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Characterization of Glutenite Reservoir based on Digital Core Technology: A Case Study of Upper Wuerhe Formation in Mahu Depression

Liu Sai [1], Li Xiang [2,*], Wang Pengli [1] and Wei Yun [1]

[1]Research Institute of Experiment and Detection, PetroChina Xinjiang Oilfield Company, Xinjiang 834000, China
[2]Operation Department, I Rock Technologies, Beijing 100089, China

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Abstract

Exploring the sensitivity of reservoir is the foundation of oil and gas exploration and exploitation. The damage degree of water sensitivity is affected by the clay mineral content and microscopic pore throat structure of the illite/smectite mixed layer. This study proposed a method for reservoir characterization based on digital core technology to reveal the influence of clay mineral content and micropore structure on the production of the illite/smectite mixed layer. The micropore throat characteristic parameters of the reservoir were obtained by using high-resolution micro computed tomography technology. The mineral quantitative analysis technology was used to determine the clay mineral content of the illite/smectite mixed layer. The distribution characteristics, pore radius distribution characteristics, throat length distribution characteristics, shape factor, and coordination number of the clay minerals of the illite/smectite mixed layer of the glutenite reservoir were analyzed. With the Upper Wuerhe Formation in Mahu Depression as an example, the accuracy of the proposed evaluation method was verified on the basis of the production data. Results show that the clay mineral content in the illite/smectite mixed layer and the increase in production are negatively correlated. The output of the area with the clay mineral content less than 30% in the illite/smectite mixed layer gradually increases. High-quality reservoir has the following microscopic pore throat characteristics: the distribution frequency of coordination number 5 exceeds 0.12, the average pore radius is greater than 6.34 μm, and the average throat length is greater than 8.58 μm. This study provides new technical methods and study ideas for understanding the sensitivity characteristics of glutenite reservoirs.

Keywords: Digital core technology, Mahu depression, Upper Wuerhe formation, Gravel reservoir

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1. Introduction

In actual oilfield development, the water sensitivity of reservoir is seriously damaged after water flooding, and the recovery efficiency is low [1]. Different types of clay minerals are found in strata, and 70% of the damage of oil and gas reservoirs is caused by clay minerals. The type and mass fraction of clay minerals determine the oil and gas reservoir development mode [2]. Water-sensitive damage is a common form of reservoir damage in reservoirs with more clay minerals in the illite/smectite mixed layer, which is mainly caused by the incompatibility between the injected water and the formation properties. The high clay mineral content of the illite/smectite mixed layer leads to strong water sensitivity in oilfield development, resulting in the changes of physical properties, such as porosity and permeability of the reservoir, thereby affecting the seepage characteristics. A large number of clay minerals are found in the illite/smectite mixed layer of the reservoir, which is prone to hydration of external fluids. The clay of the illite/smectite mixed layer expands and blocks the seepage channel, resulting in the decrease in porosity and permeability. Reservoir sensitivity damage remarkably affects reservoir properties, which is irreversible and eventually leads to production decline. Therefore, studying the water sensitivity mechanism of glutenite reservoirs in the region and the distribution characteristics of clay minerals in the illite/smectite mixed layer is of great importance to decrease the water sensitivity damage of reservoirs. However, the conventional experimental methods for obtaining clay mineral components have low resolution and long cycle, which cannot meet the study of tight glutenite reservoirs. With the continuous development of digital core technology, the identification efficiency of clay mineral components by Advanced Mineral Identification and Characterization System (AMICS) technology increases, and the high-resolution micro computed tomography (CT) technology is more mature. The quantitative experimental results of the pore throat structure and the clay minerals in the illite/smectite mixed layer can be obtained with high efficiency. The clay mineral contents in dozens of wells and hundreds of illite-montmorillonite mixed layers must be obtained to determine the relationship between the pore throat structures of reservoirs with different clay mineral contents in the illite/smectite mixed layers and oilfield production. The resolution is 1 μm. The high experimental cost and experiments bring great challenges to the study.

Scholars have conducted numerous studies on the distribution characteristics of clay minerals in the illite/smectite mixed layer and the influence of the pore throat structure parameters of the reservoir [4-7]. However, deviation still exists in the relationship between the identification methods of clay minerals in the illite/smectite mixed layer and the oilfield production. Therefore, how to use digital core technology to accurately characterize the distribution characteristics of clay minerals in the

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*E-mail address: xiang.li@irocktech.com

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illite/smectite mixed layer of glutenite reservoir is an urgent problem to be solved.

With the Upper Wuerhe Formation in Mahu Depression as an example, this study established a pore network model combined with high-resolution micro-CT and AMICS technologies to determine the influence of the different mass fractions of clay minerals in the illite/smectite mixed layers on pore throats. The influence of the different mass fractions of clay minerals in the illite/smectite mixed layer on the yield reduction was explored on the basis of mineral quantitative data.

2. State of the art

Scholars have conducted numerous studies on digital core technology and sensitivity evaluation of clay minerals. Amiri [8] and Qaseminejad [9] proposed to use level set and fluid volume methods to establish digital core models, which focus on 2D plane and cannot accurately characterize the 3D pore throat characteristics of reservoirs. Scott [10] used scanning electron microscope imaging tools to reconstruct digital cores. However, the pore throat space in tight reservoirs is complex and changeable, and the extracted central axis has many branches, which affects the accuracy of reservoir characterization. Al-Yaseri [11] evaluated the change in pore throat characteristics of sandstone after salt sensitivity by using nuclear magnetic resonance and CT scanning technologies. Only the change in reservoir micropore structure is characterized, and the influence of mineral distribution characteristics is inaccurately quantified. Hansen [12] investigated the application of an improved parameter algorithm in multipoint geostatistical modeling and compared it with experimental data. However, few parameters can be calculated and simulated by numerical software. To generate high-definition images with higher resolution, Andrew [13] proposed BIGGANs method in 2018, which accurately controls the diversity and fidelity of samples. Kerimov [14] proposed a complete system of theoretical analysis and practical application of digital core physics in the study of digital petrophysics. However, the content of various clay minerals in pore space is not obtained. Luo [15] studied the pore structure characteristics of 3D digital core by using process method. Yu Chunyong [16] proposed the relationship between the gray value and rock density in digital core image to accurately characterize the pore space of reservoir in accordance with the range of gray value. Shi Jianchao [17] used a bilateral noise reduction algorithm to reduce the noise of digital core image and ensured the clear boundary between reservoir pore and rock skeleton. Yang and Li [18-20] combined high-resolution CT and visualization technologies of seepage simulation characterized by microscopic pore throat structure. Chen Jianxun [21] performed a digital core image digitization experiment and found that the noise in the experimental results caused by imaging equipment and external environmental noise obviously affects the accuracy of pore throat identification and extraction. Zhao Jianpeng [22] obtained a high-precision 3D digital core image of reservoir rock through CT image processing and 3D reconstruction, and used digital core technology to analyze rock microstructure and realize 3D visual representation of pore space. Yan Weilin [23] proposed a modeling method for oil saturation of reservoir based on the image of micropore structure analysis of digital core. Liu Ning [24] summarized the equipment operation process and experimental method of digital core CT imaging technology. In terms of micromechanism, Li Junjian [25] conducted a comparative analysis of mineral distribution maps by QEMSCAN and obtained the gray map by micro-CT scanning core slices. The corresponding relationship between CT scanning gray values and different mineral components is established. The causes of the water-sensitive damage of glutenite are explored. The throat damage is more serious than that of pores, which is the main reason for the decrease in permeability.

The above studies use single experimental means to characterize the microscopic pore throat structure of reservoir and sensitivity damage evaluation method. However, few studies focus on the influence of water-sensitive minerals on the microscopic pore structure of reservoir, especially the correlation between the quantitative distribution characteristics of minerals and high-resolution CT scanning results. In this study, AMICS mineral quantitative analysis technology was used to obtain the distribution map of clay mineral content in the plane illite/smectite mixed layer in the study area. Combined with high-resolution micro-CT technology, a 3D rock pore network model was established by using the “maximum sphere” algorithm. The distribution characteristics of clay mineral content in different illite/smectite mixed layers and reservoir pore radius distribution, throat length distribution, shape factor, and coordination number were discussed. The relationship between reservoirs with different clay mineral contents in illite/smectite mixed layer and the oilfield production was analyzed.

The remainder of this study is organized as follows. Section 3 describes the principles and methods of high-resolution micro-CT and AMICS technologies. Section 4 established the digital rock pore network model of glutenite reservoir and analyzes the pore radius, throat length, and coordination number of the reservoir. The characteristic parameters of the dominant reservoir with different clay mineral contents in the illite/smectite mixed layer are obtained. Section 5 summarizes this study and draws relevant conclusions.

3. Methodology

3.1 AMICS mineral quantitative analysis technology

AMICS is a comprehensive automatic mineral petrology detection method [32]. A HITACHI FlexSEM1000 mineral quantitative analysis electron microscope was used. The whole system is composed of a scanning electron microscope with a sample room, two X-ray energy spectrum analyzers, and a set of special software that can automatically acquire, analyze, and process data. The phases were distinguished by using the backscattered electron image of scanning electron microscope, and the composition of minerals was determined by X- ray energy spectrum. Automatic identification of minerals was completed by using Species Identification Program, which was a database of mineral energy spectrum components. Energy spectrum analysis data were compared with the data in this database to identify minerals.

AMICS can scan sample surface by high-energy electron beam accelerated along the preset raster scanning mode and obtain the color map of mineral aggregate distribution characteristics (Fig. 1). The instrument can emit X-ray energy spectrum and provide information of element content at each measuring point. The content of elements can be obtained and transformed into mineral phase by combining the gray scale of backscattered electron image and the intensity of X-ray. AMICS data include a complete set of mineralogical parameters and the calculated chemical analysis results. The quantitative analysis results can be generated for any selected sample, independent particle, and particle with similar chemical composition or structural characteristics (particle size, rock type, etc.).

In this study, 200 samples were examined with AMICS. The scanning sample area is a square with a side length of 10 mm, and the scan resolution is 1 µm.

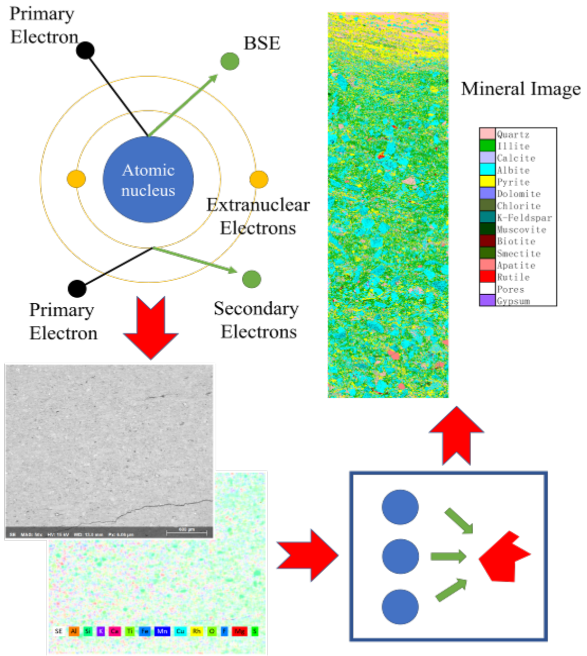


Fig. 1. Schematic of AMICS mineral quantitative analysis technology

3.2 Pore network modeling technology based on CT scanning images

In this study, "Maxima-Ball" method was used to extract and model the pore network structure, which improved the speed of network extraction and ensured the accuracy of pore distribution and connectivity characteristics [29].

The "Maxima-Ball" method fills a series of spheres with different sizes into the pore space of the three-dimensional core image, and a connection is found between the filled spheres with different sizes in accordance with the radius from large to small. The pore structure of the whole core is characterized by overlapping and contained balls. The "pore" and "throat" are established in the pore structure by finding the smallest ball between the local largest ball and the two largest balls in the club, thereby forming the pairing relationship of "pore–throat–pore." The whole club structure is simplified into a pore network structure model with pores and throats as units. "Throat" is a unit that connects two "pores." The number of throats connected to each pore is called the coordination number.

In the process of extracting the pore network structure by using the "Maxima-Ball," the real pores and throats with irregular shapes are filled with regular spheres and then simplified into regular pores and throats in the pore network model. In this process, the shape factor G is used to store the shape features of irregular pores and throats. The shape factor is defined as $G=A/P^2$, where A is the cross sectional area of the pore, and P is the cross sectional perimeter of the pore (Fig. 2).

In the pore network model, the real pores and throats in the rock core are replaced by columns with equal cross sections, and the cross sections are regular geometric bodies, such as triangles, circles or squares. When regular geometry is used to represent the real pores and throats in the rock core, the shape factor of regular geometry should be equal to that of pores and throats. Although the regular geometry is visually different from the real pore space, they have the corresponding geometric characteristics. The triangular and square sections have corner structures, which can effectively simulate the residual water or oil in the two-phase flow, which is similar to the seepage situation of the two-phase flow in the real rock core.

In accordance with the extracted pore network, the pore network size distribution is summarized, and the network connectivity characteristics are analyzed. The pore structure and connectivity of the real rock core can be determined through the statistical analysis of the pore network model. Statistical analysis of the pore model includes: (1) Size distribution (including pore and throat radius distribution, volume distribution, throat length distribution, pore–throat radius ratio distribution, shape factor distribution); (2) Connectivity characteristics (including pore coordination number distribution and Euler connectivity equation curve); (3) Correlation characteristics (correlation analysis between any two physical quantities, such as size, volume, and length of pore and throat).

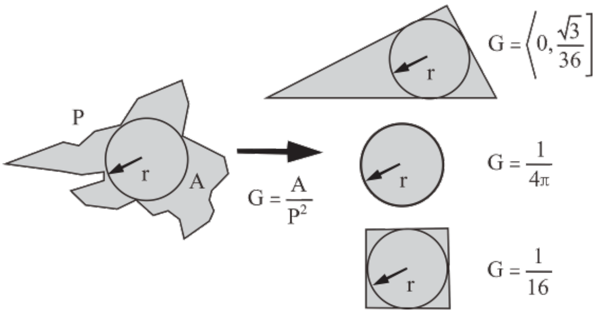


Fig. 2. Pore and throat division and shape factor

4 Result Analysis and Discussion

4.1 Distribution characteristics of clay minerals

The principle of AMICS is to judge the element characteristics of a single point object by using the element spectrogram of characteristic X-ray generated by energy spectrum electron probe in the process of exciting backscattered electrons on the sample surface and then match the mineral names of the same spectrogram in the mineral library in accordance with the distribution interval of the element spectrogram characteristics to determine the 2D mineral distribution characteristics of the whole sample.

In accordance with previous studies, the main problems of reservoir development are great productivity difference, poor effect of conventional water injection, and large degree of reservoir damage. The study results of [7] show that the main reason is that the high content of clay minerals in the illite/smectite mixed layer causes reservoir water sensitivity. Therefore, finding the superior reservoir space with relatively low clay mineral content in the illite/smectite mixed layer and protecting the reservoir in the development stage are urgent problems that need to be solved.

On the basis of the quantitative analysis results of more than 200 rock samples of Wuerhe Formation in 30 wells of Mahu well area 1, the plan of the relative content of the illite/smectite mixed layer in the first member of Upper Wuerhe Formation in the northwest of the study area was obtained. Combined with the sedimentary facies characteristic plan, the relative content of the illite/smectite mixed layer is the highest in the sedimentary microfacies of debris flow close to the material source, followed by fan channel sedimentary microfacies, intertributary bay sedimentary microfacies, and clastic flow sedimentary microfacies. The relative content of sedimentary microfacies in underwater distributary channel is the lowest. Material basis and hydrodynamic environment are important reasons for the change in the relative content of the illite/smectite mixed laye (Fig. 3).

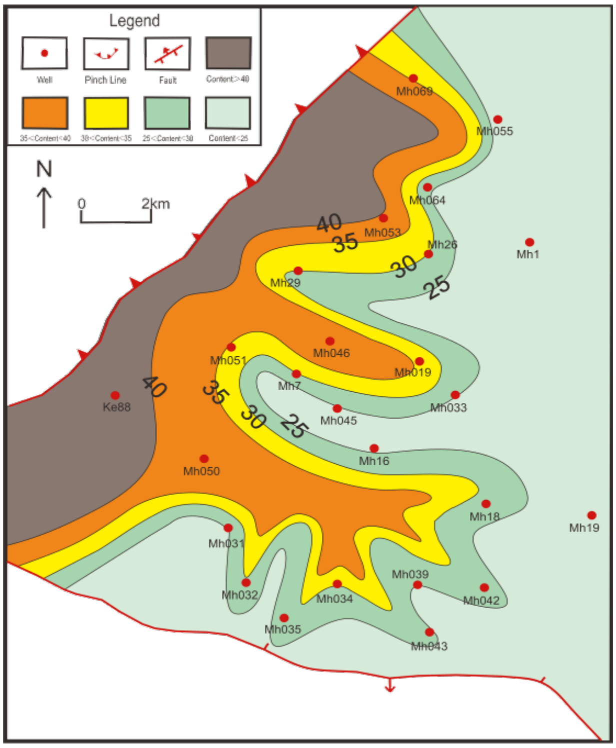


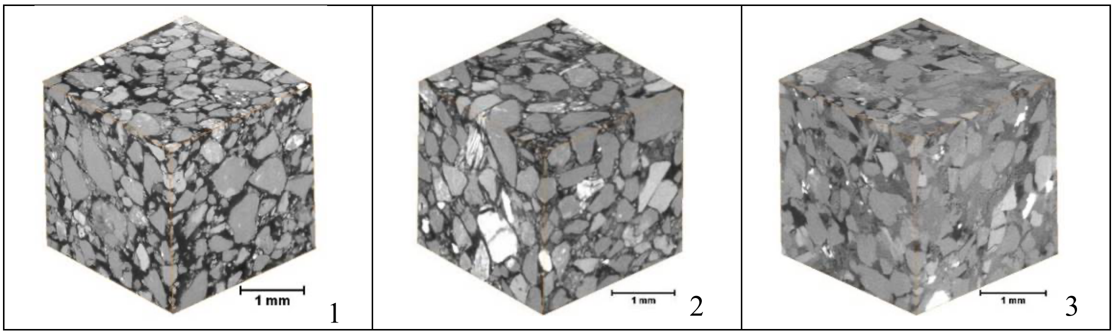
Fig. 3. Plan of Mahu 1 area P_3W_1 illite/smectite interstratified clay minerals

4.2 Characterization of clay-rich mineral glutenite reservoir by CT

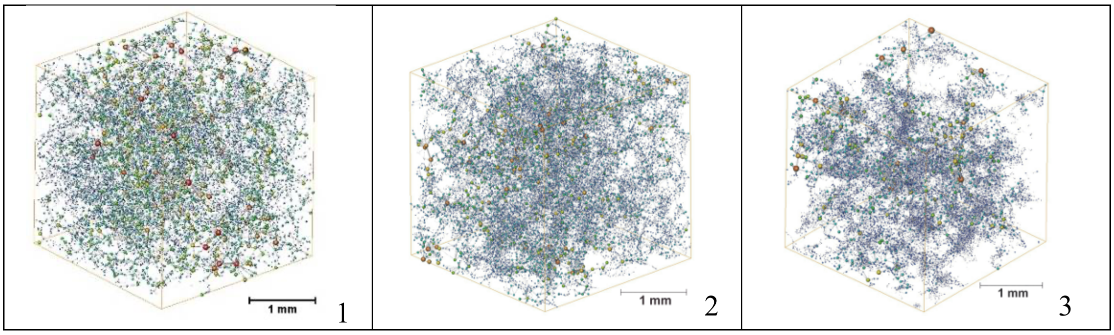
High-resolution micro-CT scanning technology reconstructs a 3D model from a large number of X-ray attenuation images obtained by 360° rotation of images enlarged by objective lenses with different multiples after X-rays pass through the object [8]. High-resolution micro-CT images are internal slices that reflect the real core. A 3D rock structure model is formed after the reconstruction of tens of thousands of 2D slices, which can truly represent the pore types and characteristic parameters of the core. In [9], X-CT technology was used to reconstruct the 3D pore throat structure of rock. In [10], the 3D pore structure information of Berea sandstone was extracted by micro-CT technology, and the 3D pore structure characteristics were studied. In [11], the 3D pore network model was numerically simulated by using the Maxima Ball method.

(1) Multidimensional reconstruction of core pore throat structure

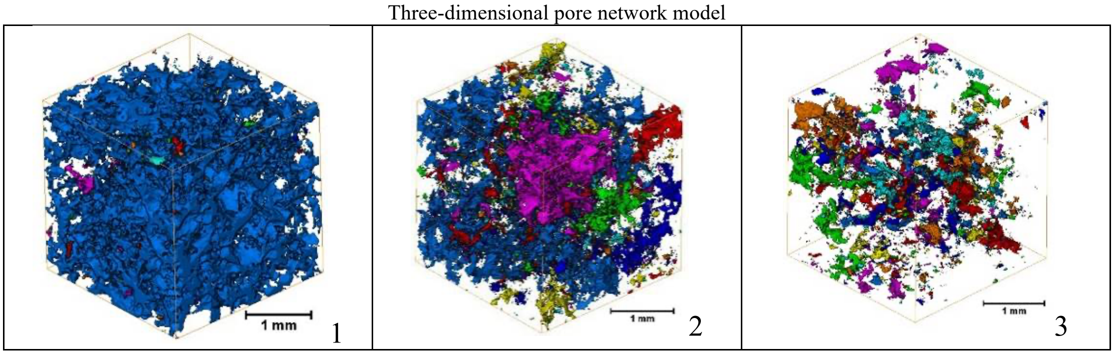
The 3D pore network model of the cores was obtained by reconstructing the CT scanning samples of the three cores of Upper Wuerhe Formation in Mahu Well Area 1. Sample 1 is a sedimentary microfacies sample of underwater distributary channel, with a total clay content of 15%. Sample 2 is a clastic flow sedimentary microfacies sample with a total clay content of 28%. Sample 3 is a fan channel sedimentary microfacies sample with a total clay content of 37%. The reconstructed pore network model was "thresholded" by using PerGeos rock modeling software, and the particle facies and pore facies were identified and extracted. The "Maxima Ball" method was used to extract and calculate the pore throat structure [13]. The pore characteristic parameters, such as pore radius distribution curve, pore shape characteristic distribution curve, and pore matching throat number, were obtained, and the micron-submicron 3D pore structures of the three samples were characterized (Fig. 4).



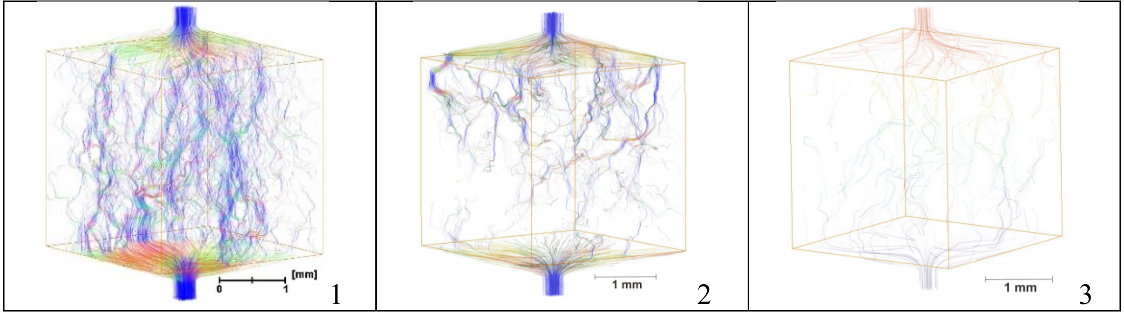
Three-dimensional rock model



Three-dimensional pore network model



Three-dimensional connected pore model



Three-dimensional absolute permeability model

Fig.4. Core CT pore network model

(2) Seepage simulation based on micro-nano pore throat connectivity analysis

The calculated results of the pore throat characteristic parameters can reflect the distribution characteristics of the pore throat size of the core samples.

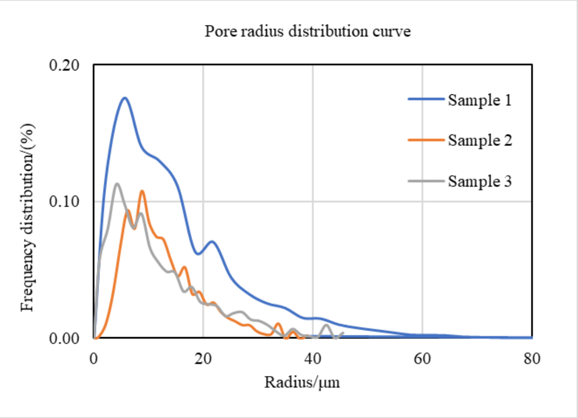
In accordance with the distribution curve of the pore throat radius, the average pore radius of sample 1 is 10.31 µm, and the main distribution interval of pore radius is 2–44 µm. The average pore radius of sample 2 is 9.38 µm, and the pore radius is mainly 2–19 µm. The average pore radius of sample 3 is 6.34 µm, and the pore radius is 0.9–14 µm. On the whole, the pore radius of glutenite sample 1, which belongs to the sedimentary microfacies of underwater distributary channel, is the largest.

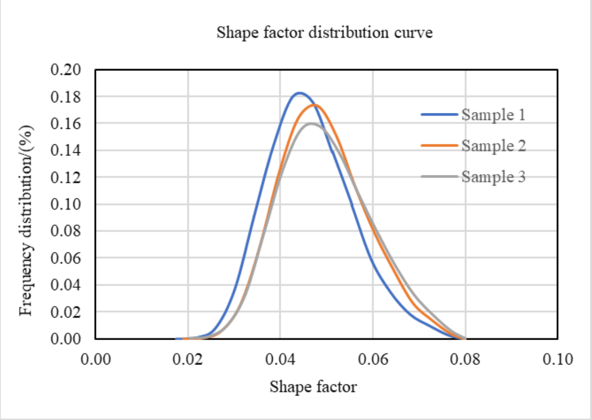
In accordance with the shape factor distribution curve, the three samples belong to micron-sized spindle-shaped and triangular pore throat structures.

As shown in the distribution curve of the throat length, the average throat length of sample 1 is 23.93 µm, and the main distribution range of the throat length is 5–53 µm. The average throat length of sample 2 is 15.87 µm, and the main distribution range of the throat length is 2–21 µm. The average throat length of sample 3 is 8.58 µm, and the main distribution range of the throat length is 1.7–12 µm. Glutenite sample 1, which belongs to the sedimentary microfacies of underwater distributary channel, has the largest throat length.

In accordance with the histogram analysis of coordination number distribution, the number in the distribution range greater than 5 is the highest for sample 1, which indicates that the number of throats matched by each pore in sample 1 is the highest, followed by sample 2, and the number of throats matched by sample 3 in each pore is the lowest. The more the throats matched by pores, the better the connectivity of the sample, and more seepage channels are available for crude oil.

The absolute permeability of the core sample in a certain direction was calculated and simulated by means of computational fluid dynamics simulation (Table 1), which was visually displayed by PerGeos software (Fig. 5).





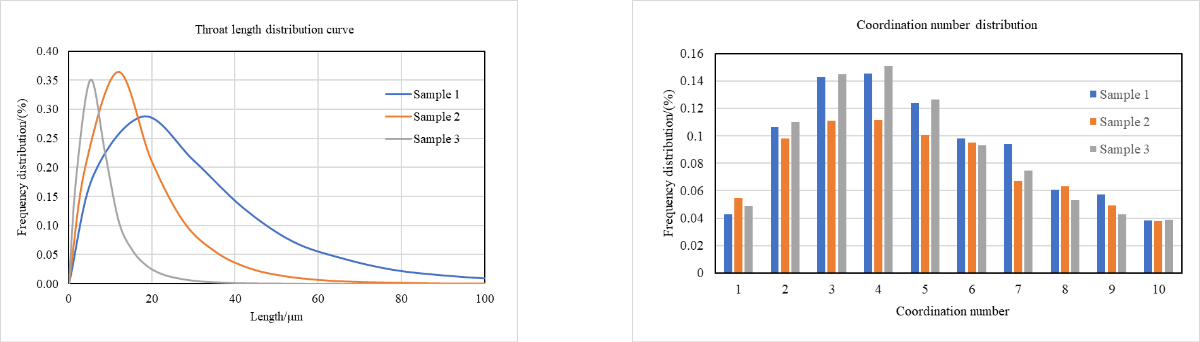


Fig. 5. Calculation results of core pore throat characteristic parameters

Table 1. Calculation results of core porosity and permeability

Serial number	Sedimentary microfacies	Relative content of illite/smectite layer (%)	Porosity (%)	Permeability (mD)
Sample 1	Underwater distributary channel	15.23	24.1	6393.5
Sample 2	Debris flow	28.01	15.9	1203.3
Sample 3	Fan-shaped channel	37.42	9.0	159.2

In accordance with the calculation results, sample 1, which belongs to the sedimentary microfacies of underwater distributary channel, has the best storage space. Under the influence of gravity flow sedimentary environment, the intergranular pores of clastic flow sedimentary microfacies samples are partially filled with clay minerals, which reduce the storage space of the samples and destroy the seepage channel of the reservoir. Sample 3 belongs to fan-shaped channel sedimentary microfacies. The material supply is more sufficient, and the hydrodynamic force is stronger. A large amount of clay minerals block the reservoir seepage channel, seriously damage the storage space of the core sample, and decrease the porosity and permeability.

4.3 Evaluation of the application effect of glutenite reservoir based on the distribution characteristics of clay minerals

The water sensitivity phenomenon of Upper Wuerhe Formation in Mahu Well Area 1 is serious [15]. In the development and production stage, foreign fluids (such as fracturing fluid or oil displacement polymer) enter the formation, and hydrophilic clay minerals swell, disperse, and migrated, thereby destroying the seepage channel of crude oil and leading to the decrease in permeability. The high relative content of clay minerals in the illite/smectite mixed layer is the main reason for the strong water sensitivity of reservoir. The clay expands and blocks the effective seepage channel of the reservoir after the occurrence of water sensitivity phenomenon, resulting in ineffective development measures, such as hydraulic fracturing, large difference in productivity, and a remarkable decrease in output after water injection.

In accordance with the profile map of Mahu well area 1, the output of the same layer is different, which is caused by the difference in clay mineral content in the illite/smectite mixed layer.

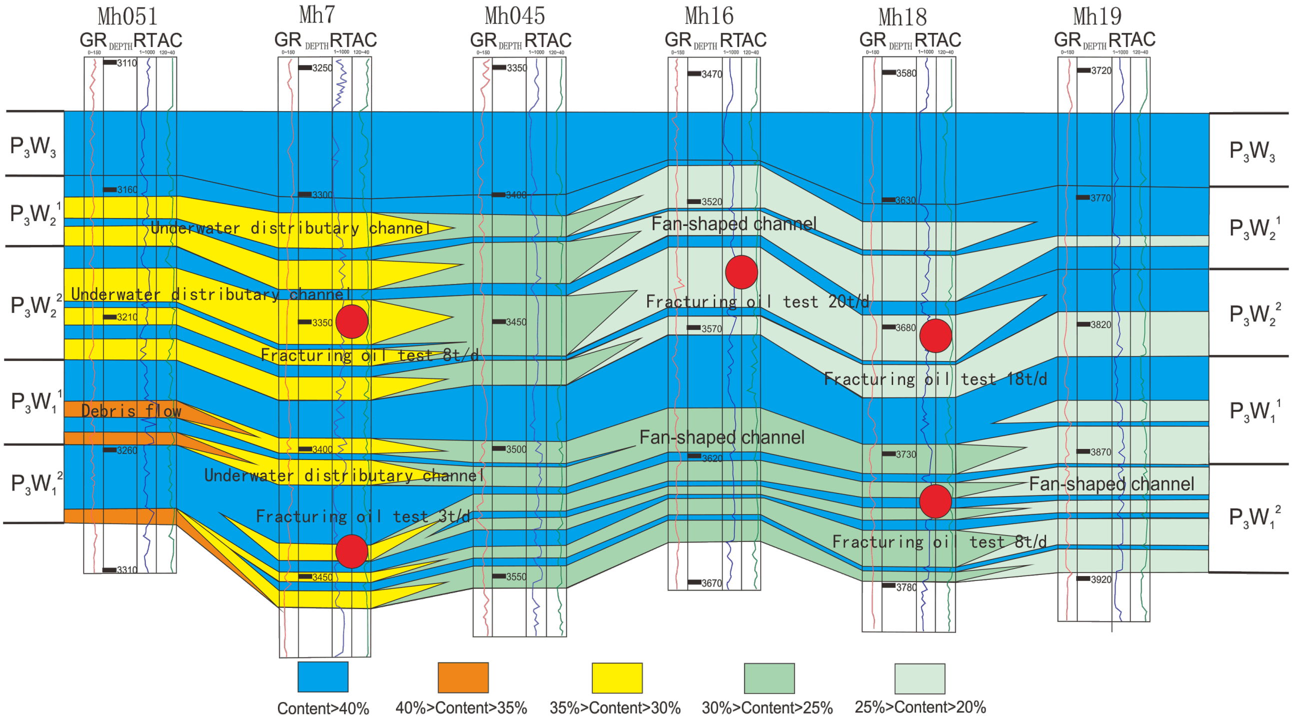


Fig.6. Clay content profile map of Mahu 1 area

The relative content of the illite/smectite mixed layer is high in the sedimentary microfacies of the sector main channel, which affects the fracturing oil testing effect. The relative content of the illite/smectite mixed layer gradually decreases, and the fracturing effect is remarkably improved after the transition to the sedimentary microfacies of underwater distributary channel. The relative content of the illite/smectite mixed layer far from the source position gradually decreases, and the fracturing oil testing effect gradually improves.

The oil testing results are poor in the areas with relatively high illite/smectite mixed layer, especially in the reservoirs with debris flow sedimentary microfacies and fan channel sedimentary microfacies in the gravity flow sedimentary environment. The relative content of the illite/smectite mixed layer is relatively low, which belongs to the sedimentary microfacies reservoir of underwater distributary channel. The oil testing results are good, and stable industrial oil flows can be obtained (Fig. 6).

5. Conclusions

The relationship between the glutenite reservoir and the oil field production in the water-sensitive formation was explored by using digital core technology. The regional distribution characteristics of clay minerals in the illite/smectite mixed layer were obtained by using high-resolution micro-CT technology. The distribution characteristics of pore radius and throat length, coordination number, and shape factor of glutenite reservoir were analyzed by means of numerical simulation and experiment. The conclusions are summarized as follows:

Mineral quantitative analysis technology was used to determine the spatial distribution characteristics of the relative content of the illite/smectite mixed layer in the study area. The closer the denudation line, the more abundant the material supply, the stronger the hydrodynamic force, and the higher the relative content of the illite/smectite mixed layer.

The pore throat characteristic parameters of glutenite reservoir were obtained by using high-resolution micro-CT technology. The microscopic pore throat characteristics of high-quality reservoir are as follows: the distribution frequency of coordination number 5 exceeds 0.12, the average pore radius is greater than 6.34 μm, and the average throat length is greater than 8.58 μm.

In the oilfield development block, the spatial distribution characteristics of the illite/smectite mixed layer should be emphasized. The wells and intervals with low content of illite/smectite mixed layer should be selected for fracturing and water injection to enhance oil recovery. The potential effect of water sensitivity on the later stage of oilfield production can be avoided.

This study proposed a new method for characterizing glutenite reservoir by combining digital core, high-resolution micro-CT, and AMICS technologies. The study results are more in line with the field practice and have certain reference value for studying reservoir sensitivity characteristics. Given that other influencing factors in actual oilfield production are ignored, the proposed theory is only applicable to the water sensitivity damage of reservoir caused by the illite/smectite mixed layers. Therefore, the proposed method will be improved by combining other factors that influence oilfield production in the future study to more accurately understand the sensitivity characteristics of glutenite reservoir.

References

1. Li, J. J., Cheng, B.Y., Liu, R.J., “Microscopic mechanism of water sensitivity of pore-scale sandy conglomerate based on digital core”. *Acta Petrolei Sinica*, 40(5), 2019, pp.595-603.
2. Yu,J.W.,Wei,F.,Wen,H.G., “Analysis on distribution of illite/ montmorillonite mixed layer and its controlling factors in the Toutunhe formation of Fudong slope area of Junggar basin”. *Journal of Henan Polytechnic University (Natural Science)*, 38(6), 2019, pp.39-46.
3. Jiang, H. Q., “*Fundamentals and methods of reservoir engineering*”. Beijing: Press of the China University of Petroleum, China, 2006, pp.22-27.
4. Ma,Y.P., Zhang,X.W., Zhu,K., “Sedimentary characteristics and controlling factors of fan-delta of the Upper Urho Formation of Permian in Mahu Sag”. *Lithologic Reservoirs*, 33(1), 2021, pp. 58-70.
5. Chang,T.Q., Zhao,B., Liu, K., “Study on Oil Reservoir Identification Standard of Lower Wuerhe Formation in Mahu-1 Well Area”. *Xinjiang Geology*, 39(2), 2021, pp. 271-274.
6. Ma,C., Wang,J., Lian,L., “Application of CT Scanning in Study on Pore Features of Mud Rich Reservoir: A Case of Well block Ma-18 in Mahu Sag”. *Xinjiang Petroleum Geology*, 40(6), 2019, pp. 737-744.
7. Guo,X., “*Study on the Petrologic Characteristics and Evaluation of the Pyroclastic Rock Reservoir-Taking Tanan Depression of Tamtsag Basin for Example*”. Master thesis of Jilin University, China, 2013, pp. 27-30.
8. Amiri,H.A.,Hamouda, A. A.,“Pore-scale modeling of non-isothermal two phase flow in 2D porous media: Influences of viscosity, capillarity, wettability and heterogeneity”. *International Journal of Multiphase Flow*, 61, 2014, pp.14-27.
9. Qaseminejad,R.A., “*Modelling multiphase flow through micro-CT image of the pore space*”. Master thesis of Imperial College London, U.K., 2013,pp.135.
10. Scott, G., Wu,K., Zhou, Y., “Multi-scale image-based pore space characterization and pore network generation: Case study of a North Sea sandstone reservoir”. *Transport in Porous Media*, 129(3), 2019, pp. 855-884.
11. Al-Yaseri, A.Z., Lebedev,M., Vogt,S.J., “Pore scale analysis of formation damage in Bernheimer sandstone with in-situ NMR and micro-computed tomography experiments”. In: Journal of Petroleum Science and Engineering, 129, 2015, pp:48-57.
12. Hansen,T. M. , Vu,L. T., Mosegaard,K., “Multiple point statistical simulation using uncertain (soft) conditional data”. *Computers & Geosciences*, 114, 2018, pp. 1-10.
13. Andrew, B., Jeff, D., Karen, S., “Large Scale GAN Training for High Fidelity Natural Image Synthesis”. In: *Paper Presented at the International Conference on Learning Representations*, New Orleans, USA: IEEE, 2019, pp.20-26.
14. Kerimov, A., Mavko, G., Mukerji, T., “The influence of convex particles’ irregular shape and varying size on porosity, permeability, and elastic bulk modulus of granular porous media: Insights from numerical simulations”. *Journal of Geophysical Research:Solid Earth*, 123(12), 2018, pp.563-582.

15. Luo, M., Glover, P. W. J., Zhao, P., “3D digital rock modeling of the fractal properties of pore structures”. *Marine and Petroleum Geology*, 122, 2020, pp. 104706.
16. Yu,C.Y., “Pore structure characteristics and formation mechanism of Chang8 member tight sandstone reservoir in Fuxian area”. *Unconventional Oil & Gas*,8(1), 2021, pp.15-24.
17. Shi, J. C., Qu, X. F., Lei, Q. H., “Distribution characteristics and controlling factors of movable fluid in tight oil reservoir:A case study of Chang 7 reservoir in Ordos Basin”. *Natural Gas Geoscience*, 27(5), 2016, pp. 827-834.
18. Yang, Y., Yang, H., Tao, L., “Microscopic determination of remaining oil distribution in sandstones with different permeability scales using computed tomography scanning”. *Journal of Energy Resources Technology,* 141(9), 2019, pp. 092903.
19. Li, K., Kong, S., Xia, P., “Microstructural characterization of organic matter pores in coal-measure shale”. *Advances in Geo-Energy Research,* 4(4), 2020,pp.372-391.
20. Sun, S., Zhang, T.,“A 6M digital twin for modeling and simulation in subsurface reservoirs”. *Advances in Geo-Energy Research*, 4(4), 2020, pp.349-351.
21. Chen, J. X., Yang, S. L., Li, J. J., “Study on percolation characteristics and permeability lower limit of low permeability sandstone gas reservoir”. *Science Technology and Engineering*, 20(20), 2020, pp.157-162.
22. Zhao, J. P., Cui, L. K., Chen, H., “Quantitative Characterization of Rock Microstructure of Digital Core Based on CT Scanning”. *Geoscience*, 34(6), 2020, pp. 1205-1213.
23. Yan, W. L., Zhang, H. B., Zheng, J. D., “Digital core-based modeling method and application of oil saturation in Gulong shale oil reservoir”. *Petroleum Geology & Oilfield Development in Daqing*, 41(3), 2022, pp. 92-102.
24. Liu, N., Fang, Z. W., “Digital Core Modeling and Parameter Characterization Based on Micro-CT Imaging”. *Industrial Technology Innovation*, 8(4), 2021, pp. 48-53.
25. Li, J. J., Cheng, B. Y., Liu, R. J., “Microscopic mechanism of water sensitivity of pore-scale sandy conglomerate based on digital core”. *Acta Petrolei Sinica*, 40(5), 2019, pp. 594-603.
26. Liu, X. J., Xiong, J., Liang, L. X., “Study on the characteristics of pore structure of tight sand based on micro-CT scanning and its influence on fluid flow”. *Progress in Geophysics*, 32(3), 2017,pp. 1019-1028.
27. Sakdinawat, A., Attwood,D., “Nanoscale X-ray imaging”. *Nature Photonics*, 267(4), 2010, pp. 840-848.
28. Bera, B., Mitra, S. K., Vick, D., “Understanding the micro structure of Berea sandstone by the simultaneous use of micro-computed tomography（micro-CT）and focused ion beam-scanning electron microscopy（FIB-SEM）”. *Micron*, 42(5), 2011, pp. 412-418.
29. Dong,H., “*Micro-CT imaging and pore network extraction*”. Doctoral Dissertation Imperial College, U.K., 2007, pp.101-110.
30. Yang, S. H., “*Study on the Adaptive and Fast Algrithm of Gray Scale Image Thresholding*”. Master thesis of Chongqing University, China, 2014, pp. 50-102.
31. Li, Q., Wu, J. B., Zhou, W., “Study on Physical Properties of Tight Sandstone Conglomerate Reservoir in Urho Formation in Mahu 1 Well Area”. *Science Technology and Engineering*, 21(14) 2021,pp.5778-5783.
32. Liu, N., Tao, D. P., “Mineralogical analysis of collophane in Yunnan using AMICS and exploration of difficult flotation mechanisms”. *Chinese Journal of Engineering*, 43(4), 2021, pp. 503-511.