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Research Article

Reservoir Sensitivity Analysis of Tight Sandstone and Its Controlling Factors: A Case Study from Chang 4+5 to Chang 6 Reservoirs in N 212 Well Block of Nanniwan Oilfield, Ordos Basin

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Reservoir sensitivity can lead to the physical or chemical reactions to block the pore throat. It is helpful for reducing the damage on tight sandstone reservoir to study the reservoir sensitivity and its controlling factors. This paper mainly focuses on the tight sandstone of the Chang 4+5 and Chang 6 reservoirs of the Yanchang Formation in the Nanniwan Oilfield, Ordos Basin. The reservoir sensitivity characteristics were evaluated through the core sensitivity experiment after the petrological and petrophysical analysis and pore structure study. The influencing factors on tight sandstone reservoir sensitivity were discussed from several aspects, such as clay mineral composition, porosity, permeability, and pore structure. The results show that the rock type of the Chang 4+5 and Chang 6 reservoirs in the N 212 well block of the Nanniwan Oilfield is mainly arkose, with the mean porosity of 11.2% and 8.45% and the mean permeability of $0.35 \times 10^{-3}\ \mu m^2$ and $0.44 \times 10^{-3}\ \mu m^2$, respectively. The clay mineral components mainly include chlorite and illite/smectite. Both the two reservoirs are characterized by moderate to weak velocity sensitivity, moderate to weak water sensitivity, moderate to strong salt sensitivity, weak acid sensitivity, and moderate to weak alkali sensitivity. In specific, the Chang 4+5 reservoir is stronger in velocity and salt sensitivities, while it is weaker in water, acid, and alkali sensitivities than those of the Chang 6. The major controlling factors on reservoir sensitivity are clay mineral component, petrophysical property, and pore structure. Among these, the velocity sensitivity displays the positive correlation with pore structure, porosity, and permeability. The water sensitivity will become strong with the increase of the volume content of illite/smectite, but weak with the getting better of pore structure. The acid sensitivity is positively correlated with the volume content of chlorite but is negatively correlated with pore structure. With the getting better of pore structure, the salt sensitivity and alkali sensitivity will become strong and weak, respectively. The research results can be as the guidance for the tight sandstone reservoir protection in the study area and the adjustment and optimization of the regional reservoir development scheme.

1. Introduction

With the improvement of newly advanced technologies, especially the hydraulic fracturing technology [1–3], the production rate of tight gas has rapidly increased [4]. However, it is vital to study the reservoir sensitivities under different fluid rates and types before conducting hydraulic fracturing, which can help to optimize fracturing fluid types and operation parameters [5]. Reservoir sensitivity can be explained as the phenomenon of reservoir damages, such as destruction of pore structure, decline of permeability [6], and decrease of yield resulted from the incompatibility between reservoir fluids and injected fluids in the development process [7]. This can lead to the physical or chemical reactions, such as expansion, particle fragmentation, migration, and precipitation of clay minerals to block the pore throat [8–11]. So, it is helpful for reservoir protection and reducing reservoir damage to study the reservoir sensitivity including water, velocity, acid, alkali, and salt sensitivities [12].

Tight sandstone reservoir has more complex pore structure, worse petrophysical property, higher contents of clay minerals and microfractures, and stronger heterogeneity than those of conventional sandstone reservoir. A strong reservoir reaction will cause reducing of oil yield and damaging reservoir when fluid is injected into tight sandstone [13–17]. Therefore, studying on reservoir sensitivity of tight sandstone and its controlling factors is helpful for reducing the damage on tight sandstone reservoir [18, 19].

Previous studies mainly focused on the characteristics of reservoir sensitivity through lithographic observation, X-ray diffraction, petrophysical property test, and scanning electron microscopic observation [20–23], and the controlling factors on reservoir sensitivity also were discussed by qualitative analysis from several aspects such as mineral composition, porosity, and permeability. But, with the rapid development of modern analytical and testing techniques, the reservoir sensitivity was gradually quantitatively evaluated from the plane and vertical through a large number of core flow experiments combined with artificial neural network, fuzzy algorithm, and numerical simulation [24–26]. In recent years, the sedimentary facies [27], pore structures [28–31], clay minerals [32–34] and diagenesis [35, 36] have been widely accepted as the primary controlling factors on reservoir sensitivity. In specific, the velocity sensitivity is closely related to pore structure and quartz content, and the water sensitivity is majorly influenced by pore structure, I/S and illite contents, while the alkali sensitivity ranges with pore structure and kaolinite, I/S, and feldspar content [37].

The Chang 4+5 and Chang 6 reservoirs, as the major oil production layers of Yanchang Formation in the Nanniwan Oilfield, Ordos Basin, mainly develop tight sandstone reservoir with poor petrophysical property, complex pore structure, and serious reservoir damage, resulting in the poor development effects. So, clearing the reservoir sensitivity characteristics and its influencing factors is the key to open the door of decreasing reservoir damage. In this paper, the two reservoirs of N 212 block of Nanniwan Oilfield were taken as an example, and the reservoir sensitivity characteristics were evaluated through the core sensitivity experiment after the petrological and porosity and permeability analysis, as well as pore structure study. The influencing factors on tight sandstone reservoir sensitivity were discussed from several aspects, such as clay mineral composition, porosity, permeability, and pore structure. The research results can be as the guidance for the tight sandstone reservoir protection in the study area and the adjustment and optimization of the regional reservoir development scheme.

2. Geological Setting

After multistage tectonic movements, such as Caledonian orogeny, Hercynian orogeny, Indosinian movement, Yanshanian orogeny, and Himalayan movement, the present structural pattern of the Ordos Basin has been formed. Its topography is characterized by low in the west and south, while high in the east and north, and six structural units include two uplifts, two belts, one slope, and one depression.

The Nanniwan Oilfield is located in the southeastern Yishan Slope, central Ordos Basin, China (Figure 1). Ten reservoirs, namely, from the Chang 1 to Chang 10 with lithological differences, are developed in the Yanchang Formation from top to bottom [38, 39]. During the sedimentary period of Chang 6 reservoir dominated by lacustrine delta sedimentary environment, the lacustrine area shrank and the sedimentation strengthened. While during the Chang 4+5 sedimentary period, lake transgression happened again, weakened the process of delta construction.

The Chang 4+5 and Chang 6 reservoirs of the study area, characterized by complex geological conditions, strong heterogeneity, and low formation energy and yield, belong to typical tight sandstone reservoir. The sedimentary environments are all dominated by delta plain subfacies, including distributary channel and inter channel microfacies. In the former microfacies, the favorable sand body mainly is developed and is characterized by the lithology of medium and fine sandstone.

3. Samples and Experimental Methods

3.1. Sample Collection. All the sandstone samples were primarily collected from the Chang 4+5 and Chang 6 in wells N 212, N 214, X 33, X 820, and N 447 in the study area. These five wells cover the regions from south to north in the plane; the wells X33, X820, and N 447 were mainly sampled in the Chang 6; and the wells N 212 and N 214 were sampled in the Chang 4+5 and Chang 6 reservoirs in the vertical direction, indicating that these samples can represent the reservoir characteristics of the whole study area in the plane and vertical directions. The rock type of the tested samples is mainly arkose, followed by some lithic arkose.

3.2. Experimental Methods. The analytical methods include X-ray diffraction analysis, micropetrography analysis, physical property analysis, high press mercury injection test, and reservoir sensitivity. These analytical tests were conducted at Xi'an Alberta Resources and Environment Analysis and Testing Technology Co., Ltd. The test purposes, instruments, standards, and accuracy of different experiments are as below.

3.2.1. X-Ray Diffraction Analysis. X-ray diffraction analysis is mainly used for testing the components and volume contents of various minerals such as quartz, feldspar, debris,

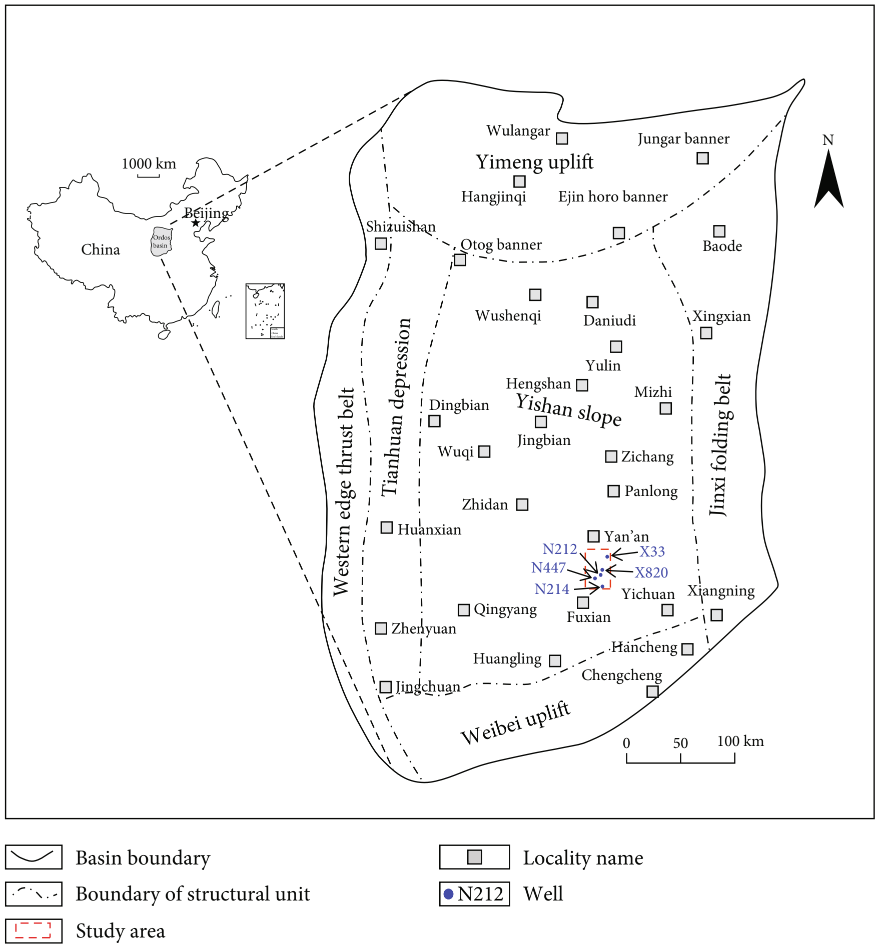

Figure 1: Structural units of Ordos Basin and location of the study area.

carbonate minerals, and clay minerals in rock. This test was conducted through using an instrument of D/MAX-3C at a room temperature. The detection standard used for analysis is SY/T 5163-2010 with a data accuracy of ±0.5%.

3.2.2. Micropetrography Analysis. Both cast thin section (CTS) and scanning electron microscopy (SEM) observations were involved in micropetrography analysis. In the casting sheet image observation, based on the standard of the SY/T 5368-2016, the rock structure, texture, and pore type of 40 sandstone samples were detected by using polarized microscope of 59XC-PC at a room temperature. While in the SEM experiment, the FEI Quanta 450 FEG was mainly used to detect the mineral composition, sedimentary structure, and pore type of rock. The vacuum IGP and acceleration voltage of the instrument are between 5×10^{-4} Pa and 5×10^{-4} Pa and between 500 kV and 30 kV, respectively. The images we acquired have the dispersion less than or equal to 50 μm, the magnification between 7 and 10^6 times, and the image resolution less than or equal to 3.5 nm.

3.2.3. Physical Property Analysis. The analysis was conducted on 40 sandstone samples using a KX-07F-type gas porosity tester and a DX-07G-type gas permeability tester, respectively, to determine the porosity and permeability of rocks under the standards of GB/T 29172-2012 (6.2.3, 6.3.2.1) and GB/T 29172-2012 (7.3.1), respectively.

3.2.4. High-Pressure Mercury Injection Test. This test was conducted on 15 sandstone samples to analyze the pore and throat size and characterize the pore structure by using a YG-97A-type capacitive mercury porosimeter. The GB/T 29171-2012 standard was used as a guide for the test at a room temperature.

3.2.5. Reservoir Sensitivity Experiment. This experiment was performed on 12 sandstone samples to examine the water, velocity, acid, alkali, and salt sensitivities of rocks by using a MD-04-type reservoir sensitivity tester. The SY/T 5358-2010 standard was used as a guide for the experiment at a temperature of 20°C.

4. Results

4.1. Reservoir Characteristics

4.1.1. Petrographic Characteristics. The rock type of Chang 4+5 and Chang 6 reservoirs is mainly arkose, following by lithic arkose (Figure 2), and the debris composition of sandstone includes feldspar, quartz, rock cuttings, and clastic

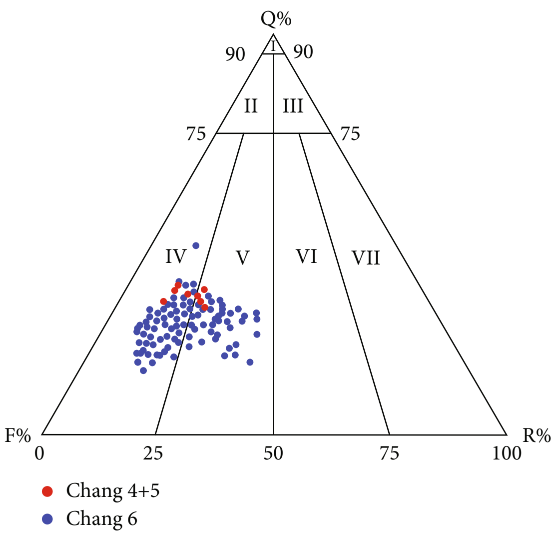

FIGURE 2: Ternary diagram illustrating the framework compositions of the Chang 4+5 and Chang 6 reservoirs in the N 212 well block in Nanniwan Oilfield. Q = quartz; F = feldspar; R = rock fragments; I = quartz arenite; II = subarkose; III = sublitharenite; IV = arkose; V = lithic arkose; VI = feldspathic litharenite; VII = litharenite.

mica (Figure 3). The sandstone of Chang 4+5 reservoir is characterized by a total debris volume content ranged from 84% to 92%, with a mean of 88.3%. Among which, the volume contents of quartz, feldspar, and rock fragment vary from 26.7% to 32.0% (with a mean of 29.3%), from 42.0% to 49.0% (with a mean of 45.5%), and from 8.0% to 16.6% (with a mean of 13.6%). Compared with Chang 4+5 reservoir, the sandstone of Chang 6 reservoir is featured by a relatively less total debris volume content ranged from 69% to 95%, with a mean of 85.9%. Among which, the volume contents of quartz, feldspar, and rock fragment range from 15.0% to 41.0% (with a mean of 23.3%), from 32.0% to 63.0% (with a mean of 49.4%), and from 7.0% to 31.0% (with a mean of 13.2%). The source of rock fragment in these two reservoirs is all dominated by volcanic rock with the highest volume content of eruptive rock (the average volume contents are 7.0% and 3.9%, respectively).

Cement is dominated by the interstitial fillings with a little difference in its total volume content in the Chang 4+5 and Chang 6 reservoirs; it ranges from 8% to 16% with a mean of 11.7% and from 5% to 31% with a mean of 14.1% in these two reservoirs, respectively (Figure 4). This volume content difference is also shown in each kind of minerals such as laumontite (the volume contents are 6.0% and 5.2%, respectively), chlorite (the volume contents are 4.0% and 3.6%, respectively), and calcite (the volume contents are 3.7% and 3.5%, respectively). In addition, a small amount of clay matrix is also developed in the space between debris, with the volume contents of 5.6% and 5.3% in Chang 4+5 and Chang 6 reservoirs, respectively.

The clay mineral components of Chang 4+5 and Chang 6 reservoirs in the study area mainly include chlorite (Figures 5(a) and 5(b)), illite-smectite (Figure 5(c)), and little amount of illite (Figure 5(d)). It can be observed that most chlorites which filled in the pores display a needle-shaped under the scanning electron microscope (SEM). The relative mass fraction of chlorite to total clay minerals of Chang 4+5 and Chang 6 reservoirs varies from 36.0% to 64.0% (with a mean of 52%) and from 49.0% to 77.0% (with a mean of 60.4%), respectively. The flake illite-smectite also can be seen under the SEM and with the relative mass fraction of these two reservoirs ranged from 36.0% to 64.0% (with a mean of 48%) and from 23.0% to 51.0% (with a mean of 39.6%), respectively.

4.1.2. Porosity and Permeability. The porosity and permeability of Chang 4+5 reservoir ranged from 8.07% to 14.56% (with a mean of 11.21%) (Figure 6(a)) and from $0.02 \times 10^{-3}\,\mu m^2$ to $4.78 \times 10^{-3}\,\mu m^2$ (with a mean of $0.44 \times 10^{-3}\,\mu m^2$) (Figure 6(b)), respectively, are greater than those of Chang 6 reservoir, which is characterized by the porosity varied from 1.08% to 17.60% (with an average value of 8.45%) (Figure 6(a)) and the permeability varied from $0.04 \times 10^{-3}\,\mu m^2$ to $1.12 \times 10^{-3}\,\mu m^2$ (with a mean of $0.35 \times 10^{-3}\,\mu m^2$) (Figure 6(b)), respectively. According to the classification criteria for tight sandstone reservoir featured by a porosity less than 12% and a permeability less than $2 \times 10^{-3}\,\mu m^2$ supposed by Zhao et al. [40], Chang 4+5 and Chang 6 reservoirs all belong to tight sandstone reservoir.

4.1.3. Pore Type. The Chang 4+5 reservoir mainly develops intergranular pore (Figures 7(a)–7(c)) with a porosity ranged from 1% to 10% (with a mean of 4.4%) and dissolved pore in feldspar (Figures 7(d) and 7(e)) with a porosity varied from 0.2% to 2% (with a mean of 1.02%), following by dissolved pore in debris and a little amount of dissolved pore in matrix. The surface porosity of Chang 4+5 ranges from 3.5% to 11.5%, with an average value of 6.56%, while the Chang 6 reservoir space is dominated by intergranular pore (Figure 7(f)) with a porosity ranged from 1% to 9% (with an average value of 3.9%) and dissolved pore in debris (Figures 7(g) and 7(h)) with an average porosity of 2.0%, following by intercrystalline pore and microfractures (Figure 7(i)). The surface porosity of Chang 6 reservoir ranges from 2.0% to 9.0%, with an average value of 5.0% (Figure 8). The pore assemblages of these two reservoirs are all dominated by dissolved pore-intergranular pore.

4.1.4. Pore Structure. The parameters of mercury pressure test are shown in Table 1. The pore structure of Chang 4+5 reservoir is characterized by the relatively high displacement pressure ranged from 0.64 to 5.07 MPa (with an average value of 2.605 MPa) and the low maximum throat radius, skewness, and median throat radius of 0.0625 μm as well as a heterogeneous distribution of pore throat, while the Chang 6 reservoir displays relatively lower displacement with an average value of 1.791 MPa and median throat radius of 0.04 μm than the Chang 4+5 reservoir. The above analysis reflects that the fine pore-fine throat pore structure is dominated in these two reservoirs. In addition, most intergranular pores are filled by clay minerals under the scanning electron microscope (SEM), displaying fine lamellar throat, which resulted in a decrease of permeability; because of that,

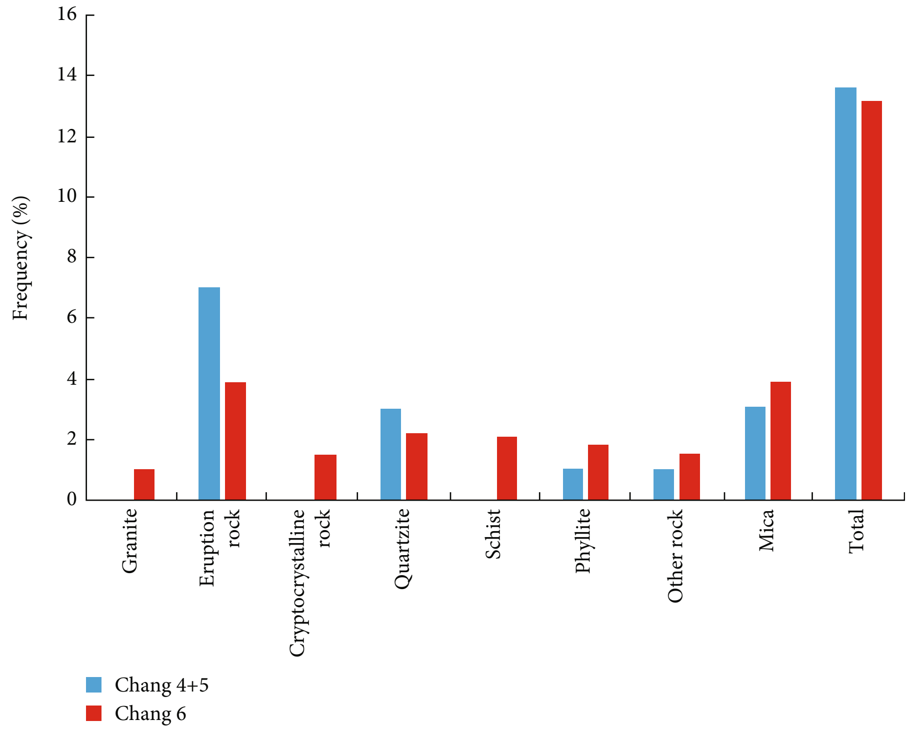

FIGURE 3: Debris component characteristics of the Chang 4+5 and Chang 6 reservoirs in the N 212 well block in Nanniwan Oilfield.

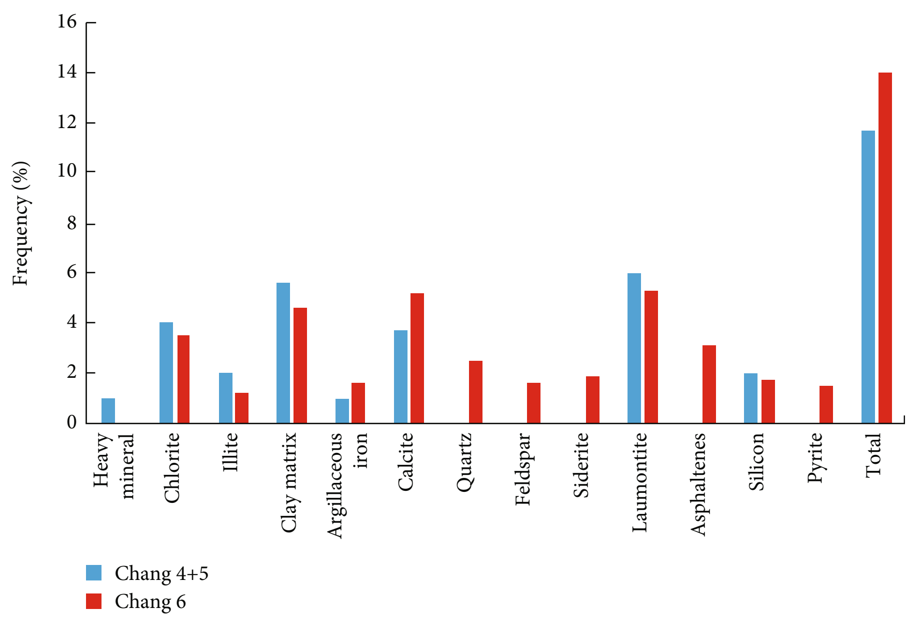

FIGURE 4: Interstitial filling component and their contents of the Chang 4+5 and Chang 6 reservoirs in the N 212 well block in Nanniwan Oilfield.

the pore throat is easily blocked when the pore fluids flow in the reservoir.

4.2. Reservoir Sensitivity Characteristics. The variation of the fluid conditions, such as flow velocity, fluid pH and salinity, and formation pressure within the reservoirs, may lead to the migration of particles and blocking of pore throats, which will further result in a decrease of the reservoir permeability [11]. In order to investigate the reservoir sensitivity characteristics in the N 212 well block of Nanniwan Oilfield, six sandstone samples were used in the sensitivity experiment. The rank of reservoir sensitivity was evaluated on the basis of the Industry Standard (SY/T535—2010).

4.2.1. Velocity Sensitivity. Velocity sensitivity refers to the phenomenon that the particle migration and blocking of pore throat within the reservoir resulted from fluid flowing, leading to the permeability decrease. The parameters

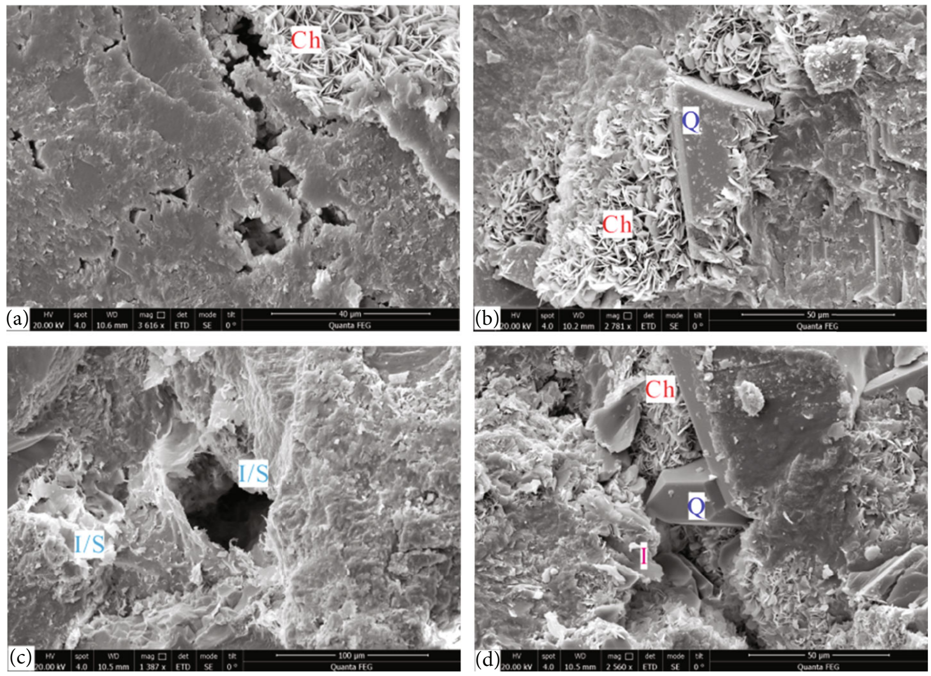

Figure 5: Microstructural characteristics of the Chang 4+5 and Chang 6 reservoirs in the N 212 well block in Nanniwan Oilfield. Ch = chlorite; Q = quartz; I/S = illite/smectite; I = illite. (a) Chlorite can be seen at the edge of the particles, Chang 4+5, well N 212, 691.69 m; (b) chlorite and secondary quartz filling the intergranular pore, Chang 6, well N 212, 773.70 m; (c) illite and illite/smectite filling the intergranular pores, Chang 4+5, well N 212, 691.69 m; (d) secondary quartz, chlorite, and illite filling them intergranular pores, Chang 4+5, well N 212, 702.39 m.

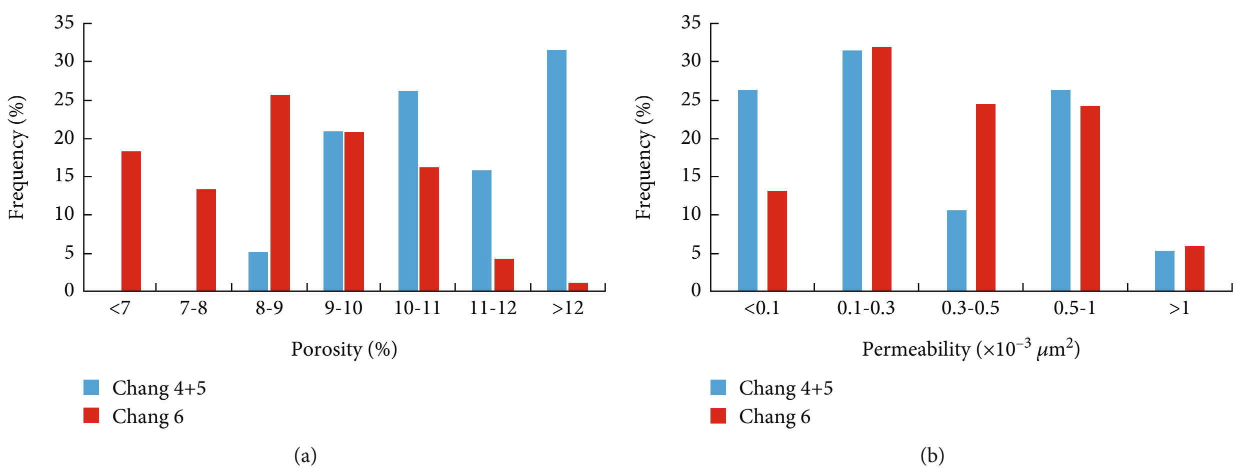

Figure 6: Distributions of porosity and permeability of the Chang 4+5 and Chang 6 reservoirs in the N 212 well block in Nanniwan Oilfield: (a) porosity distribution; (b) permeability distribution.

including degree of damage, velocity sensitivity index, and critical velocity usually can be used to determine reasonable velocity rates of water injection and oil recovery.

As shown in Table 2, the damage degree of permeability ranges from 45.6% to 47.4% within the Chang 4+5 reservoir, which exhibits an average velocity sensitivity index of 0.465 and a critical flow rate of 0.02 mL/min. The Chang 6 reservoir displays the relatively lower permeability damage degree ranged from 42.6% to 45.2% and velocity sensitivity index with a mean of 0.436, as well as a relatively higher critical velocity ranged from 0.02 to 0.25 mL/min than those of the Chang 4+5 reservoir. On the basis of the above analysis, both the two reservoirs exhibit moderate to weak velocity sensitivity [41].

4.2.2. Water Sensitivity. The clay minerals' expansion, migration induced by the incompatibility between the external fluids and reservoir fluids, can result in the blocking of pore throat within the reservoir, and the permeability decrease [18, 42].

The water sensitivity experiment was conducted to analyze the compatible degree of injected water with the Chang 4+5 and Chang 6 reservoir fluids. As shown in Table 3, the

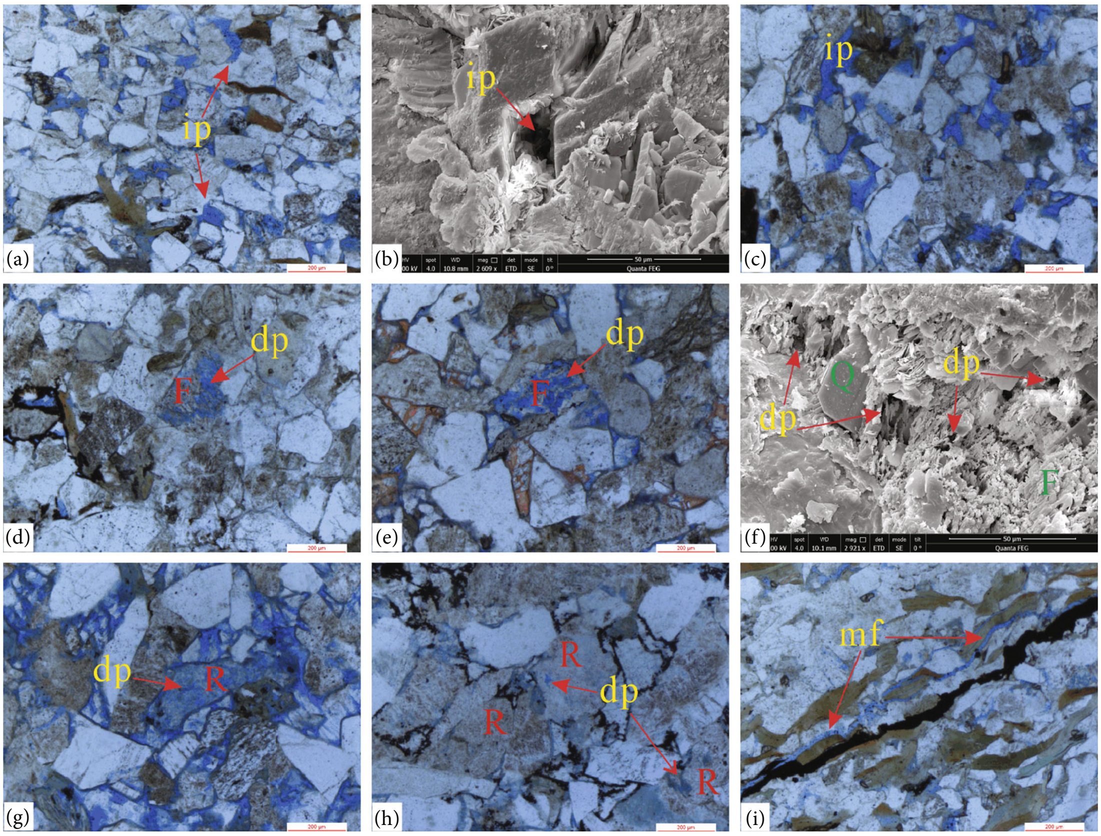

Figure 7: Pore characteristics of the Chang 4+5 and Chang 6 reservoirs in the N 212 well block in Nanniwan Oilfield. ip = intergranular pore; dp = dissolved pore; Q = quartz; F = feldspar; R = rock fragment; mf = microfracture. (a) Intergranular pores, Chang 4+5, well N 212, 692.59 m, CTS; (b) intergranular pores, Chang 4+5, well N 212, 691.69 m, SEM; (c) intergranular pores and dissolved pores in feldspar, Chang 4+5, well N 212, 770.52 m, CTS; (d) dissolved pore in feldspar, Chang 4+5, well X33, 791.77 m, CTS; (e) dissolved pore in feldspar, Chang 4+5, well X820, 825.0 4 m, CTS; (f) dissolved pores and quartz filling in the intergranular pore, Chang 6, well X33, 767.30 m, SEM; (g) dissolved pores in debris, Chang 6, well N 212, 765.00 m, CTS; (h) dissolved pores in debris, Chang 6, well X33, 768.00 m, CTS; (i) microfractures, Chang 6, well X820, 760.99 m, CTS.

permeability damage degree of water sensitivity varies from 40.9% to 44.0% (with a mean of 42.45%) within the Chang 4+5 reservoir, which is less than that of the Chang 6 reservoir, exhibiting a damage degree between 42% and 48.2% (with a mean of 44.73%). This result reflects that both the two reservoirs exhibit moderate to weak water sensitivity [41].

4.2.3. Salt Sensitivity. Salt sensitivity refers to the phenomenon that the physical and chemical change of clay minerals accompanied with decrease of reservoir permeability, induced by the salinity difference between injected fluids and formation water [43]. In specific, within the reservoir, the injected fluid with a relatively higher salinity than that of formation water will lead to the shrinking, instability, and shedding of clay minerals. However, when the injected fluid has a relatively lower salinity than that of the formation water, it will induce the clay minerals' expansion and dispersion [8]. Therefore, the critical salinity can be determined through salt sensitivity experiment and used to protect the reservoir from being damaged by raising up the injected fluid salinity greater than critical salinity.

As shown in Table 4, the Chang 4+5 reservoir displays a relatively higher critical salinity with an average of 18939 mg/L than that of the Chang 6 reservoir with a mean of 18507 mg/L, demonstrating that both the two reservoirs exhibit moderate to strong salt sensitivity [41].

4.2.4. Acid Sensitivity. When acid fluids are injected in the reservoir, they will react with the acid sensitivity minerals or crude oil in the reservoir, then produce gel and precipitation, or release particles, resulting in the decrease of reservoir permeability. As the most typical reservoir damages are accompanied with chemical reaction, acid sensitivity is the result of the interaction of acid fluid with rock, acid fluid with crude oil, acid with reaction products, and organic compounds in acid solution with rock and crude oil. Reservoir damage induced by acid sensitivity can be divided into two types, including the formation of chemical precipitation or gel and the destruction of the original rock structure, which also can accelerate the velocity sensitivity [43].

As shown in Table 5, the Chang 4+5 reservoir exhibits a relatively lower acid sensitivity index with an average of

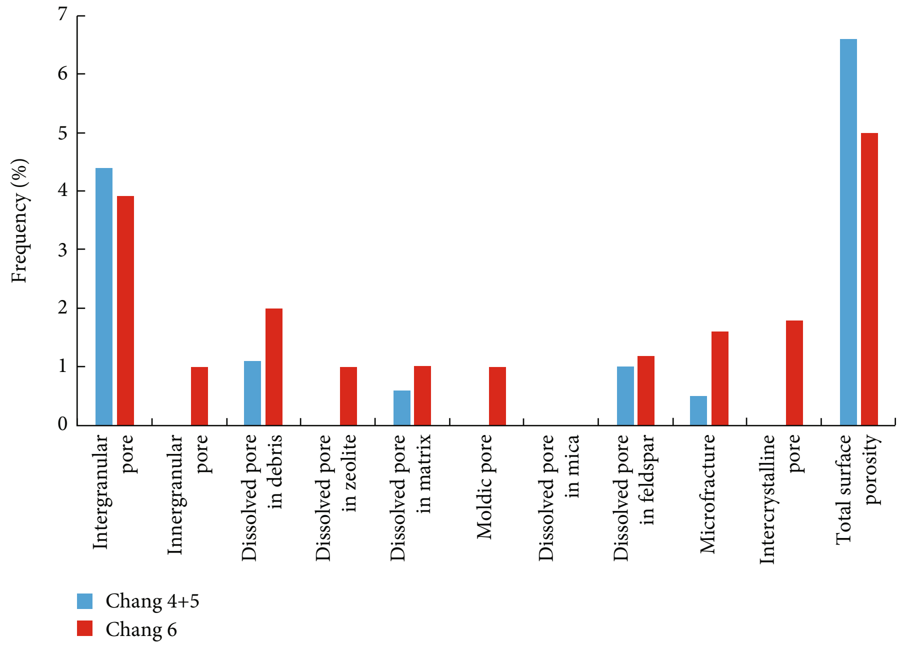

Figure 8: Type and frequency distribution of tight sandstone reservoir pore for the Chang 4+5 and Chang 6 reservoirs in the N 212 well block in Nanniwan Oilfield.

Table 1: Characteristics of pore structure parameters of tight sandstone on the basis of mercury pressure test.

Stratum	Parameters	Displacement pressure (MPa)	Skewness	Sorting coefficient	Median radius of throat (μm)
Chang 4+5	Maximum	5.07	1.91	0.18	0.12
	Minimum	0.64	1.64	0.02	0.02
	Mean	2.61	1.75	0.09	0.06
Chang 6	Maximum	5.22	2.43	0.14	0.13
	Minimum	0.71	1.09	0.02	0.01
	Mean	1.79	1.77	0.07	0.04

Table 2: Statistics of dynamic core flow tests for velocity sensitivity of samples from Chang 4+5 and Chang 6 reservoirs of N 212 well block.

Sample number	Depth (m)	Stratum	Lc (cm)	Dc (cm)	Kg ($\times10^{-3}\,\mu m^2$)	Φ (%)	Critical velocity (mL/min)	I_{ac}	I_v	Rank
S2	692.59	Chang 4+5	3.82	2.49	0.0439	10.03	0.02	47.4	0.474	Moderate-weak
S5	702.39		3.81	2.50	0.642	9.30	0.02	45.6	0.456	Moderate-weak
S31	767.00	Chang 6	3.84	2.49	0.0325	4.86	0.02	45.2	0.452	Moderate-weak
S38	778.92		3.91	2.50	0.208	8.26	0.2	42.6	0.426	Moderate-weak
S40	791.77		3.81	2.50	0.265	8.12	0.2	44.0	0.44	Moderate-weak
S41	760.99		3.89	2.49	0.291	9.08	0.25	42.7	0.427	Moderate-weak

0.153 than that of the Chang 6 reservoir with a mean of 0.209, reflecting that both the two reservoirs exhibit weak acid sensitivity [41].

4.2.5. Alkali Sensitivity. When alkali fluids are injected in the reservoir, the interaction between injected fluids and reservoir minerals will happen, resulting in the mineral dispersion and shedding, new precipitation, or gel formation, blocking the pore throat and leading to the permeability decrease. The alkali sensitivity experiment conducted in our research mainly focuses on the damage possibility and degree induced by multiple alkali fluids, such as drilling fluid, cement slurry, and fracturing fluid.

The Chang 4+5 reservoir exhibits a relatively lower damage degree ranged from 33.6% to 47.0% (with an average value of 40.3%) than that of the Chang 6 reservoir varied from 44.3% to 48.8% (with an average value of 46.53%) (Table 6), indicating that both the two reservoirs exhibit moderate to weak alkali sensitivity [41].

Table 3: Statistics of dynamic core flow tests for water sensitivity of samples from Chang 4+5 and Chang 6 oil reservoir of N 212 well block.

Sample number	Depth (m)	Stratum	Lc (cm)	Dc (cm)	Kg ($\times10^{-3}\,\mu m^2$)	Φ (%)	K_{fw} ($\times10^{-3}\,\mu m^2$)	K_{fw} after 50% dilution ($\times10^{-3}\,\mu m^2$)	K_{dw} ($\times10^{-3}\,\mu m$)	D_w (%)	Rank
S2	692.59	Chang 4+5	4.10	2.49	0.0478	9.43	0.00830	0.00602	0.00465	44.0	Moderate-weak
S5	702.39		3.83	2.49	2.595	12	1.0595	0.8103	0.9886	40.9	Moderate-weak
S31	767.00	Chang 6	3.93	2.49	7.748	14.06	3.3916	2.7028	2.0256	42.0	Moderate-weak
S38	778.92		3.93	2.49	0.188	8.30	0.0130	0.00973	0.00674	48.2	Moderate-weak
S40	791.77		3.81	2.49	0.278	9.50	0.0484	0.0346	0.0259	46.5	Moderate-weak
S41	760.99		3.81	2.49	0.326	10.04	0.0495	0.0359	0.0286	42.2	Moderate-weak

Lc = core length; Dc = core diameter; Kg = gas permeability; Φ = porosity; K_{fw} = formation water permeability; K_{dw} = deionized water permeability; D_w = damage ratio of water sensitivity.

Table 4: Statistics of dynamic core flow tests for salt sensitivity of samples from Chang 4+5 and Chang 6 reservoirs of N 212 well block.

Sample number	Depth (m)	Stratum	Lc (cm)	Dc (cm)	Kg ($\times 10^{-3}\ \mu m^2$)	Φ (%)	K_{fw} ($\times 10^{-3}\ \mu m^2$)	K_{fw} after dilution ($\times 10^{-3}\ \mu m^2$)		K_{dw} ($\times 10^{-3}\ \mu m$)	Critical salinity (mg/L)	Rank
								50%	25%			
S2	692.59	Chang 4+5	3.80	2.50	0.0456	9.61	0.00410	0.00287	0.00240	0.00213	18939	Moderate-strong
S5	702.39		3.82	2.50	0.617	9.52	0.0284	0.0214	0.0196	0.0171	18939	Moderate-strong
S31	767.00	Chang 6	3.80	2.49	0.0309	5.95	0.00130	0.000922	0.000819	0.000677	18507	Moderate-strong
S38	778.92		3.99	2.49	0.199	8.25	0.00760	0.00552	0.00483	0.00434	18507	Moderate-strong
S40	791.77		3.89	2.50	0.214	9.44	0.0817	0.0621	0.0520	0.0461	18507	Moderate-strong
S41	760.99		3.82	2.49	0.281	9.48	0.0440	0.0311	0.0268	0.0238	18507	Moderate-strong

Table 5: Statistics of dynamic core flow tests for acid sensitivity of samples from Chang 4+5 and Chang 6 reservoirs of N 212 well block.

Sample number	Depth (m)	Stratum	Lc (cm)	Dc (cm)	Kg ($\times 10^{-3}\ \mu m^2$)	Φ (%)	K_{fw} ($\times 10^{-3}\ \mu m^2$)	Name	Acid fluid Concentration (%)	Content (PV)	K_{fw} after acidification ($\times 10^{-3}\ \mu m^2$)	D_{ac} (%)	I_{ac}	Rank
S2	692.59	Chang 4+5	3.99	2.49	0.0470	10.18	0.00683	HCL	15	1.0	0.00603	11.7	0.117	Weak
S5	702.39		4.00	2.50	0.637	9.04	0.00359	HCL	15	1.0	0.00291	18.9	0.189	Weak
S31	767.00	Chang 6	3.81	2.49	0.0354	4.91	0.00286	HCL	15	1.0	0.00234	18.2	0.182	Weak
S38	778.92		3.90	2.49	0.194	8.20	0.00549	HCL	15	1.0	0.00469	14.6	0.146	Weak
S40	791.77		3.83	2.49	0.275	8.65	0.0631	HCL	15	1.0	0.0451	28.5	0.285	Weak
S41	760.99		3.79	2.49	0.311	10.19	0.0386	HCL	15	1.0	0.0299	22.5	0.225	Weak

Table 6: Statistics of dynamic core flow tests for alkali sensitivity of samples from Chang 4+5 and Chang 6 reservoirs of N 212 well block.

Sample number	Depth (m)	Stratum	Lc (cm)	Dc (cm)	Kg ($\times 10^{-3}\,\mu m^2$)	Φ (%)	K_{fw} ($\times 10^{-3}\,\mu m^2$)	Critical pH	K_{fw} after alkalization ($\times 10^{-3}\,\mu m^2$)	D_{alk} (%)	I_{alk}	Rank
S2	692.59	Chang 4+5	3.97	2.49	0.0417	9.60	0.00538	8.5	0.00284	47.0	0.472	Moderate-weak
S5	702.39		3.84	2.50	0.688	9.38	0.00616	8.5	0.00409	33.6	0.336	Moderate-weak
S31	767.00	Chang 6	3.93	2.50	0.0302	5.23	0.00127	8.5	0.000669	47.3	0.473	Moderate-weak
S38	778.92		3.79	2.49	0.191	8.34	0.0166	8.5	0.00850	48.8	0.488	Moderate-weak
S40	791.77		3.83	2.50	0.262	9.03	0.0811	8.5	0.0440	45.7	0.457	Moderate-weak
S41	760.99		3.85	2.49	0.326	9.78	0.0806	8.5	0.0449	44.3	0.433	Moderate-weak

5. Discussions

5.1. Reservoir Sensitivity Difference between Chang 4+5 and Chang 6. Based on the results of reservoir sensitivity experiments, both the two reservoirs are characterized by the moderate to weak velocity sensitivity, moderate to weak water sensitivity, moderate to strong salt sensitivity, weak acid sensitivity, and moderate to weak alkali sensitivity. Even though the same sensitivity degrees are shown in the different reservoirs, the differences of damage degree and sensitivity indexes still exist in these two reservoirs.

In specific, the Chang 4+5 reservoir has a velocity sensitivity index ranged from 0.456 to 0.474, which is a little higher than that of the Chang 6 (varied from 0.426 to 0.452), indicating that the velocity sensitivity of the Chang 4+5 is stronger than that of the Chang 6 reservoir. This conclusion also can be verified by the damage degree, which is higher in the Chang 4+5 reservoir (ranged from 45.6% to 47.4%) than in the Chang 6 (ranged from 42.6% to 45.2%).

With regard to the water sensitivity, the Chang 4+5 has a damage degree between 40.9% and 44.0%, which is lower than that of the Chang 6 (ranged from 42.0% to 48.2%), demonstrating that the water sensitivity of the Chang 4+5 is weaker than that of the Chang 6.

About the salt sensitivity, the Chang 4+5 reservoir has an average critical salinity of 18939 mg/L, which is lower than that of the Chang 6 reservoir (with a mean of 18507 mg/L), indicating that the salt sensitivity of the Chang 4+5 reservoir is stronger than that of the Chang 6 reservoir.

The Chang 4+5 reservoir has an acid sensitivity index ranged from 0.117 to 0.189, which is higher than that of the Chang 6 (varied from 0.146 to 0.285), indicating that the acid sensitivity of the Chang 4+5 is weaker than that of the Chang 6 reservoir. This also can be proved by the damage degree, which is lower in the Chang 4+5 (ranged from 11.7% to 18.9%) than in the Chang 6 reservoir (ranged from 18.2% to 28.5%).

In relation to the alkali sensitivity, the Chang 4+5 reservoir has an alkali sensitivity index ranged from 0.336 to 0.472, which is lower than that of the Chang 6 (ranged from 0.433 to 0.488), reflecting that the alkali sensitivity of the Chang 4+5 reservoir is weaker than that of the Chang 6 reservoir. This still can be supported by the damage degree, which is lower in the Chang 4+5 (ranged from 33.6% to 47.0%) than in the Chang 6 reservoir (ranged from 44.3% to 48.8%).

5.2. Controlling Factors on Reservoir Sensitivity

5.2.1. Clay Minerals. The existence of clay minerals in the reservoir is dominated in the reasons for reservoir sensitivity. The damage mechanism from clay minerals on reservoir sensitivity can be concluded into two types, including the direct damage and indirect damage. Various clay minerals in reservoir exhibit different types of reservoir sensitivity, which will lead to a direct damage on tight sandstone reservoir, while the physical and chemical interactions between clay minerals within reservoir and external fluids with different salinity, pH, and flow velocity will induce an indirect damage. So, it is necessary to analyze the clay mineral type and occurrence before evaluating the damage mechanism and degree.

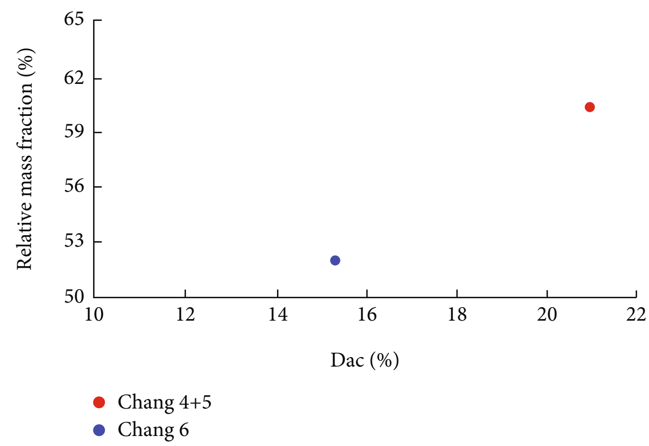

Figure 9: Plot of relative mass fraction of chlorite versus damage degree of acid sensitivity for the Chang 4+5 and Chang 6 reservoirs in the N 212 well block in Nanniwan Oilfield. Dac = damage degree of acid sensitivity.

Previous results show that the sensitivity degree will increase with the rising up of clay mineral content [4, 36, 37]. This maybe caused by the occupation on pore space by a great deal of clay minerals, which can block the pore throat. So, the volume content of clay minerals is the fundamental factor determining the sensitivity degree.

The reaction of chlorite and acid solution can produce $Fe(OH)_3$ precipitation, then block the pore throat, and cause a decrease of the permeability [37]. In the study area, the relative mass fraction of chlorite is lower in the Chang 4+5 (with a mean of 52%) than that in the Chang 6 reservoir (with a mean of 60.4%) (Figure 9). This maybe the reason why the Chang 4+5 oil reservoir exhibits a relatively weaker acid sensitivity than the Chang 6 oil reservoir. Generally, the illite/smectite is characterized by semihoneycomb distribution, which blocks the pores and decreases the reservoir permeability. In addition, the illite/smectite will absorb water and expand to varying degrees when the salinity of injected water is incompatible with the formation water, which also leads to the block of pore throat and permeability decrease, while the relative mass fraction of illite/smectite is higher (ranges from 36% to 64%) in the Chang 4+5 reservoir than that in the Chang 6 reservoir (ranges from 23% to 51%). From the above analysis, there is no direct relation between the relative mass fraction of illite/smectite and the strong water sensitivity of Chang 6, implying that the water sensitivity may be influenced by other factors more.

5.2.2. Petrophysical Property. There is a good correlation between the porosity and permeability of the Chang 4+5 and Chang 6 reservoirs (Figure 10). However, due to the blockage of the reservoir pores and throats, the fluid is difficult to flow in the pore space, leading to the small change of sensitivity characteristics except for acid and alkali sensitivities. The velocity sensitivity damage degree is related to the cementation, which can affect the development of reservoir

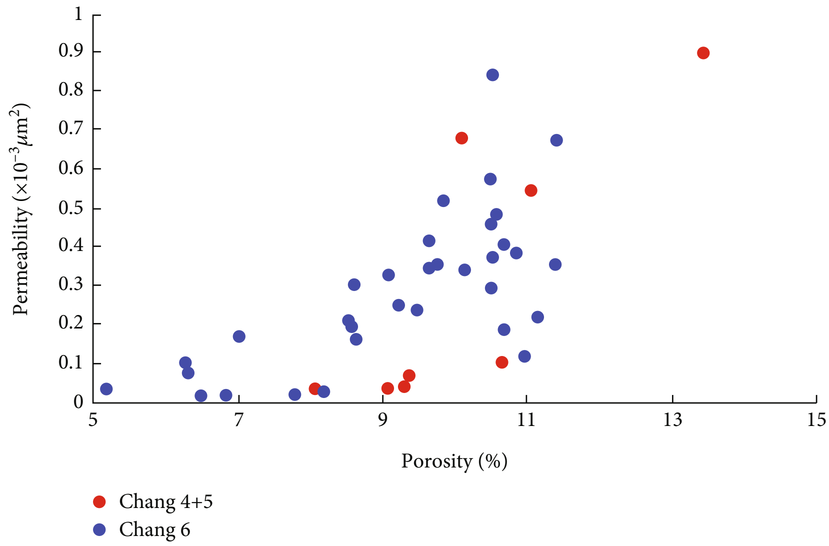

Figure 10: Plot of porosity versus permeability of tight sandstone reservoir for the Chang 4+5 and Chang 6 reservoirs in the N 212 well block in Nanniwan Oilfield.

pores. The clay mineral, which is dominated in the cements of Chang 4+5 and Chang 6 reservoirs, generally can block pores and throats except for the chlorite film cement. Therefore, the velocity sensitivity damage degree is stronger in the Chang 4+5 reservoir than that in the Chang 6 reservoir in the study area.

5.2.3. Pore Structure. The surface porosity of 6.56% and intergranular pore porosity of 4.4% in Chang 4+5 reservoir are greater than those in the Chang 6 (with a surface porosity of 5% and an intergranular pore porosity of 3.9%), showing a better pore structure. The sensitivity experiment results exhibit that the water, acid, and alkali sensitivities are higher in the Chang 6 than those in the Chang 4+5 reservoir, while the velocity and salt sensitivities are higher in the Chang 4+5 than those in the Chang 6 reservoir. Based on the above analysis, the pore structure is positively correlated with the velocity and salt sensitivities but negatively correlated with the water, acid, and alkali sensitivities.

5.2.4. Suggestions to Reservoir Protection. The Chang 4+5 and Chang 6 reservoirs show moderate to weak velocity, water and alkali sensitivities, moderate to strong salt sensitivity, and weak acid sensitivity. The salt sensitivity should be paid more attention first, followed by velocity, water, and alkali sensitivities. From a geological point of view, the average critical flow rate of the Chang 4+5 and Chang 6 reservoirs is 0.02 mL/min, indicating that the flow rate needs to be kept less than 0.02 mL/min to decrease the velocity and water sensitivities. The average critical salinity of Chang 4+5 and Chang 6 reservoirs is 18939 mg/L and 18507 mg/L, respectively, demonstrating that the salinity of injected fluids should be less than 18507 mg/L to avoid the salinity sensitivity. The two reservoirs show a same critical pH of 8.5 for the alkali sensitivity test, reflecting that the pH of injected fluid should be controlled less than 8.5. In short, the geological conditions need to be considered firstly on reservoir protection. In combination with the reservoir conditions of the study area and the results of reservoir sensitivity analysis, the fluids with a flow rate less than 0.02 mL/min, a salinity less than 18507 mg/L, and a pH less than 8.5 are suggested to be injected in the Chang 4+5 and Chang 6 reservoirs in the study area to decrease the reservoir damages.

6. Conclusions

(1) The rock type of the Chang 4+5 and Chang 6 reservoirs in the N 212 well block of the Nanniwan Oilfield is dominated by arkose with the mean porosity of 11.2% and 8.45%, respectively, and the mean permeability of $0.35 \times 10^{-3}\,\mu m^2$ and $0.44 \times 10^{-3}\,\mu m^2$, respectively. The clay mineral components mainly include chlorite and illite/smectite, and the Chang 4+5 reservoir is higher in the relative mass fraction of illite/smectite (with a mean of 48%), while it is lower in the relative mass fraction of chlorite (with a mean of 52%) than that in the Chang 6 reservoir (with a mean of 39.6% and 60.4%, respectively)

(2) Both the Chang 4+5 and Chang 6 reservoirs are characterized by moderate to weak velocity, water and alkali sensitivities, moderate to strong salt sensitivity, and weak acid sensitivity. In specific, the velocity and salt sensitivities are stronger in Chang 4+5 than those in Chang 6 reservoir, while the water, acid, and alkali sensitivities are stronger in Chang 6 than those in Chang 4+5 reservoir

(3) The major controlling factors on reservoir sensitivity are clay minerals, petrophysical property, and pore structure. In detail, the velocity sensitivity displays a positive correlation with the pore structure, porosity, and permeability. The water sensitivity will

become strong with the increase of the volume content of illite/smectite but will become weak with the getting better of pore structure. The acid sensitivity is positively correlated with the volume content of chlorite but is negatively correlated with pore structure. With the getting better of pore structure, the salt and alkali sensitivities will become strong and weak, respectively

Data Availability

All data that support the conclusions of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that the paper does not have any conflict of interest with other units and individuals.

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