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Article

Dynamic Characterization of Microscopic Pore Structure in Mid-High Permeability Sandstones during Long-Term Water-Flooding

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Abstract: Most of the mid-high permeability sandstone oilfields in China have entered the ultra-high water cut stage, accompanied with the highly-dispersed residual oil, and the control effect of micro-heterogeneity on the residual oil is increasingly prominent. Understanding the microscopic characteristics of pore structural and its evolution during the long-term waterflooding is critical for enhancing the accuracy and efficiency of oil field exploitation. While the previous insights paid more attention to the geometrical and morphological features of pore structure and ignores the relation of pore structure with the fluid flow capacity. In this study, we propose a microscopic pore structure classification method considering pore size and local permeable capacity, which realizes the physical classification and quantitative evaluation of pore structure characteristics for different permeability rocks. The micro-pore structure is classified into 6 types based on the key evaluation parameters of pore diameter and flow flux area. By taking six mid-high permeability sandstone core samples from Daqing oilfield in China, a series of long-term waterflooding experiments are carried out and the interior pore structure was captured using high precision CT scanning technique. The results reveals that high-permeability reservoirs exhibit concentrated pores diameters and finer throats, whereas mid-permeability reservoirs exhibit smaller pores and throats in greater quantity. With the increase of water injection volumes, the permeable capacity and connectivity of the high-connectivity pore space in ultra-high- and high-permeability reservoirs are enhanced, and in mid-permeability reservoirs, the micro-heterogeneity intensifies the increase in low-connectivity small pores. These findings provide new insights for the microscopic heterogeneity and a solid theoretical basis for investigating the occurrence of microscopic residual oil and optimizing enhanced oil recovery strategies at the late stage of ultra-high water cut.

Keywords: pore classification; local permeable capacity; pore size; mid-high permeability sandstone; pore structure variation; long-term waterflooding

1. Introduction

Most of the mid-high permeability sandstone oilfields in China have entered the ultra-high water cut stage and confronted challenges such as elevated water cuts, diminished oil extraction rates, and the difficulty in exploiting the residual oil. In this context, advanced development strategies for residual oil recovery and recovery rate enhancement have become major concerns [1–3]. In the ultra-high water cut stage, the residual oil is spatially distributed with high dispersion and local concentration, which is determined by the interplay between oil and water displacement within the reservoir [4,5]. Storage and permeable capabilities of reservoirs are intrinsically controlled by their micro-porous structure [6–10], in which the pore structure not only serves as the basic storage space of fluids, but also provides the important flow paths for oil recovery. The structural heterogeneity directly influences the distribution, fluid migration, and the residual oil volume at the micro level, and the accurate characterization of pore structure is essential for engineering applications such as strategically selecting macro-scale oil recovery techniques and precisely tapping the residual oil, as well as the subsurface water contaminant treatment.

The mid-high permeability sandstones always contain pore structure at microscopic scale, while the complexity and irregularity of the pore geometry make it difficult to characterize the microscopic characteristics. The characterization of pore structure in rocks refers to the geometry shape, pore size and distribution, and their interconnections as well as the spatial distribution of all these properties in rocks. Various techniques and methods have been developed to describe the pore structure in rock, primarily containing the imaging analysis and the experimental analysis. The former approach can make a qualitative and quantitative assessment of pore dimensions and shapes using techniques such as cast thin sections, scanning electron microscopy (SEM), computed tomography (CT) scanning, focused ion beam (FIB) SEM, and synchrotron radiation, which visually represent the micro-heterogeneity of pore structure in rocks [11–18]. The latter methodology is to derive various parameters that indicate pore structure using high-pressure mercury intrusion, constant-rate mercury intrusion, nuclear magnetic resonance (NMR), gas adsorption, and small-angle scattering [19–26]. To understanding the effect of pore structure on residual oil recovery in reservoir rocks, it is necessary to investigate the pore structure characteristics from the perspective of fluid flow capacity. Therefore, we used the high-resolution microscopic CT to characterize the micro-heterogeneity of pore structure during the long-term waterflooding.

Significant research efforts focus on the microscopic morphologies and sizes in sandstone reservoir rocks, although the porosity and permeability measurements have provided important insights into the microscopic pore structure of sandstones. The microscopic pore structure of sandstone in image analysis has been characterized by complex pore geometry, average pore radius, pore connectivity, heterogeneity coefficient, and the anisotropy. Ren et al. [27] demonstrated the distribution characteristics of core pores and throats and their contributions on permeability in dense sandstone reservoirs with different permeabilities in the Ordos Basin, by using casting flakes and capillary seepage models in core displacement experiments. They also highlighted that submicron pores and throats in reservoirs play a dominant role in seepage, but they did not discuss the impact of different pore structures within the same core on seepage. Guo et al. [28] clarified the main pore structures of different dense reservoirs, and analyzed the influence of the major throat-interval controlling factors on fluid mobility in reservoirs having different permeability levels using the conventional core analysis method, NMR, and a gas-water high-speed centrifugation method. However, they did not investigate the effect of different pore spaces on fluid mobility in detail. Pei et al. [29] summarized the differences between micro-pore structures by comparing and analyzing the core experimental results of the cast sheet, scanning electron microscope, and mercury piezoelectric curve, nevertheless, they did not elucidate the variations in permeation capability across different pore structure types. These studies confirmed that the pore structure should be quantitatively evaluated considering the emplacement and recovery of residual oil in mid-high permeability sandstones. However, there is still a gap between the microscopic characterization of pore structure and macroscopic fluid flow. Additionally, understanding the evolution of microscopic pore structure

during the long-term waterflooding is also a challenging task when the relation between the microscopic pore structure and fluid flow remains ambiguous.

The goal of this paper is to investigate the pore structure characteristics and its evolution during the long-term waterflooding of mid-high permeability sandstones. To quantitatively characterize the pore structure, a new classification of microscopic pore structure is proposed based on the pore size and local permeable capacity. By taking a series long-term waterflooding experiments of 6 natural cores using the high-resolution CT imaging, the pore structure characteristics are described and classified based on digital rock analyses. Furthermore, the gradual differences with long-term water flooding in the micro-porous structure of several reservoir types are also revealed. These findings offer the fundamental insights for investigating the micro-occurrence of residual oil in the advanced ultra-high water cut and for optimizing enhanced oil recovery methodologies.

2. Materials and Methods

2.1. Sample Selection

Mid-high permeability sandstone reservoirs are classified as ultra-high-permeability reservoirs characterized by air permeability of 2000 mD or greater, high-permeability reservoirs with air permeability ranging from 500 mD to 2000mD, and mid-permeability reservoirs with air permeability ranging from 50 mD to 500 mD, according to the Evaluation Methods for Oil and Gas Reservoirs (SY/T 6285-2011), which is the oil and gas industry standard of the People's Republic of China. Taking the permeability, porosity, and median particle size of reservoirs in Songliao Basin into account, two representative core samples from each category—ultra-high-, high- and mid-permeability—were selected. The physical property parameters of the sandstone samples used in this study are presented in Table 1.

Table 1. Physical properties of rock samples.

Sample Number	Reservoir Type	Lithologic feature	Porosity (%)	Air Permeability (10 ⁻³ μm ²)	Length (cm)	Diameter (cm)
1	Ultra-high-permeability reservoir	Fine sandstone	30.96	3956	3.53	2.47
2	Ultra-high-permeability reservoir	Fine sandstone	30.26	2568	3.83	2.47
3	High-permeability reservoir	Siltstone	29.32	1890	4.94	2.49
4	High-permeability reservoir	Siltstone	28.84	1398	4.73	2.48
5	Mid-permeability reservoir	Siltstone	27.79	381	4.03	2.47
6	Mid-permeability reservoir	Siltstone	27.33	238	3.91	2.48

2.2. Representative Elementary Volume (REV) for Reservoirs with Different Permeabilities

This research was conducted by fusing micro-CT scanning with water-flooding oil displacement experiments, which enabled the non-destructive analysis of the core samples at various displacement process stages. By performing micro-CT scans at multiple stages of displacement, the micro-porous structure and its dynamic evolutionary traits across reservoirs with different permeability were discussed using the imaging analysis based on the digital rocks reconstructed from the micro-CT scanning images.

However, it is worth noting that two key contradictions must be weighed before core samples scanned. Firstly, there is an inverse correlation between the sample size and the scanned resolution. Specifically, an increase in sample size leads to a proportional decrease in resolution, which may hide the fine nuances of structure within the core. Conversely, pursuing high resolution reduces the sample size that can be scanned, which may cause inadequate REV coverage of the overall core characteristics, thereby reducing representativeness. Secondly, the cost of scanning is directly proportional to the increase in resolution; that is, with a higher resolution, the increase in scanning cost leads to a decline in economic benefit. Moreover, taking into account that the sweeping contribution of small pore channels is poor in practical waterflooding displacement process, the resolution level satisfies the requirements of practical engineering applications when reaches a certain resolution threshold and further enhancements do not confer substantial benefit from the effect of seepage through tiny pores.

Hence, a critical task in the accurate portrayal of micro-porous structural characteristics using digital rock models is to determine the minimum REV and the scanning resolution threshold for reservoir rocks with different permeabilities. Using permeability as the benchmark for determining the representative unit size, this study employed the size expansion method illustrated in Figure 1 and Lattice Boltzmann numerical simulation [30–32] to capture CT scanning structures of varying sizes from the core maximum position towards the core centre gradually. The specific parameters of the simulations are configured in Table 2. Through the above method, the changes in the pore structure across different dimension size and their consequential effects on permeability can be better understood and quantified.

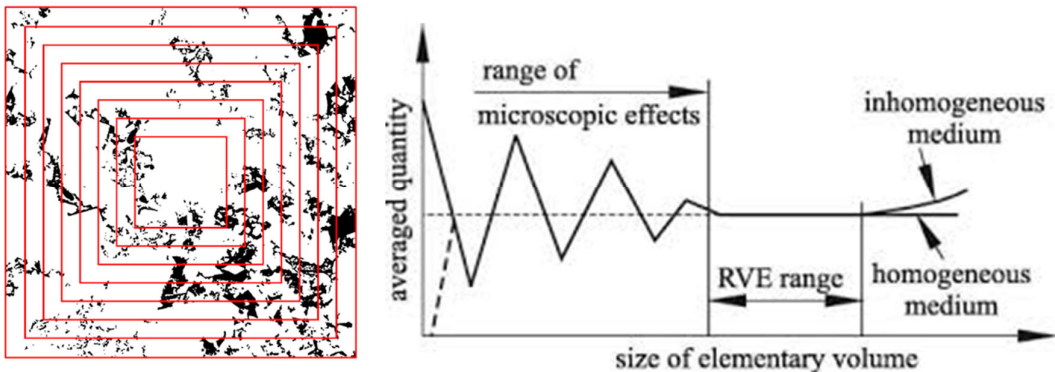


Figure 1. Changes in microscopic parameters of digital cores extracted from the same rock sample at different sizes.

Table 2. Selection of rock samples at different sizes and simulated parameter settings.

Reservoir Type	Sample Number	Resolution size (μm/voxel)	Dimension Size (μm)	Boundary Condition	Reynolds Number
Ultra-high – permeability & high-permeability reservoirs	2, 4	2, 4, 8	800, 1200, 1600, 2000	Pressure Boundary	~0.01

Mid-permeability reservoir	5	1, 2, 4	440, 520, 580, 640
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Based on the simulation results for the velocity field of pore structure, the changes of permeability in the various samples with different dimension sizes and scanning resolutions can be calculated by the Darcy’s equation, as shown by the scatter data in Figure 2, the following conclusions were drawn by comparatively analysing the changes with the measured values obtained from permeability measurement, as shown by the solid red line in Figure 2:

1. As the dimension size increases and scanning resolution size decreases, the calculated permeability stabilizes, and the difference between the calculated and measured values decreases. This proves that a digital rock model constructed at a reasonable size can effectively determine fluid flow characteristics within the interior pore structure of the rock core.
2. Considering the economy and the allowable margin of error in engineering practice, maintaining the calculated permeability error within 10%, as indicated by the red dashed line (Figure 2), is deemed to fulfil the optimal alignment requirement for the REV and the critical resolution.
3. For different reservoir rocks ranging from ultra-high permeability to middle permeability, the required minimum REV decreases along with a decrease in the pore characteristic size, with a corresponding increase in the required scanning resolution size. Specifically, for ultra-high permeability reservoirs, the minimum REV should not fall below 1200 μm , and the upper limit of resolution size should be less than 8 $\mu\text{m}/\text{voxel}$. In the case of high permeability reservoirs, the minimum REV should be no less than 800 μm , and the upper limit of resolution size is suggested to be lower than 4 $\mu\text{m}/\text{voxel}$. For mid-permeability reservoirs, the minimum REV should be not less than 600 μm , and the accurate capture of pore structure requires high scanning resolution, with the maximum resolution size not exceeding 2 $\mu\text{m}/\text{voxel}$.

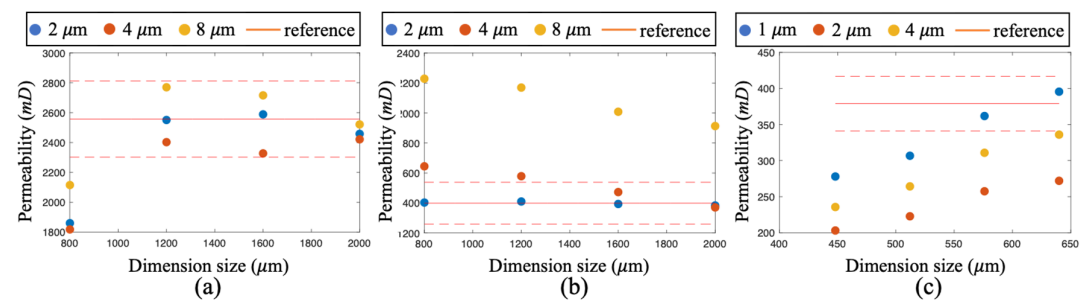


Figure 2. Simulated results of rock samples at different resolution sizes and domain sizes for the sandstone samples with varied permeabilities: (a)ultra-high permeability sample; (b) high-permeability sample; and (c)-mid-permeability sample. The red line labelled as reference represents the experimental measurements.

2.3. Long-term waterflooding experiments

Following the determination of the minimum REV and optimal scanning resolution size for sandstone rocks with different permeabilities, this study proceeded to perform long-term waterflooding experiments. Specifically, the spatial distribution information within the sandstone sample during the water-oil displacement experiment were identified using high-resolution micro-CT scanning technique at different displacement stages. Meanwhile, the scanning data information were segmented to isolate and extract the oil, water, and solid rock phases using the specialised image analysis software such as Avizo and ImageJ. This process achieved the dynamic quantification of the micro-porous structural variations in the digital rock models at different displacement stages. The sample sizes and design for the displacement stages are shown in Table 3.

Table 3. Design of displacement-collaborative computed tomography (CT) scan experiment.

Sample Size	Diameter 4 mm, Length 8 mm, Scanning resolution 2 μm							
Displacement Nodes	Dry sample	Oil-bearing	0.5PV	1.0PV	3.0 PV	10.0PV	50.0PV	500.0 PV
Displacement Speed	/	/	1 m/d	1 m/d	1 m/d	3 m/d	10 m/d	10 m/d

2.4. Construction of Pore Network Model

To further investigate the connectivity of the micro-porous structures and the characteristics of fluid flow within the structure, a pore network model was established using the maximum sphere method, as shown in Figure 3. This method, which was developed based on the foundational theory proposed by Fatt [31] and substantially advanced over the past 20 years, has evolved as a pivotal means for effectively constructing pore network models.

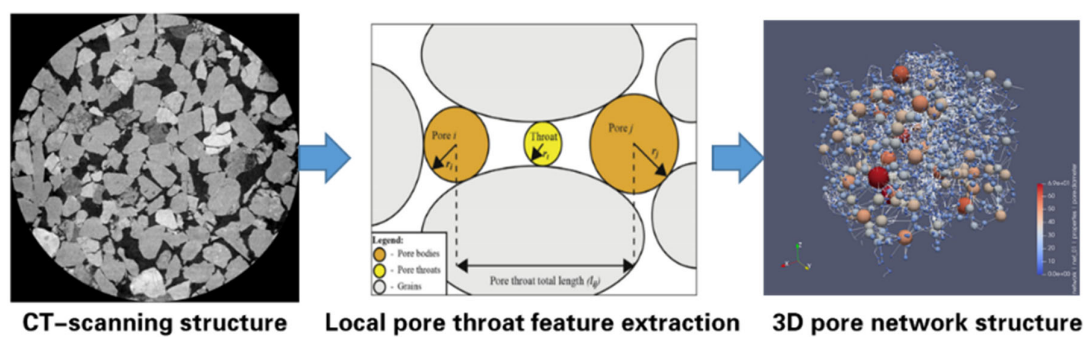


Figure 3. Pore network model principle.

In this study, the pore-throat segmentation method based on local hydraulic resistance equivalence [34] was applied to extract localised features, pore body and pore throat, based on the CT scan images for sandstone samples with different permeabilities. By balancing the local hydraulic resistance equivalence between the real void space and the simplified pore-throat geometry, this method transforms the porous structure into a network of pores and connecting throats and generates pore network models for ultra-high-, high-, and mid-permeability sandstone samples, as presented in Figure 4. The extraction of the characteristic parameters for pore structure, which are presented in Figure 5, indicates that ultra-high permeability reservoirs have a broad range of pore sizes (varying from 10 μm to 130 μm in diameter, with diameters concentrated around approximately 50 μm), with high pore-to-throat connectivity (a ratio of total throats to total pores as high as 3.81). As the permeability decreases, high permeability sandstones exhibit a more focused distribution of pore sizes (ranging from 10 μm to 80 μm in diameter, with diameters concentrated around 32 μm) and increasingly refined throats (a throat-to-pore ratio close to 2.76). In addition, middle permeability reservoirs are characterised by a greater number of smaller pores and throats (with the pore sizes clustered around 18 μm). With a further reduction in the ratio of total throats to total pores to approximately 2.71, the decreased throat dimensions generally contribute to lower permeability.

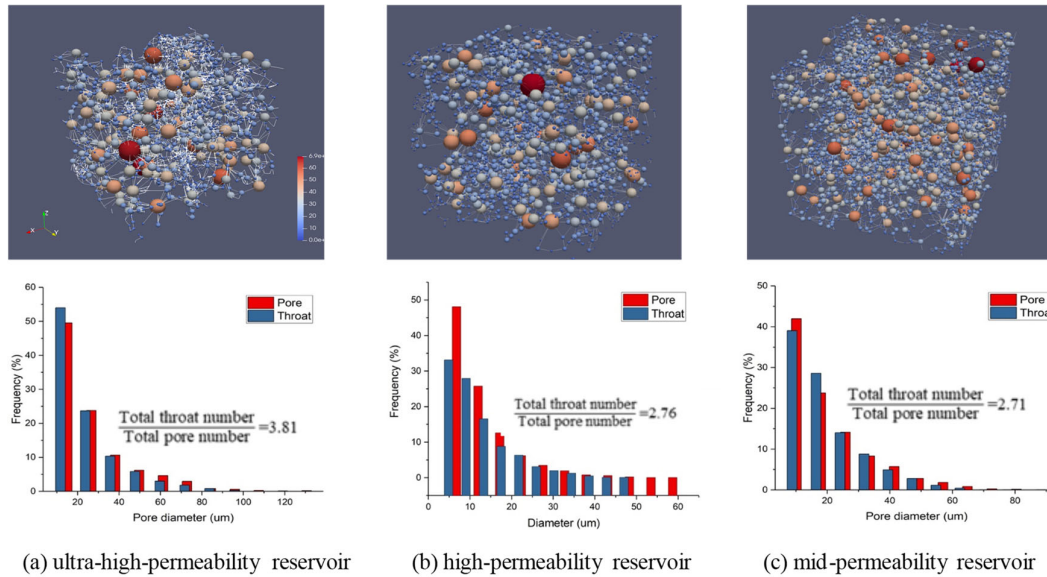


Figure 4. Extraction of core-pore network model and pore-throat distribution in middle permeability reservoirs.

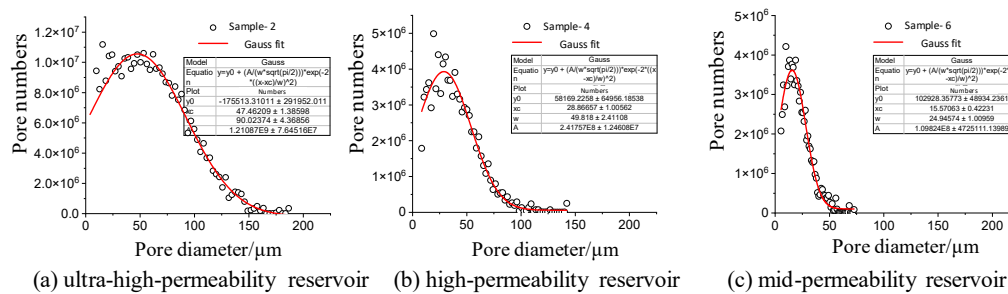


Figure 5. Pore structure characteristic for different oil reservoirs.

3. Three-Dimensional Characterization of Microscopic Pore Structure

3.1. Pore Structure Classification Method

The physical properties of pore structure, particularly the permeable capacity, plays a significant role in the sandstone rock permeability at local and global scales and affects the flow paths of the contained fluids, such as oil and water. Traditional pore classification and evaluation methods [35–37] depend on parameters such as the average throat radius, sorting coefficient, and homogeneity coefficient. These parameters, which emphasise the geometric morphology and distribution patterns for pores, provide only a reflection of the pore structural characteristics without a thorough consideration of the porous structure impact on the fluid flow. It is intended to more accurately describe the connectivity characteristics of the pore space and its contribution to rock permeability. In this study, we introduce a new characteristic parameter, the flow flux area, to quantify the local permeable capacity. Simultaneously, the pore diameter is used to represent the global permeability of the pore structure. The threshold of the aforementioned two crucial characteristic parameters can be more easily determined, as illustrated in Figure 6, by analysing pore characteristics from the pore network representation for the digital rock samples.

4. **Pore diameter R .** This parameter is used to represent the distribution and morphological characteristics of the granular pores within the sandstone, as the pore diameter directly influences the resistance experienced by fluids during interior fluid flow in pore structure. By comprehensively analysing the distributional features for throat diameters across sandstone rocks with different permeabilities, pore structure was classified into three categories—large, mid, and small pores—by employing a pore diameter-versus-pore volume percentage curve. The boundaries were set to pore diameters corresponding to 33.3% and 66.6% volume percentages of the total pore volume with reference to the contribution of pore volume.
5. **Flow flux area S .** As a new characterisation parameter for pore structure, the flow flux area quantifies the connectivity of pores by counting the areas of all throats associated with each pore. This treatment can be derived from the product of the coordination number (or the number of throats linked to a single pore) and the average throat area. The flow flux area is a more direct representation of the low permeable capacity, which is vital for comprehending and evaluating the connectivity within the sandstone rocks and the effect of pore and throat dimensions on variations in local permeability. Given the negative skew distribution observed in the relationship between the flow flux area and the corresponding pore volume percentage, the median value of the flow flux area from this curve ($313\text{ }\mu\text{m}^2$) was selected as the boundary for classifying the pores into high and low connectivity.

Based on the boundary division of the two key parameters abovementioned, this study established a set of micro-pore structure classification criteria for mid-high permeability rocks. The pores were subdivided into high-connectivity large pores, low-connectivity large pores, high-connectivity mid pores, low-connectivity mid pores, high-connectivity small pores, and low-connectivity small pores, as shown in Table 4. Thus, the pore structure of sandstone rocks with different permeabilities can be classified effectively.

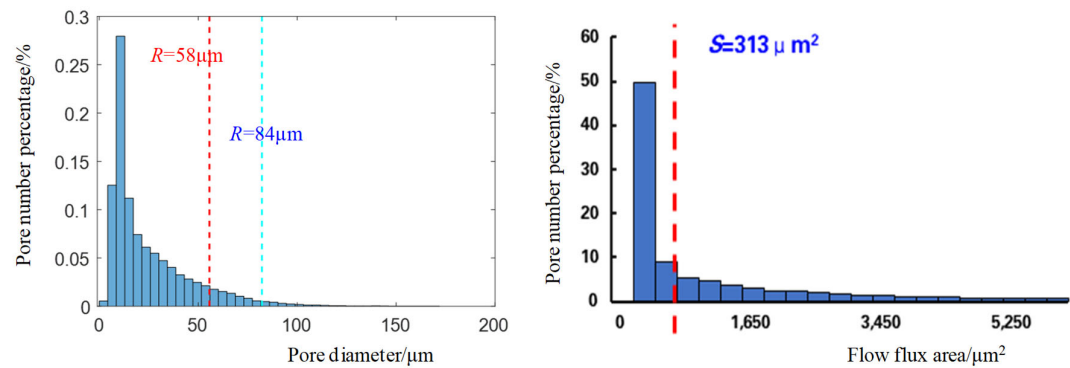


Figure 6. Thresholds of pore structure classification parameters.

Table 4. Classification criteria for reservoir micro-pore structure.

Pore Structure Type		Criteria for classification	
		Pore Diameter/μm	Flux area/μm²
Large-pore	High connectivity	>84	>313
	Low connectivity	>84	≤313
Mid-pore	High connectivity	(58, 84]	>313
	Low connectivity	(58, 84]	≤313
Small pore	High connectivity	≤58	>313
	Low connectivity	≤58	≤313

3.2. Evaluation on Classified Reservoir Pore Structure

According to the aforementioned pore structure classification approach, this study categorised and comparatively analysed the pore structures over ultra-high-permeability, high-permeability, and mid-permeability reservoirs and defined the different distributions of pore structures between reservoirs of varying permeabilities, as shown in Figure 7. From the perspective of pore volume proportion, ultra-high- and high-permeability reservoir rocks are dominated by high-connectivity mid-to-large pores, which indicate their satisfactory storage and permeation capabilities. Furthermore, mid-permeability reservoir rocks are predominantly composed of small pores, indicating that the connectivity is significantly dependent on the effective connectivity within these small pores. Regarding the proportions of pore numbers, low-connectivity small pores have a remarkable prevalence in all reservoir types. These low-connectivity small pores, however, have different influence on connectivity in reservoir rocks with different permeabilities. In ultra-high-permeability rock, over 50% of low-connectivity small pores account for only 2% of the volume, and they exert a negligible effect on the oil-water flow dynamics. Low-connectivity tiny pores, which account for 64% of all pores in mid-permeability reservoir rock, have an effect on fluid movement because they make up 10% of the volume. After the non-connected pores were excluded, the pores within various oil-bearing strata demonstrated favourable connectivity, although there was a marked different distribution between large and small pores. In ultra-high-permeability reservoirs with optimal permeability, high-connectivity large pores are dominant, accounting for 50%. In contrast, in mid-permeability reservoirs that have weak permeability, the volume proportion of mid- and high-connectivity large pores drops sharply to less than 1%, with a limited proportion of pore numbers. Apparently, a transformation occurs within the pore structure of mid-permeability reservoirs in which high-connectivity small pores dominate, which decreases the overall seepage capacity.

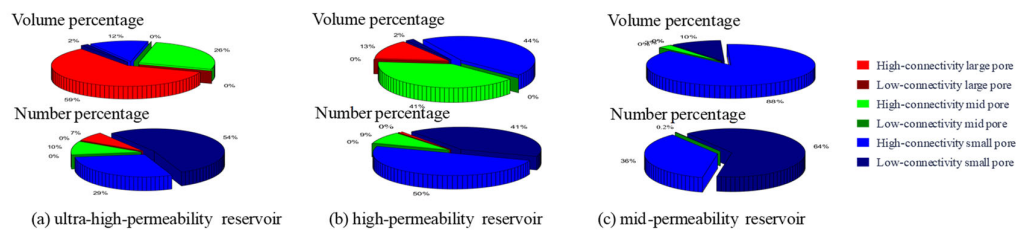


Figure 7. Proportion of different pores in varied permeability reservoirs.

4. Pore Structure Variation Characteristics

4.1. Evolutionary Patterns of Classified Reservoir Pore Structures

By precisely calculating and analysing the pore size distributions based on the digital rock models at various displacement stages, this study uncovered the evolution of pore structures in diverse sandstone samples under the influence of long-term water flooding. After the core samples underwent different displacement stages, the pore size of different permeability cores exhibited a similar distribution trend of pore diameters, with a broad range from 0 μm to 200 μm . However, when the water displacement of oil reached 500 PV, the pore size distribution in the range of 130 μm to 160 μm was moderately enhanced, as shown in Figure 8. As the displacement process advanced, the mean and median pore diameters of all sandstone rocks increased in synchronisation. Notably, the variation amplitude in the pore diameter is greater in ultra-high- and high-permeability reservoirs, with a small variation in pore diameters for mid-permeability rock, as shown in Figure 9. A robust linear correlation was observed between the porosity at different displacement stages and the displacement PV value. As indicated by the study, there is an overall upwards trend in the porosity of rock samples from the ultra-high- and high-permeability sandstone, which suggests an increased connectivity and better permeable capacity of the pore structure during long-term water

flooding. Conversely, the variation in porosity remained stable in mid-permeability rock, as shown in Figure 10.

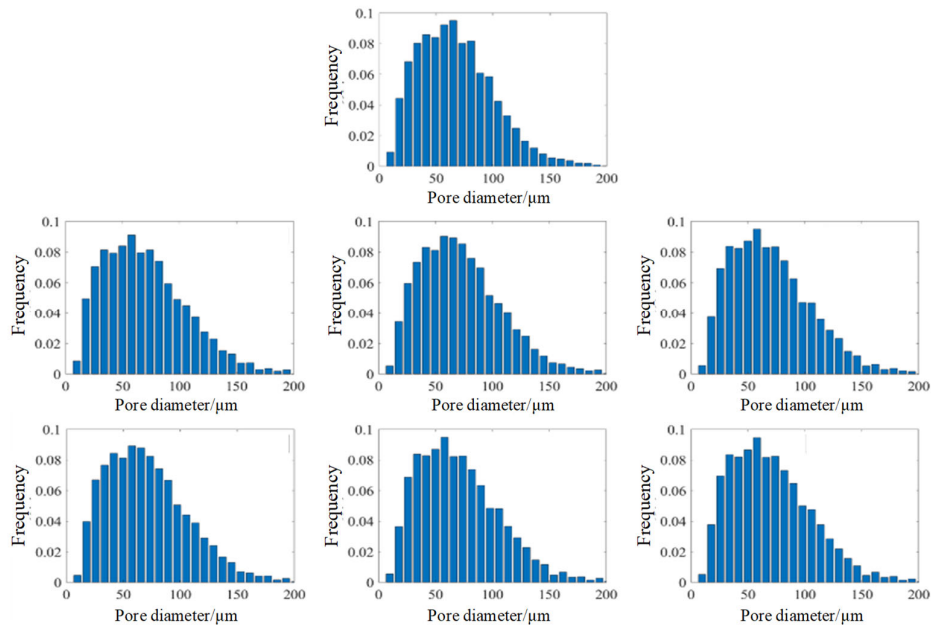


Figure 8. Distribution curves for different displacement nodes (taking Sample 1 as an example).

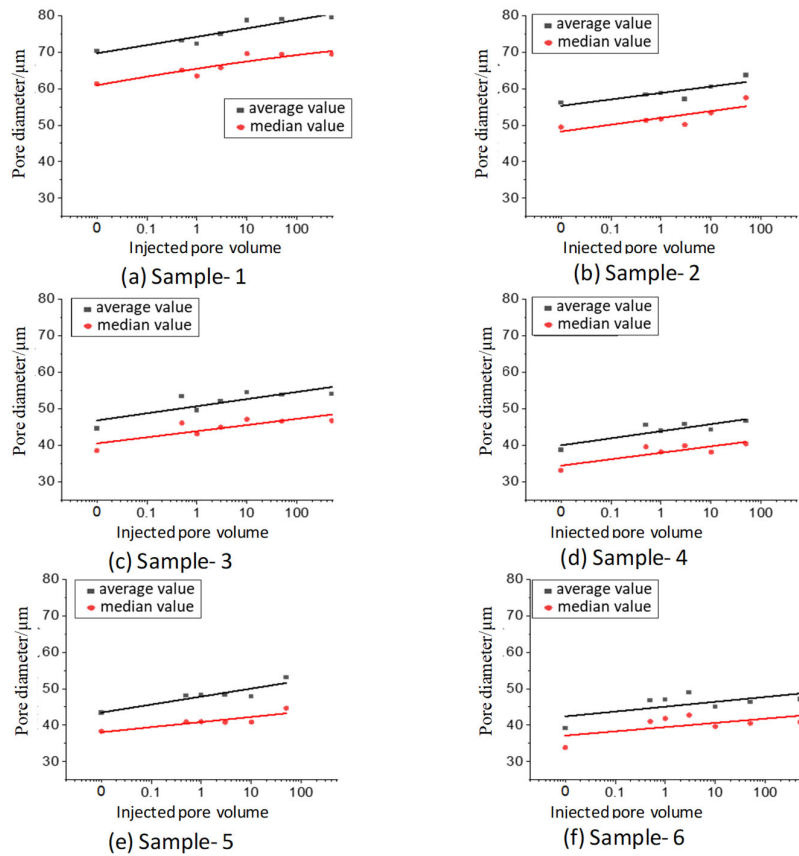


Figure 9. Varied characteristic values for digital distribution of core-pore size at different displacement stages.

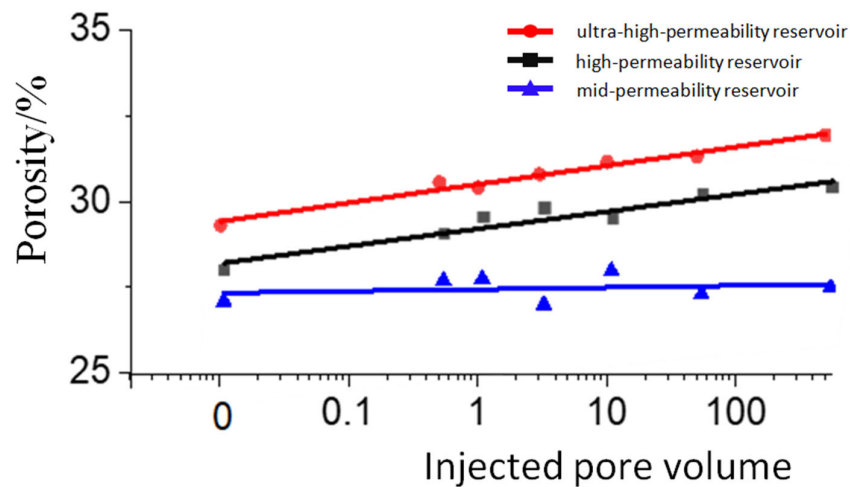


Figure 10. Porosity Variations in reservoir cores under long-term water flooding.

4.2. Variation Characteristics for Different Pore Types

We extracted and analysed the volume and number proportions of different digital rock models with different permeabilities at four critical displacement stages, including initial oil saturation, 0.5 PV, 3.0 PV and 500.0 PV, to reveal the dynamic changes in various pore types.

According to our findings, the micro-heterogeneity within all sandstone rocks intensifies as the displacement process advances. Specifically, a pronounced expansion trend was observed in large- and mid-pores within the rock under long-term water flooding. In ultra-high-permeability and high-permeability rocks, especially, changing pore size is observed in the pore systems above 25 μm , with significant expansion observed in these pores. This expansion directly causes a substantial increase in the permeable capacity of high-connectivity pore spaces and an expansion in the spatial extent of connected pathways, as well as the expanded dominant pores and the intensified preferential flow pathways.

In mid-permeability rock, however, changes in pore size are mainly confined to pore systems between 20 μm and 40 μm , whereas the overall connectivity of pores improves, as shown in Figure 11. During this process, the increasing low-connectivity small pores and their extensive distribution indicate that the connectivity characteristics become complex within the pore space of mid-permeability rock, and there is enhanced interconnectivity among small pores. However, the advantage over large pores in mid-permeability rock does not increase as significantly as in ultra-high- and high-permeability rocks. To a certain degree, the evolution of the pore structure in mid-permeability reservoirs is observed to be unique. These discoveries offer a scientific foundation for the study on the occurrence of micro-residual oil and an optimised strategy for enhancing oil recovery, and they enhance our understanding on the evolved pore structure in various reservoir types during water replacement.

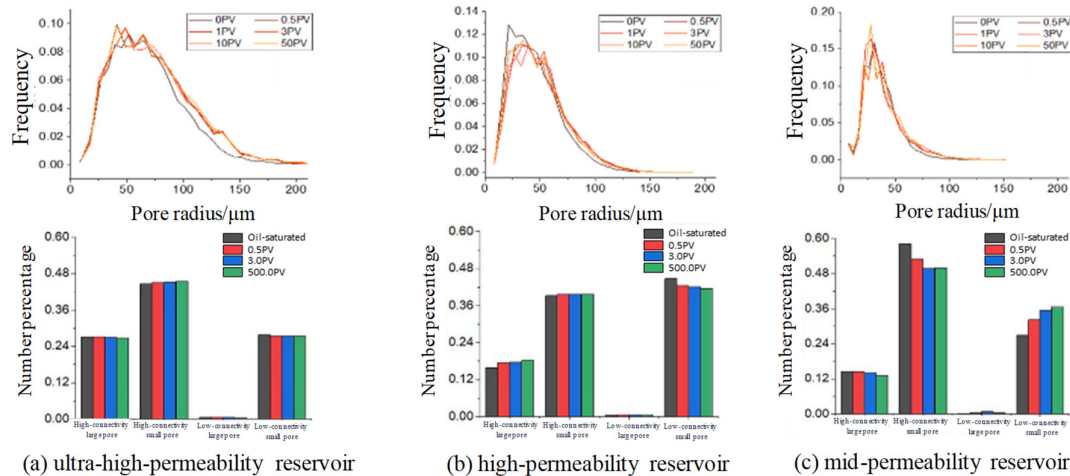


Figure 11. Changes in pore size distribution and proportions of classified pores in different reservoirs under long-term water flooding.

5. Conclusions

- (1) Different pore structures among different reservoir types are identified in mid-high permeability reservoirs. Ultra-high-permeability reservoirs in Daqing oilfields are significantly varied in pore diameter and distribution, featuring extensive pore diameters and high pore-throat connectivity. As permeability decreases, high-permeability rock demonstrates narrower pore diameter ranges with finer throats, whereas mid-permeability rock exhibits numerous smaller pores and throats and the low penetrating quality due to the reduced throat size.
- (2) An evaluation method for pore structure classification is established based on local and global permeable capacity. This study creatively introduces the flow flux area to indicate throat flow capacity. By proposing a classification approach of the complex porous system in rocks, the micro-pore structure is categorised into high-connectivity large pores, low-connectivity large pores, high-connectivity mid pores, low-connectivity mid pores, high-connectivity small pores, and low-connectivity small pores, which further reflects the differences of conveyance strength at pore scale.
- (3) Micro-pore structure differences between sandstone rocks with different permeabilities are presented. Ultra-high- and high-permeability rocks are dominated by mid- and high-connectivity large pores and show robust storage and permeation capabilities, whereas mid-permeability rock is composed of small pores, which indicates that the pore connectivity rely on the effective interconnectivity of these small pores and their permeable capacity declines as the pore type changes.
- (4) The long-term water flooding variation in pore structure is defined for classified sandstone rocks. As water injection increases, the permeable capacity and connectivity of high-connectivity pore spaces are strengthened in ultra-high- and high-permeability rocks. In contrast, despite the overall improvement in connectivity, the mid-permeability rock witnesses an increase in low-connectivity small pores and an expansion in their distribution, which accelerates micro-heterogeneity.

The findings of this study support future research on the micro-residual oil occurrence mechanism at ultra-high water cut late stage and research on optimal strategies for enhancing oil recovery.

Author Contributions: Conceptualization, J. Wu; methodology, Y. Zhu; data curation, Y. He, Q. Wang, and Y. Bao; formal analysis, S. Shao; investigation, R. Li; funding acquisition, J. Guo; writing—original draft preparation, J. Wu and Y. Zhu; writing—review and editing, J. Guo. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The pore network extraction in this work is based on the open-source software local resistance equivalence pore-throat segmentation (LoRePorTS). The library is available at Mendeley Data via <https://data.mendeley.com/datasets/mwsxdb2tpm/3>.

Conflicts of Interest: The authors declare no conflicts of interest.

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