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Study on Sensitivity Evaluation and Mechanism of Offshore Fluvial Reservoir

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Abstract: ***The CFD oilfield is located in the western waters of the Bohai Sea, and the reservoir rock types are mainly lithic feldspar sandstone, followed by feldspar lithic sandstone, belonging to high porosity to medium high permeability reservoirs. During the process of water injection development, the production capacity of oil wells continues to decline. The effect of injecting water to increase oil is poor. This study conducted rock mineralogical analysis such as casting thin sections and scanning electron microscopy based on on-site data. Through core experiments, the sensitivity of the reservoir was evaluated, and data analysis showed that clay minerals damage the reservoir in the form of swelling, particle transport, etc. Theoretically, the damage mode of clay minerals to the oil reservoir was analyzed. Provide a basis for the development of similar oil fields.***

Keywords: The CFD oilfield, Sensitivity, Clay minerals, Reservoir damage, Experiment.

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1. Introduction

The practice of oilfield development shows that in the process of oilfield development, it may damage the oil and gas reservoir, reduce the reservoir's productivity, and even wholly lose the production capacity of oil and gas wells. It would also affect the discovery of new oil and gas reserves. It causes significant losses to oilfield development, so reservoir protection is a subject that must be studied in the oilfield, and the most important thing to protect the reservoir is to find out the possible damage types and degree of the reservoir, to take corresponding countermeasures. In the study of reservoir damage evaluation, reservoir sensitivity evaluation is one of the essential means [1-5].

Reservoir sensitivity evaluation includes two aspects. One is to evaluate the sensitive mineral characteristics of the reservoir from the perspective of petrographic analysis and study the potential damage factors of the reservoir. Second, based on petrographic analysis, select representative samples for sensitivity experiment, and evaluate the damage degree of working fluid to the reservoir by measuring the change of permeability before and after rock contact with various external working fluids [6-10].

Once the oil and gas industry was born, there must be the problem of formation damage. Since the 1950s, reservoir protection technology has been studied. In recent years, reservoir protection technology has attracted more and more attention from oil-producing countries. Many large oil companies have set up particular institutions to study reservoir damage. Bishop S. R. combined with the content of clay minerals in the reservoir, the existing state of clay minerals in the reservoir is divided into ten cases in detail, and the formation damage index (FDI) is proposed. Hatcher G. B. summarized the data of about 4000 wells worldwide and obtained the comparative law and ranking of formation damage severity in various downhole operations. R. N. valdya explained the effects of value and ion exchange on particle migration and reservoir damage. It is considered that low salinity and high ion conditions do great harm to reservoir permeability and are easy to cause particle migration and strong formation damage. The Daqing Oilfield has carried out sensitivity research on satellite oilfield, transition zone in Sazhong area, formation zero siltstone, and other reservoirs from the aspects of petrography. At the same time, due to the further improvement of petrographic diagnosis technology. The application of microsimulation visible technology, development and scanning technology, nuclear magnetic resonance scanning imaging technology, applied physical model, and numerical simulation method. The migration of solid particles, the invasion depth of particles, the movement state of the fluid, and the changes of reservoir permeability with time, fluid properties, and flow velocity are studied. Gradually deepen the understanding of oil and gas reservoir damage and the evaluation of damage degree. It has made some new developments in reservoir protection technology in recent years [11-18].

However, due to the complex nature of oil and gas reservoirs, the influencing factors often change. Therefore, there are still many problems to be studied and solved. To ensure the oilfield's effective development, formulate a reasonable adjustment scheme, water injection scheme, measure direction, and conduct reservoir sensitivity flow experimental analysis and evaluation.

2. 2The reservoir physical properties

2.1 Porosity and permeability characteristics

According to core data statistics, the maximum value of reservoir porosity is 38.0%, the minimum value is 8.1%, and the average value is 27.8%. It is mainly distributed above 25.0%, and some are distributed between 15% - 25%. The maximum reservoir permeability is 6055.1mD, min. 5.1mD, with an average of 469.8mD, mainly distributed in 50mD -2000mD. The reservoir belongs to a high porosity medium-high permeability reservoir.

2.2 Clay mineral composition

92 thin-section samples of The CFD oilfield are analyzed. The reservoir rock type is mainly lithic arkose, followed by feldspathic lithic sandstone (see Figure 1).

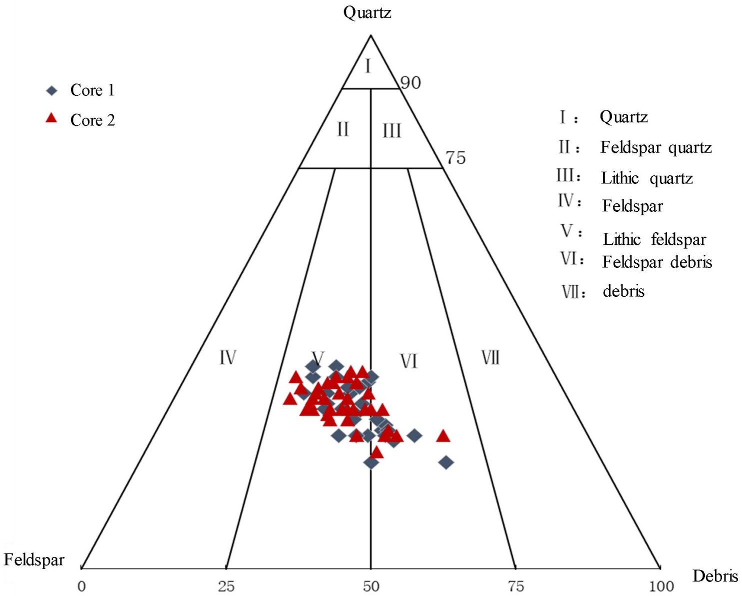


Figure 1: The CFD oilfield rock type diagram

Cast thin-section data show that the overall sorting of rock debris particles is mainly medium, followed by weak medium; The clastic grain size is mainly medium grain, followed by fine grain and a small amount of coarse grain. The particle contact relationship is multi-point and point line contact, the cementation type is mainly pore type, feldspar weathering is medium, and a small amount is a weak medium.

SEM data show that the pores in feldspar grains are developed. The intergranular pores are filled with authigenic quartz, scaly kaolinite, spherical pyrite, silk flocculent smectite, illite, and rock salt; Vermicular kaolinite, honeycomb smectite, and illite smectite mixed layer can be seen on the particle surface.

2.3 Formation water properties

The formation water of The CFD oilfield is high salinity formation water, the chloride ion content is 1974 ~ 3600mg/L, the average value is 2655mg/L, the total salinity is 5205~7107mg/L, the average value is 5675mg/L, and the water type is $NaHCO_3$.

3. Study on reservoir damage mechanism

Sensitivity evaluation experiments are divided into single-phase velocity sensitivity evaluation experiment, water sensitivity evaluation experiment, acid sensitivity evaluation experiment, alkali sensitivity evaluation experiment, and stress sensitivity evaluation experiment. The experimental method is shown in Figure 2.

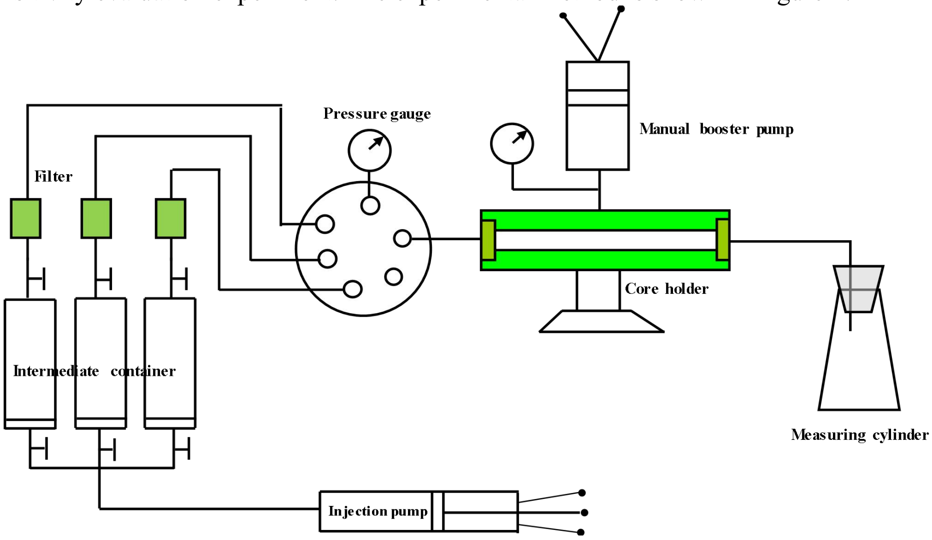


Figure 2: Schematic diagram of sensitivity test

18 sensitive samples were analyzed, and the experimental results are shown in Table 5. Because the pore structure and rock minerals of different samples are different, the experimental results of sensitivity evaluation are slightly different.

Table 1: Analysis results of the CFD oilfield reservoir sensitivity evaluation

Analysis project	Sample No	Permeability damage rate %	Degree of damage	empirical conclusion
Speed sensitivity	1-013F	118.8	strong	Critical velocity: 0.1mL/min
	2-007F	569.31	strong	Critical velocity: 0.1mL/min
	3-023F	60.6	Medium to strong	Critical velocity: 0.1mL/min
Water sensitivity	1-013H	77.97	strong	Critical salinity: 2500mg/L
	2-007H	63.47	Medium to strong	Critical salinity: 1600mg/L
	3-023H	74.47	strong	Critical salinity: 1500mg/L
Acid sensitivity	1-013D	22.93	weak	/
	2-007D	19.61	weak	/
	3-023D	21.32	weak	/
Alkali sensitivity	1-013E	71.2	strong	Critical pH：8.5
	2-007E	54.6	Medium to strong	Critical pH：11
	3-023E	39.78	Moderately weak	Critical pH：10
Stress sensitivity	1-013C	91.7	strong	/
	2-007C	73.2	strong	/
	3-023I	52.8	Medium to strong	/

4. Study on reservoir sensitivity mechanism

Clay minerals in rocks are one of the reasons for reservoir sensitivity [19]. Due to the different types, contents, and occurrence of clay minerals, they have different sensitivity to external fluids, resulting in different forms and degrees of formation damage. Therefore, the focus of reservoir sensitivity mechanism research is the study of clay minerals in the reservoir; On this basis, combined with the physical property characteristics of the reservoir, we can more clearly understand the damage caused by reservoir sensitivity to the reservoir [20].

4.1 Reservoir rock mineralogical analysis

4.1.1 Rock composition and structural characteristics

92 cast thin sections were analyzed. The overall sorting of rock debris particles is mainly medium, followed by the weak medium. The debris particle size is mainly medium, followed by fine particles and a small number of coarse

particles. The particles are mainly sub-circular sub-prismatic, followed by sub-prismatic sub-circular. The particle contact relationship is multi-point and point line contact, the cementation type is mainly pore type, feldspar weathering is medium, and a small amount is a weak medium.

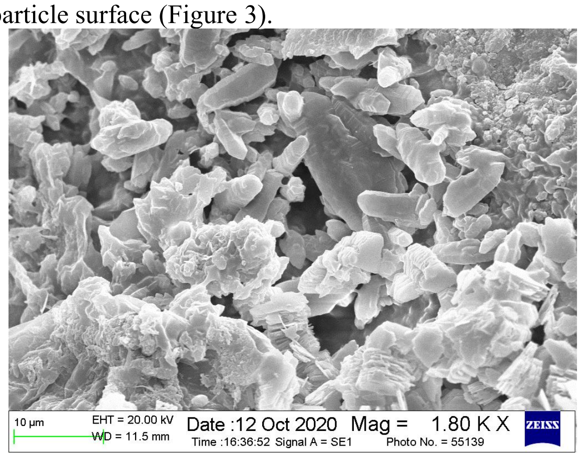
(1). Quartz is the main component of framework particles, with a content of 20%-38%.

(2). Feldspar: it is another main component of framework particles, with a content of 25% - 48%. Plagioclase content is 3% - 19%; The content of potassium feldspar is between 18% - 40%.

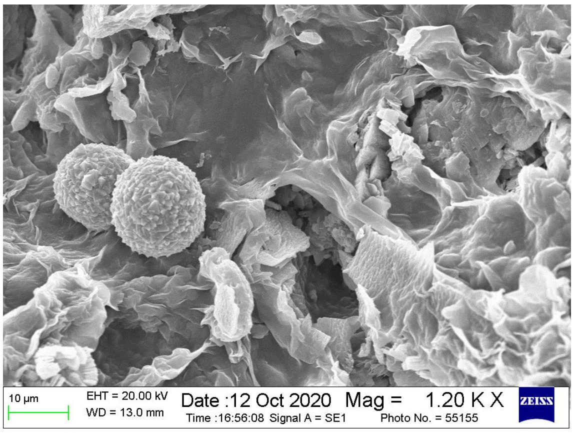
(3). Rock debris is the main component of framework particles, with a content of 19% - 53%. The rock block assemblage is mainly metamorphic rock and magmatic rock block, with a small sedimentary rock block. The content of metamorphic rock blocks is between 5% - 28%; The content of magmatic rock blocks is between 5% - 28%; The content of sedimentary rock blocks is between 1% - 6%. Metamorphic rock is quartzite, magmatic rock is extrusive acid rock, sedimentary rock is mudstone, and a small amount of mica can be seen.

(4). Interstitial materials: intergranular interstitial materials are mainly siderite, pyrite, kaolinite, and argillaceous, with kaolinite content of 2%-26%, argillaceous content of 1%-27%, siderite content of 1-7%, pyrite content of 1%-11%, calcite content of 1%-2%, iron calcite content of 1%-15%, dolomite content of 1%-4% and iron dolomite content of 0.5%-5%.

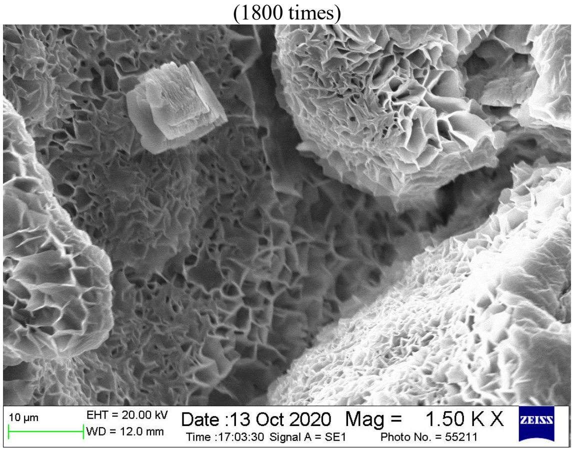
92 times of SEM analysis showed that the pores in feldspar grains were developed, and the intergranular pores were filled with authigenic quartz, flake and page kaolinite, spherical pyrite, dolomite, flocculent smectite, illite, and halite; Vermicular and scaly kaolinite, honeycomb smectite and illite smectite mixed layer can be seen on the particle surface (Figure 3).



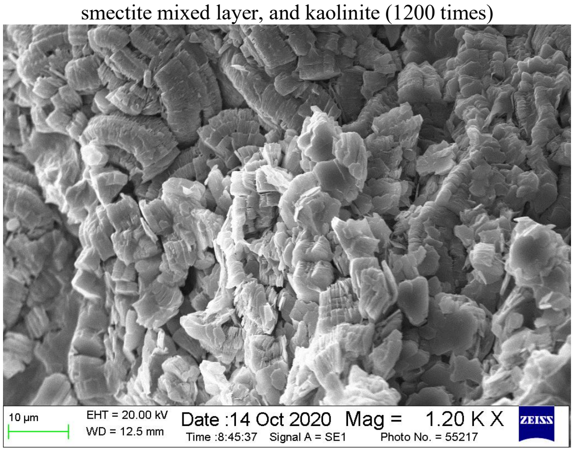
Authigenic quartz, halite, illite, and kaolinite fill intergranular pores (1800 times)



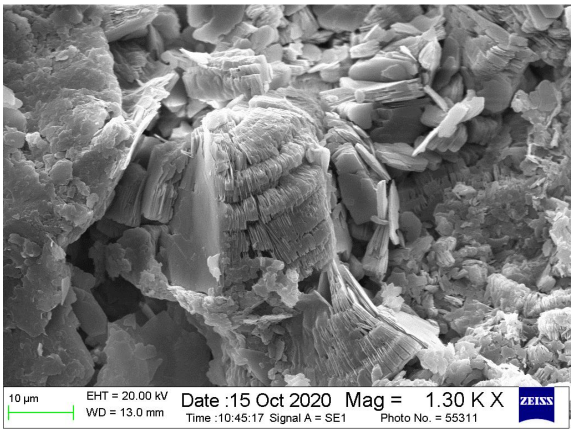
Intergranular pores filled with spherical pyrite, silk flake illite, smectite mixed layer, and kaolinite (1200 times)



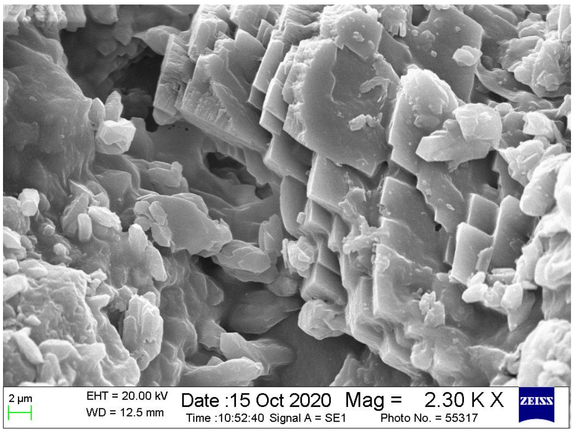
Honeycomb smectite and scaly kaolinite fill intergranular pores (1500 times)



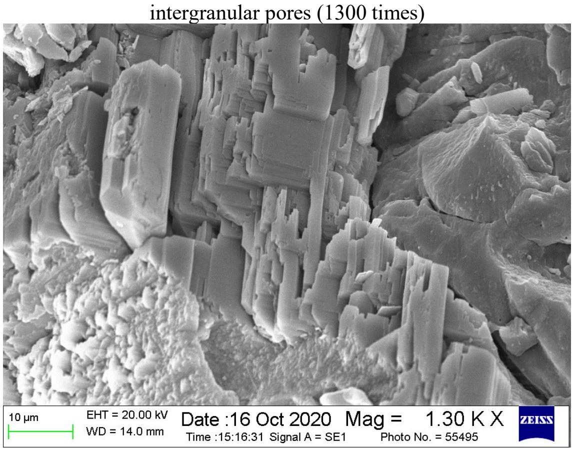
The mixed layer of scaly kaolinite, illite, and smectite fills intergranular pores, and the stone fills intergranular pores (1200 times)



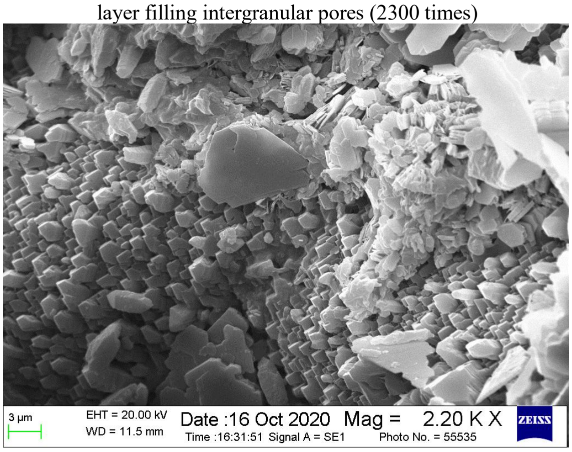
Book leaf kaolinite and illite smectite mixed layer filling intergranular pores (1300 times)



Authigenic quartz, dolomite, kaolinite, illite, and smectite mixed layer filling intergranular pores (2300 times)



Feldspar dissolution along cleavage (1300 times)



Authigenic quartz, scalelike kaolinite, and illite smectite mixed layer filling intergranular pores (2200 times)

Figure 3: SEM chart of the reservoir

The clay minerals of rock debris samples were analyzed. Through the systematic analysis of clay minerals in the sample (Table 2), the content of S% in I/S is between 50%-85%.

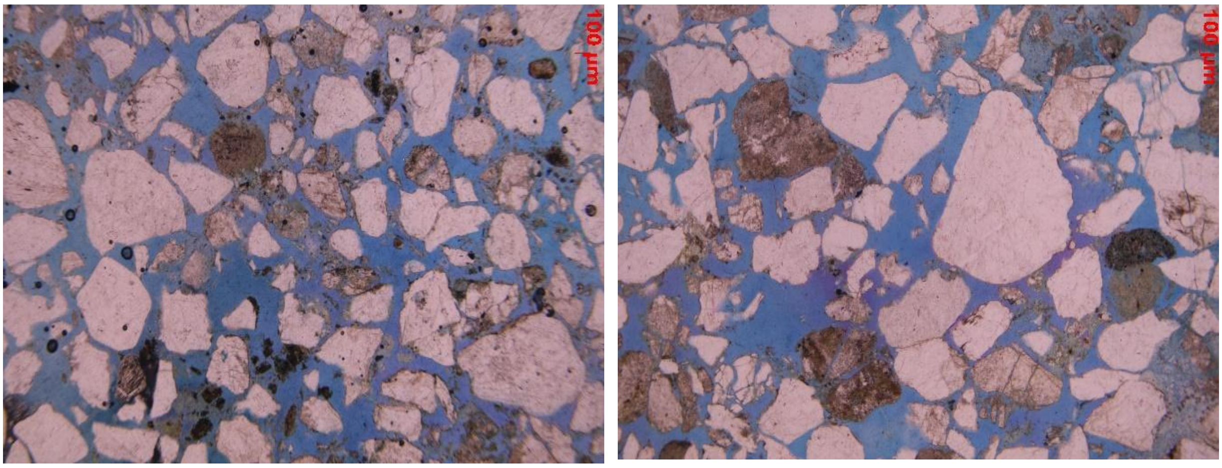
Table 2: Statistical table of clay mineral analysis data

Serial number	Clay mineral content (%)						Illite smectite mixed layer ratio	
	Smectite	Illite	kaolinite	Chlorite	Illite smectite mixed layer	Chlorite smectite mixed layer	Smectite	Illite
	S	I	K	C	I/S	C/S	S%	I%
1	0	3	77	3	17	0	50	50
2	0	3	73	3	21	0	50	50
3	0	2	78	5	15	0	50	50
4	0	2	78	3	17	0	55	45
5	0	2	26	4	68	0	85	15
6	0	2	13	1	84	0	85	15
7	0	1	6	1	92	0	85	15
8	0	1	25	3	71	0	85	15
9	0	1	12	2	85	0	85	15
10	0	1	5	2	92	0	85	15
11	0	1	6	2	91	0	85	15
12	0	1	26	2	71	0	85	15
13	0	7	37	10	46	0	65	35
14	0	6	35	5	54	0	70	30
15	0	5	50	6	39	0	65	35
16	0	6	40	5	49	0	70	30
17	0	11	76	3	10	0	50	50
18	0	4	69	3	24	0	60	40
19	0	14	73	4	9	0	15	85
20	0	7	82	3	8	0	15	85
21	0	5	74	3	18	0	65	35

22	0	2	49	6	43	0	75	25
23	0	3	81	3	13	0	60	40
24	0	3	86	2	9	0	50	50
25	0	5	85	3	7	0	50	50
26	0	4	85	3	8	0	50	50
27	0	6	88	3	3	0	50	50
28	0	7	79	4	10	0	60	40

4.1.2 Compaction

With the increase of burial depth, the contact relationship of clastic particles does not change significantly (Figure 4). Therefore, according to the existing analysis data, the compaction of the well has a weak impact on the reservoir.

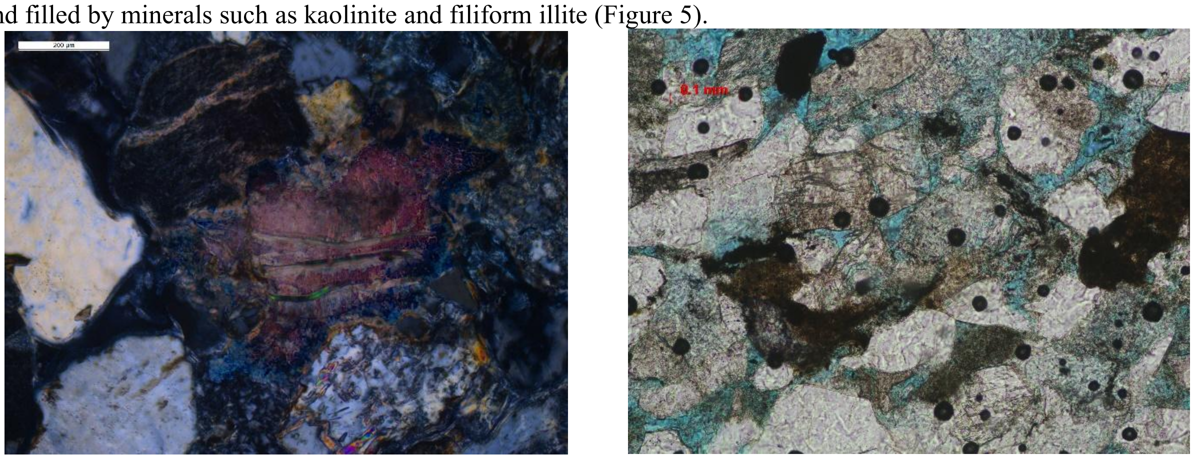


Line point contact (2.5 times) Line point contact (2.5 times)

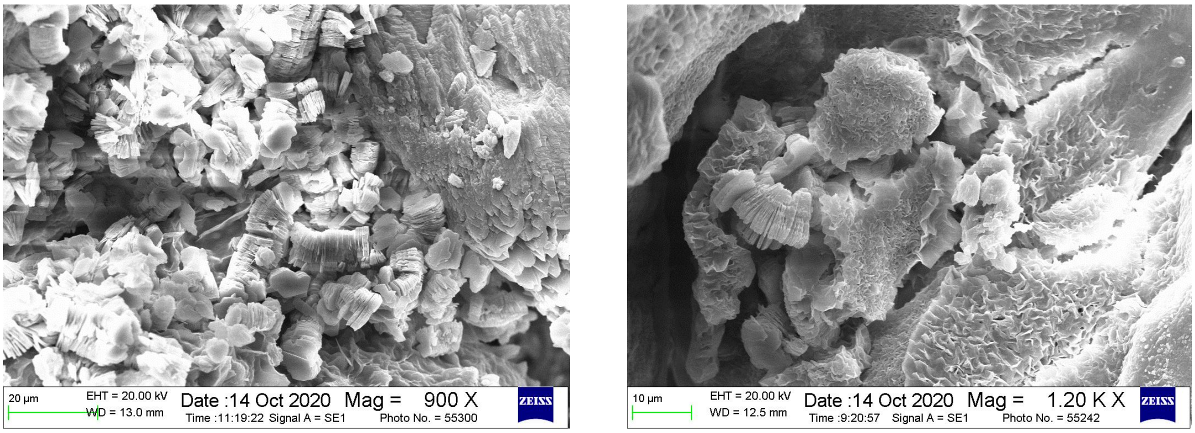
Figure 4: The reservoir rock compaction chart

4.1.3 Cementation

Cementation is mainly siderite, pyrite, kaolinite, calcite, dolomite, and argillaceous. Argillaceous recrystallization is distributed among particles in flake shape, kaolinite is distributed in Millet shape, and siderite and pyrite are distributed in block shape. Under the electron microscope, it can be seen that the intergranular pores are cemented and filled by minerals such as kaolinite and filiform illite (Figure 5).



Calcite cementation (10 times) Argillaceous cementation (10 times)



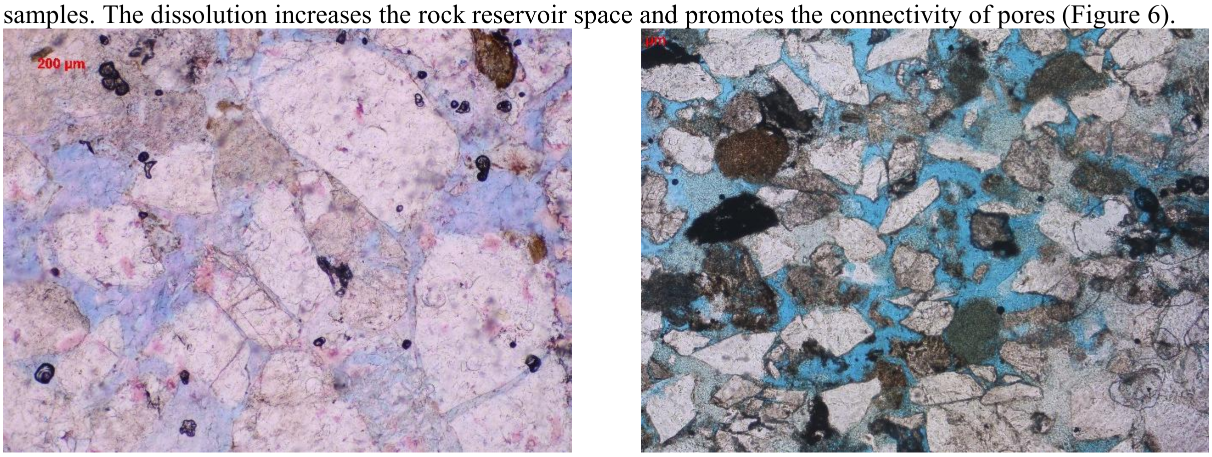
Filling intergranular pores with scaly kaolinite (900 times)

Silk flocculent smectite, illite smectite mixed layer, and book leaf kaolinite fill intergranular pores (1200 times)

Figure 5: Plate of rock cementation

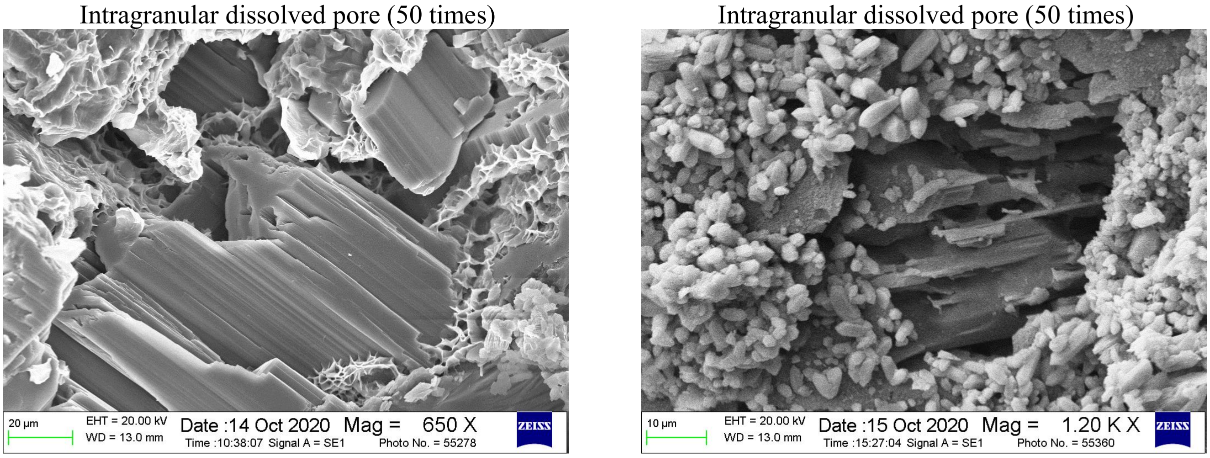
4.1.4 Dissolution

Through thin section observation and electron microscope analysis of existing samples, intergranular dissolution pores and feldspar dissolution pores are found in the well section's rock thin section and electron microscope samples. The dissolution increases the rock reservoir space and promotes the connectivity of pores (Figure 6).



Intragranular dissolved pore (50 times)

Intragranular dissolved pore (50 times)



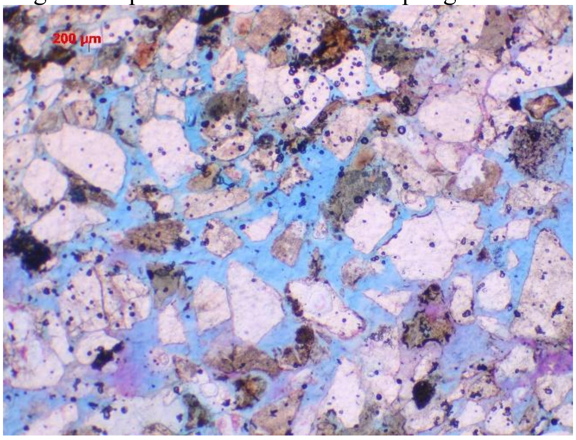
Feldspar dissolution, silk flocculent smectite, and illite smectite mixed layer filling intergranular pores (650 times)

Feldspar leaching corrosion hole, with authigenic quartz around (1200 times)

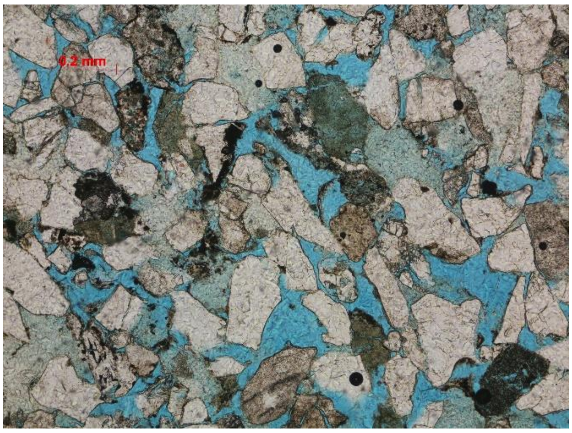
Figure 6: The reservoir dissolution chart

4.1.5 Reservoir space

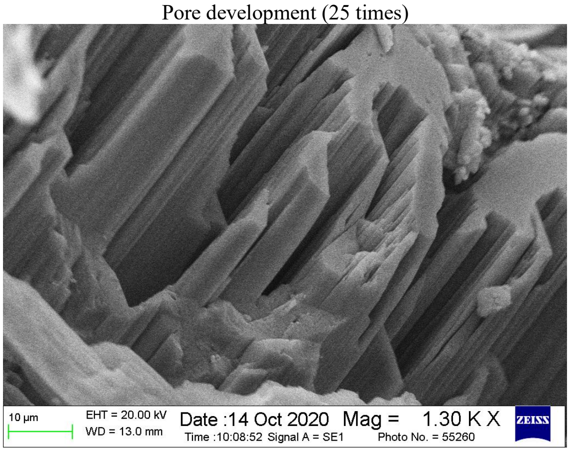
The primary lithology is clastic rock. According to the thin cast section and scanning electron microscope analysis, the rock pores in the reservoir analysis section of the well are well developed. The pore types are intergranular pores, a small amount of dissolution intergranular pores, and dissolution granular pores (Figure 7). The dissolution of granular pores can be seen in feldspar grains.



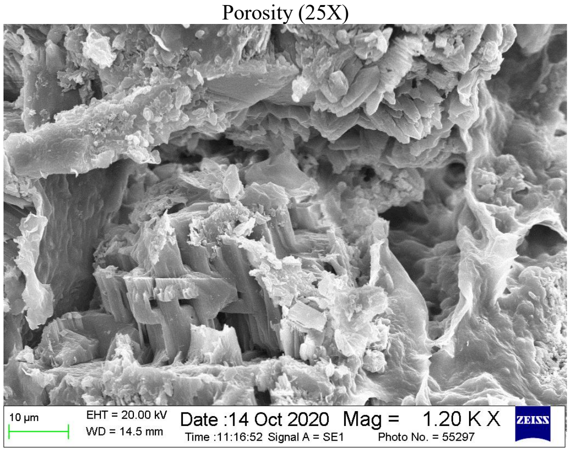
Pore development (25 times)



Porosity (25X)



Feldspar leaching and dissolution (1300 times)

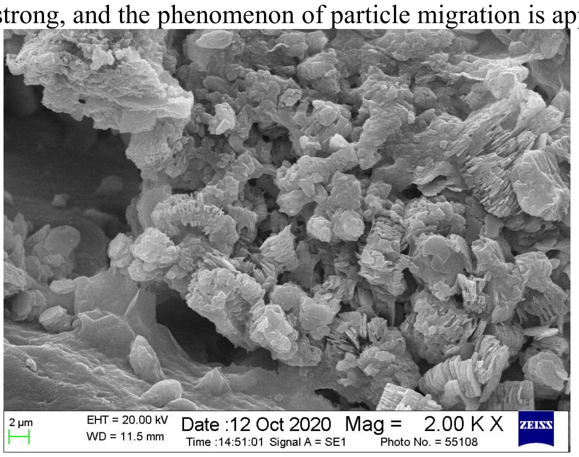


Feldspar dissolution is strong (1200 times)

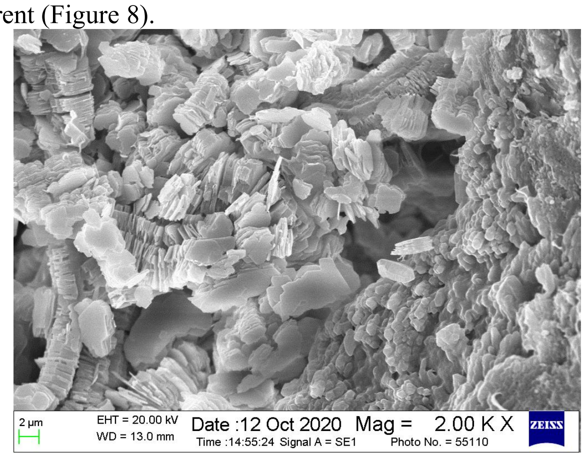
Figure 7: Pore plate

4.1.6 Velocity sensitivity mechanism

Kaolinite and bridged illite are the main clay minerals that can cause velocity sensitivity. They fall off and migrate particles under fluid ground scouring, resulting in pore throat blockage. The rock contains the above two clay minerals, in which the content of kaolinite in clay minerals is as high as 5% ~ 88%, with an average of 54%, and the intergranular pores are filled in the form of interstitial materials. The illite content in clay minerals is 1% ~ 14%, with an average of 4% . When the fluid flows at high speed in the rock core, illite can easily be broken into fragments and block the pore throat with the fluid migration. Therefore, the velocity sensitivity is medium to strong, and the phenomenon of particle migration is apparent (Figure 8).



Scale kaolinite, authigenic quartz, and filamentous illite fill intergranular pores (2000 times)



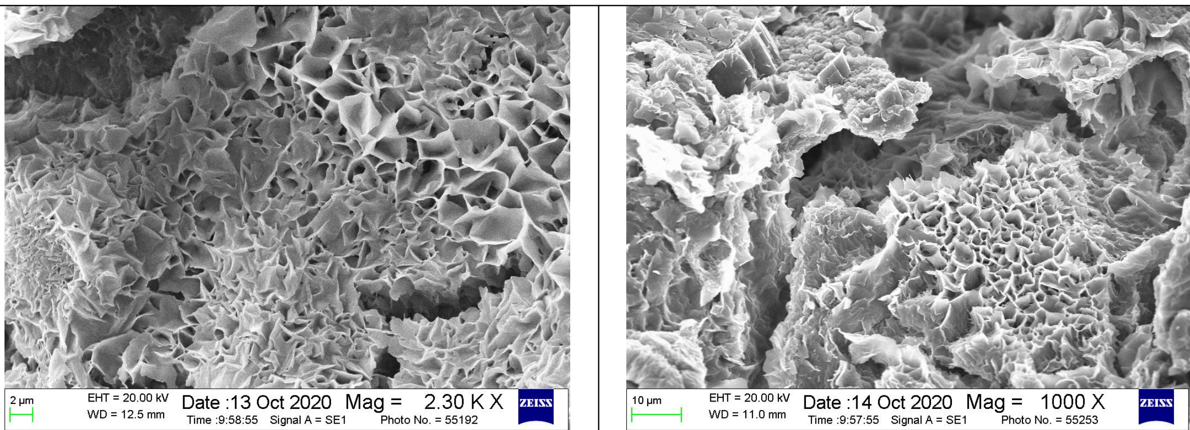
Scaly kaolinite, halite, and illite filler Interstitial porosity (2000 times)

Figure 8: Speed sensitivity mechanism

4.2 Water sensitivity mechanism

The water-sensitive minerals in clay minerals are smectite, illite, kaolinite, and interlayer minerals. When these clay minerals are in contact with incompatible water, they expand, fall off and migrate, blocking the pore throat . According to the properties of clay minerals, their ability to expand with water is smectite > interlayer minerals > illite > kaolinite.

Illite smectite mixed layer is the most common type of mixed clay mineral. Generally speaking, the illite smectite mixed layer has the reservoir sensitivity of illite and montmorillonite. It has a strong expansion rate and cation exchange capacity and is easy to adsorb many polar water molecules, resulting in the volume expansion of clay minerals, blocking the throat, and damaging the reservoir. The relative content of the illite smectite mixed layer in this area is 3% ~ 92%, with an average of 38%. And in the illite smectite mixed layer, the smectite content reaches 50% - 85%. At the same time, honeycomb smectite can be seen on the particle surface (Figure 9). CFD reservoir shows strong water sensitivity.



Honeycomb smectite can be seen on the particle surface(2300 times)	Silk flake illite smectite mixed layer, honeycomb smectite, and dolomite fill intergranular pores (1000 times)

Figure 9: Water sensitivity mechanism

4.3 Acid sensitivity mechanism

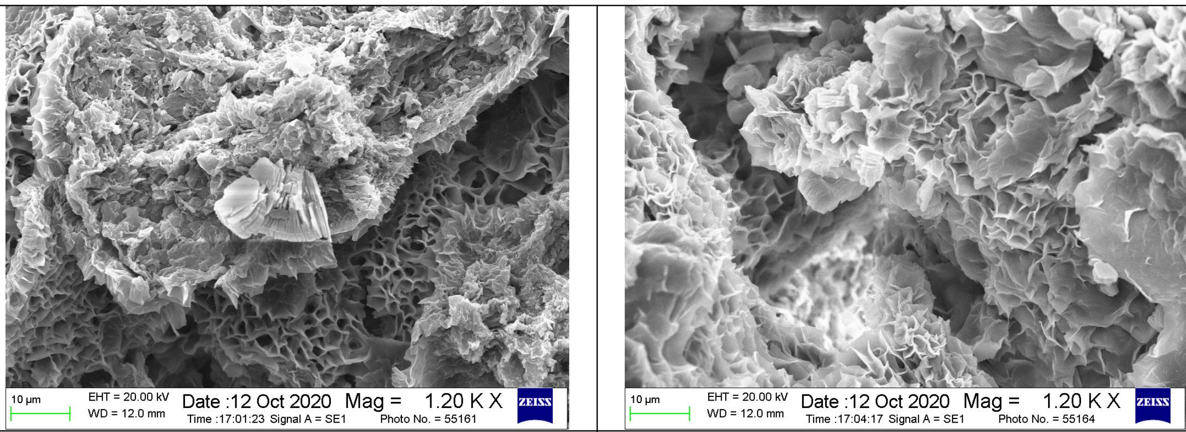
Chlorite in clay minerals is extremely sensitive to acid. Clay minerals react with acid to form precipitation, which is not easy to flow, blocking the pore throat and causing damage (Changjun et al. 2006).

The hydrochloric acid sensitivity evaluation test shows weak sensitivity because the chlorite content in clay minerals is 1% ~ 10%, with an average of 3% (Table 6), and the content is negligible.

4.4 Alkali sensitivity mechanism

All clay minerals are sensitive to lye. There are three alkali sensitivity mechanisms: (1) under the action of alkali solution, clay minerals undergo cation exchange, which enhances the water sensitivity of clay, mainly manifested in the conversion of Ca smectite to Na smectite, which is easier to hydrate and expand. (2) OH radicals would neutralize cations on the clay surface, destroy the charge balance, and cause particle migration. (3) Alkali solution can dissolve clay minerals (such as kaolinite) and quartz-rich in silicon, resulting in the increase of soluble silicon concentration in the solution and the generation of silicon colloidal precipitation.

Honeycomb smectite, illite smectite mixed layer, and scaly kaolinite fill intergranular pores in this area (Figure 10). At the same time, the relative content of the pure illite smectite mixed layer is 3% ~ 92%, with an average of 38%. Under the action of alkali solution, clay minerals undergo cation exchange, which enhances the water sensitivity of clay and makes it easier to hydrate and expand. The kaolin content in clay minerals is as high as 5% ~ 88%, with an average of 54%. Kaolinite can be dissolved in alkali solution, increasing soluble silicon concentration in the solution and colloidal silicon precipitation. The pore throat radius is minimal for low permeability samples, and silicon colloid precipitation blocks the pore throat, resulting in strong sensitivity. For samples with relatively high permeability, the pore throat radius is significant, and a small amount of sediment can not block the pore throat, and its sensitivity is medium to weak sensitivity.



Honeycomb smectite and scaly kaolinite fill intergranular pores (1200 times)	Honeycomb smectite, illite smectite mixed layer, and scaly kaolinite fill intergranular pores (1200 times)

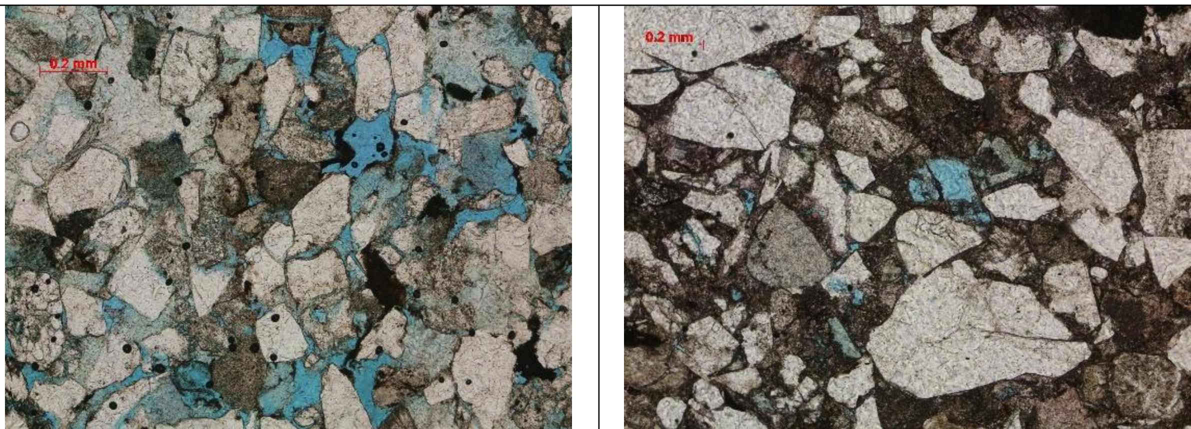
Figure 10: Alkali sensitivity mechanism

4.5 Stress sensitivity mechanism

All clay minerals are sensitive to stress. Because clay minerals are layered silicate minerals, their stable existence depends on the electrostatic attraction of unit wafer and interlayer cations. When external stress exists, clay minerals are stressed, and electrostatic attraction is destroyed, resulting in particle migration (Figure 11). During the stress sensitivity test, the stress would rise and fall.

The compressibility of clay minerals and the narrowing of the pore throat under stress lead to the decrease of permeability in the process of stress rise. When discussing the narrowing of the pore throat under stress, the contact relationship of particles should be considered. If line contact is the primary contact, it is greatly affected by external stress; The pore throat dominated by point contact is less affected by external force due to the mutual support of particles. According to the identification results of rock slices, the rock particles in the coring section are mainly in point contact, especially in the formation with relatively large permeability value; In the formation with relatively small local permeability, the rock particles are in line contact and locally in line contact.

In depressurization, due to the reduction of external stress, under the influence of reaction force, the reaction force of compressed clay minerals is greater than the electrostatic attraction between layers, resulting in particle migration, blocking the throat, reducing and irreversible recovery of permeability. The stress sensitivity of the reservoir is medium to strong.



Rock debris particles are mainly in line point contact with each other and locally in concave-convex contact	Strong compaction reduces pore space and throat connecting pores and even causes pores and throat to disappear

Figure 11: Stress sensitivity mechanism

5. Conclusions

(1) The reservoir rock type of the CFD oilfield is mainly lithic arkose, followed by feldspathic lithic sandstone. According to core data statistics. The maximum value of reservoir porosity is 38.0%, the minimum value is 8.1%, and the average value is 27.8%. It is mainly distributed above 25.0%, and some are distributed between 15.0%-25.0%. The maximum value of reservoir permeability is 6055mD, the minimum value is 5mD, and the average value is 470mD, mainly distributed between 50mD and 2000mD. The reservoir belongs to a high porosity medium-high permeability reservoir.

(2) The clay minerals in the reservoir of the CFD oilfield mainly include kaolinite, illite, and smectite mixed layer. The kaolinite content in clay minerals is as high as 5%~88%, with an average of 54%; The relative content of illite smectite mixed layer is 3%-92%, with an average of 38%. Intergranular filler mainly includes siderite, pyrite, kaolinite and argillaceous, with kaolinite content of 2%-26%, argillaceous content of 1%-27%, siderite content of 1-7%, pyrite content of 1%-11%, calcite content of 1%-2%, iron calcite content of 1%-15%, dolomite content of 1%-4% and iron dolomite content of 0.5%-5%. SEM analysis shows that the pores in feldspar grains are developed, and the intergranular pores are filled with authigenic quartz, flake and page kaolinite, spherical pyrite, dolomite, flocculent smectite, illite, and halite; Vermicular and scaly kaolinite, honeycomb smectite and illite smectite mixed layer can be seen on the particle surface.

(3) The reservoir sensitivity of the CFD oilfield shows medium to strong-very strong velocity sensitivity, strong water sensitivity, weak acid sensitivity, medium to weak - very strong alkali sensitivity and medium to strong - strong stress sensitivity. The occurrence and location of clay minerals are the main reasons for reservoir sensitivity.

(4) Due to the strong water sensitivity of the reservoir in the CFD oilfield, during water injection production, the salinity of injection water should be controlled to be greater than 4500mg/L, and the compatibility between injection water and formation and between injection water and formation water should be evaluated. The reservoir of the CFD oilfield is weak acid sensitive so that acidizing operation can be considered. The stress sensitivity is medium to strong. If energy is not supplemented during oilfield development, the net overburden pressure would increase too much. At this time, energy supplements would cause irreversible loss of permeability. Therefore, the timely supplement of formation energy would reduce formation damage.

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