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Mechanism of the Production Impact in Shale Gas Wells Caused by Water Invasion during Interwell Interference

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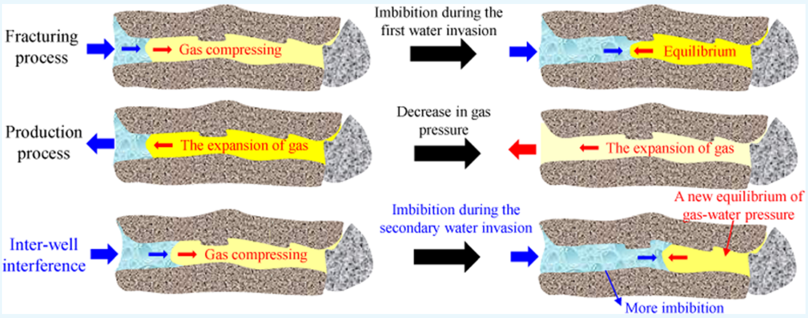

ABSTRACT: Interwell interference is a universal problem in shale gas development and can cause severe reductions in the productivity of producing wells. Studies have attempted to identify the root cause of interference in producing wells, but the mechanisms of production reduction and recovery in impacted wells are still not clear. Thus, an effective preventive strategy is needed for producing wells when fracturing is performed in adjacent wells. According to the mechanism of spontaneous imbibition and water drainage in shale mico- and nanoscale pores, this paper introduces the water−gas distribution during fracturing and production and reveals that water drainage in micro- and nanoscale pores is mainly controlled by the amount of stored gas and follows the order of pore size. Based on this analysis, the mechanism by which interwell interference impacts the production of producing wells is explained for the first time. It is concluded that the secondary water invasion caused by interwell interference completely blocks the pores associated with long-term gas production but has little influence on the pores that have not yet drained or have produced only a small amount of gas, and smaller pores face a greater risk of water blockage. The proportion of drained pores formed during long-term gas production determines the effect of interwell interference on production; when more pores are drained by long-term gas production, greater damage occurs to the productivity of the producing well. The suggestion for preventing interwell interference is to reduce the time interval between fracturing operations at two adjacent wells, thereby diminishing the reduction in production.

1. INTRODUCTION

Annual shale gas production in China has grown rapidly over the past 10 years[1] due to the development of drilling and fracturing technology.[2,3] However, the production from shale gas wells declines rapidly in the first year,[4,5] and an increasing number of infill wells are planned to be drilled and stimulated in the main shale gas producing areas to increase shale gas production to meet the national goal of 80−100 billion cubic meters by 2030.[1,6,7] Increasing the number of shale gas wells per unit area increases the recovery ratio, but it increases the risk of interwell interference, especially when the commonly used techniques of infill multibranch horizontal wells and multistage and massive hydraulic fracturing are employed.[8−11] It is known that the average cost of a shale gas well can reach millions of dollars, while the main way to recover the cost is gas production; thus, high yield is the goal of oil and gas companies. However, interwell interference is becoming a major obstacle to increasing production.[5,12−15]

Currently, interwell interference is one of the most common problems in the main shale gas development areas in the Sichuan Basin.[10,16] Once a producing well is impacted by fracturing of an adjacent well, its production decreases to a certain degree.[9,17,18] The main causes of interwell interference are as follows:[16,18−20] (1) When there is no fracture communication between the two adjacent wells (Figure 1a), interference occurs through water imbibition in a number of

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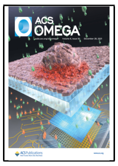

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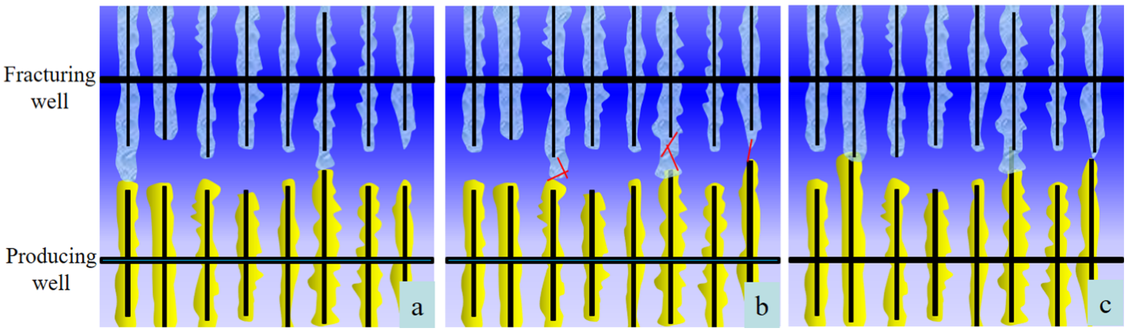

Figure 1. Different patterns of interwell interference through (a) water imbibition in pores, (b) natural fractures, and (c) hydraulic fractures.

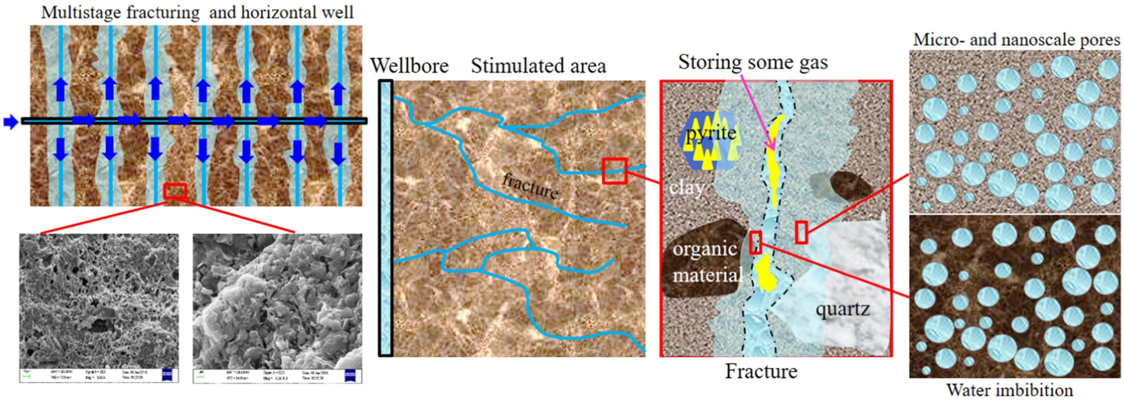

Figure 2. Fracturing fluid distribution and water imbibition in shale gas wells. A large amount of fracturing fluid in fractures will spontaneously enter matrix pores during crack propagation due to the characteristics of shale; thus, the fractures and the pores connected with the fractures fill with fracturing fluid.

pores. Although the fracturing fluid in the fracturing well will not rush into the producing well, it can still affect the pressure and production of the producing well. (2) Interwell interference can occur through natural fracture communication (Figure 1b) or hydraulic fracture communication (Figure 1c). A large amount of fracturing fluid in the fracturing well will rush into the producing well, which will increase the water production in the producing well and cause obvious reservoir damage.[16] Moreover, the stimulated efficiency of the fracturing well decreases.[19,21]

The influence of interwell interference on producing wells is serious. First, the invasion of large amounts of high-pressure fracturing fluid can impact the cementing stability, causing casing failure and even wall collapse.[22] Second, proppants in fractures can be drawn out into the wellbore along with the injected water,[16−18,23,24] which reduces the fracture conductivity. Third, the invasion of a large amount of fracturing fluid can reduce gas production and increase water production.[16,17,19] The mechanism of reducing production in producing wells caused by interwell interference is complex.[21,25] For two adjacent wells with no fracture communication, interference is mainly generated by the pressure difference between the fracturing well and the producing well.[6,16] The width of fractures decreases, and the conductivity decreases owing to the pressure difference. For two adjacent wells with water communication, casing failure can interfere with production,[16] proppant flowback can decrease fracture conductivity,[23] and there can be a reduction in gas flow efficiency.[26,27] Additionally, Swanson et al.[28] suggested that a large number of clay mineral particles, mainly illite, can migrate in sand-packed fractures and eventually expand to plug effective seepage paths, thus reducing the reservoir permeability. Esquivel and Blasingame[18] proposed that the extraction of injected water results in the use of additional energy for producing wells; moreover, the reservoir pressure of the producing wells decreases faster due to the connectivity of the two adjacent wells. The above cases illustrate the phenomenon of gas production reduction but do not clarify the reason for the different degrees of production recovery in various impacted wells.

Several studies have studied the production recovery of impacted producing wells as a function of the remaining reservoir energy. From a statistical analysis of the Arkoma basin, Ajani and Kelkar[23] concluded that the probability of being impacted by interwell interference increases with the production age of producing wells. He et al.[16] analyzed the relation between the production recovery degree and production age through a statistical analysis of the Sichuan Basin and found that the difficulty of production recovery increases with the production age of the well. Mukherjee et al.[29] explained that the probability of fracture propagation toward the producing well increases when the pressure difference between the producing well and the fracturing well increases. However, these studies are just statistical analyses, and the detailed mechanism remains unclear.

In this study, the mechanism of the impact of interwell interference on producing wells is analyzed according to the principles of spontaneous imbibition and water−gas extraction in shale pores. It is concluded that the secondary water invasion caused by interwell interference completely blocks the pores undergoing long-term gas production but has little influence on the pores that have not yet drained or have

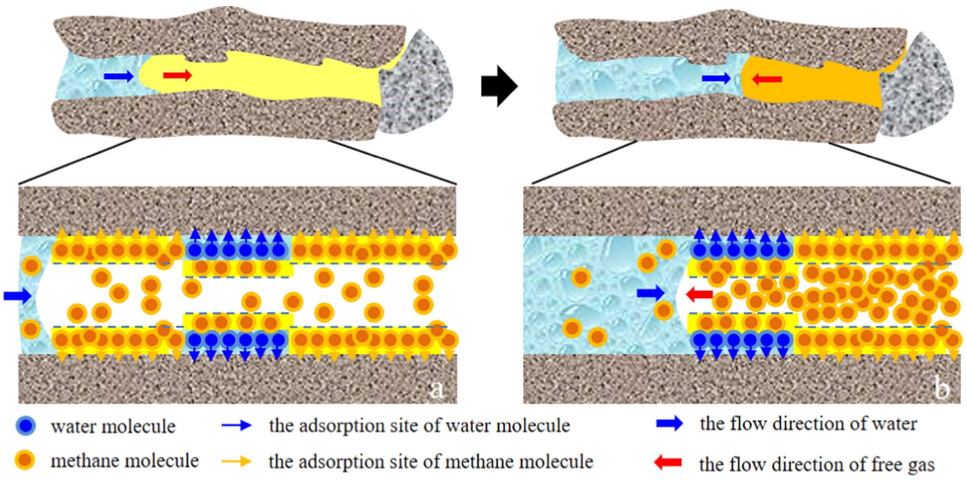

Figure 3. Effects of imbibed water on adsorbed gas and free gas. (a) The imbibition process and (b) the equilibrium state of imbibition. The imbibed fracturing fluid will compete to control the adsorption sites of adsorbed gas; thus, adsorbed gas desorbs as free gas. The imbibition of water compresses the free gas until the increasing gas pressure is equal to the water phase pressure.

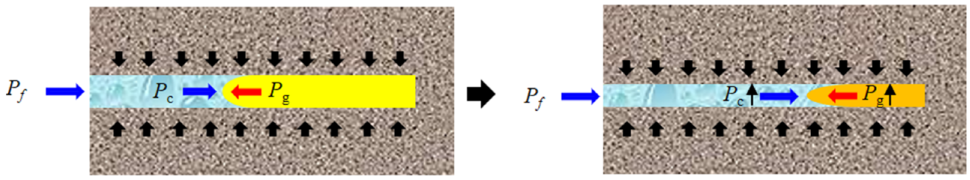

Figure 4. Pore compression increases capillary pressure and then promotes imbibition until a new gas−water equilibrium state appears.

produced only a small amount of gas. The proportion of pores drained by long-term gas production determines the degree of production damage by interwell interference; when more pores have been drained by long-term gas production, greater damage occurs to the productivity of producing wells.

2. BASIC THEORY AND EXPERIMENTS

2.1. Micro- and Nanoscale Pores are Impacted by Imbibition for the First Time during the Fracturing Process. *2.1.1. Water is Easily Imbibed into Micro- and Nanoscale Pores.* The original water of shale gas wells is very little and generally irreducible, but actually, water is extracted along with gas throughout the life of shale gas wells, and less than 30% of water is extracted during the initial period.[30−32] The only reason is that the produced water is mainly the fracturing fluid imbibed in microfractures and matrix pores during the fracturing process.[33,34] During the fracturing period, a large amount of fracturing fluid in fractures will spontaneously enter matrix pores during crack propagation; thus, the fractures and the pores connected with the fractures fill with fracturing fluid,[35,36] as shown in Figure 2. During the flowback period, the fracturing fluid in the fractures and wellbore is easily extracted with a high yield during the next 100 days, while the imbibed fluid in pores is extracted with difficulty at a lower and more stable rate during the lifespan of the shale gas well. This phenomenon is mainly a function of the capillary pressure that promotes the imbibition of fracturing fluid by matrix pores[37,38] and prevents the outflow of imbibed fracturing fluid from matrix pores.[39,40]

The mechanism of spontaneous imbibition in reservoir shales is complex due to the characteristics of shale gas reservoirs, such as the quantity of micro- and nanoscale pores, large surface area-to-volume ratio, low original water saturation, and high content of clay minerals.[41,42] The pore distribution in shale is mainly composed of micro- and nanoscale pores, and a large amount of fracturing fluid may be imbibed under the high capillary pressure of these pores during fracturing.[43,44]

2.1.2. Gas is Trapped in Pores after Water Imbibition. As shown in Figures 2 and 3, gas will be trapped in pores after water imbibition during fracturing, which can be extracted until fracturing fluid in fractures and pore entrances connected with the fractures is discharged. The main trapping mechanism is: first, the imbibed fracturing fluid will compete to control the adsorption sites of adsorbed gas owing to the stronger adsorption capacity of water molecules; thus, when the adsorbed gas is affected by the imbibed water, it desorbs as free gas;[45−49] second, because of the limited pore length in shale and the high imbibition pressures generated mainly by the capillary pressure and the displacement pressure, the imbibition of water compresses the free gas until the increasing gas pressure is equal to the water phase pressure,[35,50] as shown in Figure 3. The following equations can be proposed for the gas−water equilibrium state

$$P_f + P_c = P_g \tag{1}$$

For circular pores, the capillary pressure is

$$P_c = \frac{4\sigma\cos\theta}{d} \tag{2}$$

Gas pressure in circular pores can be obtained by the following gas-state equation

$$P_g = \frac{4nZRT}{\pi d^2 L} \tag{3}$$

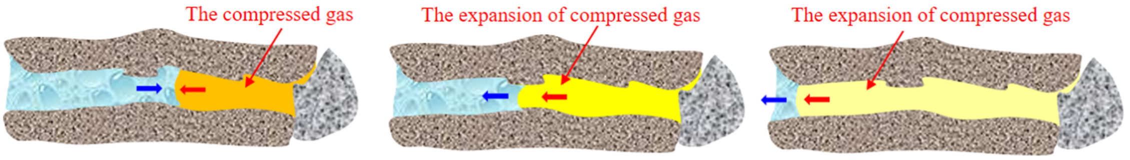

Figure 5. Principle of water drainage in pores. Gas expansion is the main cause of water drainage in micro- and nanoscale pores in reservoirs.

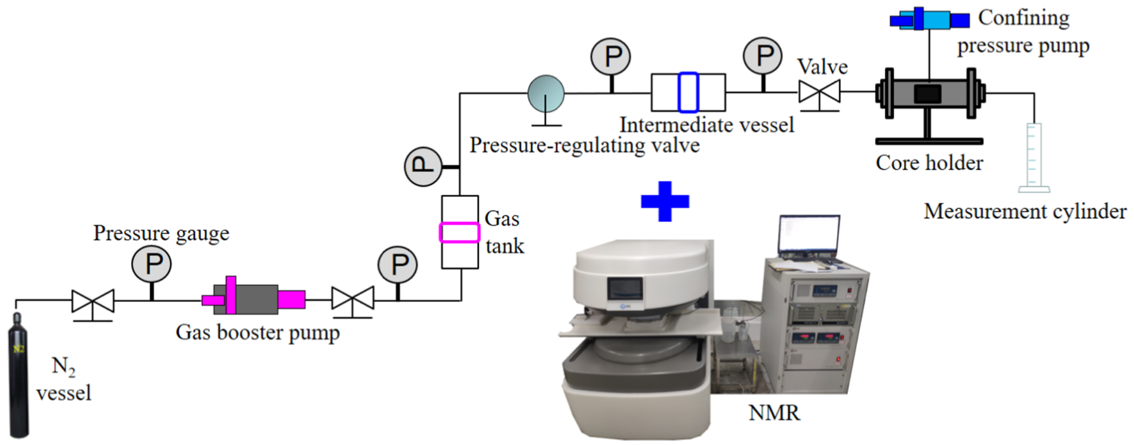

Figure 6. Displacement device and the NMR device.

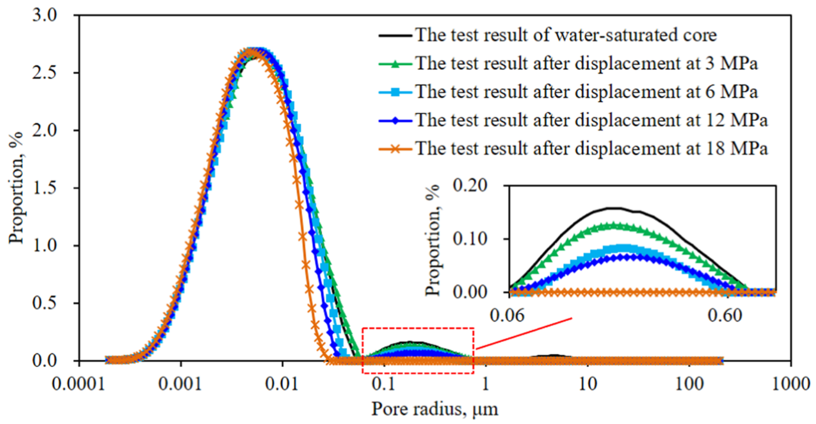

Figure 7. NMR test results after gas displacement with different displacement pressures.

2.2. Gas Expansion is the Main Driving Force of Water Drainage in Micro- and Nanoscale Pores.

2.2.1. Power of Water–Gas Extraction in Shale Pores. For micro- and nanoscale pores in shale gas reservoirs, gas expansion is the main cause of water drainage. Statistically, the pore size of shale mainly ranges from the microscale to the nanoscale. Thus, the capillary pressure in these pores can reach several or even dozens of megapascals, and such pressures can promote imbibition and prevent drainage. Pore compression squeezes water out of macrofractures and macropores owing to the smaller capillary pressure, while it increases the difficulty of drainage in shale micro- and nanoscale pores because capillary pressure in these pores will be sharply increased with pore compression. As shown in Figure 4, pore compression first increases capillary pressure, and the increase in capillary pressure then promotes imbibition until a new gas–water equilibrium state appears. Therefore, the main cause of water drainage in shale micro- and nanoscale pores is gas expansion but not pore compression.

It is known from eq 1 that when the liquid pressure P_f in fractures first decreases, the elastic expansion of gas overcomes the resistance of capillary pressure, and the imbibed water is discharged from the pores, as shown in Figure 5.

2.2.2. Drainage Mode under the Influence of Gas Expansion. According to eq 1, the prerequisite of drainage is

$$P_g - P_f \geq P_c \tag{4}$$

which means that only when the difference between the gas pressure in pores and the liquid pressure in fractures is larger than the capillary pressure, can the retained water be discharged. Because the value of the gas pressure is dominated by the capillary pressure and the liquid pressure in fractures, the ratio of P_g and P_c can be transformed by eq 1

$$\frac{P_g}{P_c} = 1 + \frac{P_f}{P_c} \tag{5}$$

According to eq 2, the smaller the pore size, the greater the capillary pressure P_c (the drainage resistance); meanwhile, according to eq 3, the smaller the pore size, the greater the gas

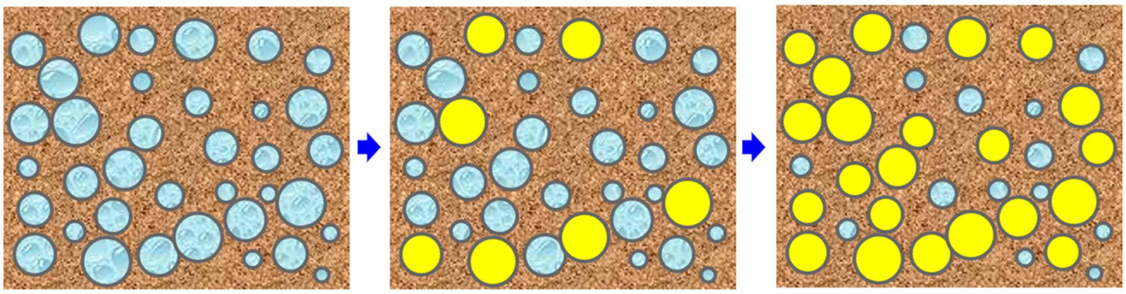

Figure 8. Drainage order of pores with different diameters (fracture profile). Water displacement occurred first in larger pores and then in smaller pores.

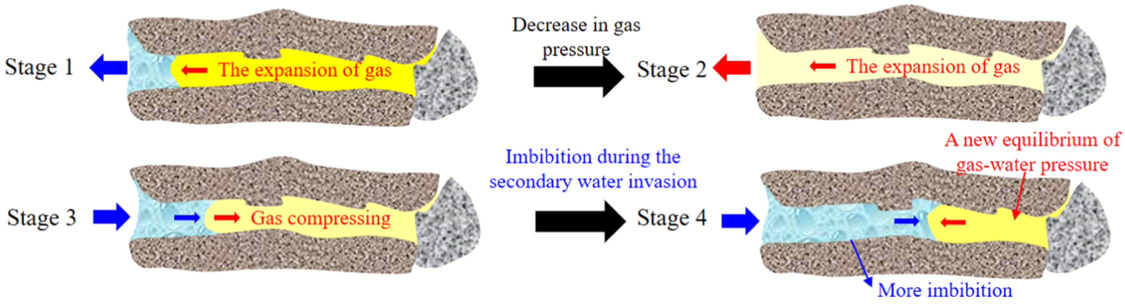

Figure 9. Diagram of gas production and secondary imbibition related to interwell interference in drained pores. Stage 1 to Stage 2: gas production before interwell interference. Stage 3 to Stage 4: the second phase of water imbibition during interwell interference. Owing to the decreased gas pressure, more imbibition occurs in such pores than in the first phase of imbibition.

pressure P_g (the drainage power) in the equilibrium state. In other words, both the capillary pressure (the drainage resistance) and the gas pressure (the drainage power) are greater when the pore has a smaller diameter. Consequently, it remains unclear whether water will be drained first from smaller pores or from larger pores. But according to eq 5, the confusion can be answered: the liquid pressure P_f is basically equal in a unit area of fractures; therefore, in a unit area of fractures, the smaller connected pore has greater capillary pressure and has a smaller value of $1 + P_f/P_c$; thus, the ratio of P_g and P_c is smaller for smaller pores, which means that it is more difficult for gas expansion to overcome the capillary resistance in smaller pores. Therefore, imbibed water in micro- and nanoscale pores is discharged first from larger pores and then successively from smaller pores.

2.2.3. Experimental Validation of the Drainage Mode in Shale Micro- and Nanoscale Pores. To verify the law of gas—water extraction in shale micro- and nanoscale pores described above, experiments were conducted to study water discharge by gas flooding, as shown in Figure 6. The gas tank and the intermediate vessel stabilize the gas pressure, and the pressure-regulating valve regulates the displacement pressure. The experimental core was obtained from an outcrop in the Changning Block, Sichuan Basin. The first step was to immerse the core in a solution containing 2% KCl for 48 h under a vacuum environment and then test its pore size distribution using NMR monitoring. The results are shown as the black curve in Figure 7. The next step was to displace water in the core by gas flooding for 1.5 h with a constant confining pressure of 20 MPa and different displacement pressures of 3, 6, 12, and 18 MPa. The resulting pore size distribution was measured through NMR monitoring under a low-evaporation environment after each displacement.

The NMR testing curves of the water distribution in different sized pores after gas displacements with different displacement pressures are shown in Figure 7. An obvious phenomenon can be expressed in the section of 0.01 μm to 1.0 μm that drainage occurs first in larger pores, followed by smaller pores. With the increase of displacement pressure, drainage occurs in much smaller pores, as shown in Figure 8, which indicates that smaller pores have greater resistance of water drainage and need higher displacement pressure for water drainage.

3. RESULTS AND DISCUSSION

3.1. Mechanism Analysis: Gas Production is Impacted by Imbibition for the Secondary Time during Interwell Interference. The effect of water invasion caused by interwell interference differs in shale gas wells with different production ages, mainly for reasons related to the residual energy of producing wells.[23] If the energy of the producing well is sufficient, the interference from the adjacent fracturing well is small; otherwise, the interference is greater. Regarding the mechanism and the degree of interwell interference for producing wells, the numerous pores in the producing wells are affected by secondary imbibition, in which water is fracturing fluid invading from adjacent fracturing wells. However, not all pores are affected by interwell interference; thus, the pores in producing wells can be divided into two types.

3.1.1. Undrained Pores. Gas expansion is the major cause of water drainage. Therefore, pores are not affected if the gas content in the pores does not change during the water invasion due to interwell interference. The retained water that blocks the inlets of the pores can be regarded as a barrier protecting the inner gas from interwell interference; thus, no matter how much water invades the fractures of the producing well, the elastic energy in the undrained pores remains constant. Therefore, these undrained pores are not affected by the invasion of water from an adjacent fracturing well. According

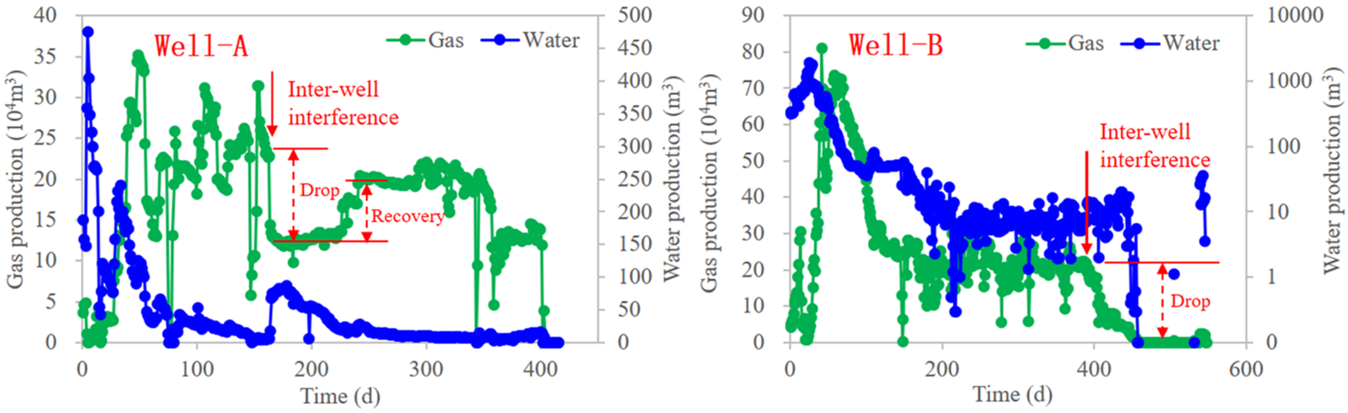

Figure 10. Two shale gas wells in the Sichuan Basin exhibiting interwell interference at different production ages. Well-A was affected during its high-yield period; Well-B was affected during its low-yield period. The gas production of Well-A decreased nearly 50% but returned to normal within only 80 days; the gas production of Well-B decreased 80% to a shut-in state and has not yet recovered.

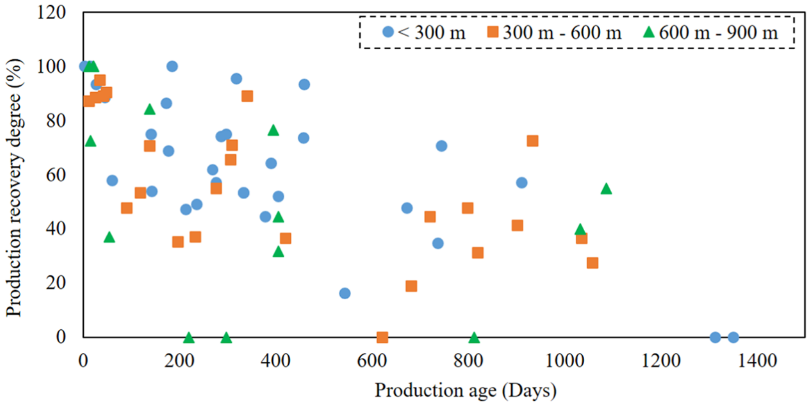

Figure 11. Statistical characteristics of the relation between the production age and PRD. There is an obvious negative correlation between the production age and the production recovery degree for each type and for the entire data set.

to the above analysis in Section 2.2, smaller pores have a smaller probability to be impacted by water invasion.

3.1.2. Drained and Gas Producing Pores. As shown in Figure 9, gas is gradually produced due to the elastic expansion of the gas in drained pores, and the gas pressure in the pores gradually decreases. If water from an adjacent fracturing well suddenly invades the producing well, it can be drawn spontaneously into these pores and macroscale fractures by capillary pressure. Owing to the decreased gas pressure, namely, the decreased resistance to imbibition, more imbibition occurs in such pores than in the first phase of imbibition during the fracturing operation.

If the residual elastic energy of the gas in the pores is sufficient to discharge the secondary imbibed water from the pores, the pores still have potential for water and gas extraction. In other words, these drained pores with the ability to discharge water are not affected by the secondary water invasion due to interwell interference.

If the residual elastic energy of the gas in the pores is not sufficient to discharge the secondary imbibed water, then these pores are completely blocked.

3.1.3. For Drained Pores, Does Water Blockage Easily Occur in Smaller Pores or Larger Pores in a Unit Area? According to the above analysis in Section 2.2, water drainage and gas production happen first in larger pores, followed by smaller pores, in a unit area, as shown in Figure 8. In this case, pores with larger size in a unit area will produce more gas owing to the longer production age. Although the drained and gas producing pores with smaller size have greater capillary pressure and need more gas to discharge water, less gas production occurs later in these pores; it is confusing that does water blockage easily occur in smaller pores or larger pores in a unit area? The confusion can be explained as follows.

All these pores obey the relationship given in eq 1, which means that these pores after secondary water imbibition during interwell interference still obey the drainage law of pores after water imbibition during the fracturing operation, as given in Section 2.2. Because no matter how much the gas in pores is extracted before water invasion, there is a new equilibrium of water and gas phase pressure during the process of secondary water imbibition, and then the drainage law is suitable for these pores during secondary water imbibition; in other words, water blockage easily occurs in smaller pores. Therefore, if the shale gas well has a longer production age, more and more smaller pores participate in gas production; thus, a lower capacity of water drainage exists for the shale gas well during water invasion due to interwell interference.

3.2. Engineering Phenomenon of the Production Impact in Shale Gas Wells Caused by Water Invasion.

The amount of residual gas in pores is the determining factor for water drainage. If the residual gas in pores is unable to discharge the secondary imbibed water out of the pores, these pores are blocked. Examples from the Weiyuan shale gas field in the Sichuan Basin (China) are discussed below.

3.2.1. Relation between Production Age and the Effect of Interwell Interference. An example is shown in Figure 10. Two shale gas wells with different production ages, Well-A and Well-B, were affected by interwell interference. Well-A was affected on the 165th day during its high-yield period. Its water production increased quickly, and its gas production decreased nearly 50%; however, its gas production returned to normal within only 80 days. Well-B was affected on the 395th day during its low-yield period. Its water production also increased quickly, but its gas production decreased 80% to a shut-in state and has not yet recovered. The comparison of Well-A and Well-B illustrates that the shorter the time interval between fracturing operations at fracturing wells and producing wells, the smaller the influence interwell interference will have on the producing well.

The main reason for this behavior is that as the production age of a producing well increases, more pores and more gas are involved in gas production, which results in a greater reduction in reservoir pressure. Because the artificial fractures of a fracturing well tend to extend toward areas of low pressure and the fracturing fluid tends to flow toward areas of low pressure, the degree of contact between a producing well and an adjacent fracturing well increases. If the producing well has been in production for a longer time, then there will be a more serious influence on the producing well.

3.2.2. Statistical Characteristics of the Relation between the Production Age and the Production Recovery Degree (PRD). Sixty-nine producing wells affected by interwell interference in the Weiyuan Block of the Sichuan Basin were analyzed, as shown in Figure 11. To eliminate the factor of interference distance, these producing wells were divided into three types according to the interference distance, namely, less than 300, 300−600, and 600−900 m. It can be seen from Figure 11 that there is an obvious negative correlation between the production age and PRD for each type and for the entire data set. Thus, the longer the production time of the producing well, the lower the PRD.

4. CONCLUSIONS

The theoretical basis of this study is the principle of water imbibition and drainage in micro- and nanoscale pores in shale, and relevant conclusions are obtained based on theory, production data, and experiment analysis.

(1) A large amount of water is easily imbibed into shale micro- and nanoscale pores and impacts the shale gas occurrence state. Owing to the characteristics of shale gas reservoirs, such as the quantity of micro- and nanoscale pores and low original water saturation, a large amount of fracturing fluid in fractures can be imbibed spontaneously by pores connected to the hydraulic fractures, thereby blocking the pores and promoting the desorption of adsorbed gas and the compression of free gas until the gas pressure equals the water phase pressure.

(2) Gas expansion is the main cause of water drainage in shale micro- and nanoscale pores, and imbibed water in these pores is discharged first from larger pores, followed by smaller pores, in a unit area of fractures. Capillary pressure in micro- and nanoscale pores can reach several or even dozens of megapascals, and such pressures can promote imbibition and prevent drainage. Meanwhile, capillary pressure in these pores will be sharply increased with pore compression, and the increase in capillary pressure will promote imbibition until a new gas−water equilibrium state appears. Additionally, because smaller pores have greater capillary pressure, they need more gas to discharge the imbibed water out of the pores. Therefore, the main cause of water drainage in shale micro- and nanoscale pores is gas expansion but not pore compression, and water drainage follows the order of pore size.

(3) The secondary water invasion caused by interwell interference completely blocks the pores in wells with long-term gas production but has little influence on pores that have not yet drained or have produced only a small amount of gas. The proportion of drained pores in wells with long-term gas production determines the degree of damage to production caused by interwell interference. The more the drained pores in wells with long-term gas production, i.e., wells with longer production times, the greater the damage to the productivity of the producing well. Therefore, older shale gas wells in which production has taken place for a long time have lower proportions of undrained pores and drained pores with sufficient energy for secondary drainage and experience greater damage to production as a result of interwell interference.

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Notes

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ABBREVIATIONS

$P_f$liquid pressure in fractures generated by the overburden pressure and pump pressure (MPa)
$P_c$capillary pressure (MPa)
$P_g$gas pressure of initial free gas and desorption of adsorbed gas (MPa)
σsurface tension of the water−gas phase (mN/m)
Zgas compressibility factor
Lpore length (m)
$n$total gas content of initial free gas and desorption of adsorbed gas (mol)
$d$pore diameter (m)
θwetting angle of the wetting fluid on a solid surface (deg)
Rgas constant (J/(K·mol))
Treservoir temperature (K)

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