength of organic-rich gas shale," *SPE Journal*, vol. 22, no. 1, pp. 148–161, 2017.

[93] L. Yang, H. Ge, Y. Shen et al., "Imbibition inducing tensile fractures and its influence on in-situ stress analyses: a case study of shale gas drilling," *Journal of Natural Gas Science and Engineering*, vol. 26, pp. 927–939, 2015.

[94] J. Du, L. Hu, J. N. Meegoda, and G. Zhang, "Shale softening: observations, phenomenological behavior, and mechanisms," *Applied Clay Science*, vol. 161, pp. 290–300, 2018.

[95] O. M. Akrad, J. L. Miskimins, and M. Prasad, "The effects of fracturing fluids on shale rock mechanical properties and proppant embedment," in *SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers*, OnePetro, Denver, Colorado, USA, 2011.

[96] Z. Yang, L. Wang, G. Zhang, and C. Ho, "Micromechanical characterization of fluid-shale interactions via nanoindentation," in *SPE Asia Pacific Hydraulic Fracturing Conference*, Society of Petroleum Engineers, 2016.

[97] J. Pedlow and M. Sharma, "Changes in shale fracture conductivity due to interactions with water-based fluids," in *SPE Hydraulic Fracturing Technology Conference*, Society of Petroleum Engineers, 2014.

[98] T. A. Jansen, D. Zhu, and A. D. Hill, "The effect of rock mechanical properties on fracture conductivity for shale formations," in *SPE Hydraulic Fracturing Technology Conference*, OnePetro, 2015.

[99] B. K. Atkinson, *Fracture Mechanics of Rock*, Elsevier, 2015.

[100] B. K. Atkinson, "A fracture mechanics study of subcritical tensile cracking of quartz in wet environments," *Pure and Applied Geophysics*, vol. 117, no. 5, pp. 1011–1024, 1979.

[101] B. K. Atkinson and P. G. Meredith, "Stress corrosion cracking of quartz: a note on the influence of chemical environment," *Tectonophysics*, vol. 77, no. 1-2, pp. T1–T11, 1981.

[102] R. J. Martin, "Time-dependent crack growth in quartz and its application to the creep of rocks," *Journal of Geophysical Research*, vol. 77, no. 8, pp. 1406–1419, 1972.

[103] C. H. Scholz, "Static fatigue of quartz," *Journal of Geophysical Research*, vol. 77, no. 11, pp. 2104–2114, 1972.

[104] M. V. Swain, J. S. Williams, B. R. Lawn, and J. J. H. Beek, "A comparative study of the fracture of various silica

modifications using the Hertzian test," *Journal of Materials Science*, vol. 8, no. 8, pp. 1153–1164, 1973.

[105] Y. Nara, K. Morimoto, N. Hiroyoshi, T. Yoneda, K. Kaneko, and P. M. Benson, "Influence of relative humidity on fracture toughness of rock: implications for subcritical crack growth," *International Journal of Solids and Structures*, vol. 49, no. 18, pp. 2471–2481, 2012.

[106] L. Ji and T. Geehan, "Shale failure around hydraulic fractures in water fracturing of shale gas," in *SPE Unconventional Resources Conference Canada*, Society of Petroleum Engineers, 2013.

[107] R. P. Steiger, "Fundamentals and use of potassium/polymer drilling fluids to minimize drilling and completion problems associated with hydratable clays," *Journal of Petroleum Technology*, vol. 34, no. 8, pp. 1661–1670, 1982.

[108] M. Xu, A. Gupta, and H. Dehghanpour, "How significant are strain and stress induced by water imbibition in dry gas shales?," *Journal of Petroleum Science and Engineering*, vol. 176, pp. 428–443, 2019.

[109] R. Nuesch, F. T. Madsen, and W. Steiner, "Long time swelling of anhydritic rocks: mineralogical and microstructural evaluation," in *8th ISRM Congress*, International Society for Rock Mechanics and Rock Engineering, 1995.

[110] K. Makhanov, A. Habibi, H. Dehghanpour, and E. Kuru, "Liquid uptake of gas shales: a workflow to estimate water loss during shut-in periods after fracturing operations," *Journal of Unconventional Oil and Gas Resources*, vol. 7, pp. 22–32, 2014.

[111] X. Weng, V. Sesetty, and O. Kresse, "Investigation of shear-induced permeability in unconventional reservoirs," in *49th US Rock Mechanics/Geomechanics Symposium*, American Rock Mechanics Association, 2015.

[112] T. Zhou, S. Zhang, L. Yang, X. Ma, Y. Zou, and H. Lin, "Experimental investigation on fracture surface strength softening induced by fracturing fluid imbibition and its impacts on flow conductivity in shale reservoirs," *Journal of Natural Gas Science and Engineering*, vol. 36, pp. 893–905, 2016.

[113] R. Feng, S. Chen, S. Bryant, and J. Liu, "Stress-dependent permeability measurement techniques for unconventional gas reservoirs: review, evaluation, and application," *Fuel*, vol. 256, article 115987, 2019.

[114] B. Yuan, Y. Wang, and Z. Shunpeng, "Effect of slick water on permeability of shale gas reservoirs," *Journal of Energy Resources Technology*, vol. 140, no. 11, 2018.

[115] J. Behnsen and D. R. Faulkner, "Water and argon permeability of phyllosilicate powders under medium to high pressure," *Earth*, vol. 116, no. B12, 2011.

[116] Q. Duan and X. Yang, "Experimental studies on gas and water permeability of fault rocks from the rupture of the 2008 Wenchuan earthquake, China," *Science China Earth Sciences*, vol. 57, no. 11, pp. 2825–2834, 2014.

[117] A. A. Moghadam and R. Chalaturnyk, "Laboratory investigation of shale permeability," in *SPE/CSUR Unconventional Resources Conference*, Society of Petroleum Engineers, 2015.

[118] K. K. Mohan, H. S. Fogler, R. N. Vaidya, and M. G. Reed, "Water sensitivity of sandstones containing swelling and non-swelling clays," in *Colloids in the Aquatic Environment*, pp. 237–254, Elsevier, 1993.

[119] J. A. Bergendahl and D. Grasso, "Mechanistic basis for particle detachment from granular media," *Environmental Science & Technology*, vol. 37, no. 10, pp. 2317–2322, 2003.

[120] J. Bergendahl and D. Grasso, "Prediction of colloid detachment in a model porous media: thermodynamics," *AICHE Journal*, vol. 45, no. 3, pp. 475–484, 1999.

[121] H. H. Murray, "Chapter 2 structure and composition of the clay minerals and their physical and chemical properties," in *Developments in Clay Science*, H. H. Murray, Ed., vol. 2, pp. 7–31, Elsevier, 2006.

[122] H. Roshan, M. A. Q. Siddiqui, K. Regenauer-Lieb, A. Lv, A. Hedayat, and M. Serati, "Digital multiphysics interferometry: a new approach to study chemo-thermo-hydro-mechanical interactions in geomaterials," in *52nd US Rock Mechanics/Geomechanics Symposium*, American Rock Mechanics Association, 2018.

[123] Y. Zhuang, X. Liu, H. Xiong, and L. Liang, "Microscopic mechanism of clay minerals on reservoir damage during steam injection in unconsolidated sandstone," *Energy & Fuels*, vol. 32, no. 4, pp. 4671–4681, 2018.

[124] H. Dehghanpour, H. A. Zubair, A. Chhabra, and A. Ullah, "Liquid intake of organic shales," *Energy & Fuels*, vol. 26, no. 9, pp. 5750–5758, 2012.

[125] T. Engelder, L. M. Cathles, and L. T. Bryndzia, "The fate of residual treatment water in gas shale," *Journal of Unconventional Oil and Gas Resources*, vol. 7, pp. 33–48, 2014.

[126] P. Fakcharoenphol, B. Kurtoglu, H. Kazemi, S. Charoenwongsa, and Y. S. Wu, "The effect of osmotic pressure on improve oil recovery from fractured shale formations," in *SPE Unconventional Resources Conference*, Texas, USA, 2014.

[127] H. Roshan, A. Z. Al-Yaseri, M. Sarmadivaleh, and S. Iglauer, "On wettability of shale rocks," *Journal of Colloid and Interface Science*, vol. 475, pp. 104–111, 2016.

[128] H. Roshan, M. S. Andersen, H. Rutlidge, C. E. Marjo, and R. I. Acworth, "Investigation of the kinetics of water uptake into partially saturated shales," *Water Resources Research*, vol. 52, no. 4, pp. 2420–2438, 2016.