Experimental study on stress sensitivity of high-temperature and high-pressure sandstone gas reservoirs in Yingqiong Basin

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Abstract
Performing stress-sensitivity evaluation on a high-temperature and high-pressure gas reservoir is essential for correctly understanding the characteristics of physical property changes and reasonably designing the development scheme of a reservoir under stratum conditions. By focusing on six core samples with different physical properties in a gas field in the Yingqiong Basin, stress-sensitivity experiments have been conducted along with mercury intrusion porosimetry and X-ray diffraction measurements to study the relationship among porosity, permeability, and effective stress at a temperature of 140°C and effective stress ranging from 2 MPa to 70 MPa. Our results showed that the stress-sensitivity curve characterized by three-stage segmentation is primarily affected by average pore radius and mineral composition but has no direct relation with porosity and permeability. Meanwhile, the stress sensitivity of permeability is mainly related to the average pore throat radius and mineral composition of core specimen. The smaller the pore throat radius and the higher the clay content, the stronger the stress sensitivity of permeability. Under high-temperature and high-pressure conditions, the stress sensitivities of permeability and porosity can be characterized by power functions although the stress sensitivity of permeability is about 2–11 times higher than that of porosity.

KEYWORDS
effective stress, high temperature and pressure, pore radius, stress sensitivity, throat radius
1 | INTRODUCTION

In the process of reservoir production, the effective stress in the core pore system increases due to the pressure reduction, and the detailed pore geometry of the reservoir core changed, and resulting in changes in porosity and permeability.1,2 Experimental studies were carried out by lots of researchers. Fatt and Davis3 found out the existence of stress sensitivity by experiment in 1952. On this basis, the difference between permeability stress sensitivity and porosity stress sensitivity was found by Fatt4 and Wang et al.5 Since then, more cores have been used to study permeability stress sensitivity.6,7 With the deepening of the research, researchers8-10 began to analyze the microscopic mechanism of the stress-sensitive effect. McLatchie et al11 and Dou et al12 found the stress sensitivity of permeability is negatively correlated with permeability. Tian et al13 and Gao et al14 thought the mineral composition of rock is related to the resistance of pore throat to pressure. Some scholars had also studied the variation law of stress-sensitivity curves. Li et al15,16 and Dong et al17 studied the experimental method for determining effective pressure law for permeability. The "slide method" used for analyzing permeability data was developed by Zhao et al.18 Shapiro19 thought pressure dependence of permeability is a function of stiff and compliant porosities. The difference between the scales of microfracture and micropore will affect the stress sensitivity obviously.20 And Cao and Lei21 thought the curve changed in stages. Liu et al22,23 studied the effect of particle composition, grain size, clay minerals, and pore and throat types on stress sensitivity with electron microscopy and X-ray diffraction techniques.

Some researchers investigated the deformation of porous media theoretically. The pore-scale network model based on pore structure reconstruction is established24-26 Zhang et al27 and Dou et al28 presented models for calculating permeability stress sensitivity. Based on the fractal theory, prediction models for the permeability and porosity of porous media were proposed.29-35 A new stress-sensitive permeability analysis model was proposed by Zhu et al.36 And Zhu et al37 thought the permeability performance under reservoir condition was divided into two stages through a semi-analytical model. The relationship between stress and permeability was studied through numerical simulation by Zhang et al38 and Zhao et al.39,40 In addition, some scholars41-43 have studied the changing of permeability in the production process.

The relationship between porosity, permeability, and stress has been studied from the aspects of pore shape, pore structure, and sorting characteristics. More often than not, these influencing factors are analyzed on the basis of qualitative understanding rather than quantitative judgment. Besides, as these experiments are performed at room temperature, the influence of temperature on the empirical relationship or the theoretical calculation model established on this basis is doubtlessly not taken into account. But it is clear that the formation temperature will be higher or much higher than the room temperature when stress sensitivity occurs in the reservoir. Yang et al44 and Liu et al45 found the temperature (from 20°C to 100°C) is negatively correlated with the rock permeability: When the temperature rises, the rock becomes denser and the rock permeability decreases. Meng et al46 considered the stress sensitivity increased at high temperature in low permeability sandstone. Guo et al47 discovered temperature has a significant effect on the permeability of the rock, and it is negatively correlated with rock permeability through experiments. Therefore, it can be seen that the influence of temperature must be considered in studying the stress sensitivity of the reservoir. In other words, the stress-sensitivity characteristics of the reservoir can merely be correctly characterized by conducting a study under the temperature and pressure conditions of the reservoir.

The sandstone gas reservoir in the Yingqiong Basin in the South China Sea is approximately 2800 m in depth with a temperature of 140°C and a pressure of 53 MPa, forming a typical abnormal high-temperature and high-pressure gas reservoir. As the production goes on, the reservoir pressure is gradually decreased, and the stress sensitivity is gradually strengthened, whereas reservoir parameters such as porosity and permeability are significantly altered. Consequently, a large deviation is found in the established development scheme. Thus, it is of great necessity to conduct a detailed study concerning the stress-sensitivity characteristics of the reservoir. Stress-sensitivity experiments have been conducted in the laboratory at the gas reservoir temperature through changing confining pressure and constant inner pressure to analyze the effects of porosity and permeability changes of the reservoir in a variety of effective stress conditions. Furthermore, the damage mechanism of stress sensitivity of the reservoir has been studied in accordance with the results obtained from X-ray diffraction and mercury intrusion porosimetry.

2 | PHYSICAL PARAMETERS OF ROCK SAMPLES

2.1 | Basic parameters

Six rock samples from a sandstone gas reservoir in a gas field of the Yingqiong basin in the South China Sea were selected for the experiment. Since the burial depth of the reservoir was approximately 2800 m with a temperature of 140°C, the overburden stress of overlying strata was equivalent to 73 MPa, the pore pressure was 53 MPa, and the initial effective stress of the gas reservoir was 20 MPa. The porosity and permeability of each core measured when the effective stress was 2 MPa and 20 MPa
and the temperature was 140°C through a nitrogen medium are presented in Table 1.

2.2 Mineral composition

Mineral components of each core were obtained through analysis via X-ray diffraction experiments. In addition, the hardnesses of quartz, feldspar, and clay decreased. It can be seen from Table 2 that contents of hard components (non-clay minerals) in the mineral composition of rock samples No. 1 to No. 6 decrease in sequence, while the clay content increases, indicating that the deformation resisting capability of the solid skeleton of the cores gradually diminished.

2.3 Microscopic pore throat parameters

Microscopic pore throat parameters of the six rock samples were obtained through the constant rate mercury injection experiment. On this basis, the distribution of pore radius, throat radius, and the contribution of the throat to the permeability of each core was analyzed. Analysis results were plotted in Figures 1 and 2.

As can be seen from Figure 1, the distribution of the pore radius of each rock is nearly consistent. In addition, a minor difference can be seen in the average pore radius that ranged from 119.96 μm to 132.48 μm. According to Figure 2, the average throat radius of each core ranged from 0.52 μm to 1.69 μm, presenting a relatively significant difference. The percolation capacity of cores mainly depends on the distribution of the throat. Each throat size contributes to the percolation capacity of the cores, the value of which is determined by the size and quantity of the throat. Moreover, the contribution rate is proportional to the square of the throat radius and number of throats. To be specific, the more concentrated the distribution of the dimension of the throat radius, the more concentrated the distribution of the throat to the contribution rate curve of the permeability, and the higher the peak will be; the greater the average radius of all throats, the greater the radius of the throat corresponding to the curve peak; the greater the average radius of mainstream throats, the greater the proportion of large throats contributing to the permeability.

3 EXPERIMENTAL CONDITIONS AND PROCEDURES

According to the SY/T 6385-2016 Porosity and Permeability Measurement under Overburden Pressure,48 “method for measuring porosity and permeability of cores under overburden pressure”, by altering the confining pressure to evaluate the core in the process of pressure load stress sensitivity. The experimental results are got under the constant inlet pressure. Nitrogen was used as the displacement medium in this experiment. The experiment process is shown in Figure 3. The specific experiment is carried out as follows:

1. Ensure all equipment is working properly. Connect the equipment according to the flow chart.
2. First, the No. 1 was loaded into the core holder that is applied with a confining pressure of 2 MPa. And the inner pressure was 0 MPa. Next, the temperature of the core holder was slowly increased to 140°C via the temperature control system and the temperature was kept constant for 1 hour before adjusting the effective pressure to 2 MPa.
3. When temperature and pressure data were stabilized, the equipment’s automatic test system on porosity and permeability was turned on to read parameters of porosity and permeability for the core.
4. And then, the effective pressure was adjusted to 4 MPa, 6 MPa, 10 MPa, 15 MPa, 20 MPa, 30 MPa, 40 MPa, 50 MPa, 60 MPa, and 70 MPa in a proper order to repeat the step (3).
5. When the confining pressure was gradually reduced to 2 MPa, the heating system was turned off. When the temperature declined to 25°C, the confining pressure was reduced to the atmospheric pressure, and then the core was removed.
6. Samples No. 2 to No. 6 were used separately to repeat step (2) to step (5).

| Sample no. | Diameter, cm | Length, cm | Porosity, % | Permeability, mD |
|------------|--------------|------------|-------------|------------------|
|            | ΔP_{eff} = 2 MPa | ΔP_{eff} = 20 MPa | ΔP_{eff} = 2 MPa | ΔP_{eff} = 20 MPa |
| 1          | 2.48         | 5.52       | 19.38       | 18.77            | 5.591          | 4.805          |
| 2          | 2.49         | 5.51       | 18.62       | 17.94            | 2.322          | 1.625          |
| 3          | 2.50         | 5.28       | 7.13        | 6.82             | 3.247          | 2.956          |
| 4          | 2.49         | 5.60       | 8.71        | 8.17             | 1.377          | 1.031          |
| 5          | 2.48         | 5.42       | 10.16       | 9.22             | 0.851          | 0.456          |
| 6          | 2.49         | 5.33       | 12.05       | 10.36            | 0.119          | 0.031          |
EXPERIMENTAL RESULTS AND ANALYSIS

4.1 Porosity stress-sensitivity analysis

The stress-sensitivity experiment was conducted separately on the six rock samples according to the experiment steps. Besides, to facilitate the evaluation analysis of stress sensitivity of the porosity of the samples, the dimensionless porosity (the ratio of the measured porosity to the initial porosity under various effective stresses) and the effective stress (the difference between the confining pressure and the internal pressure) are considered as the x- and y-coordinates, respectively. The experimental result is presented in Figure 4.

Based on the result of the stress sensitivity of porosity, it can be seen that the variation trends of the stress-sensitivity curves of the porosity of the six core samples are consistent. In addition, the influence of the effective stress on the porosity of the reservoir is determined by the deformation of the reservoir under overburden pressure. Also, the influence is staged. As can be observed from Figure 4, since the skeleton of the core is compressed under external force at the beginning of the experiments, pores and throats changed with a high incidence of deformation. Consequently, internal cement, soft components, and other forms also changed to fill the pore channel, leading to a rapid decline in porosity and significant stress-sensitivity range. Furthermore, as the effective stress gradually increased, the skeleton of the core became further compressed. In that case, when throats that are not easily closed and the pores that are difficult to compress and deform are changed, the stress-sensitivity range is gradually decreased with a slow decline in the pore. When the structure of the core cannot be changed continuously at the later stages of the experiment, the porosity is changed slightly with a gentle curve. Therefore, the curve is divided into three stages: Stage I with the effective stress ranging from 2 MPa to 20 MPa, Stage II with the effective stress ranging from 20 MPa to 60 MPa, and Stage III with the effective stress ranging from 60 MPa to 70 MPa. The proportion of the decreased range in porosity at each stage is shown in Figure 5.

As can be seen from Figure 5, as the stress sensitivity of the porosity of the core gradually improved, the proportion of porosity loss of the core in Stage I increased, whereas the proportion of porosity loss in Stages II and III decreased. Based on the experimental data, the average proportions of porosity loss in Stages I, II, and III are 66.16%, 30.22%, and 3.62%, respectively. It indicates that porosity loss takes place primarily in Stage I and Stage II, especially in Stage I. Moreover, Table 1 shows that the stress sensitivity of the porosity of core is not directly related to its porosity value.

| Sample no. | Nonclay minerals composition, % | Clay content, % |
|------------|---------------------------------|-----------------|
|            | Quartz | Feldspar | Calcite | Dolomite | Siderite |               |
| 1          | 70.2   | 17.3     | 6.7     | 0.7      | 0.0      | 5.1            |
| 2          | 71.1   | 13.8     | 4.0     | 5.1      | 0.0      | 6.0            |
| 3          | 70.3   | 15.0     | 4.8     | 3.0      | 0.9      | 6.0            |
| 4          | 68.7   | 13.8     | 5.7     | 3.8      | 0.0      | 8.0            |
| 5          | 64.2   | 10.0     | 6.8     | 5.0      | 4.0      | 10.0           |
| 6          | 65.2   | 16.8     | 5.0     | 1.0      | 0.0      | 12.0           |

TABLE 2 Mineral composition of rock samples
By comparing the experimental results of cores No. 3 and No. 4, we deduce that they have similar average pore radius and distribution of pore radius (as shown in Figure 1). In comparison to core No. 3, the clay content and porosity loss of core No. 4 increased by 33.33% and 41.34%, respectively. The analysis suggests that clay minerals have weaker deformation resistance among other mineral components, such as quartz and feldspar. Due to the higher clay content in the core, the corresponding content of hard components is lower, and the core is more likely to be compressed under equivalent effective stress, resulting in deformation. With shrinking pore space and higher clay content, internal cement and soft components could be squeezed and deformed due to the compression of the skeleton of the specimen. Furthermore, the pore space is further shrunk as more pore spaces are filled. As a result, the higher the clay content in the mineral composition of the core, the stronger the stress sensitivity of porosity.

By comparing the experimental results of cores No. 2 and No. 3, we found that their mineral components are similar (as shown in Table 1). In comparison with core No. 2, the average pore radius and porosity loss of core No. 3 increased by 8.23% and 16.08%, respectively. According to the analysis, the deformation resistance of the structure with a large pore is weaker than that of the structure with a small pore. Under equivalent effective stress, the core in the structure with a large pore tends to easily deform. Similarly, the structure with a large pore deforms easier compared with the structure with a small pore. It can be thus concluded that the greater the pore radius of the core, the stronger the stress sensitivity of porosity.

The above analysis suggests that the porosity loss of core No. 6 should be greater than 19.71% if the average pore radius of core No. 6 is similar to that of cores No. 3 and No. 4. The clay contents of cores No. 4 and No. 6 increased by 33.33% and 100%, respectively, while the porosity loss increased by 41.34% and 198.98%, respectively, compared with core No. 3. Therefore, the increased clay content in the core might lead to a gradual increase in the stress sensitivity of porosity.

By comparing the experimental results of cores No. 3 and No. 4, we deduce that they have similar average pore radius and distribution of pore radius (as shown in Figure 1). In comparison to core No. 3, the clay content and porosity loss of core No. 4 increased by 33.33% and 41.34%, respectively.

![Figure 3](image1.png) Process flow diagram for stress-sensitivity experiments. Figure description: 1-gas cylinder; 2-gas pump; 3-piston container; 4-inlet pressure gage; 5-drying oven; 6-core holder; 7-confining pressure valve; 8-confining pressure gage; 9-outlet pressure gage; 10-back pressure valve; 11-confining pressure pump; 12-gas flowmeter

![Figure 4](image2.png) The relationship between dimensionless porosity and effective pressure

![Figure 5](image3.png) Distribution of porosity loss at different stages

By comparing the experimental results of cores No. 2 and No. 3, we found that their mineral components are similar (as shown in Table 1). In comparison with core No. 2, the average pore radius and porosity loss of core No. 3 increased by 8.23% and 16.08%, respectively. According to the analysis, the deformation resistance of the structure with a large pore is weaker than that of the structure with a small pore. Under equivalent effective stress, the core in the structure with a large pore tends to easily deform. Similarly, the structure with a large pore deforms easier compared with the structure with a small pore. It can be thus concluded that the greater the pore radius of the core, the stronger the stress sensitivity of porosity.

The effective stress of 20 MPa as the cutoff point, the curve in Figure 4 is divided into the compaction stage (left) and actual sensitivity stage (right). The compaction stage is Stage I that restores the core to the temperature and
pressure conditions of the reservoir with the most significant stress-sensitivity range of porosity, and the actual sensitivity stage is the actual porosity stress-sensitivity area in the reservoir, which is composed of Stage II and Stage III. Thus, the actual stress sensitivity of the reservoir ranged from 1.87% to 6.62%, which is 3.53% on average and accounts for 33.85% of the entire process. Dimensionless porosity and effective stress data at the actual sensitivity stage were fitted to establish a correlation concerning the stress sensitivity of porosity at a temperature of 140°C and effective stress of 20 MPa. The function is presented as follows:

$$\frac{\phi}{\phi_0} = A \times (\Delta P - B)_{eff}$$

According to the Equation (1), fitting-related parameters $A$ and $B$ can be obtained, as shown in Table 3.

As can be seen from Table 3, related coefficients fitted by the stress-sensitivity curves of porosity of the six cores are above 0.99, indicating that the stress-sensitivity characteristic of porosity of the core can be characterized by a power function. Also, the larger the $B$ value, the stronger the stress sensitivity of porosity will be.

### 4.2 Permeability stress-sensitivity analysis

Likewise, the dimensionless permeability (the ratio of the measured permeability to the initial permeability under various effective stresses) and the effective stress are considered as the x- and y-coordinates, respectively. The experimental result is presented in Figure 6.

As can be seen from Figure 6, the stress-sensitivity curve of permeability is similar to that of porosity. As the effective stress increases, the permeability decreases at a slowing rate. The analysis shows that the stress sensitivity of permeability of the core is directly related to its clay mineral content and throat radius. Since the internal structure of the core skeleton is squeezed under the external force, pores and throats as major flow channels are deformed at the onset of increased effective stress. Consequently, loose particles are detached from the pore surface of the core, which might be accumulated at the narrow pore or the throat. In the meanwhile, upon squeezing, internal cement, and soft components are deformed to either fill or clog the pore and the throat. In that case, small pores and throats or those that are easily deformed are closed gradually, not only severely affecting the flow channel of the fluid, but also remarkably lowering the permeability of the reservoir. When the core is compressed with the further increase in effective stress, throats that are not easily closed and small pores that are difficult to compress remain with the decelerating decline in permeability. When the effective stress increases again, the structure of the core hardly changes; therefore, the permeability remains almost unchanged. Similar to the porosity stress-sensitivity analysis, the stress-sensitivity curve of permeability is also divided into three stages. The proportion of the decline in each stage is shown in Figure 7.

Figure 7 shows that as the stress sensitivity of permeability becomes stronger, the proportion of the permeability loss of the core in Stage I increases gradually, whereas the

| Sample no. | Porosity, % | $A$     | $B$     | Correlation coefficient |
|-----------|------------|---------|---------|-------------------------|
| 1         | 18.77      | 1.0460  | 0.0150  | 0.9993                  |
| 2         | 17.94      | 1.0528  | 0.0172  | 0.9992                  |
| 3         | 6.82       | 1.0606  | 0.0197  | 0.9992                  |
| 4         | 8.17       | 1.0852  | 0.0275  | 0.9985                  |
| 5         | 9.22       | 1.1229  | 0.0391  | 0.9960                  |
| 6         | 10.36      | 1.1769  | 0.0552  | 0.9910                  |
proportion of the permeability loss in Stages II and III decreases. According to the experimental data, the average proportions of the permeability loss in Stage I, Stage II, and Stage III are 71.04%, 26.54%, and 2.42%, respectively. It indicates that the permeability loss takes place primarily in Stage I and Stage II, especially in Stage I. In addition, Table 1 indicates that the stress sensitivity of permeability is not directly related to the permeability value.

By comparing the experimental results of core No. 2 and core No. 3, mineral components of both are similar (as shown in Table 1). In comparison with core No. 3, the average throat radius and the radius of the mainstream throat of core No. 2 are reduced by 51.33% and 60.88%, respectively, while the permeability loss is increased by 216.20%. Based on the analysis, as the effective stress increases, the internal structure of the core is squeezed after the core is deformed by compression under the same conditions. Moreover, cement and soft components are deformed to fill or clog the throat after squeezing. On this occasion, small throats are more likely to close or clog, thereby lowering or even losing their flow capacity. Therefore, the smaller the average throat radius of the core, the stronger the stress sensitivity of porosity.

By comparing the experimental results of core No. 2 and core No. 5, we found that the clay content of core No. 5 increased by 66.67% (as shown in Table 1), and the average throat radius and radius of the mainstream throat of core No. 2 increased by 6.15% and 10.46% (as shown in Figure 2), respectively, while the permeability loss increased by 50.21% compared with that of core No. 2. Based on the conclusion that the smaller the average throat radius of the core, the stronger the stress sensitivity of porosity.

By referring to the porosity stress-sensitivity analysis, the actual stress sensitivity of permeability ranged from 4.92% to 70.95% with an average of about 24.79%, accounting for 28.96% of the entire process. Dimensionless permeability and effective stress data at the actual sensitivity stage were fitted to establish a correlation concerning the stress sensitivity of permeability at a temperature of 140°C and effective stress of 20 MPa. The function is presented as follows:

\[
\frac{k}{k_0} = M \times \Delta P^{-N} \quad (2)
\]

According to the Equation (2), fitting-related parameters \( M \) and \( N \) can be obtained, as shown in Table 4.

As can be seen from Table 4, related coefficients fitted by the stress-sensitivity curves of permeability of the six cores are above 0.99, indicating that the stress-sensitivity characteristic of permeability of the core can be characterized by a power function. Also, the larger the \( N \) value, the stronger the stress sensitivity of permeability will be.

### 4.3 Differential analysis of stress sensitivity between porosity and permeability

The average pore radius, average throat radius, clay content, actual porosity loss, and actual permeability loss of the cores are summarized in Table 5.

It can be seen from Table 5 that the stress sensitivity of permeability of the same core is much higher than its stress sensitivity of porosity, and their ratios range between 2 and 11. The analysis shows that the porosity characterizing the pore space proportion in the core is primarily determined by the number and size of pores, while the permeability characterizing the flow capacity of the core is mainly dependent on the number and size of throats. The average throat radius of the core specimen is much smaller than its average pore radius, and their ratio range between 77 and 243. Besides, the pores in the arch structure possess good pressure and deformation resistance, whereas it is the opposite for the throat. Under the same effective stress, the throat that is more prone to deformation can be changed more easily. Besides, the throat with a smaller radius is more likely to be clogged and closed due to the deformation triggered by squeezing cement.

### Table 4 Relevant parameters of dimensionless permeability fitting results of rock sample

| Sample no. | Permeability, mD | \( M \)   | \( N \)   | Correlation coefficient |
|------------|-----------------|----------|----------|------------------------|
| 1          | 4.805           | 1.1323   | 0.0410   | 0.9955                 |
| 2          | 1.625           | 1.2157   | 0.0654   | 0.9996                 |
| 3          | 2.956           | 1.4529   | 0.1262   | 0.9961                 |
| 4          | 1.031           | 1.5862   | 0.1562   | 0.9985                 |
| 5          | 0.456           | 2.6138   | 0.3230   | 0.9951                 |
| 6          | 0.031           | 21.1753  | 1.0218   | 0.9953                 |
and soft tissues. Therefore, permeability has a stronger stress sensitivity compared with porosity. Moreover, the difference is inversely related to the average throat radius and average pore radius.

5 \mid DISCUSSION

In this paper, 6 cores with different physical properties were used to carry out stress-sensitivity experiments together with mercury intrusion porosimetry and the X-ray diffraction experiments. This article presents an experimental approach to study the impact of pore and throat radius and mineral composition on the stress sensitivity of both porosity and permeability. The relationships between the pore size, throat size, mineral composition, and rock stress sensitivity are analyzed quantitatively. Our results can pave the way for the development of high-temperature and high-pressure gas reservoirs.

However, there are still shortcomings, which have not been addressed in this work. First, the stress sensitivity of rock samples may be affected by sorting characteristics, heterogeneity and degree of cementation. Due to the limitations of experimental samples, it is difficult to find rock samples with almost identical physical properties to conduct single-factor comparative studies. The sample base will be increased to carry out a more detailed stress-sensitivity analysis in the future. Second, stress sensitivity can also be affected by rock brittleness. Brittleness is commonly used in rock engineering applications. There are various methods for rock brittleness evaluation, and Zhang et al.\textsuperscript{49} evaluated the advantages, disadvantages and applicability of these methods. Some scholars\textsuperscript{50-52} analyzed the influence of rock brittleness on the internal structure of the reservoir from theoretical and experimental perspectives. There is a clear relationship between rock brittleness and stress sensitivity. Therefore, it is of great practical significance to study the effect of the brittleness index on stress sensitivity. In the future, we will further study and make a more thorough and comprehensive study on stress sensitivity.

6 \mid CONCLUSION

Based on stress-sensitivity experiments on sandstone core samples under high temperature and high pressure and the stress-sensitivity analysis incorporating the characteristics and mineral composition of microscopic pore throats of the core specimen, the following conclusions can be made:

1. Based on variation tendency, the stress-sensitivity curve has three stages. Meanwhile, its sensitivity does not correlate with its porosity and permeability, while it is related to its mineral composition and microstructure.
2. The stress sensitivity of porosity is mainly affected by the average pore radius and mineral composition of the core. The larger the average pore radius and the higher the clay content, the stronger the stress sensitivity of porosity.
3. The stress sensitivity of permeability is largely influenced by the average throat radius and mineral composition of the core; namely, the smaller the average throat radius and the higher the clay content, the stronger the stress sensitivity of permeability.
4. Since the actual stress sensitivity of the core takes up about one-third of the entire process, the pore, and permeability parameters under the temperature and pressure conditions of the reservoir should be regarded as the starting points in the process of evaluating the stress sensitivity of the reservoir.
5. Under the same conditions, the stress sensitivity of permeability of the core is substantially higher (2-11 times) than that of the porosity, whereas the sensitivity characteristics of both can be characterized by power functions.

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NOMENCLATURE
\[ \Delta P_{\text{eff}} \] Effective stress, MPa
\[ A \] Constant
\[ B \] Porosity stress-sensitivity coefficient, dimensionless
\[ M \] Constant
\[ N \] Permeability stress-sensitivity coefficient, dimensionless
\[ \phi \] Porosity when the effective stress is \( \Delta P_{\text{eff}} \) and the temperature 140\(^\circ\)C, \%
\[ \phi_0 \] Porosity when the effective stress is 20 MPa and the temperature 140\(^\circ\)C, \%
\[ k \] Permeability when the effective stress is \( \Delta P_{\text{eff}} \) and the temperature 140\(^\circ\)C, mD
\[ k_0 \] Permeability when the effective stress is 20 MPa and the temperature 140\(^\circ\)C, mD

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REFERENCES
1. Wang F, Li X, Couples G, et al. Stress arching effect on stress sensitivity of permeability and gas well production in Sulige gas field. J Petrol Sci Eng. 2015;125:234-246.
2. Vassilieff G, Jones S. Application of stress-dependent rock properties in reservoir studies. In: SPE International Thermal Operations and Heavy Oil Symposium and Western Regional Meeting. Society of Petroleum Engineers; 2004.
3. Fatt I, Davis DH. Reduction in permeability with overburden pressure. J Petrol Technol. 1952;4(12):16.
4. Fatt I. Pore volume compressibilities of sandstone reservoir rocks. J Petrol Technol. 1958;10(03):64-66.
5. Wang L, Yang S, Meng Z, et al. Time–dependent shape factors for fractured reservoir simulation: effect of stress sensitivity in matrix system. J Petrol Sci Eng. 2018;163:556-569.
6. Vairogs J, Roadoes VW. Pressure transient tests in formations having stress-sensitive permeability. J Petrol Technol. 1973;25(08):965-970.
7. Kilmer NH, Morrow NR, Pitman JK. Pressure sensitivity of low permeability sandstones. J Petrol Sci Eng. 1987;1(1):65-81.
8. Bruno MS, Bovberg CA, Nakagawa FM. Anisotropic stress influence on the permeability of weakly–cemented sandstones. In: Proceedings of the 32nd US Symposium on Rock Mechanics. Norman, Oklahoma; 1991; ARMA-91-375.
9. Davies JP, Davies DK. Stress-dependent permeability characterization and modeling. SPE J. 2001;6(02):224-235.
10. Xiao W, Li T, Li M, Zhao J, Zheng L, Li L. Evaluation of the stress sensitivity in tight reservoirs. Petrol Explor Dev. 2016;43(1):115-123.
11. Mclatchie AS, Hemstock RA, Young JW. The effective compressibility of reservoir rock and its effects on permeability. J Petrol Technol. 2013;10(06):49-51.
12. Dou H, Zhang H, Yao S, Zhu D. Measurement and evaluation of the stress sensitivity in tight reservoirs. Petrol Explor Dev. 2016;43(6):1022-1028.
13. Tian X, Cheng L, Cao R, et al. A new approach to calculate permeability stress sensitivity in tight sandstone oil reservoirs considering micro-pore-throat structure. J Petrol Sci Eng. 2015;133:576-588.
14. Gao H, Wang C, Cao J, He M. Quantitative study on the stress sensitivity of pores in tight sandstone reservoirs of Ordos basin using NMR technique. J Petrol Sci Eng. 2019;172:401-410.
15. Li M, Bernabei Y, Xiao WL, Chen ZY. Effective pressure law for permeability of E-bei sandstones. J Geophys Res. 2009;114(B7):B07205.
16. Li M, Xiao WL, Bernabei Y, Zhao JZ. Nonlinear effective pressure law for permeability. J Geophys Res Solid Earth. 2014;119(1):302-318.
17. Dong JJ, Hsu JY, Wu WJ, et al. Stress–dependence of the permeability and porosity of sandstone and shale from TCDP Hole–A. Int J Rock Mech Min Sci. 2010;47(7):1141-1157.
18. Zhao J, Xiao WL, Li M, Xiang Z, Li L, Wang J. The effective pressure law for permeability of clay–rich sandstones. Petrol Sci. 2011;8(2):194-199.
19. Shapiro SA. The pressure dependence of permeability as a function of stiff and compliant porosities. In: Fifth Biot Conference on Poromechanics; 2013.
20. Liu B, Yang Y, Li J, Chi Y, Li J, Fu X. Stress sensitivity of tight reservoirs and its effect on oil saturation: a case study of Lower Cretaceous tight clastic reservoirs in the Hailar Basin, Northeast China. J Petrol Sci Eng. 2020;184:106484.
21. Cao N, Lei G. Stress sensitivity of tight reservoirs during pressure loading and unloading process. Petrol Explor Dev. 2019;46(1):138-144.
22. Liu G, Rai Y, Lu D, Li Y, Yang D. Determination of static and dynamic characteristics of microscopic pore-throat structure in a tight oil-bearing sandstone formation. AAPG Bull. 2018;102(09):1867-1892.
23. Liu G, Yin H, Lan Y, Fei S, Yang D. Experimental determination of dynamic pore-throat structure characteristics in a tight gas sandstone formation with consideration of effective stress. Mar Pet Geol. 2020;113:104170.
24. Blunt MJ. Flow in porous media–pore–network models and multiphase flow. Upscaling Multiphase Flow Porous Media. 2001;6(3):197-207.
25. Blunt MJ, Bijeljic B, Dong H, et al. Pore–scale imaging and modelling. Adv Water Resour. 2013:51:197-216.
26. Yang Y, Zhang W, Gao Y, et al. Influence of stress sensitivity on microscopic pore structure and fluid flow in porous media. J Nat Gas Sci Eng. 2016;36:20-31.
27. Zhang H, Liu H, Luan G, et al. A novel quantitative petrophysical model for the stress sensitivity of tight sandstones. J Petrol Sci Eng. 2014;122:657-666.
28. Dou X, Liao X, Zhao X, Wang H, Lv S. Quantification of permeability stress sensitivity in tight gas reservoir based on straight-line analysis. J Nat Gas Sci Eng. 2015;22:598-608.
29. Tan XH, Liu CY, Li XP, Wang HQ. A stress sensitivity model for the permeability of porous media based on bi-dispersed fractal theory. Int J Mod Phys C. 2018;29(2):1850019.
30. Tan XH, Li XP, Liu JY, Zhang LH, Cai J. Fractal analysis of stress sensitivity of permeability in porous media. Fractals. 2015;23(02):1550001.
31. Tan XH, Li XP, Liu JY, Zhang LH, Fan Z. Study of the effects of stress sensitivity on the permeability and porosity of fractal porous media. Phys Lett. 2015;379(39):2458-2465.
32. Tan XH, Liu JY, Li XP, Zhang LH, Cai J. A simulation method for permeability of porous media based on multiple fractal model. Int J Eng Sci. 2015;95:76-84.
33. Tan XH, Kui MQ, Li XP, Mao ZL, Xiao H. Permeability and porosity models of bi-fractal porous media. *Int J Mod Phys B*. 2017;31(29):1750219.

34. Tan XH, Jiang L, Li XP, Li YY, Zhang K. A complex model for the permeability and porosity of porous media. *Chem Eng Sci*. 2017;172:230-238.

35. Tan XH, Jiang L, Li XP, Zhang BJ, Li XC. Flow model of a multi-stage hydraulic fractured horizontal well based on tree-shaped fractal fracture networks. *J Petrol Sci Eng*. 2018;169:494-503.

36. Zhu SY, Du ZM, Li CL, et al. A semi-analytical model for pressure-dependent permeability of tight sandstone reservoirs. *Transp Porous Media*. 2018;122(7):1-18.

37. Zhu H, Tang X, Liu Q, et al. Permeability stress-sensitivity in 4D flow-geomechanical coupling of Shouyang CBM reservoir, Qinshui Basin, China. *Fuel*. 2018;232:817-832.

38. Zhang L, Lu G, Chang C, Wu J, Zhao Y, Liu W. Numerical simulation of a coupled gas flow and geomechanics process in fractured coalbed methane reservoirs. *Energy Sci Eng*. 2019;7:1095-1105.

39. Zhao Y, Lu G, Zhang L, Wei Y, Guo J, Chang C. Numerical simulation of shale gas reservoirs considering discrete fracture network using a coupled multiple transport mechanisms and geomechanics model. *J Petrol Sci Eng*. 2020;195:107588.

40. Zhao Y, Liu L, Zhang L, Zhang X-Y, Li B. Simulation of a multi-stage fractured horizontal well in a tight oil reservoir using an embedded discrete fracture model. *Energy Sci Eng*. 2019;7:1485-1503.

41. Wang F, Liang Y, Li X, Li L, Li J, Chen Y. Study on the change of permeability of gas-containing coal under many factors. *Energy Sci Eng*. 2019;7:194-206.

42. Song R, Wang Y, Liu J, Cui M, Lei Y. Comparative analysis on pore-scale permeability prediction on micro-CT images of rock using numerical and empirical approaches. *Energy Sci Eng*. 2019;7:2842-2854.

43. Zhang Y, Wang L, Li H, Zhang Y, Fu G. Experimental study of the permeability of fractured sandstone under complex stress paths. *Energy Sci Eng*. 2020;5:1-11.

44. Yang JP, Chen WZ, Tian HM, et al. Study of permeability evolutions in low permeability medium under different stresses and temperatures. *Rock Soil Mech*. 2009;30(12):3587-3595.

45. Liu X, Gao H, Liang L. Study of temperature and confining pressure effects on porosity and permeability in low permeability sandstone. *Chin J Rock Mech Eng*. 2011;30:3771-3778.

46. Meng X, Guo X, Gao T. The experimental research of extra Low permeability sandstone reservoir on temperature sensitivity. *J Southwest Petroil Univ*. 2015;37(3):98-102.

47. Guo X, Zou G, Wang Y, Wang Y, Gao T. Investigation of the temperature effect on rock permeability sensitivity. *J Petrol Sci Eng*. 2017;156:616-622.

48. National Energy Administration. *Porosity and Permeability Measurement under Overburden Pressure SYT6385–2016*. Beijing, China: Beijing Petroleum Industry Press; 2016.

49. Zhang D, Ranjith PG, Perera MSA. The brittleness indices used in rock mechanics and their application in shale hydraulic fracturing: a review. *J Petrol Sci Eng*. 2016;143:158-170.

50. Tang J, Li J, Tang M, et al. Investigation of multiple hydraulic fractures evolution and well performance in lacustrine shale oil reservoirs considering stress heterogeneity. *Eng Fract Mech*. 2019;218:106569.

51. Li Y, Long M, Zuo L, Li W, Zhao W. Brittleness evaluation of coal based on statistical damage and energy evolution theory. *J Petrol Sci Eng*. 2019;172:753-763.

52. Li Y, Zhao Y, Tang J, et al. Rock damage evolution model of pulsating fracturing based on energy evolution theory. *Energy Sci Eng*. 2020;8:1050-1067.

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