

Article

Experimental Study on Stress Sensitivity in Fractured Tight Conglomerate Reservoirs

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Abstract

Tight conglomerate reservoirs are characterized by dense lithology, significant compositional contrasts between cement and gravel, strong stress gravel content, strong heterogeneity, and uneven spatial distribution, which collectively result in low porosity, complex pore–throat structures, and low permeability. After hydraulic fracturing, the stress sensitivity of tight conglomerate reservoirs is jointly governed by the rock matrix and induced fractures. In this study, the Mahu tight conglomerate reservoir in the Xinjiang Oilfield was selected as the research target. Stress sensitivity experiments were conducted on conglomerate matrix cores and on cores with varying fracture conditions. After stress loading, the degrees of permeability damage of the matrix, through-fracture, double short-fracture, and microfracture cores were 41%, 69%, 93%, and 97%, respectively. The matrix exhibited moderate-to-weak stress sensitivity, the through-fracture cores showed moderate-to-strong stress sensitivity, while the double short-fracture and microfracture cores exhibited strong stress sensitivity. Experimental results indicate that when fractures are present, the stress sensitivity of the core is primarily controlled by fracture closure and matrix compression. As fracture development increases, core permeability is significantly enhanced; however, stress sensitivity also increases accordingly. Under net stress, gravel protrusions embed into fracture surfaces, reducing surface roughness, while irreversible alteration of fracture geometry becomes the dominant factor driving stress sensitivity in fractured cores. These findings provide a scientific basis for predicting stress-sensitivity-induced damage in tight conglomerate reservoirs.

Keywords: conglomerate reservoirs; stress-sensitivity behavior; fracture systems



Academic Editor: Qingbang Meng

Received: 11 September 2025

Revised: 23 October 2025

Accepted: 24 October 2025

Published: 27 October 2025

Citation: Wang, B.; Xing, W.; Meng, X.; Liu, K.; Zheng, W.; Li, B. Experimental Study on Stress Sensitivity in Fractured Tight Conglomerate Reservoirs. *Processes* **2025**, *13*, 3441. <https://doi.org/10.3390/pr13113441>

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1. Introduction

As conventional oil and gas resources decline, unconventional hydrocarbons have gained attention. Tight oil, a critical component, and conglomerate reservoirs have become key targets for reserve replacement and production enhancement [1,2]. Conglomerates are sedimentary rocks composed of variably sized fragments cemented by natural cements, exhibiting strong heterogeneity due to variable clastic composition and cementation. Deposited mainly along depression slopes, these reservoirs feature rapid sedimentation, facies changes, and pronounced heterogeneity [3,4]. Secondary dissolution pores dominate these

reservoirs. Compaction and cementation reduce reservoir quality, and rock mechanical properties show strong anisotropy, reflecting the complex depositional and diagenetic history. Porosity and permeability decrease with increasing effective stress and clay content, but increase with detrital mineral content. Higher brittle mineral content promotes brittle failure. Consequently, matrix permeability partially recovers, whereas fractures critically influence reservoir properties. Moreover, fracture dimensions vary significantly with production-related stress changes [5–12]. Microscopic characteristics include: (1) ultralow, heterogeneous porosity and permeability; (2) poorly sorted gravel with complex pore structure; (3) intergranular voids from gravel composition heterogeneity; and (4) intricate pore networks shaped by gravel and cementation. Random gravel accumulation generates multi-scale heterogeneity and complex pore networks, rendering fluid flow highly sensitive to in situ stress [13–15].

During production, as reservoir fluids are continuously depleted, the rock framework is compressed under stress, causing variations in pore fluid pressure. Consequently, pore–throat structures and other petrophysical parameters of reservoir rocks change with stress, among which permeability exhibits the most pronounced variation, reflecting the stress sensitivity of the reservoir [16–20]. Wang Chen et al. [21] tested stress sensitivity of unconsolidated sandstone cores via nuclear magnetic resonance. Results indicate that stress sensitivity increases rapidly with confining pressure, dominated by small- and medium-sized pores, while the development of pore–throat structures controls the degree of stress-induced damage. Tan Qigui et al. [22] showed that reservoir permeability declines in three stages—rapid, moderate, and stable—with fractures remaining highly stress-sensitive. Zhong Xinyu et al. [23] indicated that rock mechanical characteristics also affect stress sensitivity, with clay mineral content in pore fillings showing a positive correlation, while quartz and siliceous cements exhibit a negative correlation. Yu Miao et al. [24] observed in stress sensitivity tests that when net stress reaches a certain level, permeability does not stabilize immediately. Reservoirs with larger pore areas possess more stable pore structures but require longer stabilization times. Cao Nai et al. [25] investigated permeability hysteresis during loading and unloading in tight reservoirs. Results showed that permeability decreases rapidly during the initial loading stage, stabilizes after reaching a certain level, and cannot fully recover during unloading due to irreversible structural deformation. Ju Wei et al. [26] reported that compared with matrix cores, fractured cores—containing both fracture and pore systems—exhibit stronger stress sensitivity and more nonlinear behavior. Liu Kai et al. [27] found that in the case of the little difference in permeability, the stress sensitivity of Glutenite is the strongest, the Turbidite the middle, the Beach bar sand the weakest, and the loss of the permeability is 31.4%, 27.2% and 21.3% respectively after the effective stress increases to 35 MPa. This is because the different types of sedimentary rocks have different pore structures, grain size compositions and composition proportions of rocks. Han Denglin [28] found that stress sensitivity is controlled by micropores and microfractures: microfracture-rich reservoirs show rapid but less permanent permeability changes, while micropore-dominated reservoirs exhibit slower yet more irreversible variation. Zhang et al. [29] conducted stress sensitivity experiments on tight sandstones in the Ordos Basin. Under variable confining pressure, the permeability damage of the tight sandstones reached 63.3%, whereas under variable flow pressure, the damage was 46.4%. During stress loading, the rate of permeability decline exhibited a rapid-to-slow trend, while during unloading, the rate of permeability recovery followed a slow-to-fast pattern.

Tight conglomerate reservoirs feature complex depositional and diagenetic environments with high gravel content, leading to pronounced heterogeneity, strong mechanical anisotropy, highly complex pore–throat structures, and low overall porosity and permeability. Effective pores are mainly developed in the matrix, where rigid gravels coexist with a

plastic matrix, producing mixed mechanical behavior. Variations in overburden stress and pore pressure significantly affect pore and fracture flow, with production-induced pressure differences causing compression and fracture closure that rapidly reduce flow capacity. Previous studies on stress sensitivity in conglomerate reservoirs have largely neglected fractures. This study examined four core types—matrix, through-going fractures, double short fractures, and micro-fractures (simulating natural fractures)—to systematically evaluate the effects of fracture presence and development on stress sensitivity. Microscopic surface damage was also analyzed to elucidate mechanisms underlying strong stress sensitivity under different fracture morphologies, beyond macroscopic permeability changes.

2. Materials and Methods

2.1. Instruments and Materials

The materials used in this study include high-purity nitrogen gas and reservoir core samples. Nitrogen gas with a purity of 99.99% was supplied by Qingdao Xinkeyuan Technology Co., Ltd. (Qingdao, Shandong Province, China). Nitrogen, as a chemically inert and single-phase gas, minimally interacts with reservoir components such as carbonates and clays, avoiding chemical effects like dissolution, adsorption, or water sensitivity. This allows permeability changes to reflect purely mechanical stress responses without complications from phase transitions, wettability differences, or capillary effects.

Using nitrogen provides a direct measure of mechanical stress sensitivity. In actual reservoirs with multiphase fluids (oil, gas, and water), stress-sensitive behavior is more complex. Increased stress contracts pore throats, allowing the wetting phase (typically water) to occupy more small pores while non-wetting phase (oil or gas) pathways are blocked. Additionally, clay minerals may swell upon hydration, causing further pore-throat blockage and increasing permeability damage.

The experimental cores were collected from a tight conglomerate reservoir in the Mahu oilfield, Xinjiang. A total of four core samples were provided by Xinjiang Oilfield. The basic petrophysical properties of the cores, including permeability bulk density, are summarized in Table 1.

Table 1. Basic petrophysical properties of experimental cores.

Core No.	Diameter/cm	Length/cm	Permeability/mD	Fracture Characteristics
1	6.004	2.472	0.244	Matrix
2	6.018	2.460	0.258	Through-going Fracture
3	5.990	2.462	0.213	Double Short Fractures
4	6.014	2.454	0.065	Microfractures

The experimental procedure for stress sensitivity testing of tight conglomerate reservoirs is illustrated in Figure 1. The main apparatus includes a core holder, ISCO high-pressure piston pump, back-pressure valve, hand pump, pressure acquisition system, and a high-precision flowmeter. Among these, the core holder is the primary device, manufactured by Hai'an Scientific Instrument Co., Ltd. (Nantong, Jiangsu Province, China), which can accommodate cores with a diameter of 2.54 cm and a length of 5–10 cm, and withstand a maximum pressure of 30 MPa. The hand pump and back-pressure valve, supplied by Jiangsu Hai'an Petroleum Scientific Instrument Co., Ltd., are used to control the net stress applied to the core samples. The ISCO high-pressure piston pump is capable of operating in single- or dual-pump modes under constant pressure or constant flow, providing precise flow rate and pressure control over a wide operating range.

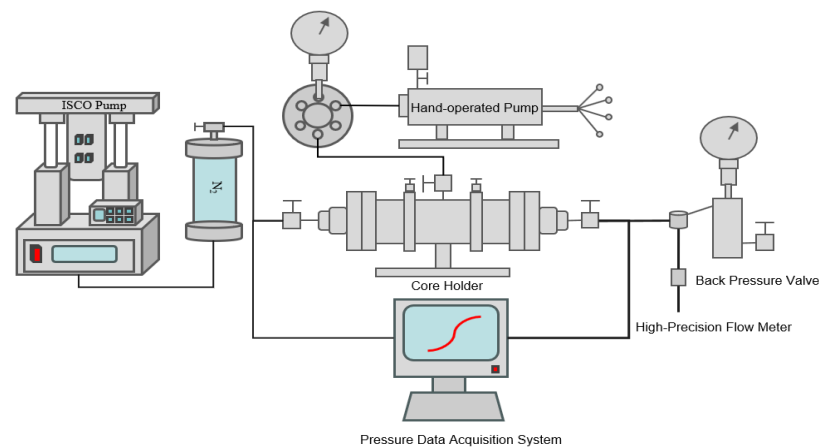


Figure 1. Experimental procedure for stress sensitivity testing of tight conglomerate reservoir cores.

Additional equipment employed in the experiments includes a three-dimensional super-depth digital microscope system, a vernier caliper, a six-way valve, a precision balance, and a drying oven.

2.2. Experimental Methods

The experimental cores were first subjected to solvent cleaning to remove residual oil. After cleaning, the cores were numbered and placed in an oven at 85 °C for 24 h to ensure complete drying. The dried cores were then measured for length and diameter, and their initial permeability were determined. Based on the experimental requirements, the cores were subsequently prepared with different fracture geometries. Representative core samples with distinct fracture configurations are shown in Figure 2. Specifically, the matrix core was left untreated; the through-fracture core was created by vertically cutting along the core axis to penetrate the entire core; the double-short-fracture core was first cut vertically along the axis to the midpoint of the core, followed by another vertical cut of equal length perpendicular to the first fracture, and finally separated at the midpoint along the axis perpendicular to the core to isolate the fractured section from the intact portion. For the micro-fractured core, the sample was first wrapped with a heat-shrink sleeve, and a 5 mm steel wire was placed at the center of the upper end face as a stress concentrator. The core was then mounted in a hydraulic fracturing press to induce fracturing. To enhance fracture development, the procedure was repeated by fixing the steel wire at the lower end face center and performing a second fracturing treatment. Four representative core samples with similar initial permeabilities were selected, and four fracture types were constructed: matrix, through-going fractures, double short fractures, and micro-fractures. Matrix cores, without induced fractures, represent fracture-free portions, while through-going and double short fracture cores simulate simple fractures. Micro-fractures mimic complex fracture networks with high density, varied development, and connectivity, enabling investigation of stress sensitivity under different fracture complexities. All four cores have similar permeabilities below 1 mD and heterogeneous gravel distributions, effectively representing the typical lithology of the Mahu Oilfield reservoir. However, due to spatial heterogeneity in lithology, pore structure, and fracture characteristics, the small sample size may limit the representativeness of the results and may not fully capture reservoir-scale variations in fracture distribution and heterogeneity.

The microfractured cores were generated by hydraulic fracturing under the action of a press. Numerous secondary fractures developed along the edges of gravels within the core and on its surface, with widths less than 0.5 mm and lengths not exceeding 6 cm. The through-fractured and double-short-fractured cores were created by mechanical cutting,

resulting in regular and well-defined fracture geometries. The through-fractured core contained a single fracture penetrating the entire core, whereas the double-short-fractured core contained two mutually perpendicular fractures, each extending through half of the core. In contrast, the microfractured core contained an irregular, stress-induced primary fracture with a tortuous path through the core, accompanied by randomly distributed secondary fractures both inside and on the surface of the core.

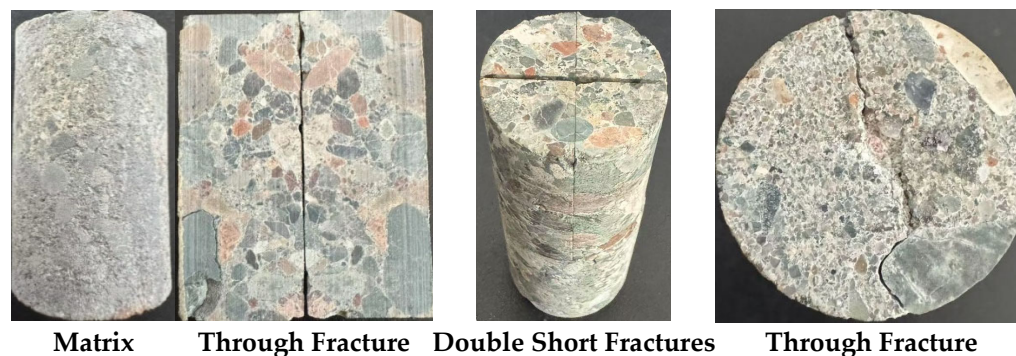


Figure 2. Core samples with different fracture morphologies.

Following fracture preparation, the cores were mounted in the core holder, and the experimental system was assembled according to the procedure shown in Figure 1. The confining pressure was maintained constant at 30 MPa, while the backpressure was adjusted to set net stress intervals of 2.5 MPa, 3.5 MPa, 5.0 MPa, 7.0 MPa, 9.0 MPa, 11.0 MPa, 15.0 MPa, 20.0 MPa, and 30 MPa. At each stress level, the core was stabilized for 30 min, after which inlet and outlet pressures and flow rates were recorded to calculate permeability. Permeability was measured under a constant pressure differential and flow rate for at least 10 min. Each test was repeated three times, and results with a relative error below 3% were reported. Upon reaching the maximum net effective stress, unloading was performed by gradually decreasing the net stress according to the same intervals. At each unloading point, the system was stabilized for 1 h, followed by measurements of inlet and outlet pressures, flow rates, and permeability. The procedure was repeated for each experimental core.

Calculated based on the irreversible permeability damage rate:

$$D'_{st} = \frac{K_i - K'_i}{K_i} \times 100\%$$

In the equation, D'_{st} represents the irreversible stress-sensitivity damage rate; K_i denotes the initial permeability (the core permeability under the initial net stress), with a unit of mD; and K'_i represents the permeability when the core is restored to the initial net stress, also in mD.

3. Results

3.1. Stress Sensitivity of Cores Under Various Fracture Morphologies

The variation in matrix permeability with net stress during loading and unloading is illustrated in Figure 3. For the matrix cores, the initial permeability before stress loading was 0.31 mD, decreasing to 0.02 mD at the maximum effective stress, corresponding to a maximum permeability damage of 94%. After returning to the initial effective stress, the permeability recovered to 0.18 mD, with a residual damage of 41%, indicating a moderate-to-weak stress sensitivity. As shown, the initial permeability of the matrix core is low, indicating that the pore structure of the tight conglomerate is dense and its flow capacity is limited. During net stress loading, the permeability exhibits distinct staged behavior. In the early stage of loading, the primary pores within the matrix rapidly compress and close

under the applied net stress, resulting in a sharp decline in core permeability. As net stress further increases, the compression of the matrix pore structure gradually stabilizes, and the rate of permeability reduction slows, showing a trend of rapid decline followed by a gradual decrease. When the net stress reaches 15 MPa, the change in permeability becomes less pronounced, indicating that the internal pore structure of the matrix remains largely stable under strong stress conditions. During the initial stage of unloading, the previously compacted pore structure does not recover immediately, and core permeability exhibits negligible change, reflecting a lag in pore structure recovery relative to the rate of net stress reduction. However, when net stress drops below 5 MPa, the previously compressed pores gradually reopen, the compressibility of the matrix decreases, and permeability is effectively restored. These experimental results indicate that the pore structure and permeability of the matrix are both stress-dependent and exhibit hysteresis, with nonlinear behavior being pronounced under high net stress. The stress sensitivity of the matrix cores has important implications for fluid flow characteristics and the efficient development of tight conglomerate reservoirs.

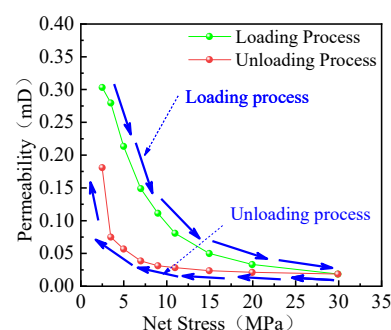


Figure 3. Permeability of matrix cores under net stress loading/unloading.

Stress sensitivity tests on tight sandstones from the Ordos Basin showed permeability damage of 63.3% under variable confining pressure and 46.4% under variable flow pressure. During loading, permeability declined rapidly at first and then more slowly, while during unloading, recovery was initially slow and then accelerated. These trends are consistent with those observed in the present study. In this experiment, the permeability damage rate of the conglomerate matrix core under variable flow pressure conditions was 41%, indicating comparable stress sensitivity to that of tight sandstone reservoirs.

The variation in permeability of the through-fracture core with net stress during loading and unloading is presented in Figure 4. Due to the presence of fractures, the initial permeability was 64.66 mD, dropping to 1.58 mD at the maximum effective stress, with a maximum damage of 98%. Upon unloading to the initial effective stress, permeability recovered to 20.05 mD, corresponding to a residual damage of 69%, indicating moderate-to-strong stress sensitivity. This increase is primarily attributed to the fractures acting as the main flow pathways under a pressure difference across the core, while the matrix pore structure plays only a supplementary role. During the early stage of net stress loading, fractures close rapidly, causing a sharp decline in core permeability. When the net stress reaches approximately 7 MPa, the rate of permeability reduction slows, and by 20 MPa, permeability remains nearly stable. At this stage, fracture closure is close to its maximum, and further changes in permeability are mainly governed by the compression of the matrix pore structure.

During the initial stage of net stress unloading, due to the strong plasticity of the core, permeability does not exhibit significant recovery, as both fractures and matrix pores cannot immediately reopen. Permeability remains at a relatively low level. As the net stress continues to decrease, when it falls below 9 MPa, the core permeability gradually increases

from a slow to a faster rate. This reflects the progressive reopening of fractures and matrix pores and the gradual restoration of fluid flow pathways. However, the fracture apertures and pore structure do not fully return to their initial states, resulting in a substantial difference between post-test permeability and the initial value, indicating a high degree of irreversible damage.

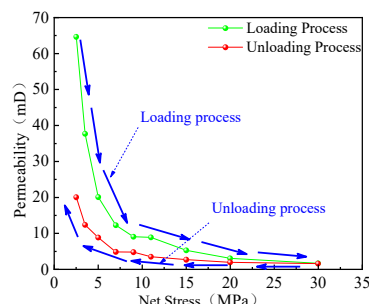


Figure 4. Permeability of through-fracture cores under net stress loading/unloading.

Overall, the permeability evolution of the through-fracture core under stress loading and unloading involves two main stages: fracture closure and matrix compression. In the early loading stage, fracture closure dominates the permeability response. Once fracture closure reaches its maximum, matrix pore compression becomes the primary control on permeability changes. When both fractures and matrix pores are fully compressed, permeability stabilizes. The presence of fractures not only significantly enhances the fluid flow capacity of the core but also increases its stress sensitivity, which has important implications for the flow characteristics and efficient development of tight conglomerate reservoirs.

The variation in permeability of the double-short-fracture core with net stress during loading and unloading is presented in Figure 5. For the double short fracture cores, the initial permeability was 27.19 mD, decreasing to 0.04 mD at the maximum effective stress, with a maximum damage of 99%. After unloading, permeability recovered to 2.02 mD, with a residual damage of 93%, indicating strong stress sensitivity. Compared with through-fracture cores, the double-short-fracture cores maintain a similar total longitudinal fracture length and total fracture surface area, but exhibit a more complex fracture morphology. During the early stage of stress loading, the permeability of the core decreases more rapidly. When the net stress reaches approximately 11 MPa, the rate of permeability reduction gradually slows, and in the later stage, permeability remains nearly stable. Comparison with the stress sensitivity of through-fracture cores indicates that the closure of the complex fracture network in the early loading stage has a significant impact on fracture flow capacity. At later stages, as the fractures are nearly fully closed, permeability stabilizes slowly, reflecting a balance between fracture closure and matrix pore compression.

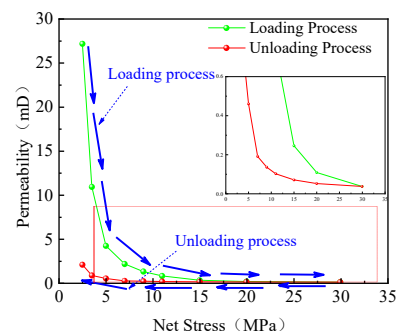


Figure 5. Permeability of double short-fracture cores under net stress loading/unloading.

During net stress unloading, the complex fracture network and the matrix pore structure do not immediately recover, resulting in a prolonged period of minimal permeability increase. This hysteresis effect is more pronounced than in through-fracture cores. Only when the net stress decreases below 5 MPa does the permeability begin to rise gradually. Compared to through-fracture cores, the post-test permeability of double-short-fracture cores deviates more from the initial value, indicating a higher degree of irreversible damage. These observations demonstrate that the complexity of the fracture network not only enhances the stress sensitivity of permeability but also amplifies the hysteresis during stress unloading. Consequently, fracture network complexity has a significant impact on fluid flow characteristics and reservoir performance during development.

The variation in permeability of the microfracture core with net stress during loading and unloading is shown in Figure 6. For the micro-fracture cores, the initial permeability was 28.20 mD, decreasing to 0.03 mD at the maximum effective stress, with a maximum damage of 99%. Upon returning to the initial effective stress, permeability recovered to 0.79 mD, corresponding to a residual damage of 97%, indicating strong stress sensitivity. Compared with through-fracture and double-short-fracture cores, the microfracture core contains a larger number of fractures, with significant differences in fracture apertures, cross-cutting patterns, and strong connectivity, forming a more complex fracture network that better simulates the conditions of real reservoir environments. During net stress loading, the permeability evolution can be divided into three stages: early (2.5–5 MPa), middle (5–15 MPa), and late (15–30 MPa). In the early loading stage, large-scale fractures close rapidly, resulting in a sharp decline in permeability. In the middle stage, deformation occurs mainly among medium- and small-scale fractures, connectivity decreases, and the rate of permeability reduction slows. In the late stage, fractures are nearly fully closed, and compression of the matrix pore structure dominates, leading to a nearly stable permeability.

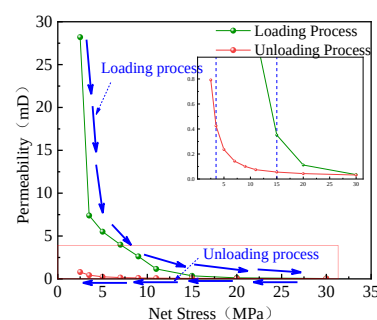


Figure 6. Permeability of microfracture cores under net stress loading/unloading.

During net stress unloading, the large number of fractures and the complex fracture network prevent effective recovery of fractures and matrix pores, and permeability remains at a low level. Only when the net stress decreases to around 5 MPa does permeability begin to exhibit a slight upward trend, but the increase is limited, and the post-test permeability differs significantly from the initial value. Moreover, the hysteresis effect of permeability is more pronounced. These results further demonstrate that, in tight conglomerate reservoirs, the complexity of the fracture network has a significant influence on fluid flow capacity and reservoir development efficiency.

The variations in core permeability under different fracture conditions during net stress loading and unloading are illustrated in Figure 7. The extent of permeability recovery during net stress unloading for cores with different fracture morphologies is presented in Table 2. Overall, both matrix cores and fractured cores exhibit a rapid permeability decline in the early stage of net stress loading. Once the net stress exceeds a certain threshold, the rate of permeability reduction gradually slows down and eventually stabilizes. However,

with an increasing number of fractures and a more complex fracture network, the initial rate of permeability decline becomes faster, and the net stress threshold at which permeability approaches stability is lower. During the initial stage of net stress unloading, core permeability remains largely unchanged because fracture apertures and matrix pore structures fail to recover effectively. As the net stress continues to decrease, permeability slowly recovers. Nevertheless, the more fractures present and the more complex the fracture network, the lower the net stress at which permeability recovery becomes noticeable, and the slower the recovery rate.

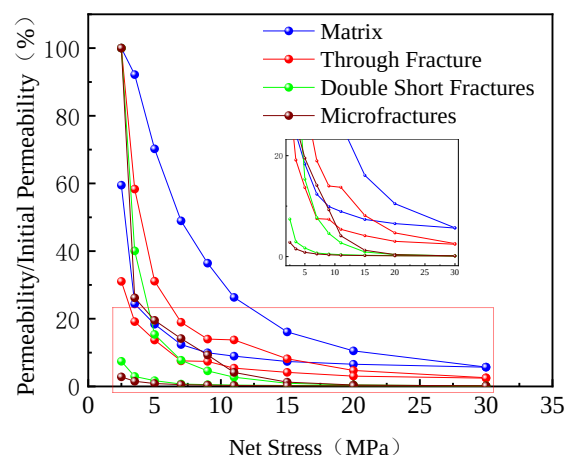


Figure 7. Ratio of core permeability to initial permeability under different fracture conditions during net stress loading/unloading.

Table 2. Permeability recovery degree under different net stresses.

Permeability Recovery Degree Under Different Net Stresses During Stress Unloading/%	Matrix	Through-Fracture	Double-Short-Fracture	Microfracture Cores
2.5 MPa	59.49	31.01	7.42	2.81
3.5 MPa	24.36	19.12	2.93	1.51
5 MPa	18.37	13.68	1.69	0.83
7 MPa	12.36	7.52	0.70	0.51
9 MPa	9.92	7.38	0.50	0.36
11 MPa	8.93	5.39	0.37	0.26
15 MPa	7.36	4.14	0.26	0.20
20 MPa	6.53	3.01	0.19	0.15
30 MPa	5.65	2.44	0.13	0.11

The degree of irreversible permeability damage under different fracture conditions is shown in Figure 8. Among all tested cores, matrix cores exhibit the lowest permeability damage (41%), followed by through-going fractures (69%), double-short fractures (93%), and microfractures with the highest degree of damage (97%). For matrix cores, permeability reduction is primarily controlled by pore structure compaction and collapse during net stress loading, with partial recovery of the pore structure upon unloading. Thus, the internal spatial configuration of the matrix core does not undergo significant changes throughout the stress cycle. In contrast, fractured cores exhibit stronger stress sensitivity due to the presence of fractures. During the initial stage of net stress loading, fracture closure dominates permeability reduction. The asperities of gravel clasts embedded along the fracture walls gradually crush into the opposing surfaces, leading to smoother fracture surfaces and a rapid decrease in effective flow channels. At later stages, as fractures are fully closed, compaction of the matrix pore structure becomes the dominant factor controlling

permeability reduction. During the unloading process, the strong plasticity of the reservoir prevents the gravel asperities from re-emerging, hindering effective fracture reopening. Meanwhile, the recovery of the matrix pore structure remains limited. Compared with the loading process, the internal spatial configuration of the core is significantly altered, with the loss of high-permeability flow channels, making it difficult for the permeability to recover to its initial state. Therefore, the more developed the internal fracture network, the more difficult it is for the spatial structure to recover, and the stronger the stress sensitivity.

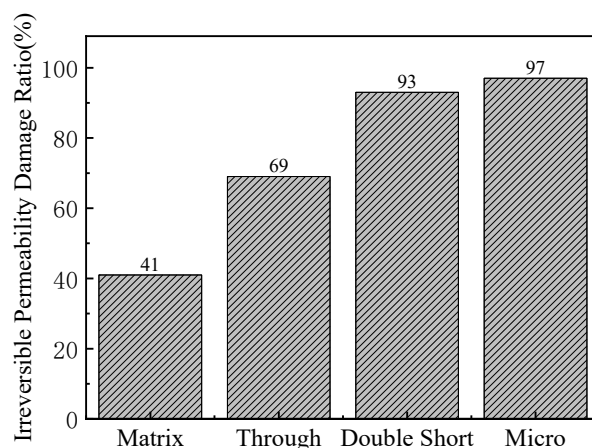


Figure 8. Irreversible permeability damage of cores under different fracture conditions.

According to the reservoir sensitivity evaluation method, the stress sensitivity damage of matrix cores can be classified as moderately weak, that of through-going fractures as moderately strong, while double-short fractures and microfractures both fall into the category of strong stress sensitivity. Although fractured cores experience significant permeability damage due to extensive fracture closure under net stress loading, fractures can never be completely closed, even at the maximum applied net stress. As a result, residual flow channels remain, and the post-loading permeability of fractured cores is still higher than the initial permeability of matrix cores. This observation demonstrates that when fracture networks are present, their flow capacity largely overshadows the contribution of the matrix, highlighting the crucial role of fractures in enhancing reservoir flow performance.

3.2. Measurement of Fracture Surface Damage in Cores Under Different Fracture Types

The micro-imaging was carried out using a Keyence VHX-D650E ultra-depth-of-field 3D digital microscope, with a magnification of 1:50 during the experiments. The ultra-depth three-dimensional microscope is equipped with an adjustable light source that illuminates the core surface during magnification. The focal point of the light source can be precisely controlled. Before stress loading, the observation point is selected, and the light source is adjusted to focus on the target position. The horizontal and vertical coordinates of the light spot on the core surface are recorded using a ruler. After stress loading, the light source is repositioned to the previously recorded coordinates, and fine adjustments are made under the microscope of the ultra-depth 3D imaging system to accurately locate the same target point as before loading.

Micro-imaging of the left and right walls of the through-going fractures before and after net stress loading is presented in Figure 9a,b. As shown in Figure 9a, prior to loading, the left fracture wall exhibits pronounced color variations, with a vertical profile showing a low center and higher edges, including a noticeable depression, resulting in a significant vertical height difference between the highest and lowest points. After net stress loading, color variations are substantially reduced, with green and yellow shadows uniformly distributed across the wall, indicating a marked decrease in vertical height differences, the

disappearance of the original depression, and a smoother wall surface. Figure 9b shows that, before loading, the right wall displays a higher left side and lower right side, whereas after loading, the height difference between the two sides decreases. This heterogeneous fracture wall geometry facilitates the formation of high-velocity flow channels, which is a primary factor contributing to the higher initial permeability of fracture cores compared with matrix cores.

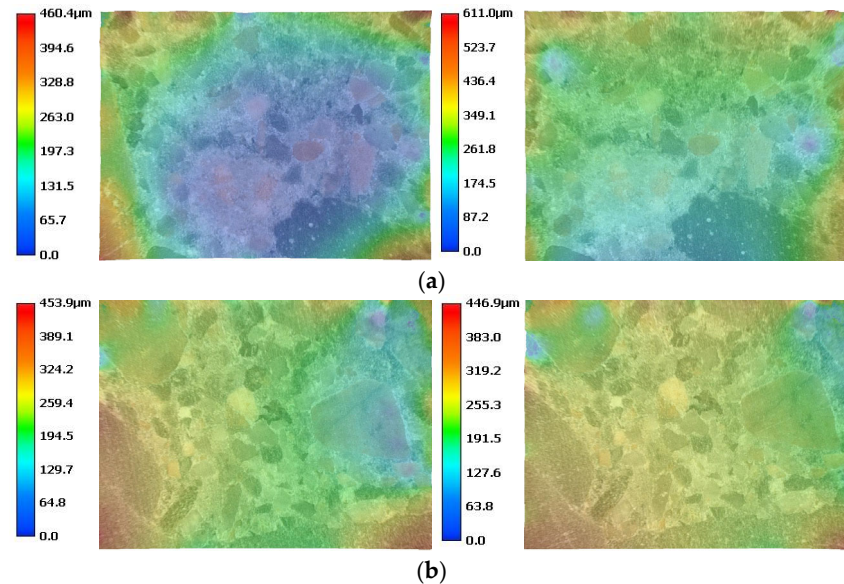


Figure 9. Micro-imaging of fracture face stress damage in through-fracture cores before and after net effective stress loading. (a) Micro-imaging of the left fracture face in through-fracture cores before and after net effective stress loading; (b) Micro-imaging of the right fracture face in through-fracture cores before and after net effective stress loading.

The roughness of the through-going fractures walls in both longitudinal and transverse directions before and after net stress loading is shown in Figure 10a,b. The surface roughness, represented by the arithmetic mean deviation (S_a), also decreased significantly after loading. For the left wall, S_a dropped from 83.30 μm to 48.45 μm (−41.84%), and for the right wall, from 39.74 μm to 30.18 μm (−24.06%), reflecting a substantial reduction in roughness. Comparison of transverse and longitudinal height profiles shows that prior to loading, both profiles fluctuated markedly with local depressions, whereas after loading, the profiles became smoother. This indicates that the fracture walls were compacted, vertical height differences decreased, roughness was reduced, and fractures closed more tightly, resulting in narrowed or partially eliminated flow channels and significant irreversible permeability damage.

Micro-imaging of the double-short-fracture walls in both longitudinal and transverse directions before and after net stress loading is presented in Figure 11a,b. As shown in Figure 11a, prior to loading, the longitudinal wall exhibits a green streak extending from the upper-left to the lower-right corner, interspersed with small purple regions, while yellow shadows on both sides gradually transition to red, indicating the presence of a longitudinal trough with pronounced height differences. This highly heterogeneous trough structure provides effective high-velocity flow channels. After net stress loading, the longitudinal wall appears predominantly uniform in green, with only small yellow patches remaining in the lower-left corner, and the original trough disappears, indicating a smoother wall surface. As shown in Figure 11b, the transverse wall initially displays a high-to-low vertical trend before loading, which is reduced after loading, resulting in a more even and planar surface.

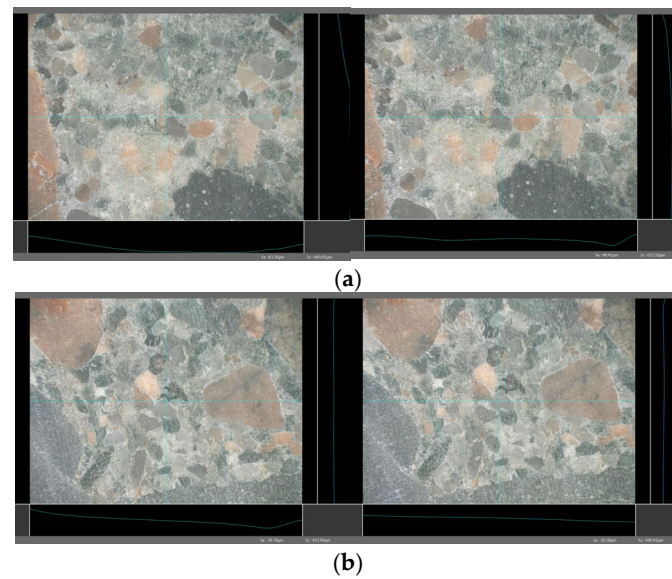


Figure 10. Surface roughness imaging of through-fracture cores before and after net effective stress loading. (a) Surface roughness imaging of the left fracture face in through-fracture cores before and after net effective stress loading; (b) Surface roughness imaging of the right fracture face in through-fracture cores before and after net effective stress loading.

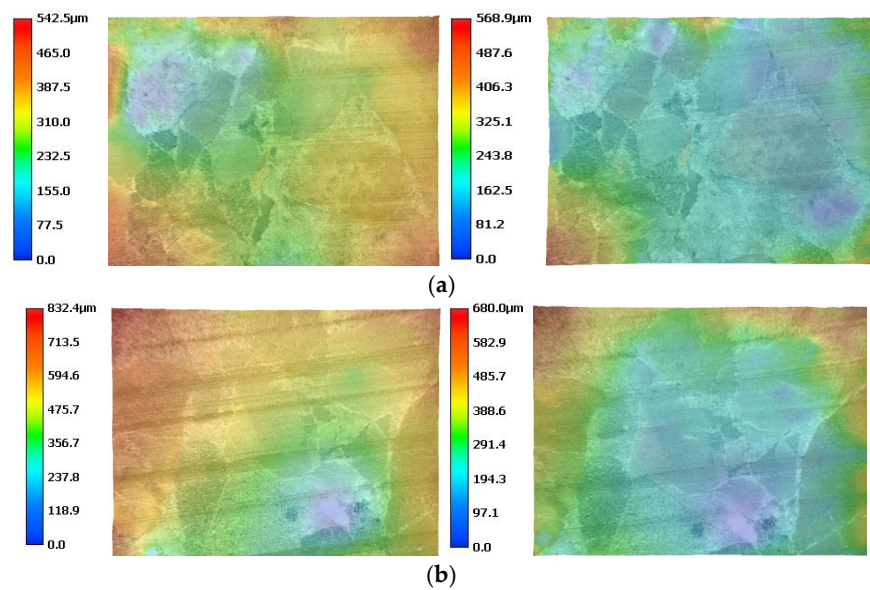


Figure 11. Micro-imaging of fracture face stress damage in double short-fracture cores before and after net effective stress loading. (a) Micro-imaging of stress damage on the longitudinal fracture face in double short-fracture cores before and after net effective stress loading; (b) Micro-imaging of stress damage on the transverse fracture face in double short-fracture cores before and after net effective stress loading.

The roughness of the double-short-fracture walls in both longitudinal and transverse directions before and after net stress loading is shown in Figure 12a,b. The S_a values decreased from $51.15 \mu\text{m}$ to $46.55 \mu\text{m}$ for the longitudinal wall and from $99.07 \mu\text{m}$ to $85.65 \mu\text{m}$ for the transverse wall, representing reductions of 8.99% and 13.55%, respectively. The reduced amplitude of height variations indicates a decline in wall roughness and damage to the flow channels.

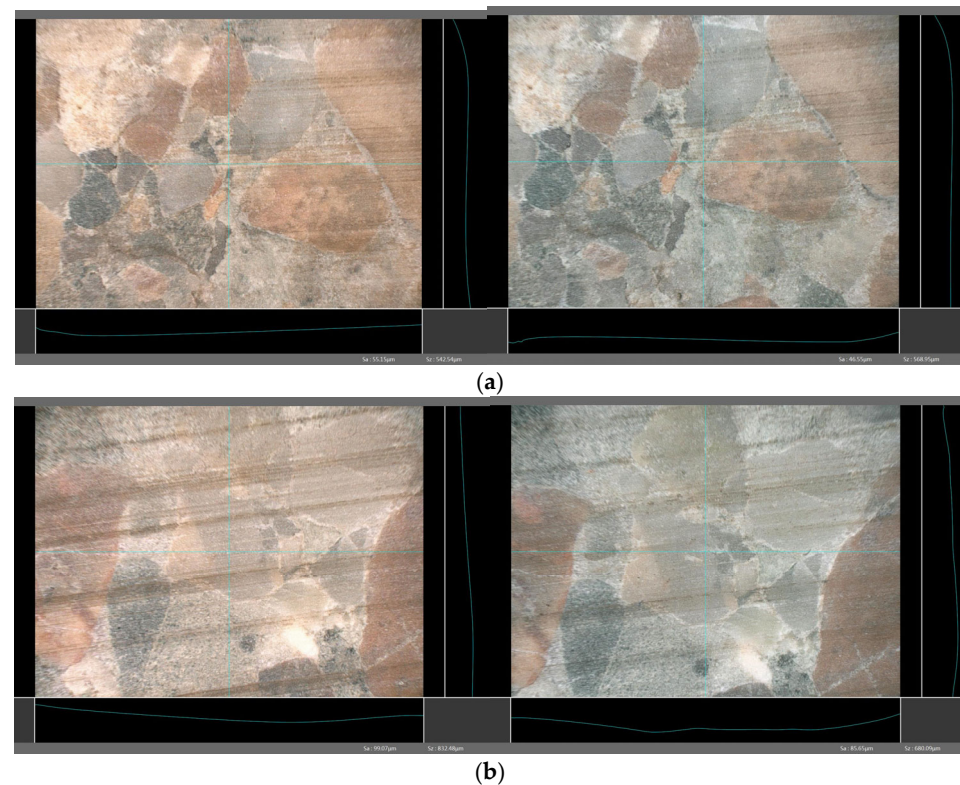


Figure 12. Surface roughness imaging of double short-fracture cores before and after net effective stress loading. (a) Surface roughness imaging of the longitudinal fracture face in double short-fracture cores before and after net effective stress loading; (b) Surface roughness imaging of the transverse fracture face in double short-fracture cores before and after net effective stress loading.

A comparative analysis of the through-going and double-short fractures before and after stress loading further indicates that the rigidity of gravel particles and the plasticity of the surrounding matrix jointly govern fracture-surface evolution. Under external stress, protruding gravel grains are more likely to become embedded into the opposing surface, resulting in reduced vertical height differences across the fracture wall. Due to the irreversible nature of this grain embedding, fracture closure prevents the surface from restoring its original morphology, leading to a substantial reduction in flow pathways. This mechanism highlights that the evolution of fracture-wall roughness under net stress loading serves as a primary controlling factor for the inability of fractured cores to recover their initial permeability and for the pronounced stress-sensitivity damage observed in such systems.

The CT imaging of the microfractured core before and after net stress loading is presented in Figure 13. Significant alterations in the spatial structure of microfractures were observed before and after net stress loading. From the perspective of fracture volume distribution, the total volume of large-scale fractures, represented by the red regions, was markedly reduced, while the sheet-like connectivity between fractures decreased substantially. This indicates that, under high confining stress, the original large-scale fractures underwent significant shrinkage and closure, leading to the destruction of inter-fracture connectivity. Simultaneously, after net stress loading, numerous small-scale fractures, represented in blue, were generated, predominantly distributed around the peripheries of large-scale fractures or near the tips of pre-existing cracks. The occurrence of these small-scale fractures suggests that the closure of large-scale fractures triggered localized stress concentration, which in turn induced the formation of secondary small fractures.

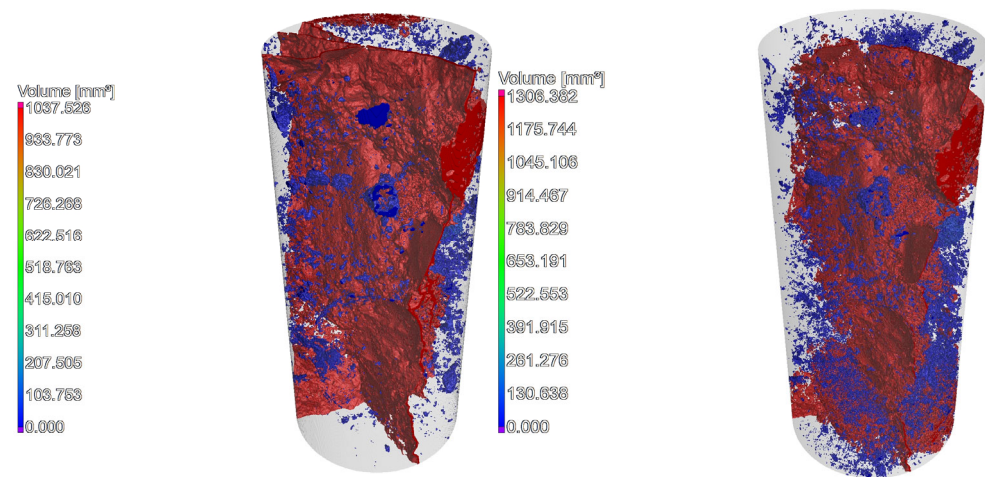


Figure 13. CT scans of core fractures before and after net stress loading.

Microfracture porosity increased from 5.93% before stress loading to 6.84% after loading, confirming the formation of secondary fractures during testing. However, despite the porosity increase, permeability declined markedly, indicating that stress-induced fracture closure and reduced connectivity are the primary factors controlling flow impairment. The generation of small-scale fractures driven by the contraction of large-scale fractures altered the overall spatial configuration of the fracture network and significantly influenced the seepage pathways between fractures. However, the closure of the large-scale fractures resulted in a dramatic reduction in sheet-like connectivity, which led to severe permeability impairment of the core. The newly formed small-scale fractures could not compensate for the loss of large-scale flow channels, thereby exerting a negative impact on the seepage capacity of the reservoir rock. This phenomenon demonstrates that, under high-pressure conditions, the coupled mechanism of large-scale fracture contraction and small-scale fracture initiation plays a critical role in controlling the strong stress sensitivity and high degree of irreversible damage in tight conglomerate reservoirs.

Besides gravel embedding, which reduces fracture wall roughness, high permeability damage in fractured cores is influenced by: (1) collapse of small, poorly connected pores under effective stress, which is difficult to recover upon unloading, further impairing flow channels; (2) local stress concentration due to heterogeneous mechanical properties of gravel and clay minerals, promoting clay migration and exacerbating fracture closure; (3) low matrix permeability, making fractures the primary flow pathways, so that fracture compression causes a significant reduction in overall permeability.

During unloading of the effective stress, the elastic energy within the core is gradually released. However, due to plastic deformation of the gravel and cementing material during stress loading, irreversible changes occur in the fracture structure. The embedded gravel cannot fully recover to its initial state, resulting in weak fracture support and only partial rebound of fracture apertures. Additionally, the collapsed pore structures within the core are difficult to restore, leading to severe impairment of the flow capacity in the fractured cores.

Mineralogical analysis of the cores was omitted, as nitrogen—employed as the working fluid in the stress-sensitivity tests—does not chemically interact with the core materials, ensuring that the observed changes are solely due to mechanical effects.

4. Conclusions

- (1) The irrecoverable permeability damage of matrix cores from the Mahu tight conglomerate reservoir reaches 41%, while that of tight sandstone matrix cores from

the Ordos Basin is 46.4%, indicating comparable stress sensitivity between the two lithologies. In the presence of fractures, the irrecoverable permeability damage of through-fracture, double-short-fracture, and micro-fracture cores increases to 69%, 93%, and 97%, respectively—representing 28–56% higher damage than that of matrix cores. These results indicate that fractures significantly amplify the stress sensitivity of tight reservoirs, and the degree of sensitivity increases with fracture complexity.

- (2) During the loading stage, permeability reduction mainly results from fracture closure and matrix compaction. In the early stage of unloading, fractures cannot reopen immediately with decreasing net stress, and the recovery of matrix pore structure remains limited, leading to a slow permeability recovery rate. As fractures gradually reopen and the matrix pores partially recover, permeability recovery accelerates. Despite high permeability loss, the final permeability of through-fracture, double-short-fracture, and micro-fracture cores—20.05 mD, 2.02 mD, and 0.79 mD, respectively—remains higher than the initial matrix permeability of 0.31 mD, confirming that fractures substantially enhance flow capacity even after stress-induced damage.
- (3) With increasing fracture development, the superimposed closure of multiple fractures, combined with pore collapse and clay mineral migration, causes severe structural degradation and increased permeability damage. For micro-fractured cores, porosity decreases from 6.48% to 5.93% after loading, suggesting that although secondary fractures are generated, reduced fracture connectivity is the dominant factor controlling flow capacity loss.
- (4) From an engineering perspective, maintaining an appropriate production pressure differential is critical for tight conglomerate reservoir development. Excessively low pressure differentials limit elastic energy release, while overly high differentials exacerbate permeability damage and hinder subsequent stimulation. During hydraulic fracturing, uniform proppant placement is essential to prevent premature fracture closure and mitigate permeability loss associated with high fracture stress sensitivity.

Author Contributions: Methodology, B.L.; Investigation, X.M. and K.L.; Resources, B.W.; Writing—original draft, W.X. and W.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Authors Bin Wang, Xue Meng, Kaixin Liu and Weijie Zheng were employed by the company PetroChina Xinjiang Oilfield Company. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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