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Factors Controlling Stress Sensitivity of Shale Oil Reservoirs: Mineral Composition and Mechanical Properties

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ABSTRACT

Shale oil reservoirs are dense and characterized by ultra-low porosity and ultra-low permeability, which are usually developed effectively by horizontal wells and large-scale volume fracturing. However, with the continuous advancement of the development process, the formation pressure decreases, and the stress sensitivity problem brought about by the force compression of the effective seepage channels in shale becomes a key factor restricting the development effect. In this paper, two shale cores with different lithologies from Xinjiang Oilfield in China are used as research objects to conduct stress sensitivity simulation experiments under simulated reservoir in-situ conditions. Meanwhile, the whole rock XRD analysis and nanoindentation mechanical property test are combined to investigate the influence of shale mineral composition and mechanical properties on stress sensitivity. The experimental results show that mudstone shale has higher clay mineral content, and its elastic modulus and hardness are lower than that of sandy shale with high brittle mineral content. In addition, the maximum permeability loss rate of both shales exceeds 50%, which indicates that the stress sensitivity is stronger, among which the mudstone shale has stronger stress sensitivity. In addition, the stress sensitivities of the two shales with different lithologies also show some differences, with mudstone shale having a higher clay mineral content, a lower modulus of elasticity, a higher plasticity, and a harder crack recovery after stress recovery, and its stress sensitivity is higher than that of sandy shale with a higher content of brittle minerals. The stress sensitivity experiments carried out in this paper under in situ conditions in shale reservoirs clarified the control law of mineral composition and mechanical properties on stress sensitivity, which can provide more accurate data reference for the optimization of production system in shale reservoirs.

Keywords: shale oil, stress sensitive, mineral composition，mechanical property, in situ condition

1. INTRODUCTION

In recent years, with the rapid growth of global energy demand due to economic development, conventional oil and gas resources have been unable to meet the needs of social development. The development of unconventional oil and gas resources such as shale oil and gas and tight oil and gas has become an important direction in the field of oil and gas exploration and development[1]。

In general, shale is a heterogeneous sedimentary rock with variable mineral composition, nanoscale pore distribution, and permeability in the Nadaxi range[2]。Horizontal wells + hydraulic fracturing have become the main technologies for developing shale oil and gas resources.

The horizontal well + multi-stage fracturing technology forms a large-scale fracture network in the reservoir, which greatly increases the oil and gas seepage area and results in higher production in the early stage of development. However, with the advancement of the development process, after oil and gas production, the internal fluid decreases, the pressure decreases, the effective stress borne by the rock skeleton gradually increases, the internal pores and fractures are compressed, and the loss of permeability leads to rapid production decline and short stable production period. This phenomenon restricts the efficient development of shale oil and gas resources[3,4].

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In recent years, many scholars have carried out a lot of research on the stress sensitivity of different types of reservoirs. Yin et al.[5] used the variable confining pressure method to study the stress sensitivity law of low-permeability sandstone reservoirs, and gained the understanding that tight oil reservoirs have strong stress sensitivity. Cheng et al.[6] used the variable internal pressure method to study the pore shape and stress-sensitive characteristics of carbonate gas reservoirs containing fractures, and summarized the microscopic mechanism of stress-sensitive damage in carbonate gas reservoirs as fracture closure, pore There are three types of elastic contraction and plastic deformation of the skeleton. Lai et al.[7] proposed that there is a big difference between traditional stress sensitivity experiments and the real conditions of the formation. They used triaxial stress deformation experiments to explore the stress sensitivity rules of the matrix and cores of carbonate gas reservoirs containing micro-cracks.

Although scholars have done a lot of research on the issue of stress sensitivity, the structure and composition of shale are changeable, a large number of artificial fractures are produced after fracturing, and the matrix and fractures coexist. It is more complex and lacks systematic research. In this paper, under the in-situ temperature and pressure conditions of simulating shale reservoirs, the stress sensitivity laws of two kinds of lithological shale were systematically studied, combined with XRD and nano-indentation mechanical experiments, the effects of shale mineral composition and mechanical properties on the influence of shale mineral composition and mechanical properties were explored. Influence law of stress sensitivity of shale reservoir, in order to provide accurate stress sensitivity data reference for optimization of shale reservoir production system after fracturing.

2. MATERIALS AND METHODS

2.1 Materials

The experimental shale samples were taken from two typical shales in Xinjiang Oilfield, China - Mudstone shale and Siltstone shale. First, the core is processed into a cylinder with a diameter of 25 mm and a length of 40 to 50 mm, and then a rock slice with a thickness of 3 to 5 mm is cut from it for nanoindentation mechanical testing. The remaining cylinder was split along the center using the Brazilian splitting method, and then plastically sealed with heat shrink film to form a micro-cracked core for stress sensitivity testing. Whole-rock XRD analysis was performed using fragments generated during the cutting process. Neutral aviation kerosene is used as the *test* fluid for stress sensitivity experiments.
Nanoindentation testing

2.2 Nanoindentation testing

The American Agilent NanoIndenter® G200 nanoindenter was used to test the mesoscopic mechanical properties of rocks by nanoindentation. The equipment and test shale samples are shown in Figure 1. The load resolution is 50nN, the standard test maximum load is 500mN, the z-direction displacement resolution is less than 0.01nm, the maximum indentation depth is greater than 500μm, the x- and y-direction displacement resolution is 1μm, and the stroke range is 100mm×100mm. The test indenter adopts a Bowers indenter whose top curvature radius is less than 20nm. The specific experimental process are:

(1) Sample processing: Use 500, 1000, 2000, 5000 and 7000 mesh silicon carbide sandpaper to polish the test surface in sequence, and finally use wide-beam argon ion equipment for secondary polishing to further reduce the test surface roughness.

(2) After selecting the indentation position, use the Glass indenter to approach the test surface at a speed of 8000nm/min. Set the maximum indentation load to 50mN, and press the indenter vertically into the specimen at a loading rate of 100 mN/min. For grid press-in, a 2×3 lattice is used. At the same time, in order to avoid mutual interference between adjacent press-in points, the minimum distance between adjacent press-in points is at least 10 times the maximum press-in depth. After reaching the maximum indentation load, maintain the load for 5 seconds, and then move the indenter away from the specimen surface at an unloading rate of 100mN/min until it is completely unloaded. The indentation load and indentation depth information were collected simultaneously during the entire experimental process.

(3)According to the test results, draw the load-displacement curve of each indentation point, and calculate the elastic modulus E_{IT} and hardness H_{IT} of each indentation point.

The material hardness H_{IT} is calculated according to formula (1):

$$H_{IT} = \frac{F_{\max}}{A_c} \quad (1)$$

where, $F_{\max}$ is the maximum force and A_c is the contact area.

The elastic modulus E_{IT} is calculated according to formulas (2) and (3):

$$E_r = \frac{\sqrt{\pi}}{2\beta}\frac{S}{\sqrt{A_c}} \tag{2}$$

$$E_{IT} = \frac{1-\upsilon^2}{\frac{1}{E_r} - \frac{1-\upsilon_i^2}{E_i}} \tag{3}$$

where, E_r is the reduced Young's modulus, $S = dp/dh$ is the contact stiffness and is equal to the initial slope of unloading curve, and β is a constant related to the geometry of the indenter, E_{IT} and v are the Young's modulus and Poisson's ratio of the indented sample, respectively, and E_i and v_i are the Young's modulus and Poisson's ratio of the indenter, respectively.

Fig. 1. NanoIndenter®G200 and shale samples

2.3 Stress sensitivity testing

The core stress sensitivity experiment uses the TC-180 ultra-high pressure multifunctional displacement experimental system. The maximum operating pressure of the system can reach 180MPa and the maximum operating temperature is 200°C.The test process is as follows:

(1) Connect the experimental instrument and check its tightness.

(2) Core saturation: The core is evacuated and the core is saturated with neutral kerosene.

(3) Place the saturated core into the high-temperature core holder and set the temperature to 80 degrees Celsius. After the temperature stabilizes, increase the confining pressure and flow pressure simultaneously to 80MPa and 50MPa.

(4) Internal pressure reduction permeability test: Keep the confining pressure at 80MPa, and gradually reduce the pressure at the inlet and outlet according to the experimental pressure difference design, keeping the pressure difference between the inlet and outlet less than 2MPa, and measure the stable flow rate at each pressure point.

(5) Liter internal pressure permeability test: Keep the confining pressure at 80MPa, gradually reduce the pressure at the inlet and outlet according to the experimental pressure difference design results, keep the pressure difference between the inlet and outlet less than 2MPa, and measure the stable flow rate at each pressure point .

(6) With the net stress as the abscissa and the ratio of the rock sample permeability to the initial permeability under different net stress as the ordinate, draw the stress sensitivity curve of the test rock sample as the net stress changes.

3. RESULTS AND DISCUSSION

3.1 Analysis of shale mineral composition

Research shows that the inorganic mineral composition in shale has a direct impact on the mechanical properties of shale oil. The mineral composition of the rock can indicate the brittleness of the rock. The experiment used an X-ray diffractometer to test the mineral types and contents of two shale samples from the Xinjiang Oilfield with reference to the X-ray diffraction analysis method standards for clay minerals and common non-clay minerals in sedimentary rocks. The test results are shown in Table 1.

Table. 1. Mineral compositions of different shale samples from the Rietveld refinemen

shale	Mineral types and contents(%)						Clay minerals (%)
	quartz	K-feldspar	plagioclase	calcite	dolomite	ankerite	
Mudstone shale	13.0	7.0	5.0	16.0	—	18.0	41.0
Siltstone shale	36.0	9.0	26.0	—	—	25.0	4.0

Mineral composition analysis shows that the mineral composition of the two shales includes quartz, feldspar, marble and clay minerals. Among them, mudstone shale has a higher clay mineral content, with its clay mineral content reaching 41.0%. While siltstone shale has more hard minerals such as quartz and feldspar, the clay mineral content of siltstone shale is only 4.0%. The mechanical properties of quartz and feldspar particles are more stable and the compressive strength is greater. When subjected to external effects, the core skeleton is less likely to deform; while clay minerals have poor mechanical stability and have weak resistance to deformation when subjected to external effects.

3.2 Nanoindentation mechanical property testin

The load-displacement curve is the basis for analyzing the deformation behavior and mechanical parameters of nanoindentation. The load-displacement curves of the two types of shale are shown in Figure 2. The curve includes three stages: loading, holding and unloading. During the loading phase, the applied load increases with penetration depth. This stage can be considered as a combination of elastic and plastic deformation, while during the unloading stage we can assume that only the elastic deformation can be recovered and use this to calculate the mechanical properties.

modulus of the rock. The calculation results are shown in Table 2.

Table. 2. Mineral compositions of different shale samples from the Rietveld refinemen

Shale	Modulus/GPa		Hardness/GPa	
	Mean	S.D.	Mean	S.D.
Mudstone shale	39.94	9.90	2.73	2.39
Siltstone shale	71.48	9.96	4.82	6.90

The analysis results of nanoindentation experiments show that there is a certain degree of fluctuation in the elastic modulus and hardness of rocks. For example, the maximum elastic modulus calculated at each indentation point of Siltstone shale is 85.24GPa, the minimum value is 58.5GPa, and its hardness has the maximum value. is 10.97GPa, and the minimum value is 2.34GPa. This is because shale is a porous composite medium material with a variety of mineral components and complex microstructure. The indentation points pressed by the indenter are often on different minerals, causing them to show differences in mechanical properties.

Table 2 shows the elastic modulus and hardness values of the two shales we tested. It can be found that the elastic modulus and hardness value of Mudstone

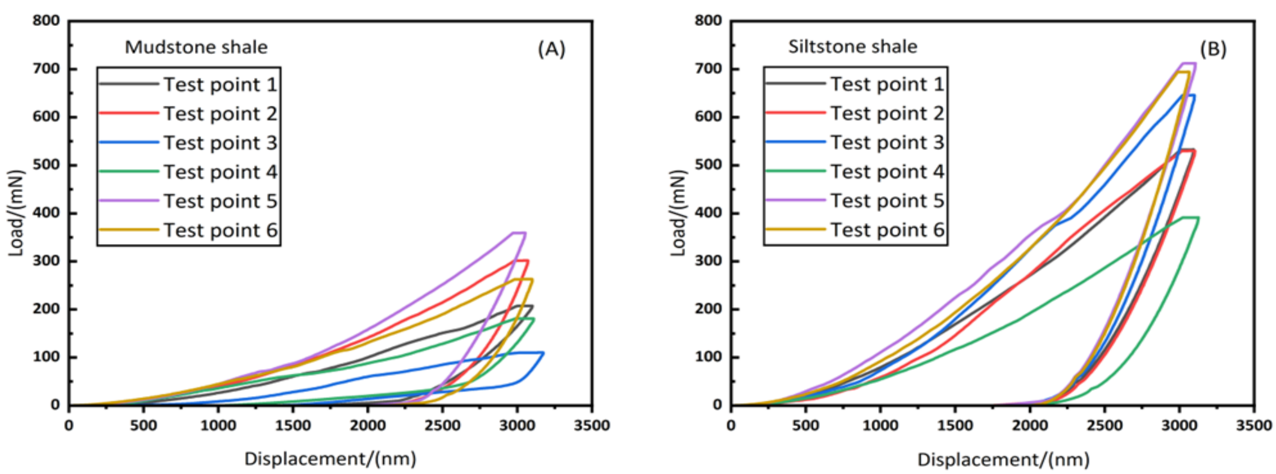

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Fig. 2. Nanoindentation load-displacement curve

By analyzing the load-displacement curve and combining with formula (1-3), the mechanical parameters such as hardness and elastic modulus of each indentation point can be calculated. For the indentation experimental data of each shale sample, we used the mean statistical method to calculate the Young's modulus and hardness data of the two lithology rock samples respectively. Calculate the hardness and elastic

shale are significantly higher than that of Siltstone shale. Combining the comparison of the whole-rock XRD test data of the two shales, we can believe that the elastic modulus and hardness value of the shale are positively correlated with the content of rigid matrix (quartz, feldspar, etc.), and negatively correlated with the content of clay minerals.

3.3 Stress sensitivity analysis

Shale reservoirs have the characteristics of ultra-low porosity and ultra-low permeability. Horizontal wells and large-scale hydraulic fracturing technology are commonly used at home and abroad for effective development. In order to truly simulate the actual situation after fracturing of shale reservoirs, the Brazilian splitting method was used to create pressure fractures in the plunger-shaped shale. Then the stress sensitivity test was conducted on the shale core after fracture creation, and the experimental results are shown in Figure 3.

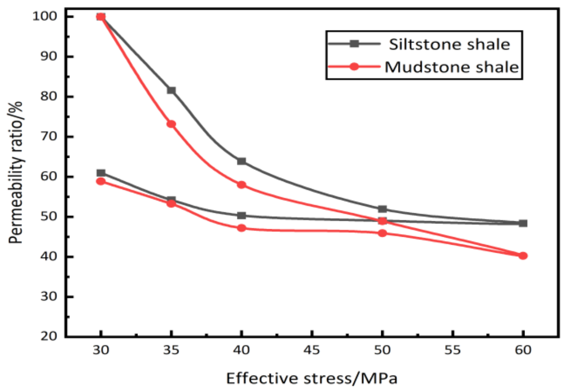

Fig. 3. Relationship between effective stress and permeability

It can be found that the stress sensitivity of both types of fractured shale cores is relatively strong. At 60MPa, the permeability damage exceeds 50%. On the whole, the permeability ratio of the fractured cores of the two lithologies increases with the trend of effective stress change and is divided into two stages. At 30MPa-40MPa, the permeability decreases sharply, and at the 40MPa-60MPa stage, the permeability decrease rate begins to slow down. This is because the seepage channels in microfractured cores are dominated by fractures and macropores. In the low-stress stage, the mechanical deformation of rocks is dominated by the closure of micro-cracks and the compression of large pores, and the permeability decreases to a large extent. In the high-stress stage, micro-cracks close. As the net stress continues to increase, the rock deformation is dominated by pore compression. Because the shale reservoir is dense, the deformation amount is small at this stage, so the permeability decreases very gently.

In addition, it can be found that there are also differences in the stress sensitivity of the two shales. The stress sensitivity of Mudstone shale is higher than that of Siltstone shale. This is due to the lower elastic modulus of Mudstone shale with higher clay mineral content. When the elastic modulus is low, its plasticity is relatively enhanced, which easily leads to crack closure and shows strong stress sensitivity.

4. CONCLUSIONS

By conducting mineral composition analysis of two different lithologies of shale, nanoindentation stress property testing and stress sensitivity experiments, the influence of shale mineral composition and mechanical properties on the stress sensitivity of shale reservoirs was studied. The following main results were obtained:

(1)The mineral composition of the two types of shale is mainly feldspar, quartz, and clay minerals. Siltstone shale has a higher content of clay minerals, and Mudstone shale has a higher content of quartz, feldspar and other brittle minerals.

(2)Nanoindentation shows that the elastic modulus and hardness of shale are positively correlated with the brittle mineral content and negatively correlated with the clay mineral content. The elastic modulus and hardness of siltstone shale are higher than those of mudstone shale with higher clay mineral content.

(3)Overall, the stress sensitivity of the two types of shale cores containing fractures is relatively strong. However, due to the high elastic modulus and hardness of siltstone shale, its pore cracks change less with changes in net stress. Mudstone shale has a high content of clay minerals, and its plasticity is relatively strong. The cracks are easy to close but not easy to recover, making it stress sensitive. The properties are slightly lower than those of siltstone shale.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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