Hindawi
Geofluids
Volume 2017, Article ID 5758046, 8 pages
https://doi.org/10.1155/2017/5758046

Research Article

Experimental Study on Water Sensitivity Difference Based on Oiliness of Porous Medium Rock

Jie Li,[1,2,3] Wei Li,[4] and Li Li[5]

[1]*School of Energy Resource, China University of Geosciences, Beijing, China*
[2]*MOE Key Laboratory of Petroleum Engineering, China University of Petroleum, Beijing 102249, China*
[3]*University of Tulsa, Tulsa, OK, USA*
[4]*Institute of CNOOC, Shenzhen Branch, Shenzhen, Guangdong 518000, China*
[5]*Pu Yang Best Oil-Gas Technology Service Co. Ltd., Henan, China*

Correspondence should be addressed to Jie Li; jil0474@utulsa.edu

Received 20 June 2017; Accepted 28 September 2017; Published 27 November 2017

Academic Editor: Zhenhua Rui

This study presents the differences of water sensitivity experiment of porous medium rock between conventional dry core samples and oil-bearing core. The comparison was made to analyze the impact of single-phase fluid and multiphase fluid on the actual sensitivity of rock. The nuclear magnetic resonance (NMR) test was carried out to reveal the distribution of oil in porous medium and the microscopic influence mechanism of oil phase. The study shows that the initial oil in place could isolate the clay from water, and then the expansion and the migration of the clay were prevented to reduce the decrease of degree of damage.

1. Introduction

Along with the continuous reduction of conventional geological reserves, the discovery of geological reserves becomes more and more difficult. With the continuous progress of development technology and continuous decrease of development cost, the low-permeability reservoir or extralow-permeability reservoir currently has become one of the main contributors of global oil production. But most of low-permeability and extralow-permeability reservoirs are facing one major problem during the development process, namely, sensitivity of reservoir. The sensitivity of reservoir can cause the reduction of reservoir production and then further impacts the recovery ratio of reservoir [1–3]. However, we have not yet come to an accurate conclusion on the impact on recovery ratio, and even when we come to conclusions, they will have a certain number of errors due to the limitation of experimental method.

The earliest sensitivity studies were based on rock composition to study various mechanisms responsible for formation damage [4–8]. Their focus is on damage directly between the formation and fluid injected into formation. Their methods used to evaluate the sensitivity of formation are usually capillary suction test (CST) which was developed in 1970s to evaluate water sensitive formations for drilling [9]. CST method evaluates the reservoir rock treatment fluid interactions. While there are many potential causes for formation damage, the focus here is only on damage due to interactions between the formation and a fluid injected into the formation. CST method is sensitive to swelling and dispersive clays, but it cannot evaluate the immigration. The dry core flooding test method is widely used in recent years to evaluate the water sensitivity in China, which is adopted to diagnose the mechanisms of formation damage. The dry core flooding test is taken into consideration to be closer to the actual situation of the oilfield [10]. But it cannot distinguish immigration and swelling of the water sensitive. CT scanning technique was used widely for quantitative evaluation of reservoir damage mechanism [11, 12]. While all these sensitivity experiment studies are made by utilization of dry core and the impact of oil-bearing is not considered in the study, it is possible that research cognition exaggerates the impact of sensitivity. This kind of impact is not conducive to the optimization of water injection match ability and that of water injection method on the one hand, and it will impact the final estimation of

Table 1: Table for evaluation results of water sensitivity.

Block	Core number	Porosity (%)	Native permeability (mD)	Damage rate (%)	Water sensitivity degree	Critical value of salinity (mg/L)
ZD	ZD1	13.425	0.0888	60.37	Medium-slightly strong	7247.18
	ZD2	16.889	5.7823	61.76	Medium-slightly strong	7247.18
	ZD3	14.618	0.209	59.47	Medium-slightly strong	7247.18
HLM	H1	7.266	0.47	37.50	Medium-slightly weak	4831.45
	H2	3.12	0.4	35.71	Medium-slightly weak	4831.45

Table 2: Table for evaluation of water sensitivity damage of saturated core.

Block	Core number	Porosity (%)	Initial permeability (mD)	Damage rate (%)	Water sensitivity degree	Critical value of salinity (mg/L)
ZD	ZD4	10.268	0.307	43.33	Medium-slightly weak	4936.85
	ZD5	15.32	7.631	44.44	Medium-slightly weak	4936.85
HLM	H4	7.135	1.634	33.33	Medium-slightly weak	2415.73
	H5	2.63	0.158	30.16	Medium-slightly weak	2415.73

recovery ratio on the other hand. Huang considers the rock sensitivity when the core bears residual oil, which still cannot completely reflect the impact of crude oil in the production process and its saturation on rock sensitivity.

This paper takes the water sensitivity damage of low-permeability core from Nanyang Oilfield as an example. In order to be more suitable with reservoir practically, this paper conducts the water sensitivity damage under the oil-bearing state and meanwhile utilizes T_2 spectral curve of NMR to compare the damage to rock pore structure and makes quantitative study on the sensitivity damage under different formation oil saturation conditions. Consequently, this paper provides a theoretical and technical basis for prevention of water injection damage in the actual production process of oilfield and quantitatively proposes the impact of water sensitivity on ultimate recovery.

2. Water Sensitivity Experiment

2.1. Reservoir Study Overview. Nanyang reservoir is a Meso-Cenozoic half graben-like rift lake basin which is deep in the south and shallow in the north. As can be known from the analysis of samples obtained from Nanyang reservoir, it is low-permeability reservoir in physical property, with the thickness of single layer of 2–20 m, reservoir porosity of 2.2~11.7%, and arithmetic mean of 6.02%. The main distribution range is less than 10%, accounting for 98.1% of 52 samples. It belongs to extralow pore and ultralow pore. The permeability distribution range is $0.09 \sim 2.98 \times 10^{-3}\,\mu\mathrm{m}^2$, so it belongs to extralow-permeability reservoir.

The content of clay in the reservoir amounts to 7.62%. The illite is 3.42%, chlorite 1.36%, muscovite 1.14%, biotite 0.12%, kaolinite 0.22%, and smectite 1.36%. It is generally acknowledged that there were two damage types in the reservoir. One is kaolinite migration with water flooding. The other is illite and smectite hydrophilic expansion. Besides, the reservoir bed of extralow-permeability reservoir itself has the characteristics of dense lithology, low permeability, large filtration resistance, and so on.

Consequently the external fluids can react with rock minerals of reservoir bed in the process of fracturing measure and water injection development implemented in the oilfield, which causes the damage to reservoir bed and consequently impacts the crude oil production. Meanwhile, because the low-permeability reservoir generally contains more argillaceous and particle minerals and the pore throat radius is small, thus the reservoir is vulnerable to contamination and damage, which has become one of the bottle necks restricting the development of low-permeability reservoir. Therefore, the study on sensitivity appears to be particularly important for the impact generated by reservoir.

2.2. Experimental Porous Medium Rock Samples and Fluids

2.2.1. Experimental Cores. The porous rock samples in this study come from two extralow-permeability reservoir blocks of Nanyang Oilfield, and the specific core parameters are as shown in Tables 1 and 2.

2.2.2. Experimental Fluids. Fluids utilized in the experiment include formation water (with salinity of 9662.9 mg/L), deionized water, and fluorocarbon oil with the viscosity close to that of initial oil in place in the research block.

2.3. Experiment and Analysis on Dry Core. The water sensitivity experiment study is conducted for conventional core, as the comparison of rock sensitivity study in the saturated core. The sensitivity experiment methods and evaluation criterion for conventional core utilize the industry standard of China National Petroleum Corporation (CNPC) SY/T 5358-2002 Evaluation Method for *Flow Experiment of Reservoir Sensitivity Flow Experiment* [13].

2.3.1. The Testing Process of Water Sensitivity. For the core to be tested, firstly, ensure the formation water is saturated and determine the permeability K_0, pore volume Φ of core sample, and T_2 spectrum by NMR; then, respectively, utilize 3/4 formation water, 1/2 formation water, 1/4 formation water,

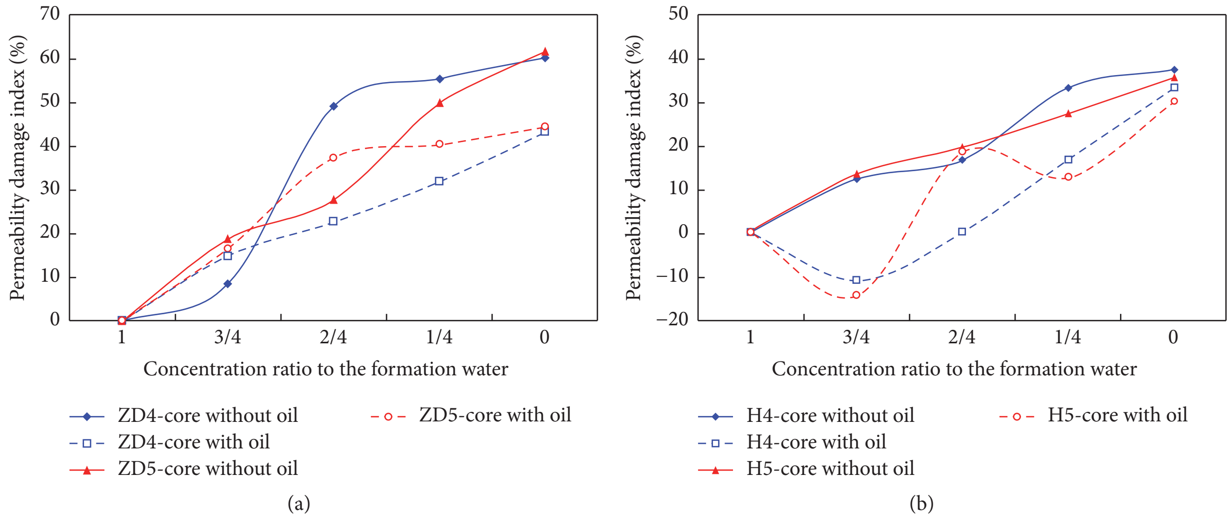

Figure 1: Comparison of water sensitivity damage degrees under dry core and oil-bearing.

and deionized water for displacement at 0.3 ml/min, let the fluid soak for 12 h after displacement of 10 PV, determine the corresponding permeability variation, calculate the permeability damage rate, and then reutilize NMR to determine T_2 spectrum.

2.3.2. The Evaluation on Conventional Water Sensitivity. Cores are used to conduct water sensitivity damage experiment for dry core, and the results are as shown in Table 1.

As can be seen from the table, the damage rates of Block ZD and Block HLM are, respectively, determined as 60% and 36% or so by dry core. According to the grading standards of water sensitivity strength by Marathon Oil Corporation, Block ZD has a moderately strong water sensitivity and critical salinity of 7,247.18 mg/L; Block HLM has a moderately weak water sensitivity and critical salinity of 4,831.45 mg/L.

2.4. Experiment and Analysis on Oil-Bearing Core

2.4.1. Saturated Oil to the Core. The core oiliness treatment is the key to the study of impact of oiliness on rock water sensitivity. We must ensure the oil-bearing state of core, as well as no impact on rock seepage and following experiments after the core bears oil.

This study utilizes the treatment methods before oiliness and ageing of core, including three stages: bound water state before ageing, HTHP ageing, and bound water state after ageing. The bound water state before ageing is based largely on the initial oil-bearing state under dry core after the wash oil is dried and provides preparations for ageing, including applying saturated water and saturated bound water to residual oil. The HTHP ageing mainly simulates the temperature and pressure conditions of target reservoir to recover the wettability of core sample in reservoir, mainly including putting core sample in 17 MPa confining pressure clamp holder for ageing at 80°C constant temperature cabinet. The bound water state after ageing is the new oil-bearing state of core sample after permeability recovery, mainly including the state of saturated oil and long-time water displacing oil to residual oil. The subsequent water sensitivity experiment process is the same as that of conventional core and will not be repeated herein.

2.4.2. The Evaluation on Water Sensitivity with Oil-Bearing Core. The experiment results are as shown in Table 2, and it can be seen from such results that Block ZD has a damage rate of 44% or so, moderately strong water sensitivity, and critical salinity of 7,247 mg/L; Block ZD has a damage rate of 32% or so, moderately strong water sensitivity, and critical salinity of 2,415 mg/L.

2.4.3. Comparison of Water Sensitivity Damage of Saturated Core and Dry Core. The degrees of damage of saturated core and dry core on formation are compared from three aspects.

(1) The Water Sensitivity Damage Degree. As can be seen from the comparison of Tables 1 and 2, the sensitivity damage degree of Block ZD decreases and becomes moderately weak from moderately strong due to the existence of oil in core. It shows that the previous experiment utilizes dry core for sensitivity experiment to expand the damage degree of water sensitivity.

(2) The Permeability Damage Degree. Figure 1 shows the water sensitivity and permeability damage, the continuous lines are the damage curves under the dry core state, and lines of dashes are damage curves under the oil-bearing state. It can be seen that damage curves of saturated core are all below those of dry core, which indicates that even the residual oil can reduce the water sensitivity damage after the rock bears oil. For the core with a stronger water sensitivity, the permeability damage rate can reduce up to 20%, while, for the core with a weaker water sensitivity, the permeability damage rate can reduce 10% or so on average.

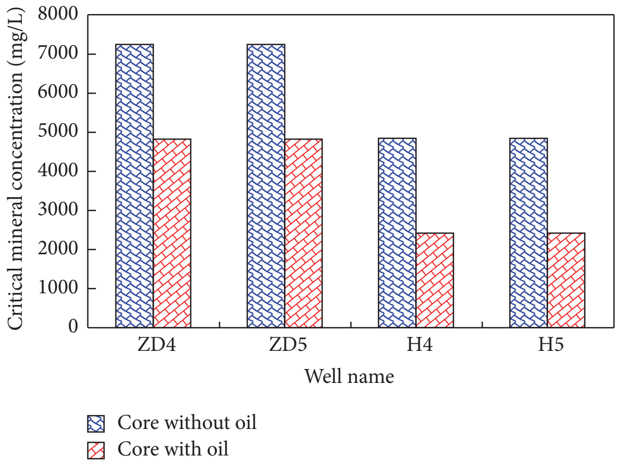

Figure 2: Comparison diagram of critical salinities under two states.

(3) The Critical Salinity. Compared with the dry core, rocks in Block ZD and Block HLM have a smaller critical salinity under the oil-bearing state (see Figure 2), which indicates that the actual reservoir has a wider degree of adaptability to external fluids. So it can save the treatment cost of injected water and has a more important guidance for actual production.

3. Oil Saturations Impact on the Water Sensitivity Damage

Cut one core into two sections, and let the two sections be saturated at the same time. Utilize formation water to displace one section and deionized water to displace the other section, and then compare and observe the impacts on sensitivity damage. During the water displacing oil process, the core oil saturation constantly changes with the displacement, and record the pressure, water cut, and degree of reserve recovery of the two cores and meanwhile test T_2 spectrum.

During the displacement process, oil saturation is calculated according to the measured NMR T_2 spectrum signals. The calculation principle: the signal amplitude of T_2 spectrum in core indicates the water content in the core, so the total signal amplitude under the saturated water state may represent the core pore volume. After the oil displacing water, the signal amplitude under the saturated oil state is the pore volume occupied by bound water, so the signal amplitude difference between the two may represent the total oil-bearing pore volume of core. At this point, the definitional equation of the remaining oil saturation is as follows:

> Crude oil saturation = (total signal amplitude in this area under saturated water − total signal amplitude in this area under remaining oil)/total signal amplitude in this area under initial saturated water.

The relation curve for pressure, water cut, and oil saturation (see Figure 3) may be drawn according to experiment results. As can be seen from the figure, the displacement pressure and oil saturation are negatively correlated during the displacement process. The displacement pressure increases while the oil saturation gradually reduces. The difference between pressure curves of formation water flooding and deionized water flooding increases gradually with the reduction of oil saturation, which indicates that the damage degree of formation water sensitivity gradually increases with the reduction of oil saturation. The damage degree of water sensitivity may increase 14.3% at the high water-cut stage when the water cut reaches over 80%. Due to the water sensitivity damage, the oil-water breakthrough occurs earlier, the rate of water-cut increase increases faster, the water-free stage and low water-cut stage are shorter, the high water-cut stage appears quickly, and the recovery ratio reduces. And we can know that the recovery ratio may reduce 10% or so through calculation.

In order to further study the impact of different saturations, this paper draws the curve between oil saturation and permeability damage, as shown in Figure 4. As can be seen from the curve, the variation of damage rate has obvious inflection points. The inflection point corresponding to the core in the study is the oil saturation of 54% or so; namely, the water sensitivity damage becomes more obvious as the high water-cut stage 80% appears, causing the sharp decrease of formation permeability. The permeability damage reaches 16% and basically corresponds to the damage degree.

4. Analysis of Microscopic Mechanism for Core Water Sensitivity Damage

This paper utilizes the T_2 spectral curve obtained from NMR experiment to analyze the microstructure of core and consequently reveal the mechanism of water sensitivity damage of oil-bearing core and dry core.

4.1. Relation between Pore Throat Size and NMR T_2 Spectrum. The pores throats were of different sizes, and each pore is related to a relaxation time T_2. The signal amplitude attenuation is slower and the relaxation time is longer with larger pore. In contrast, the smaller the pore, the more rapid the signal amplitude attenuation and the shorter the relaxation time. Therefore, the distribution of the multiple exponential decay processes in rocks which are T_2 spectrum means the pore size distribution of the core. The pore throats reflected by T_2 spectral line of core of target block are mainly divided into three categories: clay-bound water pore, capillary-bound water pore, and free fluid pore [14, 15]. T_2 spectrum cut-off value is obtained from empirical value and chart method. Empirically, according to the industry standard of China National Petroleum Corporation SY/T 5358-2002 [16], the cut-off time between clay-bound water pore and capillary-bound water pore for low permeability is 1 ms [17]. The T_2 cut-off value is 10 ms between capillary-bound water pores and movable fluid pores (as shown in Figure 5) considered with the centrifugal experiments on core sample and empirical methods from Chinese oil field [18, 19]. So three types of pores structure's cut-off time were obtained. As shown in Figure 6, 0.1–1 ms pores are micropores and main clay-bound water pores, 1–10 ms pores are mesopores and main capillary-bound water pores, and pores greater than 10 ms are macropores and main movable fluid pores (as shown in Figure 6).

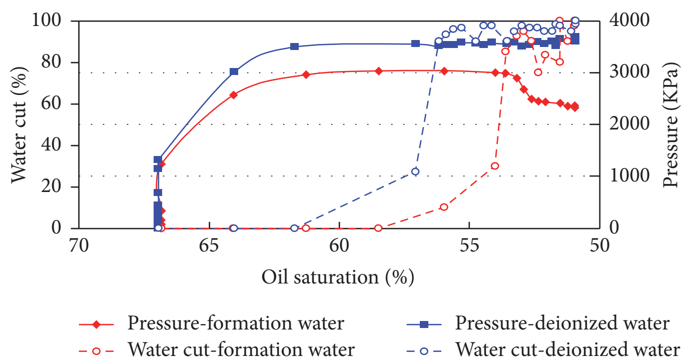

Figure 3: Curve between pressure and water cut with oil saturation change.

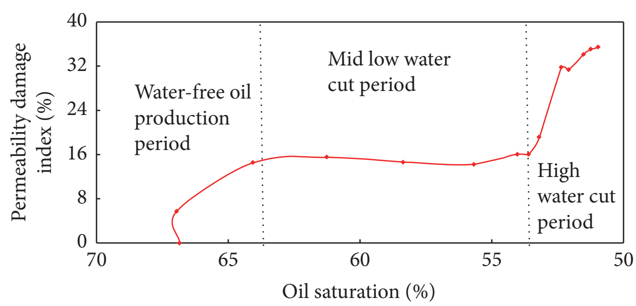

Figure 4: Damage rate curves under different oil saturations.

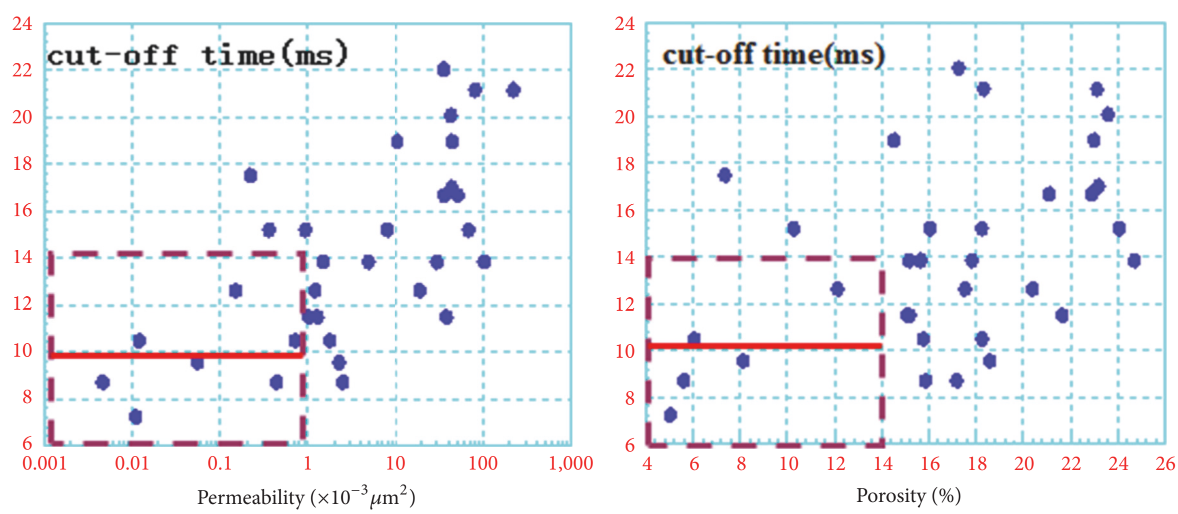

Figure 5: Movable fluid T_2 cut-off value plate.

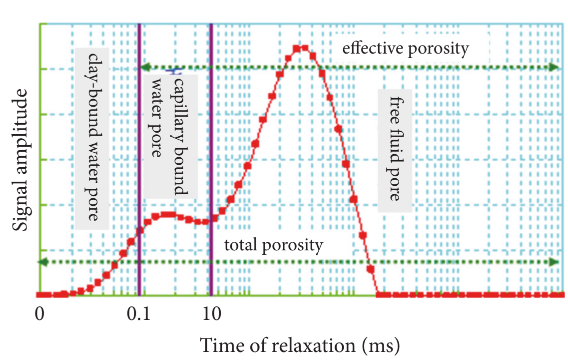

Figure 6: Relation between relaxation time and signal intensity.

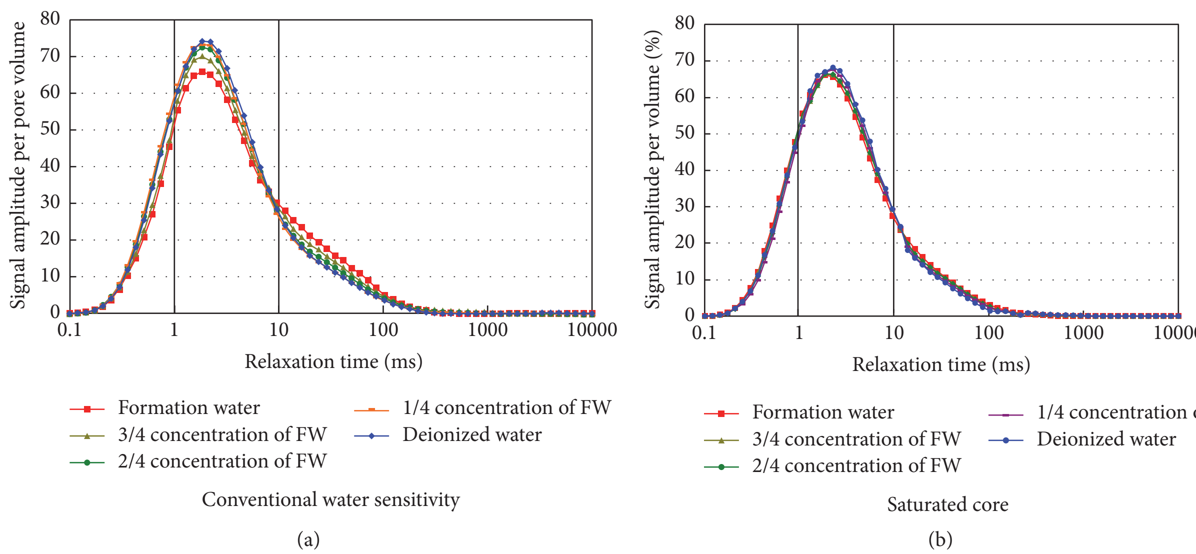

Figure 7: T_2 spectral curve of water sensitivity of conventional core and saturated core.

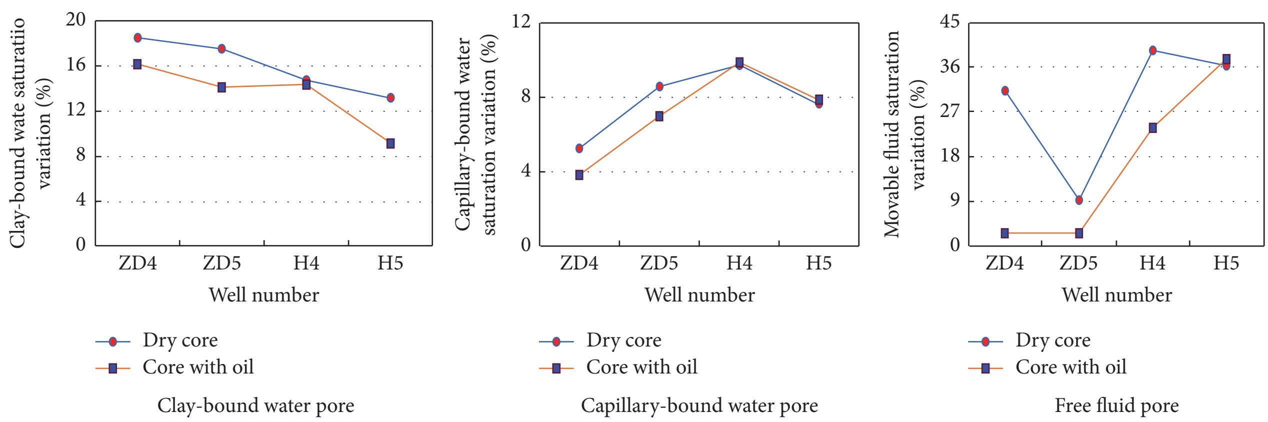

Figure 8: Variation diagram of pore structure of water sensitivity of conventional core and saturated core.

The variation and its range of different pore types can be analyzed under different situations of water injection. The microcosmic reason and mechanism of sensitivity damage can be analyzed quantitatively. In the following pore analysis, the variation of the three kinds of pore structures is also mainly studied.

4.2. Comparison of Impacts of Water Sensitivity on Pore Structure. Figure 7 is the measured T_2 spectral curve after the water sensitivity experiment of conventional core and saturated core and shows that the variation ranges of different grades of pores of saturated core are narrow. Based on previous research, T_2 spectrum can be divided into three zones which represent three pore structures. From the two T_2 spectral curves, it can be concluded that the amount of capillary-bound water pore in the zone among 1–10 ms gradually increases with water sensitivity. In contrast, the amount of free fluid pore which is more than 10 ms decreases. However, variation degree of saturated core is smaller than conventional core. We also obtain from T_2 spectrum the fact that clay-bound water pore less than 1 ms changes a little in saturated core, and conventional core increases. The fact that the conventional damage of core in water sensitivity test is more than that in saturated core is further explained. We noticed that Qi had ever conducted an experiment with conventional cores and got the same T_2 distribution as conventional water sensitivity curve in Figure 7 [20]. So they achieved exaggerated influence of water sensitivity.

This paper has also investigated the damage of three kinds of pore structures of different clay-bound water pore, capillary-bound water pore, and free fluid pore of core, as shown in Figure 8.

As can be seen from Figure 8, the variation range of clay-bound water pore is wide, while the clay-bound water pore is the part which can best describe the sensitivity damage caused by clay water-swelling. The analysis shows that the clay concentration is higher around the clay-bound water pore, and the clay water-swelling is quite strong, causing narrower space in clay-bound water pore, while, for the saturated core, the clay water-swelling is weak because the clay is wrapped

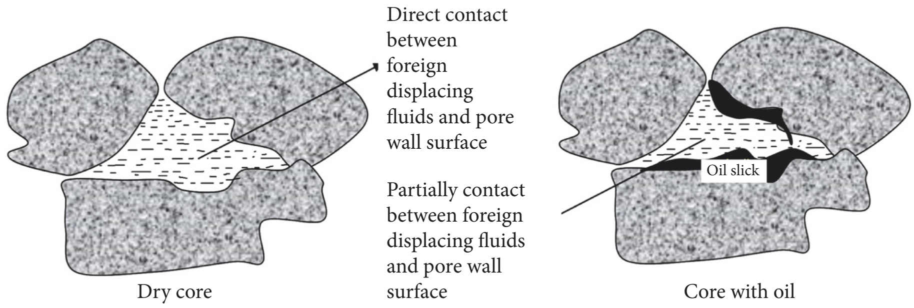

Figure 9: Schematic diagram of microcosmic reason of core damage.

by oil film under the oil-bearing state, which greatly reduces the water absorbing capacity of clay. The variation range of capillary-bound water pores is the narrowest, and capillary-bound water pores are basically capillary-bound water pores. Such pores are almost filled with bound water; the clays decrease the pore space when they swell by absorbing water. Meanwhile some free fluid pores would decrease due to the action of sensitivity and become mesopores. Pores with a wider variation range are free fluid pores which provide the main space for catchment and are also main seepage channels. In case of dry core, the water directly contacts the rock surface and causes clay swelling and migration and more serious damage to free fluid pores. As for saturated core, because the crude oil has isolation effect on water and rock, both the clay swelling and migration reduce to a certain extent, and the maximum reduction can reach 10%, which shows that the existence of crude oil in core generates a greater impact on pore structures.

4.3. Analysis of Microstructure Damage Mechanism under Oil-Bearing State. The sensitivities under the oil-bearing state and dry core state have greater differences. The main reason is that the shielding effect of oil film forms due to the existence of saturated oil in pores, which consequently reduces the contact between foreign water and clay mineral, causing the reduction of sensitivity, as shown in Figure 9.

At different water injection stages, the chance of direct contact between foreign displacing fluids and pore wall surface continuously varies, which causes the variation of damage degree.

(1) The reservoir starts to be damaged due to the injection of foreign water during the water-free oil production period. But the area of contact between foreign water and clay mineral is very small due to the fact that the displacement of crude oil is mainly for the crude oil in pores at the initial stage, which causes small damage at the low-medium water-cut stage.

(2) With the increase of injected water, the crude oil along with the wall surface starts to be displaced, and the area of contact between foreign water and clay mineral gradually increases. Especially after the high water-cut stage appears, the contact between clay and foreign fluids is maximum, and consequently sudden swelling occurs, causing sudden increase of damage. Therefore, it is suggested to conduct fracture acidizing and other experiments for reservoir at the low water-cut stage if such experiments are done so as to reduce the damage of foreign fluids of formation.

5. Conclusions and Suggestions

(1) The water sensitivity evaluation methods which are based on core flow experiment and NMR T_2 spectrum study under the oil-bearing state of rock are established. The core of reservoir is utilized for actual analysis and comparison study. The research shows that the sensitivity of formation under the oil-bearing state decreases to a certain degree, and consequently the impact of oiliness of formation should be considered for the sensitivity experiment.

(2) In case of no saturated oil, the water sensitivity damage of formation mainly reduces the permeable space of flowable pores, while the initial oil in place can generally play a role of isolation protection in core, and both the clay swelling and migration reduce to a certain extent, which consequently causes the great reduction of damage degree. Due to the existence of formation crude oil, the tolerance of formation to foreign fluids and the degree of adaptability are wider.

(3) The sensitivity can cause the increase of displacement pressure and early water breakthrough of oil well. With the increase of injected water, the damage of sensitivity on oil layers increases. It is suggested to conduct formation protection operation in advance at the low water-cut stage in practice, so as to reduce the damage of sensitivity on formation.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] Y. Lu, "Damage in reservoir formation induced by fracturing field and relevant protection technology," *Drilling field and Completion field*, vol. 12, no. 5, 1995.

[2] D. Yaoyao, G. Baoshan, X. Yun et al., "Study and application of novel low damage stimulation technology in sulige tight gas field," in *Proceedings of the SPE Oklahoma City Oil and Gas Symposium*, Society of Petroleum Engineers, Oklahoma City, Oklahoma, USA, 2017.

[3] L. Weifeng, L. Zhenpeng, L. Qingjie et al., "Reservoir sensitivity evaluation by monitoring displacement experiment with x-ray Ct imaging," in *Proceedings of the SPE/IATMI Asia Pacific Oil Gas Conference and Exhibition*, 2015.

[4] L. L. Guan, Y. Du, and Z. Wang, "Water Injectivity-What We Have Learned in the Past 30 Years," in *Proceedings of the Canadian International Petroleum Conference*, Petroleum Society of Canada, Calgary, Alberta, 2005.

[5] F. Civan, Reservoir Formation Damage. Gulf Professional Publishing.

[6] Schecther, Robert S. Oil Well Stimulation. 2015.

[7] R. F. Scheuerman and B. M. Bergersen, "Injection-water salinity, formation pretreatment, and well-operations fluid-selection guidelines," *Journal of Petroleum Technology*, vol. 42, no. 07, pp. 836–845, 1990.

[8] P. R. Howard, J. J. Hinkel, and N. C. Moniaga, "Assessing formation damage from migratory clays in moderate permeability formations," in *Proceedings of the SPE International Symposium and Exhibition on Formation Damage Control 2012*, pp. 898–908, usa, February 2012.

[9] M. Scholz, "Review of recent trends in Capillary Suction Time (CST) dewaterability testing research," *Industrial & Engineering Chemistry Research*, vol. 44, no. 22, pp. 8157–8163, 2005.

[10] M. Ruan and L.-G. Wang, "Low-permeability oilfield development and pressure-sensitive effect," *Acta Petrolei Sinica*, vol. 23, no. 3, p. 73, 2002.

[11] J. M. Huggett and P. J. R. Uwins, "Observations of water-clay reactions in water-sensitive sandstone and mudrocks using an environmental scanning electron microscope," *Journal of Petroleum Science and Engineering*, vol. 10, no. 3, pp. 211–222, 1994.

[12] R. Yang, "A New Quantitative Predicting Method for Water-Sensitivity Damage," in *Proceedings of the Offshore Technology Conference*, 2017.

[13] Z. Huang, "Evaluation method research of water sensitivity to oil rock sample," *Oil Drilling and Production Technology*, vol. 22, no. 6, pp. 57–59, 2000.

[14] R. Lewis, P. Singer, T. Jiang, E. Rylander, S. Sinclair, and R. H. Mclin, "NMR T2 distributions in the Eagle Ford shale: reflections on pore size," in *SPE Unconventional Resources Conference-USA*, Society of Petroleum Engineers, 2013.

[15] A. Al Hinai, R. Rezaee, L. Esteban, and M. Labani, "Comparisons of pore size distribution: A case from the Western Australian gas shale formations," *Journal of Unconventional Oil and Gas Resources*, vol. 8, no. C, pp. 1–13, 2014.

[16] Industry Standard Of China National Petroleum Corporation SY/T 5358-, Flow Experiment Evaluation Of Reservoir Sensitivity.

[17] Z.-M. Yang, S. Miao, X.-G. Liu, D.-M. Huang, and C.-S. Qi, "Percentage parameter of the movable fluid in ultra-low permeability reservoir and its application," *Journal of Xi'an Shiyou University, Natural Sciences Edition*, vol. 22, no. 2, pp. 96–99, 2007.

[18] J. Peng and H. Guo, "Experimental study on T_2 cutoff in low permeability sandstones," *Well Logging Technology*, vol. 34, no. 4, 2010.

[19] T. Li and T. Guo, "Experimental research on movable fluid and Nmr T_2 cutoff in tight sandstone," *Science Technology and Engineering*, vol. 13, no. 5, 2013.

[20] Z. Qi, "An application study on water sensitivity damage of tight sandstone reservoir by Nuclear Magnetic Resonance (NMR)," *Petrochemical Industry Application*, vol. 33, no. 5, 2014.