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Influence of the Pore Structures on Stress Sensitivity of Tight Sandstone Reservoir

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Abstract

The percolation of oil and gas in tight sandstone reservoir is different from conventional reservoir due to its tight lithology, tiny pore throat, Jamin effect and strong stress sensitivity. To well study the influence of pore structures on stress sensitivity of tight sandstone reservoir, the pore structures of Chang-6 reservoir were characterized using automated scanning electron microscope (QEMSCAN), casting lamella, laser scanning confocal microscope (LSCM), field emission scanning electron microscope (FESEM) and mercury intrusion porosimetry. The results indicated that the reservoir had low average surface, complex pore structure and strong heterogeneity. Intragranular and intergranular dissolved pores which were mainly potassium feldspar dissolved pores were developed in the reservoir, and some chlorites were developed around these pores. The contact types between grains were dominantly line and point-line contact; the sorting of pores and throats was fair. The ratio of micro-pores was extremely low, while the ratios of submicro-pores and nano-pores were up to 40.66% and 59.10%, respectively. Before the effective stress was increased to 20 MPa, nano-pores which were abundant in Chang-6 reservoir would be closed firstly, resulting in lager reduction of permeability. As the effective stress was increased, the reduction of permeability got smaller. As the effective stress was reduced, the equivalent liquid permeabilities of cores were increased because the chlorite developed around the pores enhanced the compression resistance of grains, and the final recovery rate was in the range of 78% to 92%.

Key words: Tight sandstone; Pore structure characteristic; Stress sensitivity; Loss of permeability; Permeability restore ratio

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INTRODUCTION

Stress sensitivity is defined as the variations of porosity and permeability of rock as a function of effective stress[1]. For the past few years, the development of tight oil and gas has been a hot research topic in oil and gas industry, and effectively solving the problems related to stress sensitivity is one of the biggest challenges for the development of tight oil and gas reservoir. A lot of works have been done on the measurement of stress sensitivity for low or ultra-low permeability reservoirs and its influence on the productivity of oil and gas[2-6], however, the key influence factors of stress sensitivity have not been studied extensively. In this work, the cores from Chang-6 reservoir in Huaqing area of Ordos Basin were chosen for testing, and the petrology as well as pore structures were characterized using automated scanning electron microscope (QEMSCAN), casting lamella, laser scanning confocal microscope (LSCM), field emission scanning electron microscope (FESEM) and mercury intrusion porosimetry. Furthermore, the stress sensitivity of the reservoir was evaluated, and the influence of rock characteristics and pore structures on the stress sensitivity was analyzed, providing basis for revealing the mechanism of stress sensitivity damage to tight sandstone reservoir.

1. OVERVIEW OF ORDOS BASIN

Ordos basin, located on the stable northern China platform, was the second largest subaerial sedimentary basin in China with an areas of 32×10^4 km^2. It is the second largest continental sedimentary basin, experiencing a long-term evolution. The junctions between the rim of Ordos basin and the surrounding tectonic units are all fault zones, with faulted fold developed. Huaqing oilfield is located in the southwest of Ordos basin, as shown in Figure 1. Chang-6 reservoir is in the Baibao area.

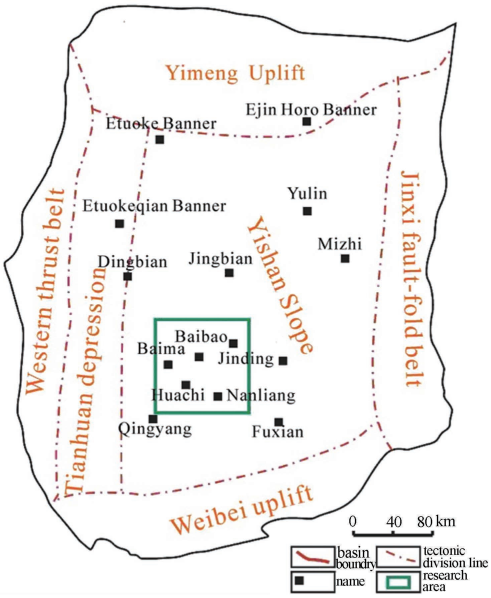


Figure 1
Geographical Location of Huaqing Oilfield

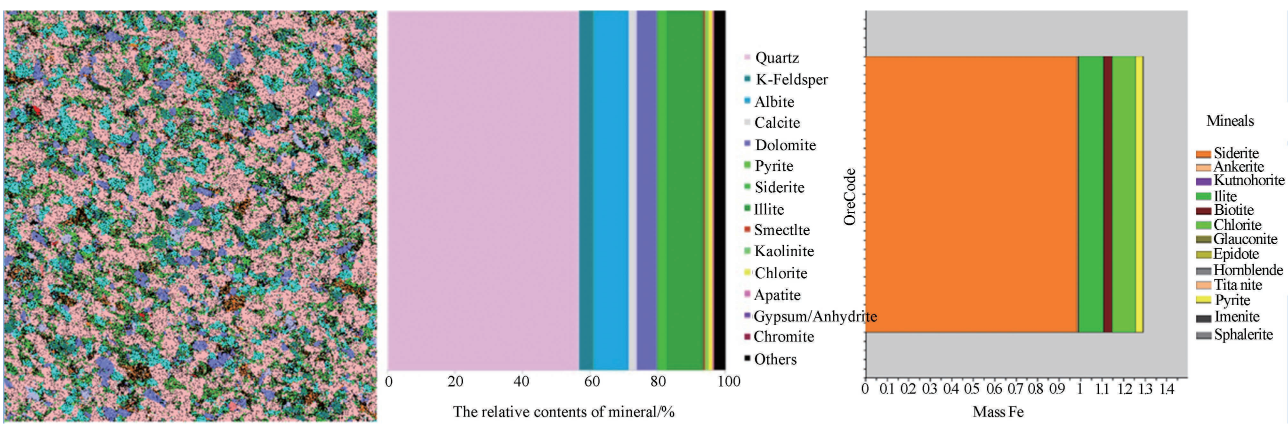
2. LITHOLOGICAL FEATURES

Lithological features include the mineral composition, sorting and rounding, arrangement and the feature of interstitial materials, having significant influence on the diagenesis, pore structures and physical properties of reservoir. The analysis of casting lamella showed that the kinds of Chang-6 reservoir rocks in Huaqing area were mainly fine-medium arkose, lithic arkose and lithic sandstone, and the content of these rocks were more than 85%. Medium-good sorting of sandstone was observed. The cements were mainly carbonatite (calcite, dolomite), chlorite and authigenic quartz, and a small amount of kaolinite could also be observed.

Three rock samples were analyzed by QEMSCAN. The field-of-view was 515 μm, and 100 images were combined for every sample, and therefore the size of scanning zone was 5 mm. The scanning resolution was 2 μm, the scanning period lasted for 10 hours for each sample, and more than one billion energy spectrum data could be obtained. Table 1 shows that the main compositions of Chang-6 tight reservoir were quartz and feldspar, including 56% to 59% quartz, 3.5% to 4.6% potassium feldspar and 10% to 14% soda feldspar. There were also some clay minerals in the reservoir, including 8% to 11% illite and 1.2% to 2% chlorite. In addition, there were also some other minerals including 0.26% to 2.6% calcite, 5% to 6% dolomite and a small quantity of iron pyrite and siderite (less than 3%). Figure 2 shows the mineral structure of the tight reservoir. The matrix was mainly formed by quartz and soda feldspar, and the pores were filling with dolomite, with some illites and a small amount of chlorite developed around the pores.

Table 1
Mineral Composition of Chang-6 Reservoir From No. 51 Well in Huaqing Area

Composition	Content/%		
	Sample 1#	Sample 2#	Sample 3#
Quartz	56.80664	56.00799	58.92974
Potassiumfeldspar	4.303637	3.537627	4.674537
Sodafeldspar	10.24994	13.69597	9.940575
Calcite	2.556672	0.26032	0.627186
Dolomite	5.917384	5.878388	5.069632
Pyrite	0.098716	0.164399	0.175268
Siderite	2.668447	0.783156	1.503151
Illite	10.83168	8.493692	10.3831
Montmorillonite	0.595241	0.680976	0.739397
Kaolinite	0.881574	2.713162	0.987197
Chlorite	1.200949	1.910126	1.450076
Apatite	0.441477	0.298304	0.281092
Gypsum	0.020895	0.012994	0.034288
Others	3.426746	5.562901	5.20476



(a) Mineral Distribution (b) Mineral Contents (c) Distribution of Minerals Containing Iron

Figure 2
Mineral Composition of Chang-6 Sandstone in Huaqing Area Obtained With QEMSCAN

3. CHARACTERIZATION OF RESERVOIR SPACE

3.1 Types of Pores

Low average surface porosity, complex pore structure and strong heterogeneity were found for Chang-6 reservoir. The two-dimensional structures of pores of Chang-6 reservoir were characterized by optical microscope, laser scanning confocal microscope and scanning electron microscope. The reservoir contains primary intergranular pores, secondary dissolution pores (feldspar dissolved pores and cuttings dissolved pores), intracrystalline pores and micro fractures, as shown in Figure 3. By means of laser scanning confocal microscope, the pore structures could be further characterized because the agents injected into pores could be highlighted under laser exciation. Figure 4 shows that there are a lot of primary intergranular pores and intergranular dissolved pores. Meanwhile, some intragranular dissolved pores and moldic pore could also be observed.

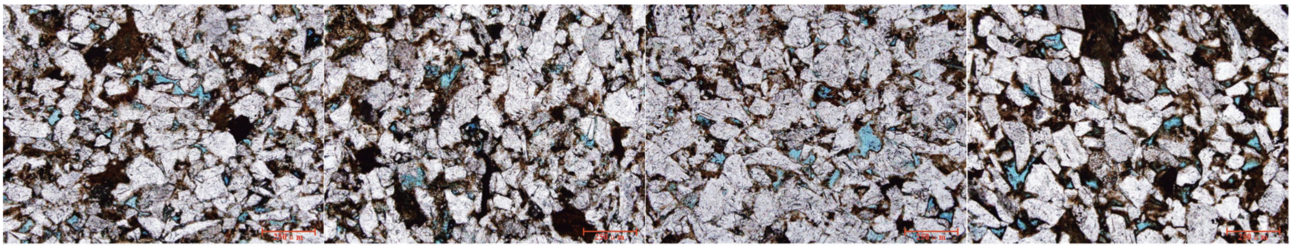
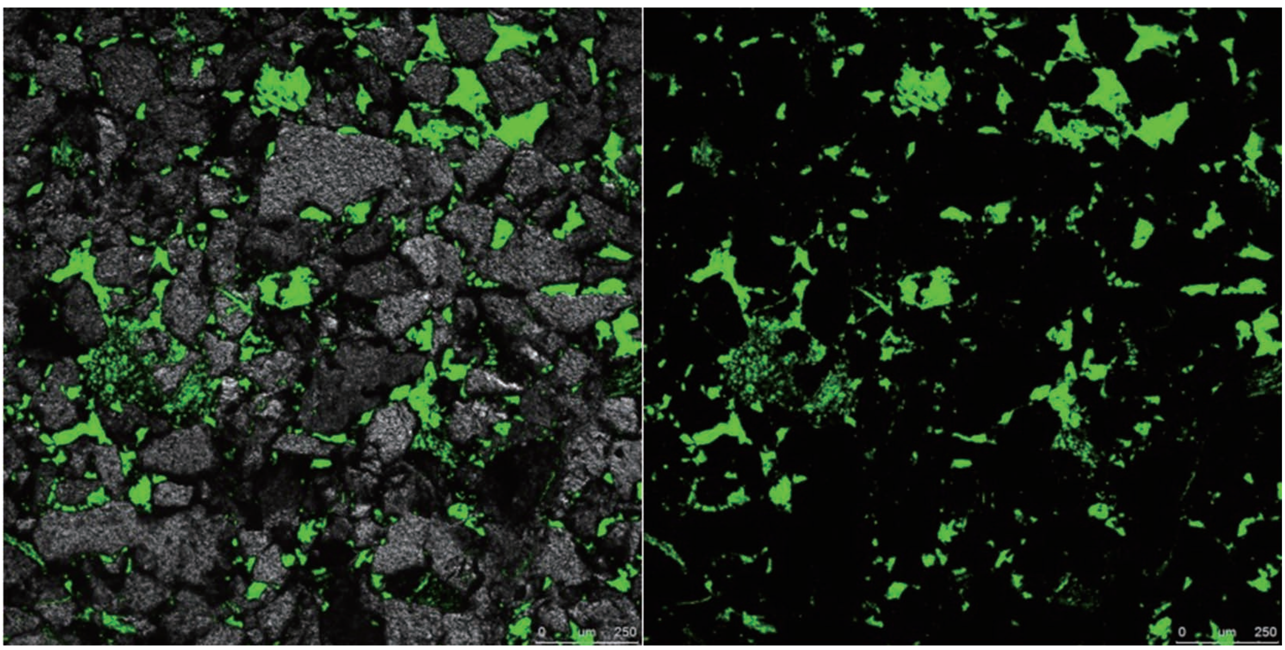


Figure 3
Casting Lamella Photographs of Chang-6 Reservoir Sandstone Rocks in Huaqing Area



(a) (b)

Figure 4
LSCM Photographs of Chang-6 Reservoir Sandstone in Huaqing Area. (a) Combination of Optical Photograph and Laster Photogragh, (b) Laster Photogragh Indicating the Pore Structure

3.2 Types of Throats

Throats are narrow paths between pores, and the storage and permeable properties of pores depend on the size and shape of throats. The degree of stress sensitivity of reservoir varies according to different kinds of throats in reservoirs. Reservoirs with necking throats have strong stress sensitivity, the next are reservoirs with laminated throats and curved lamellar throats, while that with tube bundle throats have the weakest stress sensitivity because the pores in these reservoirs are throats in fact[12]. By means of casting lamella and LSCM, it was found that the types of cements in Chang-6 reservoir were dominantly porous cement and film-porous cement, and the contact types between grains are mainly line and point contact.

3.3 Characteristics of Pores and Throats

The capillary pressure curves of twenty reservoir rock samples with different permeabilities were measured by Autopore 9,500 high pressure mercury injection apparatus, and the distribution of pore throats and their contribution to the permeability of reservoir could be analyzed. The pore throat distribution histogram was shown in Figure 5.

Nano-pores are defined as pores with the size between 0.1 nm and 0.1 m (100 nm), submicro-pores are pores with the size between 0.1 μm and 1 μm, and the size of micro pores are 1 μm to 5 μm. The capillary pressure curve obtained from high pressure mercury injection tests showed that the distribution of pore throats radius in Chang-6 reservoir was unimodal, and the sorting was fair. Only 0.24% of the pores were micro-pores, while the ratios of submicro-pores and nano-pores were up to 40.66% and 59.10%, respectively. The calculation results of capillary model showed that micro and sub-micro pore throats were the major contributors to the permeability of Chang-6 reservoirs, while the nano-pore throats had hardly any contribution to the permeability.

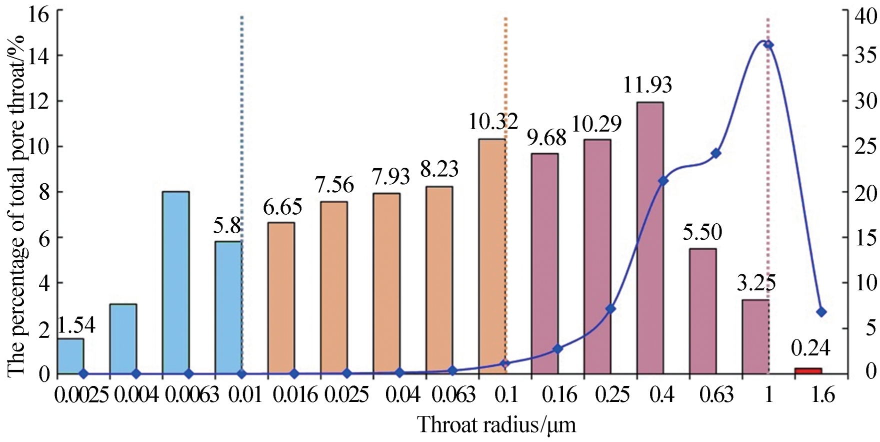


Figure 5
Pore Throat Distribution Histogram of Chang-6 Reservoir

4. STRESS SENSITIVITY TESTS

4.1 Experimental Principle

Stress sensitivity of reservoir is defined as the decrease of porosity and permeability of reservoir caused by the deformation of rocks due to the variation of stresses. When the rock is compressed, pore throats will be closed while most of pores will not. The permeability of reservoir depends on pore throats, so the permeability is sensitive to the variation of pressure. Therefore, the study of stress sensitivity is to study the relationship between permeability and effective stress.

4.2 Experimental Method

The stress sensitivity of Chang-6 reservoir in Huaqing Oilfield was measured using the recommended standard procedure for formation damage evaluation by flow test[13]. The natural cores obtained from Chang-6 reservoir were used in these tests, and the parameters of the cores were shown in Table 2. High purity nitrogen was used as experimental fluid in these tests. Based on the analysis of initial formation pressure, overburden pressure and pressure difference between production and injection, the permeabilities were respectively measured under the confining pressures of 2 MPa, 3.5 MPa, 5 MPa, 7 MPa, 9 MPa, 11 MPa, 15MPa, 20 MPa, 30 MPa and 40 MPa after stabilizing at each experimental pressure for 1 h.

The permeability measured with gas will be larger than it should be because there is slippage effect when gas passes through porous medium under low pressure. The lower the permeability, the stronger the slippage effect. In order to eliminate the influence of the slippage effect, the permeabilities at three different upstream pressures were measured under each confining pressure, and the equivalent liquid permeabilities obtained from regression method were also considered for the evaluation of stress sensitivity.

Table 2
Parameters of Cores Used in the Tests

Samples	Lithology	Length /cm	Diameter /cm	Permeability /10^{-3} μm^2	Porosity /%
1#	Silt-finestone	4.008	2.524	3.763	7.946
2#	Silt-finestone	5.234	2.524	1.236	5.3
3#	Silt-finestone	5.799	2.492	0.293	6.04
4#	Silt-finestone	5.712	2.494	0.085	6.48

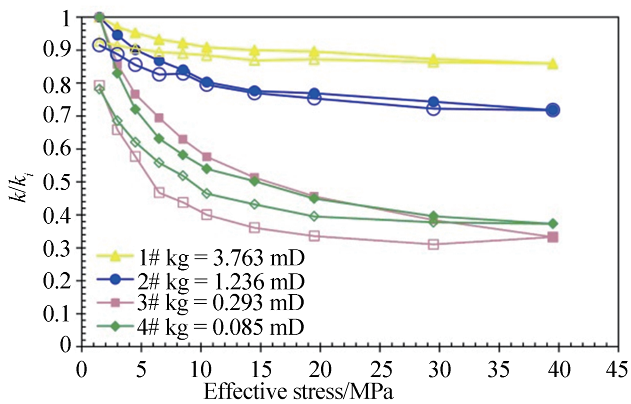
4.3 Results and Discussions

4.3.1 Stress Loading

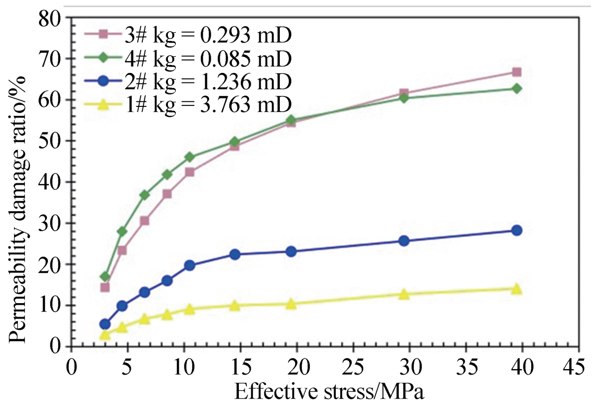
The effective stresses of cores under different confining pressures were calculated according to the equation raised by Terzaghi[14], and the variations of the equivalent liquid permeability as a function of effective stress were obtained, as shown in Figure 6. As the effective stress was increased, the permeability of cores was reduced, and the reduction rate was rather high at the initial stage and then slowed down in the rest of time. The higher the permeability, the shorter the fast reduction stage. The rates of permeability damage of 1# and 2# cores were nearly constant at 10.41% and 23.11% as the effective stresses were increased when the effective stress was higher than 20 MPa. Therefore, these cores had weak stress sensitivity. The rates of permeability damage of 3# and 4# cores were increased from 54.39% and 55.05% to 66.72% and 62.71% respectively as the effective stresses were increased to 40 MPa, indicating that these cores had medium-strong stress sensitivity.

The initial experimental pressure was 2 MPa in conventional stress sensitivity tests. However, taking the original effective stress of reservoirs as the initial pressure was more favorable for evaluating a certain reservoir. In this work, the initial pressure was set to 20 MPa based on effective stress calculation. As the effective stress was increased from 20 MPa to 40 MPa, the rates of equivalent liquid permeability damage were increased by less than 15%. Therefore, the stress sensitivity of reservoir would be exaggerated if the initial pressure was 2 MPa. The loading condition of cores agreed with the in-situ stress condition of reservoir rocks when the effective stress was increased to 20 MPa. The results of stress sensitivity tests when the pressure was higher than 20 MPa would be more reliable and accurate for the evaluation of stress sensitivity of reservoir.

The essential cause of stress sensitivity of tight reservoir was that the relationship between matrix grain and pore throat structure was changed due to the variation of stress, changing the flow paths. Pore structures of rock consisted of pores and throats. Based on the theory of deformation of pores and throats, when tight rock was pressured, the throats were firstly compressed rather than pores, and the necking throats, laminated throats and curved lamellar throats were easier to be closed under pressure. For Chang-6reservoir, the contact types between grains were mainly line and point contact (Figure 3), and the ratio of nano-pores was 59.10% (Figure 5). These pores would be closed firstly when the effective stress was increased, resulting in larger reduction of permeability. As the effective stress was increased, the matrix grains were condensed continuously. The amount of pores not closed was reduced and these pores were not easy to be closed, resulting in smaller and smaller reduction of permeability.



(a)



(b)

Figure 6
Stress Sensitivity Curve of Cores. (a) Variations of Permeability as a Function of Effective Stress, (b) Variations of the Rates of Permeability Damage as a Function of Effective Stress

4.3.2 Stress Restoration

In the process of stress restoration, the equivalent liquid permeabilities of cores with different permeabilities were increased as the effective stresses were reduced. The equivalent liquid permeability could not return to the initial level, and the final recovery rates were 78% to 92%. The higher the permeability of the cores, the higher the recovery rate of equivalent liquid permeability. The high recovery rate of equivalent liquid permeability of Chang-6 reservoir could be explained based on the characterization of pores and throats. The chlorite developed around the pores (Figure 2) increased the pressure resistance of grains, reducing the reduction degree of pore throat size and saturating the pores to some extent. If there was no chlorite developed around pores, the increase of effective stress would lead to plastic deformation of grains, resulting in low recovery rate of permeability.

CONCLUSION

Low average surface porosity, complex pore structure and strong heterogeneity were found for Chang-6 reservoir. Intragranular and intergranular dissolved pores which were mainly potassium feldspar dissolved pores were developed in the reservoir. The chlorite developed around the pores protected the pores to some extent. The contact types between grains were dominantly line and point-line contact; the sorting of pores and throats was fair, and the compression resistance was poor. The ratio of micro-pores was extremely low, while the ratios of submicro-pores and nano-pores were up to 40.66% and 59.10% respectively. As the effective stress was increased, the permeability of cores was reduced, and the reduction rate was rather high at the initial stage and then slowed down in the rest of time. Before the effective stress was increased to 20 MPa, nano-pores which were abundant in Chang-6 reservoir would be closed firstly, resulting in lager reduction of permeability. As the effective stress was increased, the reduction of permeability get smaller because the chlorite developed around the pores enhanced the compression resistance of grains. When the effective stress was increased to 40 MPa, the rate of permeability damage was in the range of 14.08% to 66.72%, indicating these cores had weak, medium-weak or medium-strong stress sensitivity. In the process of stress restoration, the equivalent liquid permeabilities of cores with different permeabilities were all increased as the effective stress was reduced, and the final recovery rate was in the range of 78% to 92%.

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