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Experimental Study on Enhanced Oil Recovery by Carbonated Water Flooding in Ultra-Low Permeability Sandstone Reservoirs

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Abstract

Ultra-low permeability sandstone reservoirs represent a crucial replacement resource for petroleum in China. However, due to extremely low reservoir permeability and severe fluid channeling, conventional development methods yield a recovery factor of less than 30%, posing significant challenges. While CO_2 flooding is a key enhanced oil recovery (EOR) technology for such reservoirs, it faces limitations including gas channeling, high minimum miscibility pressure (MMP), and water blocking effects. Carbonated water flooding (CWF), as a novel EOR technique, had not been systematically studied for ultra-low permeability reservoirs prior to this research. This study focuses on ultra-low permeability sandstone with a permeability of less than 0.3×10^{-3} μm^2. Core flooding experiments were conducted to comparatively analyze the oil recovery performance of carbonated water flooding, CO_2 Water-Alternating-Gas (CO_2-WAG) injection, surfactant flooding, and a combined carbonated water-surfactant flooding. Additionally, Scanning Electron Microscopy (SEM) was employed to investigate the impact of carbonated water on reservoir minerals and pore structure. The displacement experiment results demonstrate that carbonated water flooding increased the recovery factor by 6.43% compared to water flooding, significantly outperforming CO_2-WAG (5.33%) and surfactant flooding (3.39%). The combined carbonated water-surfactant flooding exhibited the best performance, enhancing recovery by 10.58% relative to water flooding, indicating a synergistic effect. Studies on mineral and pore structure evolution reveal that carbonated water induces selective dissolution of clay minerals, carbonate minerals, and silicate minerals. Kaolinite, illite, ankerite, and quartz are prone to dissolution, facilitating pore enlargement. In contrast, chlorite shows strong resistance to dissolution. Dissolution products from calcite, mica, and feldspar are prone to secondary precipitation, leading to pore-throat blockage. The research confirms the favorable applicability and feasibility of carbonated water flooding in ultra-low permeability sandstone reservoirs, providing a novel technical pathway and theoretical foundation for enhancing oil recovery in such reservoirs.

Keywords

Ultra-low Permeability Sandstone Reservoirs, Carbonated Water Flooding, Enhanced Oil Recovery, Mineral Dissolution, Pore Structure, Synergistic Effect.

1. Introduction

Ultra-low permeability reservoirs, serving as a critical replacement resource for stabilizing onshore petroleum production in China, possess substantial geological reserves (e.g., tens of billions of tons in the Ordos Basin). [1]However, their development is consistently challenged by low pressure levels, low recovery factors (mostly below 30%), and high operational difficulty[2][3]. Due to the extremely low matrix permeability (typically <1 mD) and the development of natural/artificial fractures, injected fluids are prone to channeling. Conventional water flooding struggles to establish an effective displacement front, leaving significant residual oil trapped in micro-nano pores and unable to be effectively mobilized.

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Currently, CO_2 flooding is a key technology for enhancing oil recovery in such reservoirs, but it faces notable limitations: susceptibility to gas channeling and gravity segregation, resulting in low sweep efficiency; high minimum miscibility pressure (MMP) between CO_2 and crude oil, making complete miscibility difficult to achieve in ultra-low permeability formations[4][5]; and exacerbation of water blocking effects, which further reduces displacement efficiency. These issues significantly constrain the effectiveness of CO_2 flooding in ultra-low permeability reservoirs[6].

Carbonated water flooding (CWF) is a method that involves dissolving a certain amount of CO_2 into water under specific temperature and pressure conditions and then injecting the mixture into the formation for oil displacement[7]. The primary mechanisms for enhanced oil recovery during CWF include the transfer of CO_2 from the aqueous phase to the oil phase, leading to oil swelling, viscosity reduction, connection of isolated oil droplets, and mitigation of water blocking effects[8]. Adding surfactants to carbonated water can reduce oil-water interfacial tension, promote the transfer of CO_2 from the aqueous to the oil phase, and improve reservoir wettability[9].

To date, research on carbonated water flooding has focused only on medium-high permeability and low-permeability reservoirs. Therefore, it is highly important and urgent to conduct CWF studies specifically targeting ultra-low permeability sandstone reservoirs. This study focuses on reservoirs with permeabilities below 0.3×10^{-3} μm^2. Through a series of laboratory core flooding experiments-including water flooding, carbonated water flooding, CO_2 water-alternating-gas (WAG) injection, surfactant flooding, and combined carbonated water-surfactant flooding on tight cores-the potential of CWF for enhancing oil recovery in tight reservoirs is clarified, and the feasibility of applying this method in such reservoirs is verified.

2. Laboratory Core Flooding Tests

The objective of the laboratory core flooding tests is to clarify the efficiency of carbonated water flooding in ultra-low permeability sandstone reservoirs, and to compare it with conventional water injection methods, thereby evaluating the oil recovery enhancement effect of the carbonated water flooding technique. This study designed a total of 4 comparative experimental groups, including carbonated water flooding, CO_2 water-alternating-gas (WAG) injection, surfactant flooding, and combined carbonated water-surfactant flooding. The experiments were conducted under reservoir conditions (average experimental pressure: 16 MPa, temperature: 60°C).

2.1. Experimental Apparatus

The experimental apparatus is a simulation system for carbonated water flooding in ultra-low permeability sandstone reservoirs (Fig. 1), which comprises five main systems: fluid injection, constant temperature control, core holding, back-pressure control, and oil/gas/water measurement.

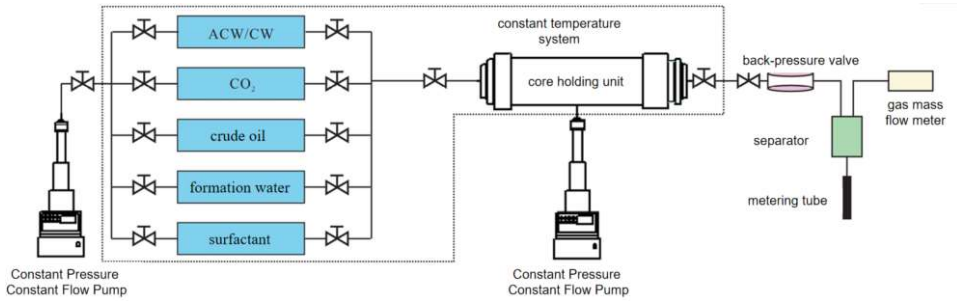

Fig. 1 Apparatus Flow Diagram

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2.2. Experimental Procedure

Four sets of displacement experiments were conducted, including carbonated water flooding (CWF), CO_2 water-alternating-gas (WAG) injection, surfactant flooding (SF), and combined carbonated water-surfactant flooding (CW+SF). After saturating the core with crude oil, water flooding was first performed with 1.5 pore volumes (PV) of water to establish residual oil saturation. Subsequently, the aforementioned displacement experiments were carried out. Following the water flooding stage, for the surfactant flooding, carbonated water flooding, and combined carbonated water-surfactant flooding experiments, 2.5 PV of the respective displacing fluid was injected. For the CO_2 WAG experiment, a total of 5 cycles were performed, with each cycle injecting 0.03 PV of CO_2 followed by 0.03 PV of water. After the alternating injection, formation water injection continued until a total injection volume of 4 PV was reached. The surfactant concentration was 0.1 wt%, and the carbonated water concentration was 0.4 mmol/cm^3. As the pore volume of the cores used in each experiment varied slightly, to ensure comparability, the experimental parameters were set under the condition that the ratio of injected CO_2 volume to pore volume remained identical for the three methods involving CO_2 (CWF, CO_2 WAG, and CW+SF). Furthermore, to maintain consistent injection rates across all experiment groups, the injection rate at the inlet end was uniformly set at 0.1 mL/min.

2.3. Experimental Results

The core parameters and experimental results for the four test groups are summarized in Table 1. Since residual oil saturation had been established after water flooding, a lag effect of approximately 0.5 PV was observed in the subsequent displacement phases for all cases. Fig. 2(a) illustrates the variation in oil recovery during the surfactant flooding stage following water flooding. The recovery factor during the water flooding stage was 30.01%, which increased to 33.40% during the surfactant flooding stage, representing a 3.39% enhancement relative to water flooding. The presence of surfactant reduces oil-water interfacial tension and improves wettability, thereby facilitating crude oil mobility. However, based on the experimental results, the incremental recovery achieved through surfactant flooding alone was relatively modest.

Table 1. Results of the core displacing experiment

Core Parameters and Experimental Results	SF	CWF	WAG	CW+SF
Core No.	1-1	1-2	1-3	1-4
Length (cm)	5.1	5.2	5.05	5.08
Diameter (cm)	2.5	2.5	2.5	2.5
Permeability (10^{-3} μm^2)	0.15	0.18	0.16	0.17
Porosity (%)	14.53	13.72	14.11	13.27
Water Flooding Recovery (%)	30.01	30.10	29.56	29.55
Ultimate Recovery (%)	33.40	36.53	34.89	40.13
Recovery Increment (%)	3.39	6.43	5.33	10.58

The variation in oil recovery during carbonated water flooding following water flooding is illustrated in Fig. 2(b). The recovery factor during the water flooding stage was 30.10%, which increased to 36.53% during the carbonated water flooding stage, representing an enhancement of 6.43% relative to water flooding. As mentioned earlier, during carbonated water flooding, CO_2 dissolved in the injected water transfers into the oil phase. This process leads to crude oil volume expansion, viscosity reduction, connection of isolated oil droplets, and mitigation of the water blocking effect, thereby improving oil recovery.

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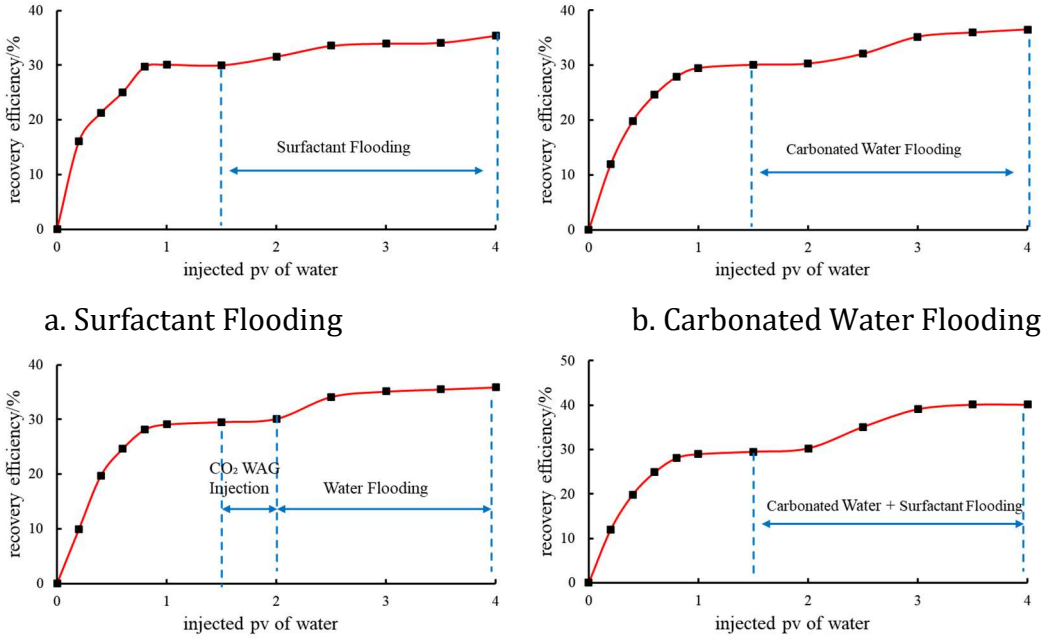

a. Surfactant Flooding b. Carbonated Water Flooding

c.CO_2 WAG Injection d.Carbonated Water + Surfactant Flooding

Fig. 2 Results of Core Flooding Experiment

Fig. 2(c) shows the variation in oil recovery during CO_2 water-alternating-gas (WAG) injection after water flooding. The recovery factor during the water flooding stage was 29.56%, which increased to 34.89% during the CO_2 WAG stage, representing a 5.33% enhancement relative to water flooding. The primary mechanisms for the improved oil recovery in WAG injection are attributed to the CO_2 in the gas slugs, which causes oil swelling, viscosity reduction, and extraction, thereby enhancing displacement efficiency. The water slugs help control mobility and stabilize the displacement front to improve the sweep efficiency of the gas phase. However, compared to carbonated water flooding, the CO_2 WAG method yielded a lower incremental recovery. The reasons are as follows: during WAG injection, the direct injection of gas results in lower sweep efficiency; whereas in carbonated water flooding, the CO_2 is dissolved in the injection water, leading to higher sweep efficiency. Under the condition of the same injected CO_2 volume, carbonated water flooding delivers better oil recovery performance.

The variation in oil recovery during combined carbonated water-surfactant flooding after water flooding is shown in Fig. 2(d). The recovery factor during the water flooding stage was 29.55%, which increased to 40.13% during the combined flooding stage, representing a significant enhancement of 10.58% relative to water flooding. The incremental oil recovery from the combined carbonated water-surfactant flooding exceeds the sum of the improvements achieved by carbonated water flooding and surfactant flooding individually. The reason lies in the synergistic combination of the advantages from both methods. The surfactant not only reduces oil-water interfacial tension but also facilitates the transfer of CO_2 from the aqueous phase (carbonated water) into the oil phase, promoting oil swelling and viscosity reduction, which collectively leads to superior recovery performance.

From the four sets of comparative experiments on carbonated water flooding, it can be concluded that carbonated water flooding is a feasible method for enhancing oil recovery in tight reservoirs. Carbonated water flooding increased recovery by 6.43% compared to water flooding and by 1.10% compared to CO_2 WAG injection. Under the condition of injecting an equivalent amount of CO_2, the oil recovery improvement from carbonated water flooding is significantly better than that from CO_2 WAG injection. The combined carbonated water-surfactant flooding increased recovery by 10.58% relative to water flooding, which is higher

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than the sum of the individual improvements from carbonated water flooding and surfactant flooding. The main reason is that the combined method integrates the advantages of both techniques: the surfactant not only reduces oil-water interfacial tension but also promotes the transfer of CO_2 from the aqueous phase to the oil phase, allowing more CO_2 to enter the oil phase and thereby increasing oil recovery.

3. Study on the Influence of Carbonated Water on Sandstone Properties under Reservoir Conditions

The experimental rock samples were obtained from the ultra-low permeability sandstone reservoirs of the Yanchang Formation in the Ordos Basin. The original rock samples were first cut into experimental cores. After cleaning and measuring basic pore-permeability properties, rock slices with a thickness of approximately 0.2 cm were cut and polished for scanning electron microscopy (SEM) experiments.

3.1. Experimental Equipment and Methodology

The prepared rock slices were subjected to carbonated water-rock reaction experiments according to the experimental plan. Before the experiment, the surface microstructure of the rock slices was observed and recorded using SEM. Subsequently, the carbonated water-rock reaction experiments were conducted following these specific steps:

(1) Place the rock slice at the bottom of the reaction vessel, inject carbonated water into the reaction vessel using a displacement pump until it is fully filled, and then pressurize the vessel to the predetermined pressure of 10 MPa using the displacement pump. Afterward, close all gas inlet and sampling lines.

(2) Use the internal heating device of the reaction vessel to heat it to the predetermined experimental temperature of 45°C and maintain it for 48 hours, allowing the reaction to proceed under the designed temperature and pressure conditions for the predetermined duration.

(3) After the experiment, remove the rock slice and dry it at 105°C until a constant weight is achieved, recording the weight. Finally, conduct SEM scanning on the reacted rock slice.

Table 2. Physical Properties of Experimental Cores

Core No.	Diameter (cm)	Length (cm)	Permeability (10^{-3} μm^2)	Porosity (%)
A	2.45	5.46	0.99	9.92
B	2.45	5.45	0.46	13.04
C	2.44	5.69	0.08	16.72
D	2.50	5.87	0.48	12.62
E	2.48	5.96	0.004	13.31
F	2.49	5.85	0.004	11.47

3.2. Results and Analysis

3.2.1. Clay Minerals

After subjecting core samples to carbonated water immersion experiments under specific temperature and pressure conditions, significant differences in the dissolution behavior of clay minerals among different core samples were observed by comparing scanning electron microscopy (SEM) images before and after immersion. Taking cores C, D, and F as examples, their clay minerals are primarily composed of chlorite, with relatively lower contents of kaolinite and illite. The experimental results show that chlorite underwent partial dissolution, with most of the detrital material attached to its surface being completely dissolved. However,

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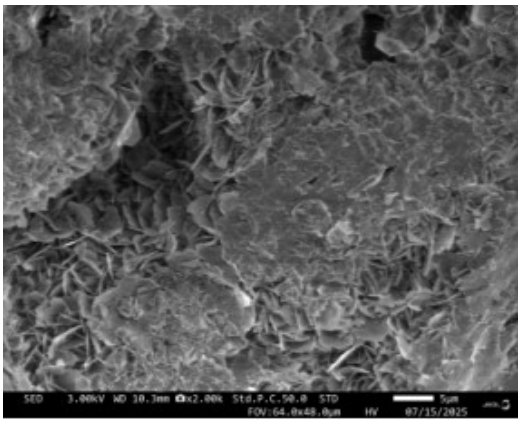
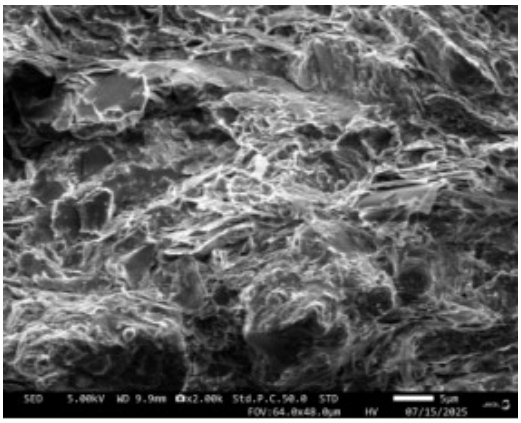
some chlorite crystals remained largely unaffected. In contrast, kaolinite and illite exhibited complete dissolution.

This phenomenon indicates that during the carbonated water-rock interaction, chlorite demonstrates higher resistance to dissolution compared to kaolinite and illite. Its crystal structure retains a certain degree of stability under acidic fluid conditions, whereas kaolinite and illite are more readily dissolved and removed by the fluid. Further comparison of the permeability and mineral dissolution characteristics of different samples reveals that cores with lower permeability typically have higher chlorite content, and chlorite dissolution is more extensive during carbonated water immersion. This suggests that in low-permeability reservoirs, chlorite is not only the main clay mineral component but also a key mineral influencing pore structure evolution.

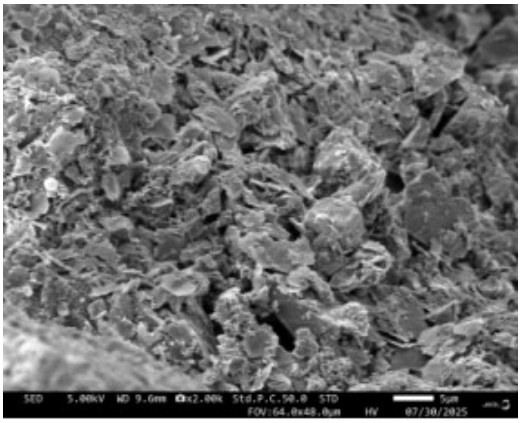
From the perspective of reservoir properties, the complete dissolution of kaolinite and illite can, to some extent, remove pore-filling materials, contributing to the release of pore space and the improvement of connectivity. In contrast, the partial dissolution of chlorite may lead to adjustments in the pore-throat structure, resulting in an increase in pore volume but limited changes in throat size, thereby affecting the extent of permeability enhancement. Therefore, the differential dissolution process of clay minerals under carbonated water conditions plays a crucial controlling role in the evolution of pore structures in low-permeability reservoirs.



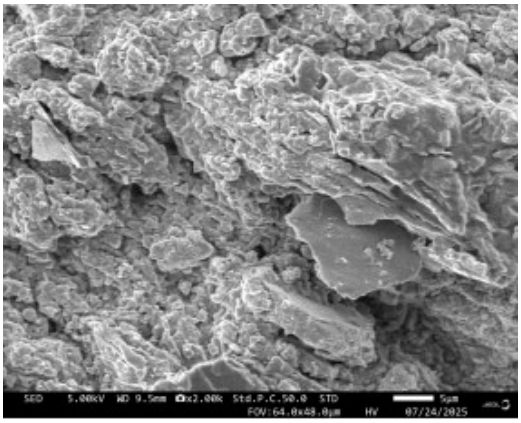
a. Chlorite before immersion



b. Mica and Illite before immersion



c. Chlorite after immersion



d. Mica and Illite after immersion

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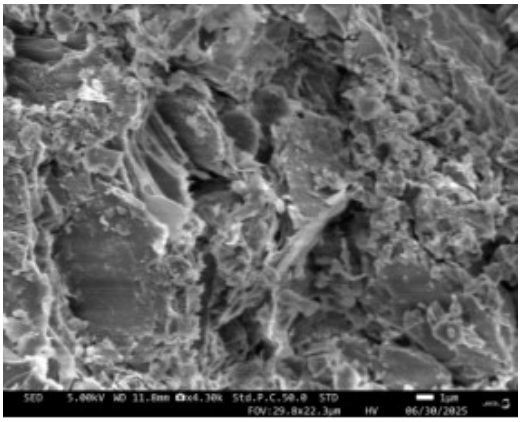
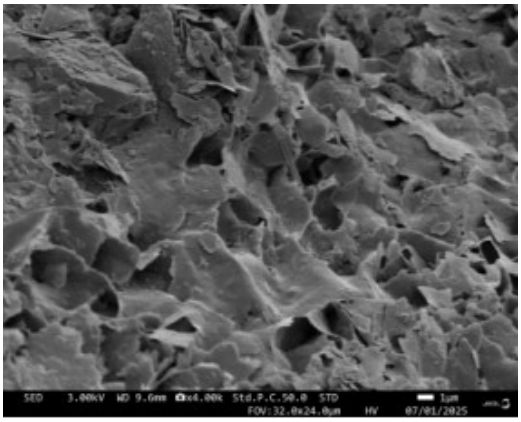
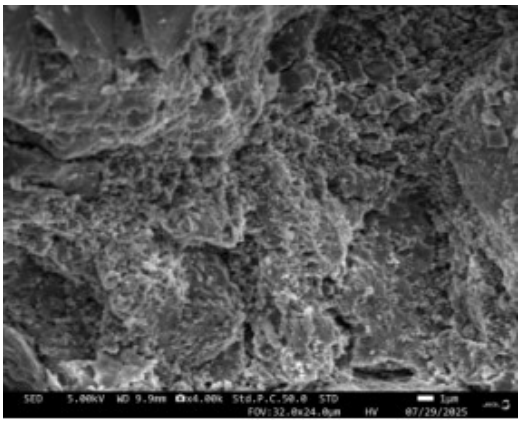


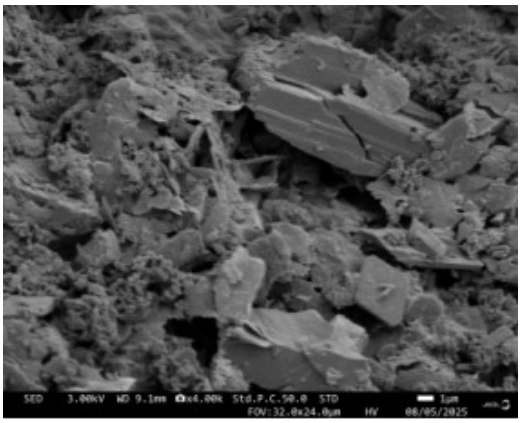
e. Quartz intergrown with Kaolinite before immersion



f. Honeycombed Illite before immersion



g. Quartz intergrown with Kaolinite after immersion



h. Honeycombed Illite after immersion

Fig. 3 Changes in Clay Minerals Before and After Carbonated Water Immersion

3.2.2. Carbonate Minerals

After subjecting core samples to carbonated water immersion experiments under specific temperature and pressure conditions and comparing scanning electron microscopy (SEM) images before and after immersion, significant differences in the dissolution and pore evolution characteristics of carbonate minerals among different core samples were observed. Taking cores E, A, B, and C as examples, their carbonate minerals are predominantly calcite, with relatively lower contents of iron-magnesium dolomite.

SEM images reveal that iron-magnesium dolomite (e.g., ankerite) underwent significant dissolution after carbonated water immersion. The detrital particles attached to its surface were essentially completely removed, and new pores appeared at the dissolution sites, leading to a localized increase in porosity. In contrast, although calcite is the major component and also underwent intense dissolution under carbonated water, its dissolution products-consisting largely of rock fragments and clay precipitates-re-deposited within the original intergranular pores and intragranular dissolution pores. This resulted in secondary clogging of the pore structure, consequently causing an overall decreasing trend in porosity.

These results indicate that different types of carbonate minerals respond differently to carbonated water. Iron-magnesium dolomite is relatively more soluble and can effectively enlarge pore space, contributing positively to porosity enhancement. However, calcite, as the primary mineral, although capable of generating new pores in the short term during dissolution, tends to produce fragments and clay materials that readily deposit within pores, thereby diminishing or even negating the pore improvement effect. Further comparison of permeability differences shows that calcite is mainly concentrated in cores with higher permeability, such as

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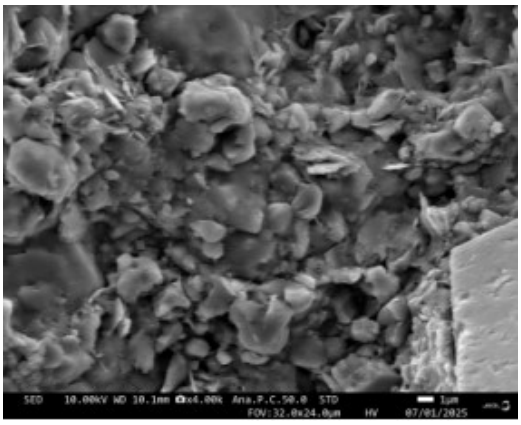
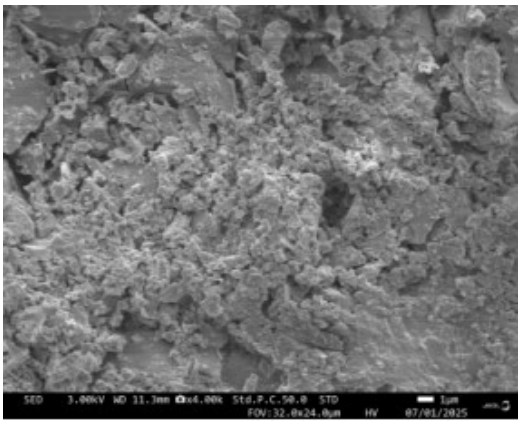
A and B, whereas carbonate mineral content is significantly lower in cores with lower permeability. This suggests a certain correlation between the distribution of carbonate minerals and reservoir permeability.

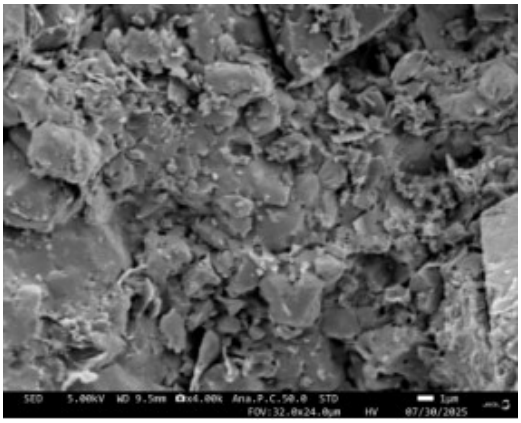
The dissolution of iron-magnesium dolomite is beneficial for improving pore structure and enhancing local storage space. In contrast, the dissolution of calcite and its secondary precipitation negatively impact reservoir properties, potentially leading to a decline in both porosity and permeability. Overall, the carbonated water-rock interaction process exhibits a dual effect on reservoir properties. At the mineralogical level, the removal of soluble components and the generation of new pores contribute to the expansion of reservoir space. Simultaneously, however, the deposition and clogging effects of dissolution products may reduce pore connectivity. Therefore, the content and distribution characteristics of carbonate minerals are key factors controlling the evolution of properties in low-permeability reservoirs.



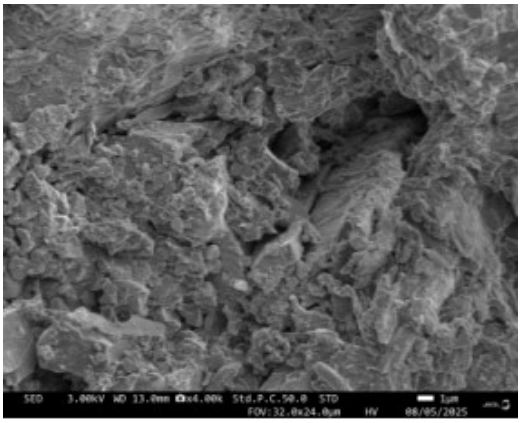
a. Iron-Magnesium Dolomite (e.g., Ankerite) Before Immersion



b. Iron-Magnesium Dolomite (e.g., Ankerite) Before Immersion



c. Iron-Magnesium Dolomite (e.g., Ankerite) after Immersion



d. Iron-Magnesium Dolomite (e.g., Ankerite) after Immersion

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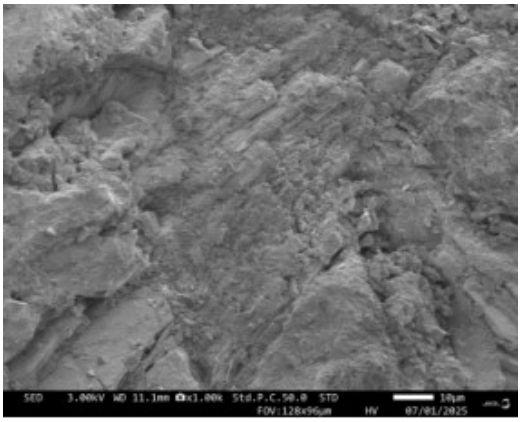
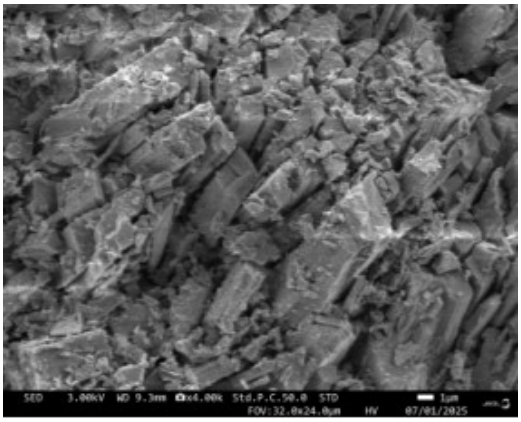
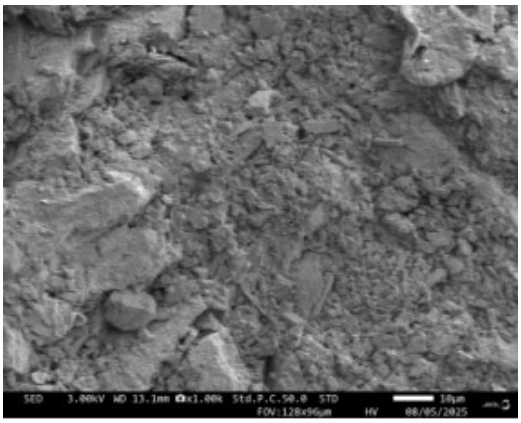

e. Calcite before immersion


f. Calcite before immersion


g. Calcite after immersion

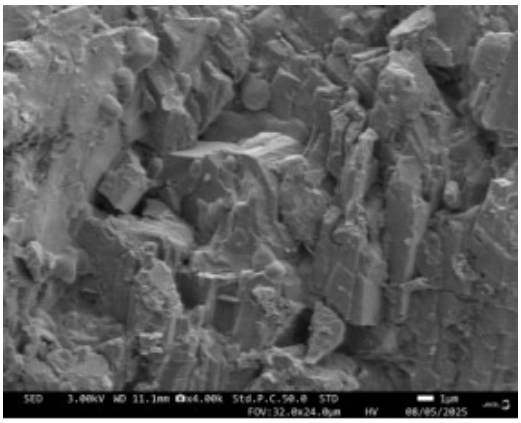

h. Calcite after immersion

Fig. 4 Changes in Carbonate Minerals Before and After Carbonated Water Immersion

3.2.3. Silicate Minerals

SEM image comparisons of core samples before and after carbonated water immersion experiments under specific temperature and pressure conditions reveal significant differences in the dissolution and pore evolution characteristics of silicate minerals among different core samples. Taking cores A, C, and E as examples, their silicate minerals are primarily composed of quartz, mica, and feldspar.

SEM images show that secondary quartz underwent noticeable dissolution during carbonated water immersion, with attached detrital particles on its surface being largely completely removed, and new pores formed at the dissolution sites. Some primary quartz also exhibited dissolution features, forming secondary dissolution pores. In contrast, mica in cores with different permeabilities showed varying degrees of dissolution under carbonated water, with the dissolution intensity increasing with higher permeability. It should be noted that the dissolution products of mica mainly consist of rock fragments and clay materials, which re-deposited within the original intergranular and intragranular dissolution pores, leading to secondary pore clogging and an overall decreasing trend in porosity. Additionally, potassium feldspar also underwent significant dissolution after immersion. However, its dissolution products similarly deposited as fragments and clay precipitates on mineral surfaces and within pores, offering limited improvement to the pore structure.

These results indicate that different silicate minerals respond distinctly to carbonated water. Quartz dissolves in the acidic environment, forming new pores and contributing to a localized increase in porosity. Although the dissolution of mica and potassium feldspar can release local space, their dissolution products are difficult to migrate and readily deposit and clog within pores, thereby diminishing the actual effectiveness of porosity enhancement. Furthermore, permeability differences also control mineral dissolution intensity, as mica dissolution is more

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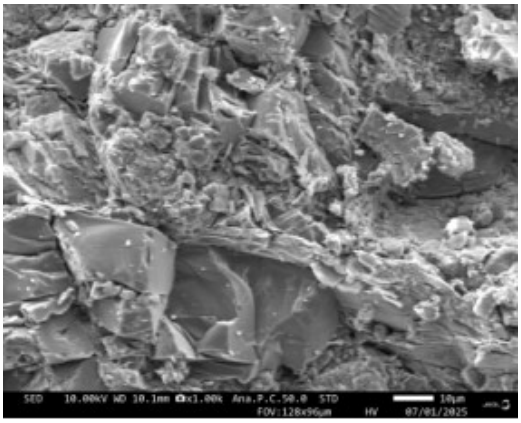
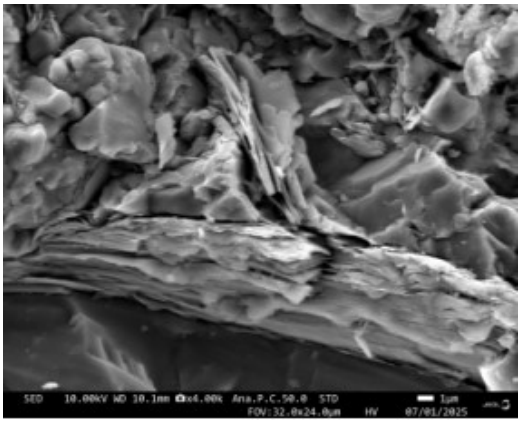
pronounced in high-permeability cores, indicating that pore fluid migration conditions directly influence the reactivity of silicate minerals.

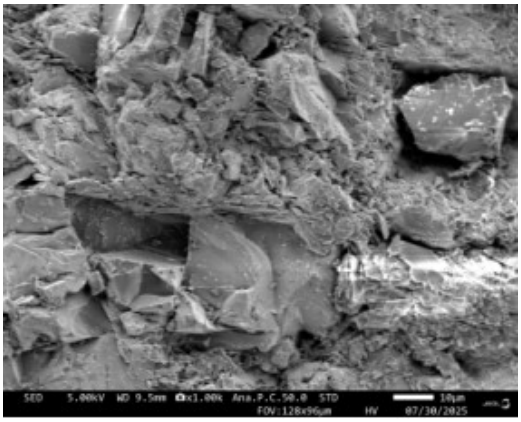
The differential dissolution of silicate minerals exhibits a dual effect on the evolution of reservoir properties. On one hand, the dissolution of quartz and potassium feldspar can generate new secondary pores, improving local storage space. On the other hand, the deposition of dissolution products from mica and feldspar can damage pore connectivity and even lead to an overall decrease in porosity. In summary, the dissolution of silicate minerals under carbonated water and the migration-deposition processes of their products are important factors controlling pore structure evolution and property differences in low-permeability reservoirs.



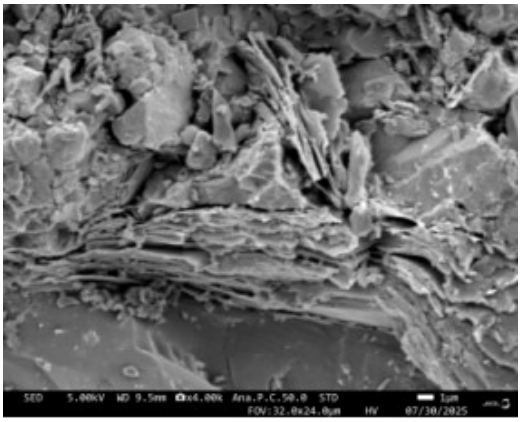
a. Secondary Quartz before immersion



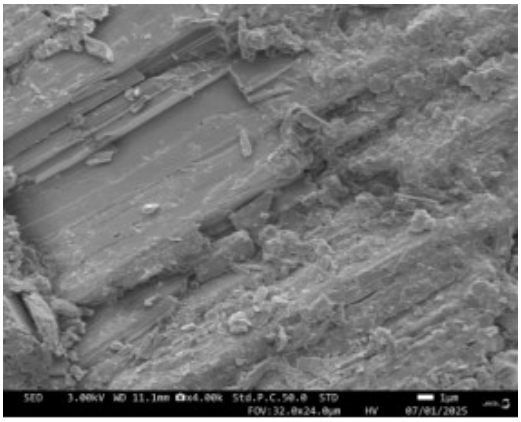
b. Mica Before immersion



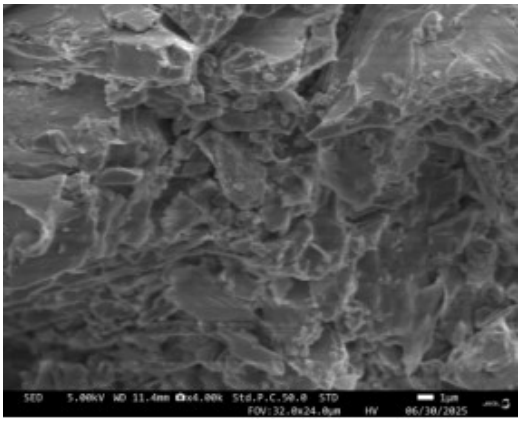
c. Secondary Quartz after immersion



d. Mica Before immersion



e. Potassium feldspar before immersion



f. Quartz before immersion

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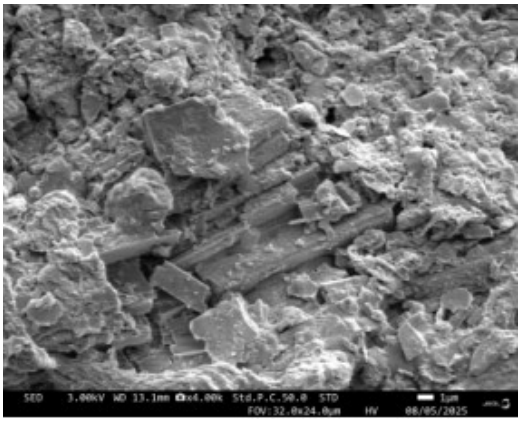
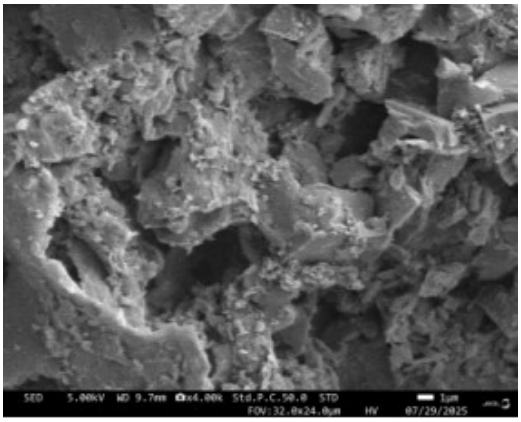


g. Potassium feldspar after immersion



h. Quartz after immersion

Fig. 5 Changes in Silicate Minerals Before and After Carbonated Water Immersion

3.2.4. Pore Volume

SEM image comparisons of core samples before and after carbonated water immersion experiments under specific temperature and pressure conditions reveal varying degrees of change in the pore volume of six representative cores. After immersion, detrital particles within intergranular pores and residual intergranular pores in the cores exhibited clear dissolution features. In most pores, the dissolution of detrital particles led to an increase in pore volume, more regular pore morphology, and improved local connectivity. However, in a minority of pores, fine fragments and clay precipitates generated from the dissolution of detrital particles re-deposited within the pores, causing pore-throat clogging and resulting in an actual decrease in pore volume.

The results indicate that during the carbonated water-rock reaction, the dissolution of detrital minerals has a dual effect. On one hand, the dissolution of detritus can release pore space, form new pores, or enlarge existing ones, contributing to the improvement of storage capacity. On the other hand, the deposition and clogging of dissolution products within pores can weaken the enhancement of porosity and permeability, or even damage the local pore structure. The variations observed among different core samples are primarily controlled by pore structure characteristics and fluid migration conditions. Cores with more developed pore-throats facilitate the expulsion of dissolution products, manifesting as increased porosity. In contrast, samples with narrower pore-throats or poorer connectivity are more prone to secondary deposition and clogging.

Overall, carbonated water immersion subjects the core pore structure to a composite process of "enlargement and clogging." Most pores experience volume increase due to detrital dissolution, positively impacting reservoir storage performance. However, localized pores may become clogged due to secondary deposition, potentially impairing pore connectivity and limiting permeability improvement. Thus, the evolution of pore structure under carbonated water action exhibits significant heterogeneity, and its impact on reservoir properties is characterized by the dual features of capacity enhancement and potential damage coexisting.

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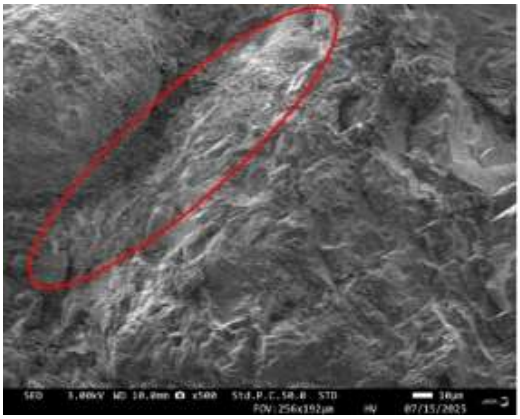
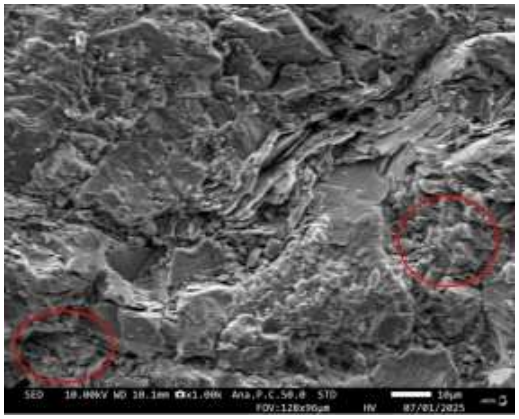
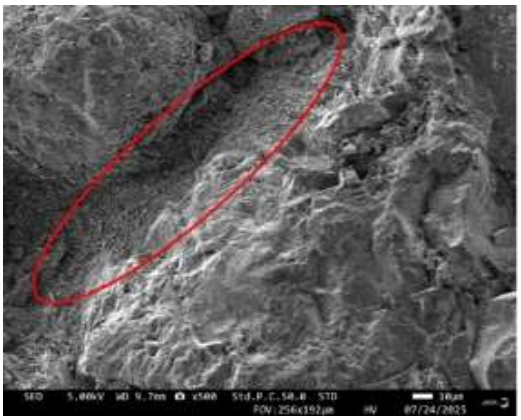
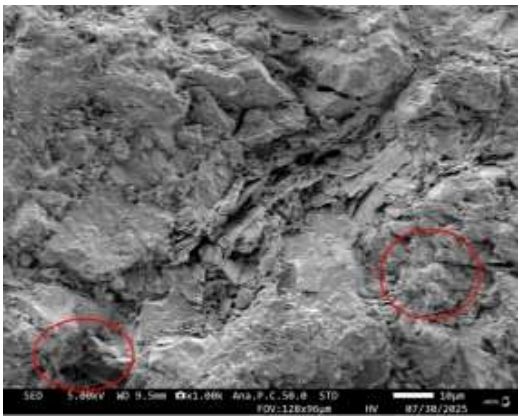
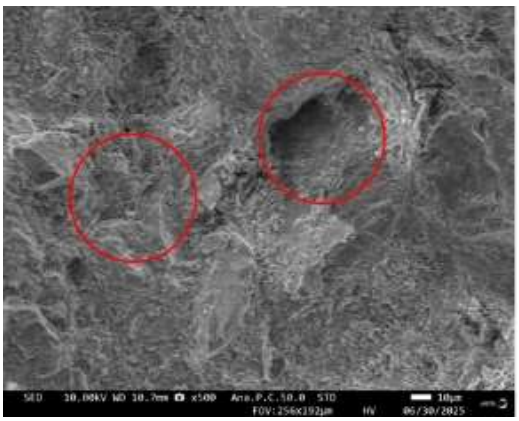

a. before immersion


b. Before immersion


c. after immersion


d. Before immersion


e. before immersion


f. before immersion


g. after immersion

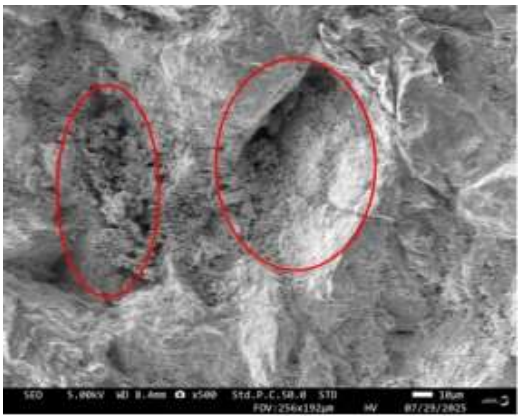

h. after immersion

Fig. 6 Changes in Pore Volume Before and After Carbonated Water Immersion

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4. Conclusion

(1) In ultra-low permeability sandstone reservoirs, both carbonated water flooding and its combined methods can effectively enhance oil recovery. Among them, the combined carbonated water-surfactant flooding yields the optimal performance, achieving a 10.58% increase in recovery compared to water flooding. This superiority stems from the synergistic effect where the surfactant reduces oil-water interfacial tension while promoting the transfer of CO_2 from the aqueous phase to the oil phase. The single carbonated water flooding method itself results in a 6.43% incremental recovery, outperforming both CO_2 water-alternating-gas (WAG) injection and surfactant flooding. This confirms that carbonated water can effectively overcome the limitations of conventional oil displacement technologies.

(2) The interaction between carbonated water and reservoir minerals exhibits significant selectivity. Among clay minerals, kaolinite and illite undergo complete dissolution, while chlorite experiences partial dissolution. For carbonate minerals, iron-magnesium dolomite dissolves and enlarges pores, whereas calcite dissolution products are prone to secondary deposition. Regarding silicate minerals, quartz dissolution creates secondary pores, while the dissolution products of mica and feldspar readily cause pore-throat clogging. This differential dissolution behavior of minerals is the core factor regulating the evolution of reservoir pore structure.

(3) The impact of carbonated water on reservoir pore volume demonstrates a dual effect of "enlargement and clogging." Most pores experience volume expansion and connectivity improvement due to the dissolution of detrital minerals. However, pores with narrower throats or poor connectivity are susceptible to the deposition of dissolution products, leading to localized clogging. Overall, the positive effect of carbonated water flooding on reservoir storage capacity is dominant.

(4) Carbonated water flooding technology demonstrates clear applicability and feasibility in ultra-low permeability sandstone reservoirs with permeabilities below 0.3×10^{-3} μm^2. Its mechanisms for enhancing oil recovery include crude oil swelling and viscosity reduction, breaking the water blocking effect, and improving reservoir pore structure. This technology provides an efficient and viable new solution to address the challenges of low recovery factors and high development difficulty in ultra-low permeability reservoirs. Simultaneously, it establishes an experimental foundation and theoretical basis for subsequent field applications and technological optimization.

References

[1] Gu Xiaoyu. Study on the Mechanism of Low-Frequency Wave-Assisted Surfactant Imbibition in Ultra-Low Permeability Sandstone [D]. China University of Petroleum (East China), 2018.

[2] Lu Xin. Feasibility Study on Enhanced Oil Recovery by Carbonated Water Flooding in Daqing Punan Oilfield [D]. China University of Petroleum (Beijing), 2020.

[3] Yu Haiyang, Yang Zhonglin, Liu Junhui, et al. Enhanced Oil Recovery Method by Carbonated Water Flooding in Tight Oil Reservoirs [J]. Daqing Petroleum Geology and Development, 2019, 38(02): 166-174.

[4] Liu Junhui. Experimental Study on Enhanced Oil Recovery by Carbonated Water Flooding in Tight Oil Reservoirs [D]. China University of Petroleum (Beijing), 2019.

[5] Wang Xingyu. Study on Enhancing Oil Recovery by CO_2 Flooding and Carbonated Water Flooding after Water Flooding in Tight Oil Reservoirs [D]. Xi'an Shiyou University, 2023.

[6] BIJELIC B R, MUGGERIDGE A H,BLUNT,M J. Effect of com position on waterblocking for multicomponent gas floods [C] / / Presented at SPE Annual Technical Conference and Exhibition,San Antonio,Texas,USA,September 29-October 2,2002.

ISSN: 2710-0588

[7] GRIGG R, Gregory M, PURKAPLE J. The effect of pressure on improved oil flood recovery from tertiary gas injection[J]. SPE Reservoir Engineering, 1997, 12 (3) : 179-188.

[8] MCGUIRE P , STALKUP F. Performance analysis and optimiza tion of the Prudhoe Bay miscible gas project [J] . SPE Reservoir Engineering, 1995, 10 (2) : 88-93.

[9] RIAZI M, SOHRABI M, JAMIOLAHMADY M. Experimental study of pore-scale mechanisms of carbonated water injection [J]. Transport in Porous Media, 2011, 86 (1) : 73-86.