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Research Article

Longitudinal Reservoir Evaluation Technique for Tight Oil Reservoirs

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Reservoir evaluation is a method for classifying reservoirs and the description of heterogeneity quantitatively. In this study, according to the characteristics of longitudinal physical properties of tight oil reservoirs, advanced experimental techniques such as nuclear magnetic resonance, high pressure mercury intrusion, and X-ray diffraction were adopted; the flow capacity, reservoir capacity, ability to build an effective displacement system, and the ability to resist damage in reservoir reconstruction were considered as evaluation indexes; average throat radius, percentage of movable fluid, start-up pressure gradient, and the content of clay minerals were taken as the evaluation parameters. On the above basis, a longitudinal evaluation technique for tight oil reservoirs was established. The reservoir was divided into four categories by using this method. The reservoirs with a depth 2306.54 m–2362.07 m were mainly type I and II reservoirs, and the reservoirs with a depth of 2362.07 m–2391.30 m were mainly reservoirs of type II and III. The most effective development was water injection in the upper section and gas injection in the lower section.

1. Introduction

China has large reserves of tight oil, and the tight oil reserves in the onshore basin are about 20.0×10^8 t, which are mainly distributed in the Ordos, Songliao, Junggar, and Sichuan basins [1–3]. At the end of the "12th Five-Year Plan," the major oil fields have been explored for the large-scale development of tight oil reservoirs. During the "13th Five-Year Plan" period, the tight oil reservoirs will become an important substitute energy source in China [4]. The primary problem that constrains the effective development of tight oil was how to accurately describe the heterogeneity of tight oil reservoirs. The physical properties of tight oil reservoirs in different oil fields in China were significantly different, and the reservoir porosity and permeability were extremely low [5, 6]. In the evaluation of low-permeability and tight oil reservoirs, Chinese scholars have done a lot of research. Yang et al. and Zhang et al. used a five-parameter method to evaluate the low-permeability reservoirs [7, 8]. Xiao used a six-parameter method to evaluate the tight oil reservoirs [9]. Jia et al. put forward 10 geological parameters to evaluate the tight oil reservoirs [10]. Zou et al. presented the six-property method for the evaluation, considering the geological and engineering factors of the reservoir [11]. The above research studies mainly focused on the differences among reservoirs in different oil fields or blocks. The evaluation parameters are generally calculated based on the mean values of reservoir physical properties, without taking the physical property parameter variations of the tight reservoirs in the longitudinal section into consideration. Therefore, the accurate description of the tight reservoirs can hardly be obtained. In this study, the multiparameters that reflect the most

significant longitudinal heterogeneity of the tight reservoirs were adopted to evaluate the tight reservoirs. The throat radius curve was plotted to describe the change of reservoir seepage capacity, the percentage curve of the movable fluid was plotted to show the change of fluid storage capacity, the pressure gradient curve was used to present the variation of reservoir displacement capacity, and the clay percentage curve was employed to explain the variation of difficulty in the reservoir energy supplement. Based on the comprehensive reservoir evaluation result, the development mode was determined, and the development "sweet spot" [12] areas in the tight reservoirs were preferred. Different types of reservoirs are suitable for different injection media. Hence, it is very important to study reservoir properties. For example, Jia et al. evaluated the effects of CO_2, CH_4, and N_2 injection on shale oil recovery [13].

2. Materials and Methods

2.1. Rock Samples. In this study, taking the tight sandstone of K1q4 of Jilin Oilfield in Songliao Basin as the research object, the rock cores were collected from the same layer of three adjacent wells (namely, No. 1 well, Qian262 Well; No. 2 well, Qian 246 Well; and No. 3 well, Qian21 Well), with the coring depth of 2,309 m, 2,321 m, and 2,371 m, respectively. Rock samples have a porosity of 13.14%–15.20% and a permeability of $(0.39–1.86) \times 10^{-3}\ \mu m^2$, which was typical for the tight reservoir.

2.2. Experimental Methodology. Scanning electron microscopy (SEM) was often used to capture high-resolution images that recognize rock structural features, mineral types, and reservoir spatial characteristics. It can not only observe the microscopic characteristics of rock samples under high magnification, but can also qualitatively and semiquantitatively analyze different components in the sample. A Zeissbeam-540 FIB scanning electron microscope (Zeiss, Germany) was employed to study the pore and mineral characteristics of tight rock samples, with a magnification of 100 times. Electron microscopy was used for visual observation of pores.

Pore distribution characteristics of tight rock samples were studied using an ASPE 730 rate-controlled mercury intrusion instrument manufactured by US Coretest. These tests were conducted with a mercury-injection pressure of 0–1000 psi (about 7 MPa), a mercury-penetration speed of 0.00005 mL/min, a contact angle of 140°, an interfacial tension factor of 485 dyn/cm, and a physical size of approximately 1.5 cm^3. During rate-controlled mercury intrusion, mercury can be injected into pore volumes of rocks under extremely low mercury-penetration speed (0.00005 ml/min) without changing the surface tension or contact angle to ensure quasistatic mercury intrusion processes [14, 15]. In accordance with changes in mercury-penetration pressures, data related to pore structures could be acquired. With the distribution of pore throats and quantities of pores known directly, pore radius, pore throat radius, and other characteristic parameters of microscopic pore structures in rocks could be obtained. Rate-controlled mercury intrusion was used to quantitatively describe the size of the pores.

The fluid distribution of pores in tight rocks was studied using the RecCore 2500 NMR instrument independently developed by the Institute of Porous Flow and Fluid Mechanics, Chinese Academy of Sciences. These tests were conducted with a resonance frequency of 2.38 MHz, an echo time of 0.3 ms, a recovery time of 6000 ms, an echo number of 2048, and an experimental temperature of 25°C. Since the oil or water was rich in hydrogen nuclei and had a nuclear magnetic moment, the nuclear magnetic moment would generate energy-level splitting in the applied static magnetic field. If a specific radio frequency magnetic field was applied, the nuclear magnetic moment would undergo an absorption transition, resulting in a nuclear magnetic resonance phenomenon. NMR was used to retrieve pore structure information of tight reservoirs by testing T_2 (transverse relaxation time) spectrum of saturated oil or water in rock cores. We used a paramagnetic substance dissolved in water to eliminate the water signal in NMR. This method could distinguish water and oil in tight reservoirs. NMR was used to describe the law of fluid occurrence in pores.

3. Results and Discussion

3.1. Development Characteristics and Evaluation Difficulties of Tight Reservoirs. Because tight oil reservoirs were characterized by source generation and source accumulation in situ and it had short-term migration, the heterogeneity of the pore distribution was relatively strong [5, 8, 16]. The results of the permeability test using different gases were significantly different [17]. In keeping with the conventional test method, in this paper, the permeability was tested using N_2. According to the SEM images of tight rock cores (shown in Figure 1; the porosity and permeability were tested using industry standard methods), it was found that the lower the porosity of the core, the more microscopic pores the rock contains and the poorer the pore connectivity, and the cement was mainly composed of an illite-smectite mixed layer and was mixed with a small amount of chlorite. With the increase in permeability, the core structure loosened increasingly, large pores appeared gradually, the number of pores increased significantly, and the connectivity became better.

The difference between reservoirs was relatively small in the horizontal plane in the same depth. Through comparison of the tight cores collected from different depths, the difference between reservoirs was significant in the longitudinal plane. As shown in Table 1, the variation of rock porosity ranges from 0.33% to 2.52%, with an average of 1.32%; the variation of permeability ranges from 7.14% to 27.96%, with an average of 16.39%. As shown in Table 2, the variation of rock porosity ranges from 11.20% to 13.27%, with an average of 12.19%; the variation of permeability ranges from 68.66% to 79.03%, with an average of 73.11%. The difference between tight reservoirs in the longitudinal direction was much larger than that in the horizontal direction; it was therefore inapplicable to evaluate the tight reservoir using porosity and permeability.

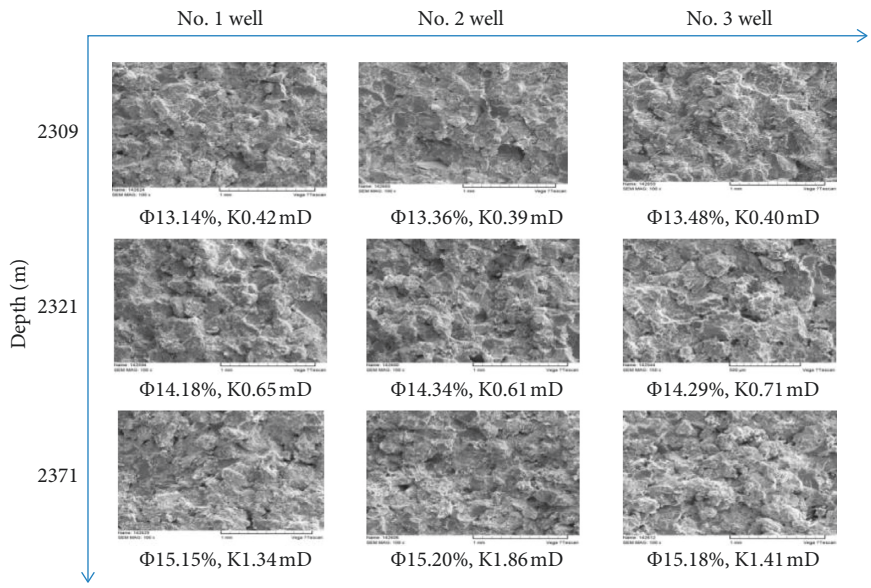

Figure 1: Scanning electron microscope images of tight reservoirs.

Table 1: Variation of porosity and permeability of tight reservoirs in the horizontal direction.

Depth (m)	Horizontal porosity average (mD)	Horizontal porosity variation (%)	Horizontal permeability average (mD)	Horizontal permeability variation (%)
2,309	13.33	2.52	0.40	7.14
2,321	14.27	1.12	0.66	14.08
2,371	15.18	0.33	1.54	27.96

Table 2: Variation of porosity and permeability of tight reservoirs in the longitudinal direction.

Well no.	Longitudinal porosity average (%)	Longitudinal porosity variation (%)	Longitudinal permeability average (%)	Longitudinal permeability variation (%)
1	14.16	13.27	0.80	68.66
2	14.30	12.11	0.95	79.03
3	14.32	11.20	0.84	71.63

In order to study the pore distribution of the tight reservoir, the core samples of Qian262 Well was continuously collected for mercury intrusion experiments. According to the mercury intrusion test results, the pore distribution curves at different scales were plotted, as shown in Figure 2(a), and the pore size was divided into five intervals using nuclear magnetic and centrifugal methods in the literature [18]. Namely, the first was nanopores with radius less than 25 nm, whose fluid cannot be developed; the second was nanopores with radius of 25–50 nm, whose fluid can be exploited by osmotic and displacement; the third was nanopores with radius of 50–100 nm, whose fluid can be mined by gas injection; the fourth was submicron pores with radius of 0.1–1 μm, whose fluid can be developed by a water injection-mixed surfactant; and the fifth was micropores with radius larger than 1 μm, whose fluid can be exploited by water injection. As seen from Figure 2(a), the pore distribution of the tight reservoir varies sharply; the third type of pores with radius of 50–100 nm has the largest variation, with the lowest content of 1.5% and the highest content of 44.6%; the content of the first type of pores with radius less than 25 nm accounts for 20%–40%; the reservoir also contains considerable amounts of the fourth type of pores with radius of 0.1–1 μm, and there was an extremely small amount of the fifth type of pores with radius larger than 1 μm.

Nuclear magnetic resonance (NMR) tests were carried out to measure the fluid content in different sizes of the pores [19, 20]. The result is shown in Figure 2(b). It was observed that the difference in fluid distribution in the reservoir was also obvious. The fluid in the nanopores accounts for about 60%, and it is as high as 90% in some depths. In addition, about 10% of the fluid exists in the micropores and 30% fluid in the submicron pores. It can be seen from Figure 2 that it was difficult to describe accurately the distribution of pores and fluids in tight reservoirs by a simple number. Since the formation of tight reservoirs mainly depends on self-generation and self-storing or short-term migration [18], the physical properties of tight reservoirs were not as

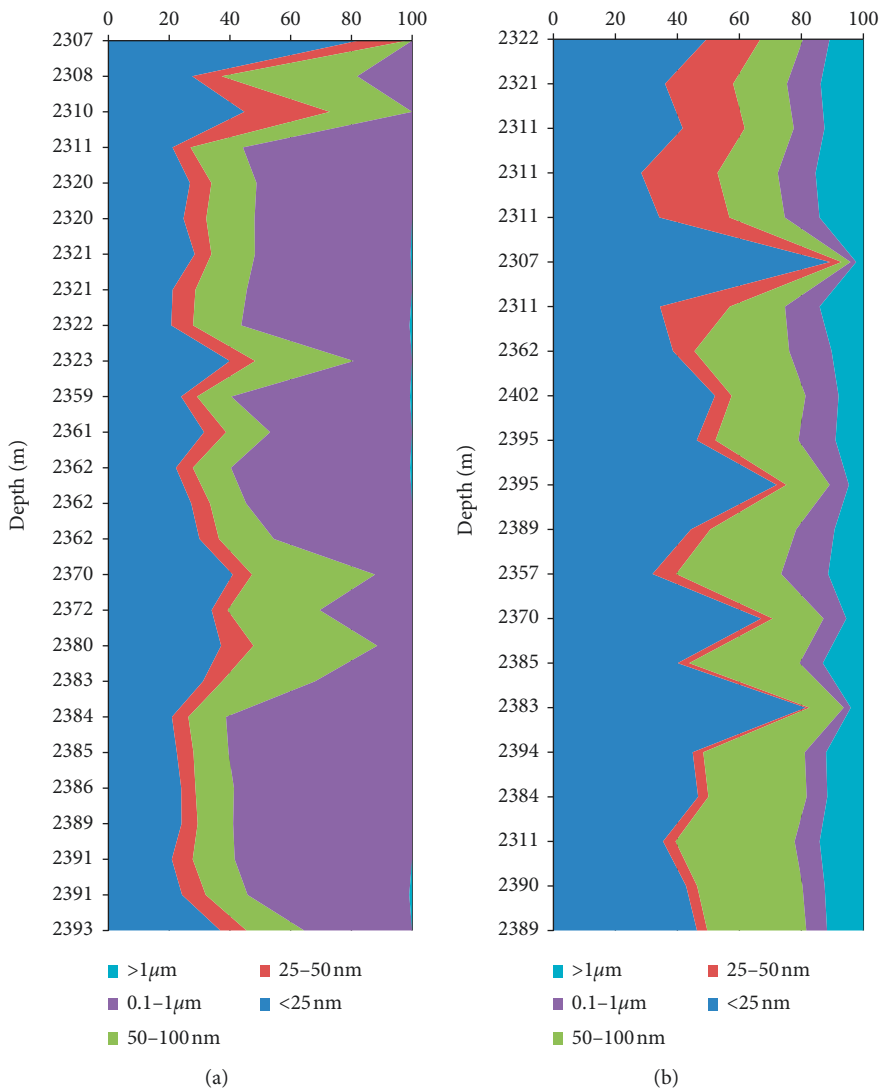

Figure 2: Pore distribution characteristics of tight reservoirs at different scales. (a) Pore distribution at different scales. (b) Fluid distribution in different pore spaces.

uniform as those of conventional sandstone reservoirs, causing dramatic changes in reservoir pores and fluid. Therefore, multiparameter evaluation of tight reservoirs with different depths was necessary.

3.2. Longitudinal Multiparameter Comprehensive Evaluation for Tight Oil Reservoirs. Four parameters were selected to characterize the longitudinal changes of reservoirs: (1) Average throat radius, whose distribution presents the change of reservoir seepage capacity [16]; (2) Percentage of movable fluid, whose distribution explains the change of occurrence characteristics of the reservoir fluid and determines the development potential of the reservoirs [21–23]. The movable fluid of the tight reservoir corresponds to the amount of fluid measured by nuclear magnetic resonance at a centrifugal force of 417 psi; (3) The start-up pressure gradient, whose distribution characterizes the difficulty degree in establishing an effective displacement system for the reservoir [24, 25]; and (4) The content of clay mineral, whose distribution shows the reservoir damage suffered from water injection [26–28]. In the reservoir evaluation in different blocks, some scholars introduced parameters such as brittleness index and pressure coefficient. However, for the same reservoir, these parameters have little change in the longitudinal direction and cannot well reflect the physical properties of the tight reservoir. Therefore, this study did not consider these evaluation parameters.

According to the test and analysis results of tight sandstone cores collected from K1q4 of the Songliao Basin, the classification evaluation intervals of each parameter were divided into four categories, as shown in Table 3. The conventional reservoir evaluation methods only obtain the evaluation results based on the single parameter, ignoring the comprehensive evaluation and the influence of various parameters on the comprehensive evaluation results. In this study, selecting the appropriate parameters [13] for evaluation the comprehensive evaluation results were divided

Table 3: Longitudinal evaluation interval of tight reservoirs.

Classification interval	Throat radius (μm)	Movable fluids saturation (%)	Starting pressure gradient (MPa/m)	Clay minerals (%)	Comprehensive evaluation
I	0.6–0.8	60–75	0–0.3	0–5.0	>5.0
II	0.4–0.6	45–60	0.3–0.6	5.0–10.0	3.5–5.0
III	0.2–0.4	30–45	0.6–0.9	10.0–15.0	1.5–3.5
IV	0–0.2	15–30	0.9–1.2	15.0–20.0	0–1.5

into four categories accordingly, and a comprehensive evaluation grading calculation formula was formed as follows:

$$D = \ln\left(\alpha * \frac{(r_0/r_{\text{sta}}) * (s_0/s_{\text{sta}})}{(\lambda_0/\lambda_{\text{sta}}) * (m_0/m_{\text{sta}})}\right), \quad (1)$$

where D was the comprehensive evaluation result; r_0 was the average throat radius, μm; r_{sta} was the evaluation limit of average throat radius, μm; s_0 was the percentage of the movable fluid, %; s_{sta} was the evaluation limit of the percentage of the movable fluid, %; λ_0 was the start-up pressure gradient, MPa/m; λ_{sta} was the evaluation limit of the start-up pressure gradient, MPa/m; m_0 was the content of clay mineral, %; m_{sta} was the evaluation limit of the content of clay mineral, %; and α was the reservoir influence factor.

In order to compare the changes of each parameter in the reservoir, the graded evaluation results of each parameter were normalized, as shown in formulas (2) and (3).

When the evaluation parameters were positively correlated with the comprehensive evaluation results,

$$D_{\text{N}} = \frac{P_0}{P_{\max} - P_{\min}}. \quad (2)$$

When the evaluation parameters were negatively correlated with the comprehensive evaluation results,

$$D_{\text{N}} = 1 - \frac{P_0}{P_{\max} - P_{\min}}, \quad (3)$$

where D_{N} was the normalized evaluation result of single parameter; P_0 was the single parameter value; $P_{\max}$ was the upper limit of single parameter evaluation; and $P_{\min}$ was the lower limit of single parameter evaluation.

The classification results of the evaluation parameters were placed in the same coordinate system to analyze the changes between the parameters. The sampling cores were collected from the tight sandstone of K1q4 of Jilin Oilfield in Songliao Basin, with a depth of 2,306.5–2,391.3 m, and mercury intrusion test, nuclear magnetic resonance test, percolation curve test, and X-ray diffraction measurement were carried out. The parameters that vary with reservoir depth were obtained, including the throat radius, the percentage of movable fluid, the start-up pressure gradient, and the content of clay mineral. Longitudinal subsection parameter evaluation results and comprehensive evaluation results of tight oil reservoirs were plotted according to formulas (1)–(3), as shown in Figure 3.

It can be seen from Figure 3 that the throat radius values in the longitudinal direction of the tight reservoir were mainly categorized into type IV reservoir, and the fluctuation range was small, indicating that the reservoir was relatively tight, the pore throat was small, and the seepage capacity was poor. The percentage values of the movable fluid were mainly categorized into type III, type II, and type I reservoirs, and the fluctuation range crosses three intervals, indicating that the occurrence difference of the reservoir fluids was large. The start-up pressure gradient was dominated by type III, II, and I reservoirs, indicating the difficulty degree of reservoir development was relatively higher, and attention should be paid to water channeling and gas channeling when replenishing energy. Clay mineral content was mainly dominated by type III and type II reservoirs, and attention should be paid to reservoir damage during development. There were five reservoir types (I-IV) in the longitudinal comprehensive evaluation of the tight reservoir, and the fluctuation range was extremely large. In the development of tight reservoirs, a rational plan and the development modes should be made according to the longitudinal comprehensive evaluation curve of the reservoir.

3.3. Optimization of Development Modes Adopting Longitudinal Evaluation of Tight Oil Reservoirs. The longitudinal distribution of tight oil reservoirs varies a lot. The recovery of reservoirs with different evaluation results was also quite different using water injection or gas injection, as shown in Figure 4. Figure 4(a) shows the time-dependent recovery curve of four different types of reservoirs with water injection. The recovery of the four types of reservoirs increased rapidly in the early stage but remained stable in the later period. Type I reached the final recovery first, and type IV was the slowest. Figure 4(b) presents the time-dependent recovery curve of four different types of reservoirs with nitrogen injection. The evaluation results showed that the recovery degree of the reservoirs with better evaluation results increased rapidly in the early stage and then gradually slowed down after a certain period of development. In the later period of development, the recovery degree of poor reservoirs with poorer evaluation results was larger than that of the reservoirs with better evaluation results. The type IV reservoir had the highest recovery degree, the type I reservoir had the lowest recovery degree, and type II and III reservoirs were in the middle.

It can be seen from Table 4 that the recovery ratios of the different types of reservoirs adopting different development modes vary significantly. In the case of all reservoir

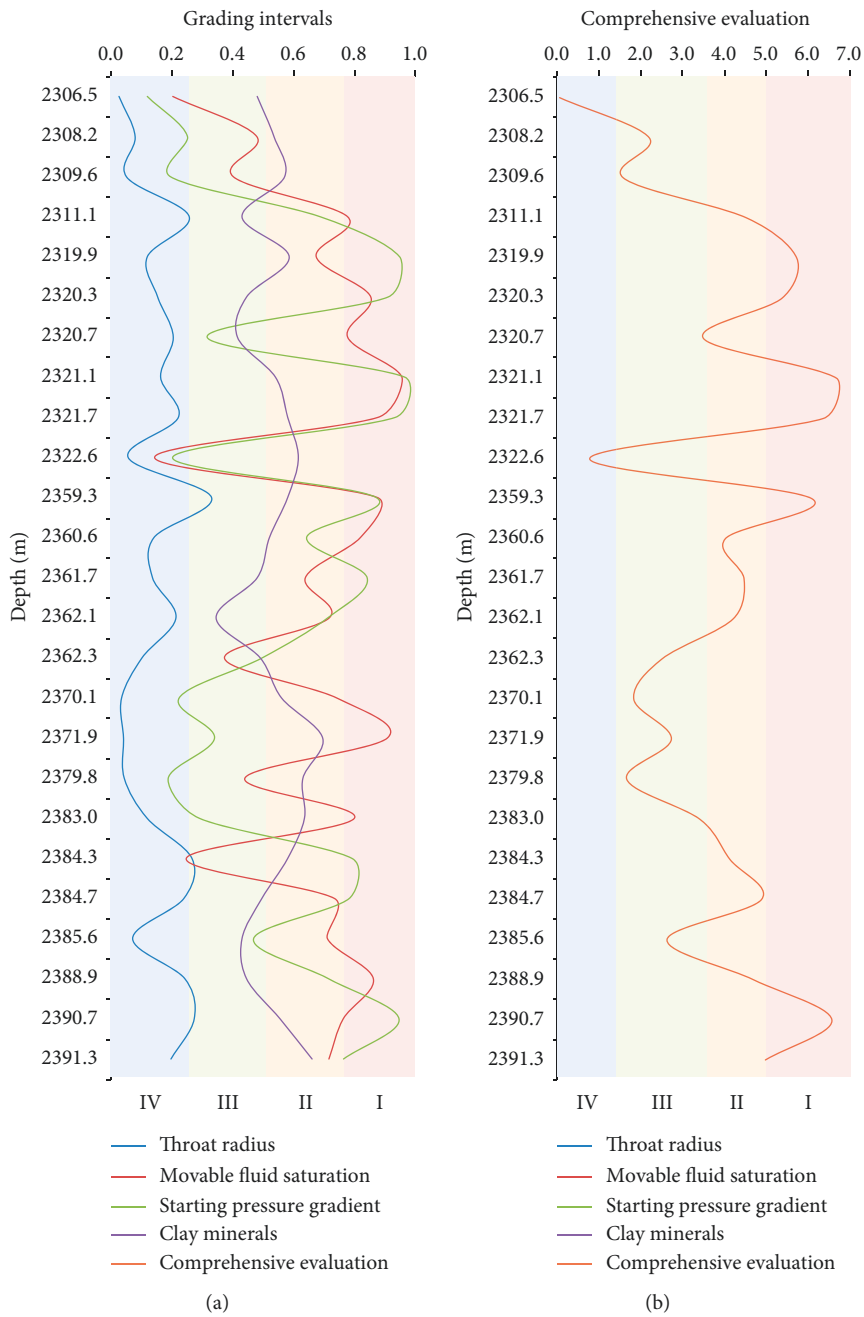

Figure 3: Comprehensive evaluation results and longitudinal grading evaluation results of tight reservoirs.

types involved, type I reservoir was most suitable for water injection development, and type IV reservoir was most suitable for gas injection development. Taking the tight oil reservoir studied in this paper as an example, the reservoirs with a depth of 2,306.54–2,362.07 m were mainly dominated by type I and II reservoirs, and the reservoirs with a depth of 2,362.07–2,391.30 m were mainly dominated by type II and III reservoirs. Through comparison of water injection in the whole reservoir, gas injection in the whole reservoir, water injection in the upper reservoir and gas injection in the lower reservoir, and gas injection in the upper reservoir and water injection in the lower reservoir, the final recovery ratio of the tight oil reservoir under different development modes can be obtained according to formula (4), as shown in Table 5:

$$E_{\mathrm{R}} = \sum_{i=1}^{4} E_{\mathrm{R}_i} * h_i, \tag{4}$$

where E_{R} was the recovery of the tight oil reservoir, %; E_{R_i} was the recovery corresponding to type I, type II, type III, and type IV reservoirs, %; h_i was the effective thickness corresponding to type I, type II, type III, and type IV reservoirs, m.

In the case of all reservoir types involved, the highest recovery (70.66%) can be obtained under the development

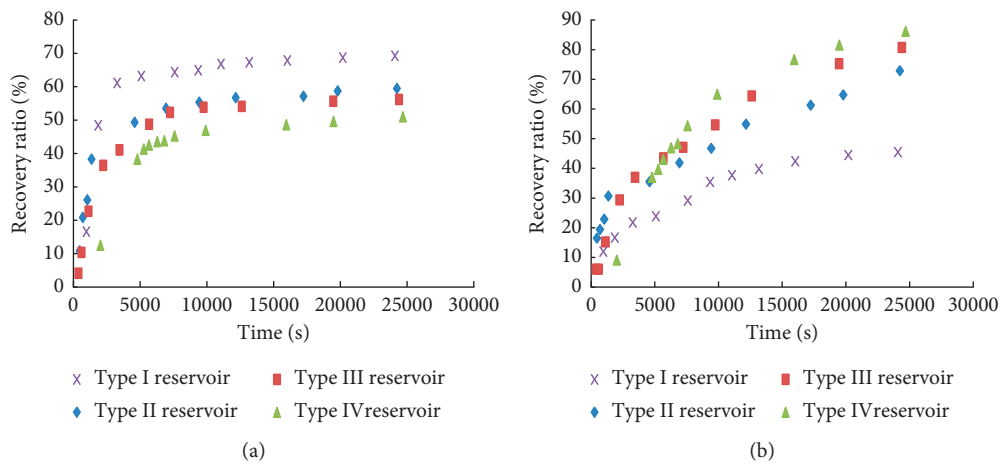

Figure 4: Recovery curve of tight reservoirs with water injection/gas injection. (a) Time-dependent recovery curve of tight reservoirs with water injection. (b) Time-dependent recovery curve of tight reservoirs with nitrogen injection.

Table 4: Recovery of different types of reservoirs.

Development mode	Type I (%)	Type II (%)	Type III (%)	Type IV (%)
Water injection	69.23	59.48	56.15	50.97
Gas injection	45.43	67.17	80.72	86.16

Table 5: Recovery of reservoirs under different development modes.

Different development mode	Water injection	Gas injection	Upper water/lower gas	Upper gas/ lower water
Recovery ratio (%)	63.98	59.62	70.66	52.94

mode of water injection in the upper reservoir and gas injection in the lower reservoir; the recovery was 63.98% using the water injection method and the recovery using the gas injection mode or gas injection in the upper reservoir and water injection in the lower reservoir were both lower than those of the previous two modes.

4. Conclusions

Microscopic pore structure, fluid occurrence conditions, start-up pressure gradient, and the content of clay minerals in the longitudinal direction of tight reservoirs were analyzed in this study. Each parameter represented a physical property of the reservoir, and these parameters were independent of each other and did not affect each other, so the evaluation results obtained in this way were objective. The longitudinal evaluation method for tight reservoirs was proposed, and the optimal development mode was selected according to reservoir evaluation results. Three innovations of this study are summarized as follows:

(1) The longitudinal variations of the microscopic pore structure were bigger than the horizontal variations. The longitudinal variations of porosity and permeability were 12.19% and 73.11%, respectively. The horizontal variations of porosity and permeability were 1.32% and 16.39%, respectively. In tight oil reservoirs, the nanopores dominate and control about 60% of the flow space, the submicron pores account for about 30% of the flow space, which is the main part in the development, and the micropores were few.

(2) Four parameters, including average throat radius, the percentage of movable fluid, start-up pressure gradient, and the content of clay mineral, were applied to evaluate the reservoir. Seepage capacity, development potential of the reservoirs, the difficulty degree in development, and the reservoir damage suffered from water injection, and the four-parameter evaluation results were normalized to obtain the influence degree of different factors on the reservoir physical property. The depth-dependent comprehensive evaluation results and grading evaluation results were plotted.

(3) The recovery of tight reservoirs under different development modes was compared. According to the longitudinal comprehensive evaluation curve and the recovery, the most appropriate development method for each type of reservoir would be chosen. It can be known that the highest recovery was obtained when the mode of water injection in the upper reservoir and gas injection reservoir was adopted.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] S. Y. Hu, R. K. Zhu, S. T. Wu et al., "Profitable exploration and development of continental tight oil in China," *Petroleum Exploration and Development*, vol. 45, no. 4, pp. 737–748, 2018.

[2] S. J. Wang, R. J. Wei, Q. L. Guo et al., "New advance in resource evaluation of tight oil," *Acta Petrolei Sinica*, vol. 35, no. 6, pp. 1095–1105, 2014.

[3] J. H. Du, H. Q. He, J. Z. Li et al., "Progress in China's tight oil exploration and challenges," *China Petroleum Exploration*, vol. 19, no. 1, pp. 1–9, 2014.

[4] G. G. Wu, H. Fang, Z. Han et al., "Growth features of measured oil initially in place & gas initially in place during the 12th five-year plan and its outlook for the 13th five-year plan in China," *Acta Petrolei Sinica*, vol. 37, no. 9, pp. 1145–1151, 2016.

[5] Y. T. Luo, Z. M. Yang, Y. He et al., "The research of lithology characteristics and effective development in tight oil reservoir," *Unconventional Oil and Gas*, vol. 1, no. 1, pp. 47–54, 2014.

[6] H. Cander, *What are Unconventional Resources*, AAPG Annual Convention and Exhibition, Long Beach, CA, USA, 2012.

[7] Z. M. Yang, Y. Z. Zhang, M. Q. Hao et al., "Comprehensive evaluation of reservoir in low permeability oilfields," *Acta Petrolei Sinica*, vol. 27, no. 2, pp. 64–67, 2006.

[8] Z. H. Zhang, Z. M. Yang, X. G. Liu et al., "A grading evaluation method for low-permeability reservoirs and its application," *Acta Petrolei Sinica*, vol. 33, no. 3, pp. 437–441, 2012.

[9] Q. H. Xiao, *The Reservoir Evaluation and Porous Flow Mechanism for Typical Tight Oil Fields*, Institute of Porous Flow and Fluid Mechanics, University of Chinese Academy of Sciences, Langfang, China, 2015.

[10] C. Z. Jia, C. N. Zou, J. Z. Li et al., "Assessment criteria, main types, basic features and resource prospects of the tight oil in China," *Acta Petrolei Sinica*, vol. 33, no. 3, pp. 343–350, 2012.

[11] C. N. Zou, R. K. Zhu, S. T. Wu et al., "Type, characteristics, genesis and prospects of conventional and unconventional hydrocarbon accumulations: taking tight oil and tight gas in China as an instance," *Acta Petrolei Sinica*, vol. 33, no. 2, pp. 173–187, 2012.

[12] Z. Yang, L. H. Hou, S. Z. Tao et al., "Formation conditions and "sweet spot"evaluation of tight oil and shale oil," *Petroleum Exploration and Development*, vol. 42, no. 5, pp. 555–565, 2015.

[13] B. Jia, J. S. Tsau, and R. Barati, "A review of the current progress of CO2 injection EOR and carbon storage in shale oil reservoirs," *Fuel*, vol. 236, pp. 404–427, 2019.

[14] W. R. Purcell, "Capillary pressures—their measurement using mercury and the calculation of permeability therefrom," *Journal of Petroleum Technology*, vol. 1, no. 2, pp. 39–48, 2013.

[15] B. F. Swanson and B. F. Swanson, "A simple correlation between permeabilities and mercury capillary pressures," *Journal of Petroleum Technology*, vol. 33, no. 12, pp. 2498–2504, 2013.

[16] A. Hakami, A. Al-Mubarak, K. Al-Ramadan, C. Kurison, and I. Leyva, "Characterization of carbonate mudrocks of the jurassic tuwaiq mountain formation, jafurah basin, Saudi arabia: implications for unconventional reservoir potential evaluation," *Journal of Natural Gas Science and Engineering*, vol. 33, pp. 1149–1168, 2016.

[17] B. Jia, J. S. Tsau, and R. Barati, "Different flow behaviors of low-pressure and high-pressure carbon dioxide in shales," *SPE Journal*, vol. 23, no. 4, pp. 1452–1468, 2018.

[18] Z. M. Yang, R. Z. Yu, Z. X. Su et al., "Numerical simulation of the nonlinear flow in ultra-low permeability reservoirs," *Petroleum Exploration and Development*, vol. 37, no. 1, pp. 94–98, 2010.

[19] D. P. Li, *The Development of the Low Permeability Sandstone Oil Field*, Petroleum Industry Press, Beijing, China, 1997.

[20] Z. M. Yang, Y. T. Luo, Y. He et al., "Study on occurrence feature of fluid and effective development in tight sandstone oil reservoir," *Journal of Southwest Petroleum University (Science & Technology Edition)*, vol. 37, no. 3, pp. 85–92, 2015.

[21] W. M. Wang, H. K. Guo, and Z. H. Ye, "The Evaluation of development potential in low permeability oilfield by the aid of NMR movable fluid detecting technology," *Acta Petrolei Sinica*, vol. 22, no. 6, pp. 40–44, 2001.

[22] D. O. Seevers, "A nuelear magnetic method for determining the permeability of sandstones," in *Proceedings of Annual Logging SymPosium Transaetions*, Soeiety of Professional Well Log Analysts, Tulsa, OK, USA, May 1966.

[23] R. J. S. Brown and I. Fatt, "Measurement of fraetional wettability of oil fields' rocks by the nuclear magnetic relaxation method," in *Proceedings of Fall Meeting of the Petroleum Branch of AIME, SPE-743-G*, Soeiety of Petroleum Engineers, Los Angeles, CA, USA, October 1956.

[24] Y. Shi, Z. M. Yang, and Y. Z. Huang, "Study on non-linear seepage flow model for low-permeability reservoir," *Acta Petrolei Sinica*, vol. 30, no. 5, pp. 731–734, 2009.

[25] C. Dabbouk, A. Liaqat, G. Williams, and G. Beattie, "Waterflood in vuggy layer of a middle east reservoir-displacement physics understood," in *Proceedings of Abu Dhabi International Petroleum Exhibition and Conference*, Abu Dhabi, UAE, October 2002.

[26] S. B. Peng, X. Yin, J. C. Zhang et al., "Evolutionary pattern of clay mineral and rock sensitivity in water-flooding reservoir," *Acta Petrolei Sinica*, vol. 27, no. 4, pp. 71–75, 2006.

[27] Y. T. Luo and Z. Yang, "Advantageous reservoir characterization technology in extra low permeability oil reservoirs," *Journal of Engineering*, vol. 2017, Article ID 6705263, 9 pages, 2017.

[28] H. Karimaie and O. Torsæter, "Effect of injection rate, initial water saturation and gravity on water injection in slightly water-wet fractured porous media," *Journal of Petroleum Science and Engineering*, vol. 58, no. 1-2, pp. 293–308, 2007.