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Experimental study of petrophysical properties of a tight formation by considering the clay minerals and flow sensitivities

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ABSTRACT

Quantitative X-ray diffraction analysis of rock, X-ray diffraction analysis of clay minerals types and components, Field Emission Scanning Electron Microscope (FESEM) and sensitivity flow experiments methods were used to research the effects of clay minerals on the porosity and permeability of Ordos Basin's tight Chang 7 reservoir (Zhenbei area). These methods were also used to analyze the type, degree, and factors affecting reservoir sensitivity. The research showed that the reservoir possessed poor water, salt, and alkali sensitivity, poor to strong acid sensitivity and none to poor velocity sensitivity. Acid sensitivity among them had comparatively large differences, mainly because acid sensitivity was not only affected by chlorite but also by components of carbonate minerals. Stress sensitivity experiment results showed that the maximum degree of permeability damage in the rocks of this reservoir was median to very strong; irreversible damage level was weak to strong. Consequently, the experimental studies are favorable to not only determine the factor dominating the petrophysical properties of the tight formation, but also to optimize the follow-up development strategies, e.g. injection schedule and hydraulic fracturing implement.

Keywords: Analysis of clay minerals, porosity, permeability, sensitivity experiments, formation damage.

Estudio Experimental de las propiedades petrofisicas de una formación compacta al considerar las arcillas minerales y las respuestas de flujo

RESUMEN

Este trabajo utilizó análisis cuantitativos de rocas por difracción de rayos X, análisis de los tipos y componentes de arcillas minerales por difracción de rayos X, análisis con el microscopio electrónico de efecto de campo (FESEM, del inglés Field Emission Scanning Electron Microscope) y ensayos de respuesta de flujo para investigar los efectos de las arcillas minerales en la porosidad y permeabilidad del depósito Chang 7, en la cuenca del Ordos (región Zhenbei). Estos métodos también se utilizaron para analizar el tipo, el grado y los factores que afectan la respuesta del depósito. La investigación demuestra que el depósito posee poca agua, sal y respuesta alcalina, baja a fuerte respuesta de acidez, y ninguna a baja respuesta de velocidad. Entre estas características, la respuesta de acidez presentó grandes diferencias comparativas debido a que está afectada tanto por el clorito como por los componentes de minerales carbonatos. Los resultados de los ensayos de respuesta de tensión muestran que el máximo grado de daño por permeabilidad en las rocas del depósito es de mediano a muy fuerte; el nivel de daño irreversible va de débil hasta fuerte. Por lo tanto lo estudios experimentales son favorables no solo para determinar el factor dominante en las propiedades petrofisicas de la formación compacta sino también para optimizar las futuras estrategias de desarrollo, como una programación de las tareas de inyección y la implementación de la fractura hidráulica.

Palabras clave: Análisis de arcilla mineral, porosidad, permeabilidad, ensayos de respuesta, daños de la formación.

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1. Introduction

Clay minerals in tight reservoirs have a significant impact on its physical properties. Reservoir sensitivity analyses have theoretical and practical significance for the prevention and treatment of tight sandstone reservoirs. Since the 1960s, experts had noticed that formation damage is caused by clay mineral (Hewitt, 1963). Hower (1974) studied the distribution of clay minerals in the United States Gulf Coast and pointed out that the formation damage degree depended on the contents, types of clay mineral and their position in the rock. Krueger (1986), Amaerule, Kersey, Norman, and Shannon. (1988), Porter (1989) and Reed (1989) comprehensively reviewed the research of formation damage, which reflected the achievements of the 80s. Aase, Bjorkum and Nadeau (1996) and Pittman, Larese, and Heald (1992) studied the influence of different types and occurrences of clay on the formation and protection of secondary porosity. Baker, Uwins, and Mackinnon (1993a, 1993b, 1994) used Environment Scanning Electron Microscope (ESEM) to research the sensitivity of clay minerals. 'Clay Mineral Cements in Sandstones,' by Worden and Morad (2003), described the relationship between clay minerals and sandstone reservoir properties and looked to the future research direction of clay minerals.

Ordos Basin is located at the western margin of North China, with an area of 25×10^4km^2. It is a large cratonic basin of a multi-configuration system and multicycle evolution (Zhao, Liu, Yu, and Wang, 2008; Feng, Huang S., Huang P., Zou and Wu, 2009; Wang et al., 2010). Zhenbei area is a typical sandstone reservoir, situated at the north-western part of the basin. It possesses closed sediment supply and fast deposition rate. Chang 7 reservoir of this region is located in the southwest lake basin, mainly affected by the Northwest provenance. Chang 7 reservoir is a deep-water turbidite fan sedimentary system with developed turbidite sand body; it is the central horizon of the Zhenbei area (Lu et al., 2011; Cui, Feng, Qin, and Peng, 2013). In this article, X-ray diffraction analysis, FESEM and sensitivity flow experiments were used to research and evaluate the clay mineral features of the Zhenbei area's Chang 7 reservoir.

2. Analysis of Reservoir Minerals

The X-ray of whole rock analysis is usually adopted in laboratories for the quantitative analysis of rocks to get the clay mineral contents and X-ray diffraction analysis of clay minerals. Thus obtaining the corresponding contents of each type of clay mineral in the reservoir. The porosity and permeability of rocks can be gotten through gas logging porosity and permeability experiment. Through those experimentations carried out on ten wells of Zhenbei area, the results were as shown in Table 1 and Table 2.

Table 1. Analysis of Reservoir Rock Minerals

Well	Rock mineral content（%）				Clay mineral content (%)	Porosity（%）	Permeability ($10^{-3}\mu m^2$)
	Quartz	Feldspar	Plagioclase	Calcite			
Z-1	36	6	14	25	19	10.23	0.385
Z-2	38	5	17	18	22	7.84	0.184
Z-3	43	4	16	17	20	9.13	0.327
Z-4	30	7	16	22	25	6.637	0.121
Z-5	42	6	18	12	22	7.06	0.149
Z-6	45	7	14	13	21	8.46	0.251
Z-7	36	8	15	18	23	8.06	0.214
Z-8	42	5	14	20	19	9.85	0.352
Z-9	36	7	18	15	24	6.837	0.132
Z-10	40	5	15	17	23	7.11	0.163

Table 2. Analysis of Clay Minerals

Well	Clay mineral relative content（%）					
	K	C	I	S	I/S	%S
Z-1	13	45	11	/	31	18
Z-2	8	39	12	/	41	22
Z-3	14	43	10	/	33	17
Z-4	6	27	18	/	49	22
Z-5	10	35	12	/	43	20
Z-6	11	33	9	/	47	18
Z-7	8	34	15	/	43	15
Z-8	16	40	8	/	36	19
Z-9	2	28	14	/	56	20
Z-10	14	34	8	/	44	16

*Note: K-Kaolinite, C-Chlorite, I-Illite, S-Smectite, I/S-illite smectite mixed layer, %S-the content of smectite in mixed-layer minerals of illite and smectite.

The data in Table 1 showed that the content of clay minerals in Zhenbei area's Chang 7 reservoir was high, the reservoir had a small porosity and ultra-low permeability. From Table 2 it could see that the main contents of clay minerals in the reservoir were the illite-smectite mixed layer, followed by illite and kaolinite; smectite was not independently developed but occupied a slight proportion in the illite-smectite mixed layer. FESEM photographs showed that kaolinite in Chang 7 reservoir often filled in the porosity with booklet shapes (as shown in Figure 1a); chlorite was usually distributed on the surfaces of particles with leaf shapes (Figure 1b) and the form of the illite and the illite-smectite mixed layer were flocculent structure (Figure 1c and Figure 1d).

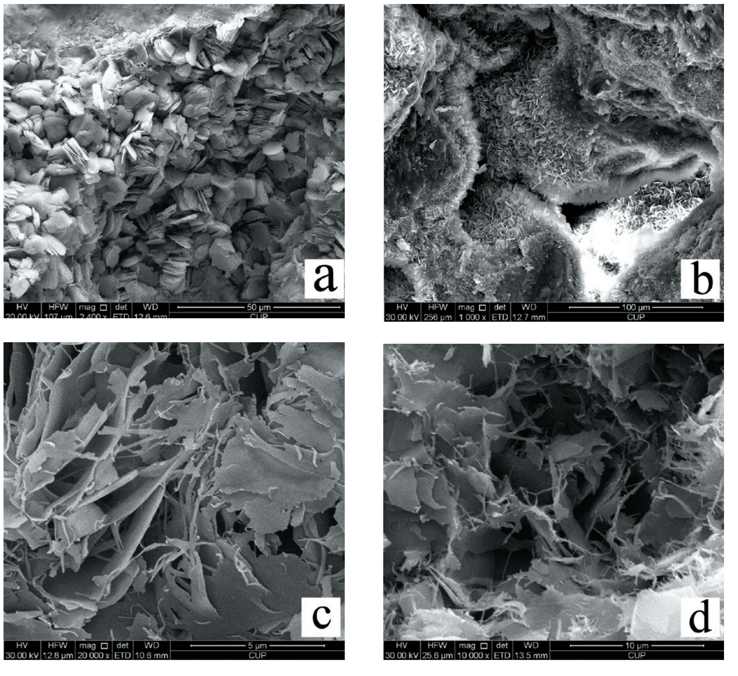


Figure 1. FESEM photographs of Zhenbei area Chang 7 reservoir.

3. Influence of clay minerals on the reservoir properties

The total content of clay minerals and types of clay minerals affected the properties of the reservoir. As shown in Figure 2, rock mineral components formed an inversely proportional relationship with both porosity and permeability. As fewer mineral content in the rock, the higher porosity and permeable the reservoir would be.

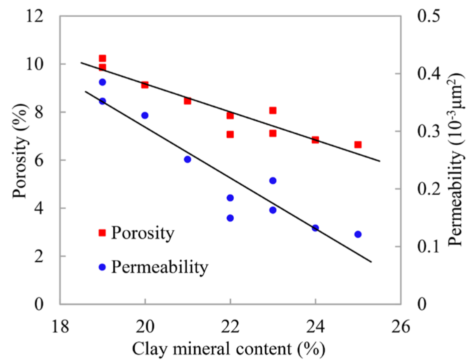


Figure 2. Influence of clay mineral content on porosity and permeability.

3.1 Influence of authigenic kaolinite on the reservoir properties

Authigenic kaolinite was the primary dissolution product of the feldspar (Huang et al., 2009), so the content change of authigenic kaolinite was closely related to the feldspar content in the sandstone reservoir. As shown in Figure 3, authigenic kaolinite and detrital feldspar had a significant negative correlation; it could be seen that authigenic kaolinite content increase with the decrease of feldspar. The content of authigenic kaolinite in Chang 7 reservoir was small and usually filled in the pores and throats. The kaolinite dissolution from feldspar grew much mineral intracrystal porosity, which had a positive effect on the reservoir property. As shown in Figure 4, as higher the content of kaolinite, higher the porosity and permeability.

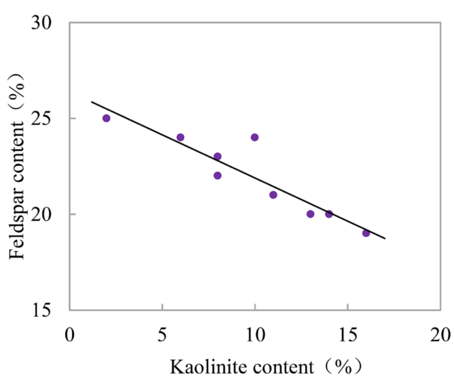


Figure 3. Relationship between authigenic kaolinite content and feldspar content.

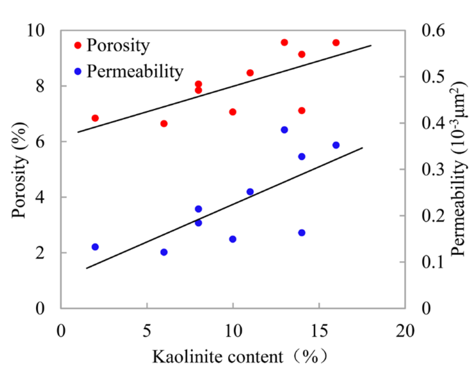


Figure 4. Influence of authigenic kaolinite content on porosity and permeability.

3.2 Influence of authigenic chlorite on the reservoir properties

The formation of chlorite membrane was suitable for the reservoir (Ehrenberg, 1993; Hurst & Nadeau, 1995; He, 2010): (1) Chlorite membrane could increase the mechanical strength of rock and resist the compaction to some extent, thus making the primary intergranular pore unable diminish further by compaction. (2) Feldspar could even be dissolved and formed a moldic pore, but the chlorite membrane would remain. If the chlorite rims had sufficient strength, they could support themselves and protect the secondary porosity formed by dissolution. (3) Quartz secondary enlargement caused porosity loss, but the chlorite film could prevent authigenic quartz cement from nucleating on the surface of detrital quartz by dividing pore water from quartz particle surface (4) Authigenic chlorite transformed part of the intergranular pores it occupied to intercrystalline pores, some of which might be effective for reservoir spaces. Therefore, the development of authigenic chlorite was favorable for reservoir physical property. As shown in Figure 5, the porosity and permeability were positively associated with the content of authigenic chlorite.

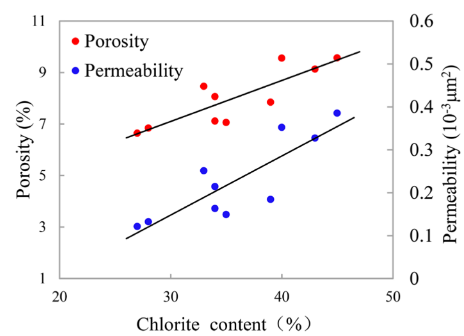
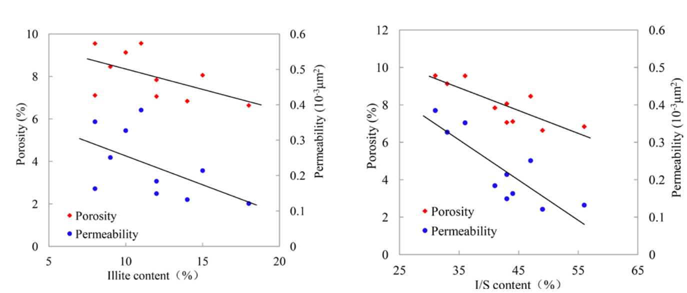


Figure 5. Influence of authigenic chlorite content on porosity and permeability.

3.3 Influence of authigenic illite and illite-smectite mixed layer on the reservoir properties

Common forms of authigenic illite are hair-like, fibrous and bridging. They often cut lots of pores and pore throats into micro bound pore and reduce the effective radius (Liu, Qu, Sun, Yue & Zhu, 1998, Lander & Bonnell, 2010). Zhenbei area Chang 7 reservoir has a high content of illite-smectite mixed layer whose main constituent is illite and FESEM showed that the attitude of the illite-smectite mixed layer was similar to illite, so the influence of it on the reservoir was also similar to that of illite. As shown in Figure 6, as higher the contents of illite and illite-smectite mixed layer, the lower the porosity, and permeability.

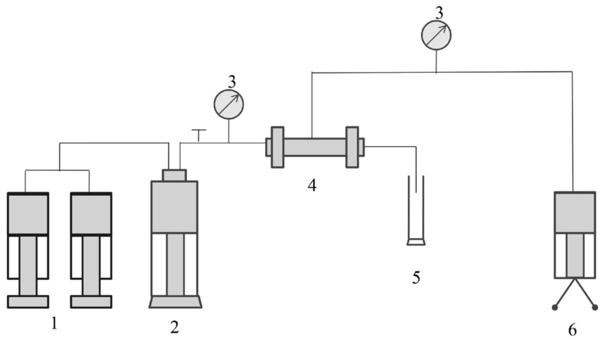


a. Illite b. I/S

Figure 6. Influence of authigenic illite and I-S content on porosity and permeability.

4. Sensitivity Evaluation

Reservoir sensitivity is referred to the degree of change in reservoir permeability caused by the physicochemical interactions between the reservoir and fluid. Tight sandstone reservoir is different from the conventional low permeability reservoir, so its experimental methods require more precise and complex (Zhang, Chen, & Yan, 2006; Ju, Fan & Wan, 2007; Wu, Wang, Cui, Zhang, 2013). This experiment used cores in six wells to make systematic sensitivity evaluation for Chang 7 reservoir. The device schematic diagram is as shown in Figure 7.



*Note: 1-Pump. 2-Intermediate container. 3-Pressure gage. 4-Core holder. 5-Measuring cylinder. 6-Confining pressure pump.

Figure 7. Experiment device schematic diagram.

4.1 Water and Salt Sensitivity Evaluation

Among reservoir clay minerals, montmorillonite has the strongest effect on water sensitivity; even a tiny amount of montmorillonite caused very strong sensitivity. Secondly, the illite-smectite mixed layer could also cause water sensitivity. The expansion of illite and chlorite upon contacted with water was feeble, and kaolinite was not easily hydrated (Cui, D. L. Liu, Tao, Li, & Y. B. Liu, 2004) The water sensitivity experiment results of Zhenbei area Chang 7 reservoir were as shown in Table 3; results of salt sensitivity were as illustrated in Figure 8.

Table 3. Results of Water Sensitivity Experiment on Zhenbei area's Chang 7 Reservoir.

Well	Permeability ratio of different fluids: Kn/Ki（%）			Water sensitivity damage rate（%）
	8% standard saline	4% standard saline	Distilled water	
Z-1	100%	94.35	72.69	27.3
Z-2	100%	97.95	92.44	7.5
Z-3	100%	94.43	78.97	21
Z-4	100%	86.25	76.68	23.3
Z-5	100%	88.54	82.49	17.5
Z-6	100%	91.24	86.71	13.3

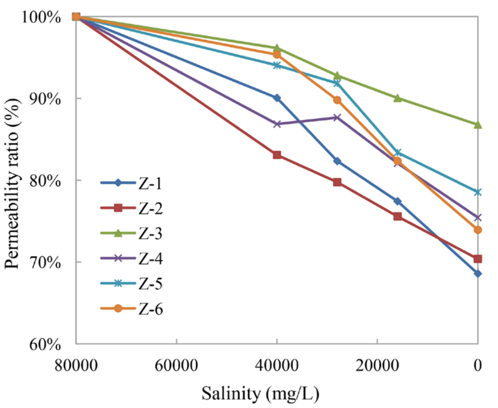


Figure 8. Salt sensitivity experiment results.

It could be seen from Table 3 that the region had weak water sensitivity. The salt sensitivity analysis results of Figure 8 shows that when formation salinity declines, the change in permeability was not obvious and had no critical salinity. The content of I-S in Zhenbei area Chang 7 reservoir was high, but the montmorillonite only took a slight percentage (less than 25%). It was close to the end-member composition of illite. The conversion content of montmorillonite was less than 10%, so the water and salt sensitivity was weak in this reservoir.

4.2 Acid Sensitivity Evaluation

In the process of water injection, tight oil reservoirs were prone to be blocked up. Therefore, acid fluids were to be infused to broken down reservoir to improve its productivity. Acid fluids upon entering the reservoir could react with sensitive acid minerals to produce deposits and released microparticles and blocked the reservoir, causing a reduction in permeability. Acid-sensitive rocks in clay were mainly chlorite, which produced ferric hydroxide upon contact with acid causing blockage in the reservoir. The acid sensitivity experiment results of Zhenbei area's Chang 7 Reservoir were as shown in Table 4.

Table 4. Acid sensitivity test results of Zhenbei area's Chang 7 reservoir.

Well	Permeability before acid injection ($10^{-3}\mu m^2$)	Permeability after acid injection ($10^{-3}\mu m^2$)	Acid sensitivity damage ratio	Degree of acid sensitivity
Z-1	0.392	0.338	13.78%	Weak
Z-2	0.159	0.064	59.75%	Medium to strong
Z-3	0.331	0.105	68.28%	Medium to strong
Z-4	0.125	0.109	12.80%	Weak
Z-5	0.162	0.031	80.86%	Strong
Z-6	0.247	0.057	76.92%	Strong

Table 4 showed that the acid sensitivity of each well at the Zhenbei area's Chang 7 reservoir had great differences. From Table 2, it could be known that difference in the chlorite content of six wells was not big, but the difference in the degree of acid sensitivity was huge. Through analysis, it could be seen that the calcite content of each well at the Zhenbei area had a particular difference. Calcite was carbonate mineral which compared to chlorite readily reacted with hydrochloric acid (Tian, Q. Guo, Y. Li, Y. Guo, & Y. Z. Li, 2009). Through X-Ray analysis, it could be seen that the contents of calcite in Z-1, Z-4 were large. Z-5, Z-6 only had small quantities of calcite and the contents of calcite in Z-2, Z-3 were between them (as illustrated in Table 1). Therefore, the acid sensitivities were different.

4.3 Alkaline Sensitivity Evaluation

During comparatively low temperatures, Ca^{2+}, Mg^{2+} on the surface of clay minerals exchanged with other alkaline minerals to produce hydroxide precipitation and the calcium ions coverage was reduced. Then the surface of clay minerals was easier to expand or to be released from the sand surface (Li, Gao, Yang & Hua, 2012). Also, under high temperature and pH>9 conditions, it reacted kaolinite to form montmorillonite and caused further damage of the reservoir. The alkaline sensitivity experiment results of Zhenbei area's Chang 7 reservoir was as shown in Figure 9.

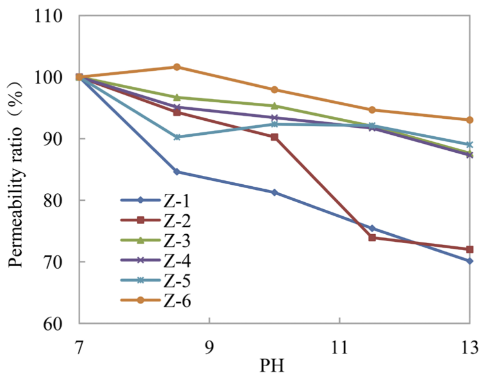


Figure 9. Alkaline sensitivity experiment results.

The results in Figure 9 revealed that Chang 7 reservoir had weak alkaline sensitivity. Data demonstrated that critical PH of Z-1 well is 7, critical PH of Z-2 well is 10 and other wells did not possess critical data.

4.4 Speed Sensitive Evaluation

Kaolinite was the clay mineral that most likely caused speed-sensitivity, and the second was hair-like illite. Results of a speed-sensitive experiment on Zhenbei area's Chang 7 reservoir were as showed in Figure 10.

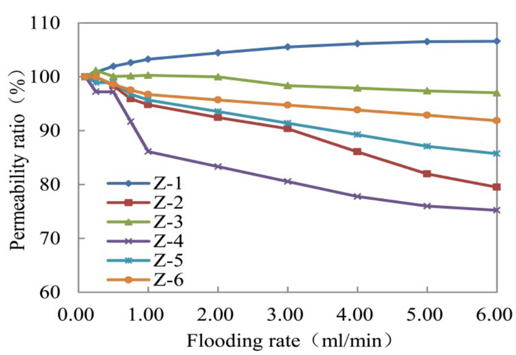


Figure 10. Speed sensitive test results.

Figure 10 showed that the speed-sensitivity of Chang 7 reservoir was none to poor and permeability of Z-1 was even improved. This phenomenon was due to different particle sizes were scoured by the fluid when the flow velocity got increased. When the particle size was greater than the pore throat radius, particles washed down by fluid would accumulate in the throats and form a 'bridge', which made the reservoir permeability decline (Yang & Wei, 2004). However, if particles size were less than the pore throat radius, particles would be carried out with fluid and the pore radius would increase, thereby the permeability of the reservoir got improved. Also, indoor experiment samples were too little, particles might be washed out of the experimental model, but these particles in the reservoir would still stay in it and block the throats. So the results gotten from the laboratory were less than that in the actual reservoir.

4.5 Stress Sensitive Evaluation

During reservoir development, with the output of the internal fluid, the pore pressure became decreasing, and the original force balance of the rocks got changed. That led to elastic-plastic deformation of the rocks and the changing of reservoir pore structure and permeability (Zhao, Yue, & Lv, 2009; Feng, Huang, Chen, Wang, Che, 2010; Ru, Liu, Fan, Li, Yu, 2011; Sun, Yang, Li, 2011). The experiment used a variable confining pressure to test the stress-sensitivity of three samples with different permeability. The trial included both ascending and descending net confining pressure processes. The results were as shown in Figure 11.

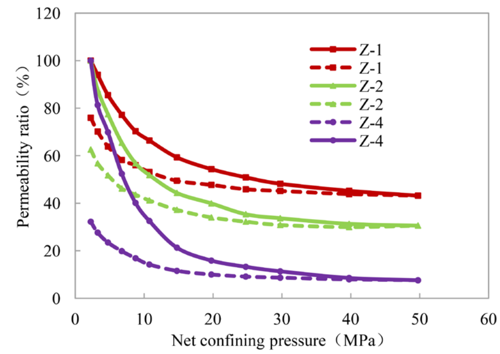


Figure 11. Stress sensitive experiment results.

As shown in the figure above, the solid lines represented ascending net confining pressure processes, and dotted lines indicated the descending net confining pressure processes. It could be seen the stress-sensitivity features of the reservoir were as below.

(1) During the ascending net confining pressure process, with the increasing of confining pressure, the core permeability reduced dramatically at first and then it slowed down to a modest pace. The smaller the core permeability was, the faster it declined and the greater the degree of permeability lost. (2) Part of the reservoir permeability loss would be restored in the process of descending net confining pressure, but it could not be returned to its initial state. So the permeability loss caused by stress-sensitivity was irreversible. The core with smaller permeability would have a greater irreversible permeability loss. (3) The content of clay mineral in Z-1, Z-2 and Z-3 are 15%, 22%, and 26% respectively (as shown in Table 1). The results showed that the higher content of clay mineral meant a higher stress sensitivity.

In general, the maximum degree of permeability damage in the rocks of this reservoir was median to very strong and irreversible damage level was weak to strong.

5. Results and Conclusions

(1) Chang 7 reservoir in the Zhenbei area had high contents of clay minerals; the main compositions of these were illite-smectite mixed layer and chlorite, illite and kaolinite only took up a small proportion of them.

(2) The reservoir porosity and permeability were negatively correlated to the total content of clay minerals. Kaolinite and chlorite were advantageous to reservoir porosity and permeability, illite and I-S were not good for them.

(3) The water, salt, alkali, speed sensitive were weak in Chang 7 reservoir in the Zhenbei area, and acid sensitive was weak to strong; the maximum degree of permeability damage in the rocks of this reservoir was median to very strong and irreversible damage degree was weak to strong.

(4) Since the reservoir heterogeneity, sensitivities of each well might be different in Chang 7 reservoir of the Zhenbei area. So it should be treated separately for each well when implementing acidification or other technological measures. Taking all sensitives into consideration, water with low salinity or high alkaline did not have severe impacts on permeability but acid fluid might

change it significantly, so weak alkaline substance could be added to protect the reservoir when fluids are injected for some technological measures. In the course of water flooding, considering the ability of wellhead pressure bearing and the formation fracture pressure, it could properly use a high injection rate. During production, it should select a consistent production pressure and control the bottom-hole pressure so that the damage degree of the stress-sensitivity to the reservoir would be reduced and the oil production would be kept.

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