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Research highlight

Characterization of pore systems in fine-grained carbonate rocks using digital core technology

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Abstract:
The characterization of pore systems in fine-grained carbonate rocks faces numerous challenges due to the significant complexity of microscopic features, including a variation of micro- and nanoscale pore sizes and the complex pore-throat distribution. In this work, digital core technology was adopted to characterize the pore systems of lacustrine fine-grained carbonate rocks in the Yingxi area of Qaidam Basin. The simulated results indicated that the pore types predominantly contain intercrystalline and dissolution pores. The former exhibit high porosity but extremely low permeability and are primarily developed in bedded dolostones. Conversely, the latter show relatively higher permeability, predominantly developed in bedded calcareous dolostones. The elevated dolomite content provides the material basis for the development of intercrystalline pores, while the extremely small throat radius constrains the fluidity of this pore system. In addition, the dissolution has a great impact on improving the permeable capability of intercrystalline pore system via increasing the radius and specific surface area of pores and throats.

1. Introduction

Carbonate rocks are prone to dissolution, migration and reprecipitation due to their high chemical activity (Morse and Arvidson, 2002). This yields significant differences in the pore system characteristics compared to conventional clastic rocks, mainly in the diverse pore types, multi-scale pore sizes, and complex pore-throat distribution (Regnet et al., 2019). The significant complexity of pore systems in carbonate rocks leads to substantial challenges in their characterization (Lønøy, 2006; Anovitz and Cole, 2015), which is particularly evident in fine-grained carbonate rocks where the main pore diameter distribution is in the micro-nano range (Pan et al., 2021). The reservoir properties of fine-grained carbonate rocks in the Qaidam Basin exhibit the above heterogeneity (Li et al., 2022Li et al., 2022), likely governed by variations in the pore system development. Therefore, conducting high-resolution characterization of the pore system in fine-grained carbonate rocks in this region is beneficial for reservoir prediction in petroleum exploration. Digital core technology combined with numerical modeling and quantitative analysis is capable of realizing the digitized quantitative characterization and evaluation of three-dimensional (3D) multi-scale pore structure in tight rocks (Knackstedt et al., 2004; Liu et al., 2022). This in fact has become a key research field regarding the internal structure of fine-grained rocks (Tang et al., 2016; Ruspini et al., 2021).

In order to investigate the developmental characteristics

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Table 1. Petrological and geochemical information of samples.

Parameters	YX-1	YX-3
Dolomite content (%)	66.7	47.3
Calcite content (%)	6.9	13.1
Porosity (%)	10.2	7.62
Permeability (mD)	0.014	0.02

and formation mechanisms of pore systems in fine-grained carbonate reservoirs, this study employed digital core technology on the fine-grained carbonate rocks from the upper member of the Xiaganchaigou Formation (E_3^2) in the Yingxi area of the Qaidam Basin.

2. Samples and methods

For digital core reconstruction and pore system simulation, two fine-grained carbonate rock samples with significant differences in mineral composition and porosity were selected. Among them, YX-1 is bedded dolostone with elevated dolomite content and high porosity, while YX-3 is bedded calcareous dolostone characterized by reduced dolomite content and lower porosity (Table 1).

2.1 Digital core reconstruction technology

Computed tomography (CT) can detect the composition and structure of non-transparent objects without causing damage (Wang, 2009). Due to the different densities of rock components, the X-ray absorption coefficients are different, so that the skeleton and pore space of the rock can be distinguished. CT was used to perform the 3D digital core reconstruction by iRock Technologies Co., Ltd. according to the steps from Li et al. (2023). All CT image processing was realized by Avizo software. Considering the multiscale pore system observed in the fine-grained carbonate rocks of E_3^2, this study employed micro-CT and nano-CT for the analysis of pore systems at different scales.

2.2 Pore network model extraction

Pore network model (PNM) refers to a structured pore and throat model extracted from binarized 3D core images through a specific algorithm. Simultaneously, this pore structure model preserves the pore distribution characteristics and connectivity features of the original 3D core image. The maxima ball algorithm currently stands as a primary method for constructing PNM in digital core analysis (Blunt et al., 2013); it not only enhances the speed of network extraction but also ensures the accuracy of pore distribution and connectivity features in 3D space (Denney, 2008).

3. Results

Digital core reconstruction revealed the development of two distinct pore systems with different origins in samples YX1 and YX3, namely, intercrystalline pores in YX1 and dissolution pores in YX3. The pore system simulation results for two samples with typical pore systems are illustrated in Table 2.

Table 2. 3D pore network model parameters.

Parameters	YX-1	YX-3
Specific surface area of pores (m^2/g)	0.631	1.125
Specific surface area of throats (m^2/g)	0.486	0.736
Peak pore radius (μm)	0.072	12
Peak throat radius (μm)	0.032	1.3
Ligand number	1.66	1.295
Total porosity (%)	11	8.26
Absolute permeability (mD)	0.0037	0.15

3.1 Intercrystalline pore system

In sample YX-1, mainly intercrystalline pores were observed; the mineral crystal boundaries around the reservoir space were flat and regular, indicating that this rock is not affected by dissolution (Fig. 1(a) and 1(b)). These intercrystalline pores generally had a diameter of less than 1 μm (Fig. 1(c), Table 2). Meanwhile, the simulated pore-throat parameters indicated the high porosity (11%) and exceptionally low permeability (0.0037 mD). Given the high dolomite content in this pore system, it features high brittleness, rendering it suitable for extensive fracturing. Consequently, it represents a crucial target for unconventional oil and gas exploration and development.

3.2 Dissolution pore system

The digital core reconstruction results of sample YX-3 indicated that the high level of karstification greatly enhanced the storage capacity, with noticeable pore expansion. The pore radius reached the micron level, and the pore morphology was transitioning from angular to irregular (Fig. 2). The PNM is significantly influenced by the dissolution processes, primarily featuring micrometer-scale dissolution pores. Moreover, the simulated pore-throat parameters also quantitatively proved the improvement effect of dissolution on the pore system. Compared with YX-1, YX-3 exhibited higher pore-throat radius and specific surface area (Table 2). Specifically, the permeability of the dissolution pore system was significantly enhanced to 0.15 mD, greatly augmenting the permeable capacity of the original matrix pore system.

4. Discussion

Both pore network simulations and conventional petrophysical tests reveal that bedded dolostones with high dolomite content exhibit high porosity and extremely low permeability. According to Liu et al. (2021), the development of intercrystalline pores in the study area occurred during the penecontemporaneous dolomitization process. Therefore, the higher dolomite content serves as a material basis for the abundant development of intercrystalline pores. Additionally, due to the inherently smaller diameter of this type of pore system, the throats are even smaller, potentially resulting in

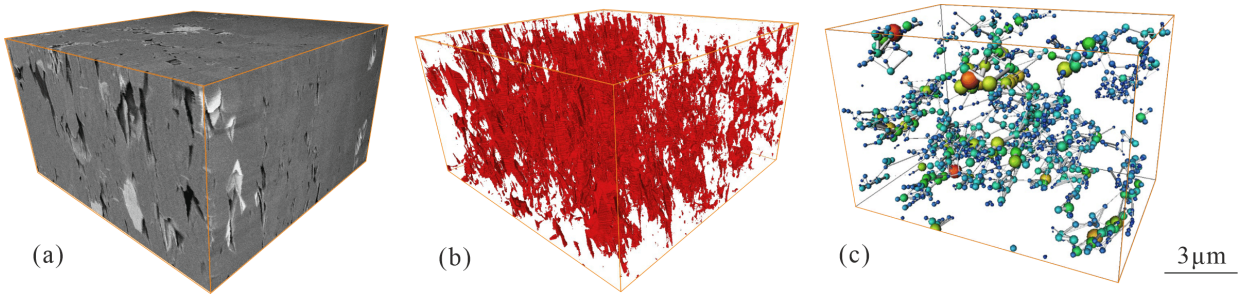

Fig. 1. Digital core reconstruction and pore system simulation of YX1. (a) Digital core body reconstructed by imaging, (b) spatial distribution of pore skeleton, (c) pore network model.

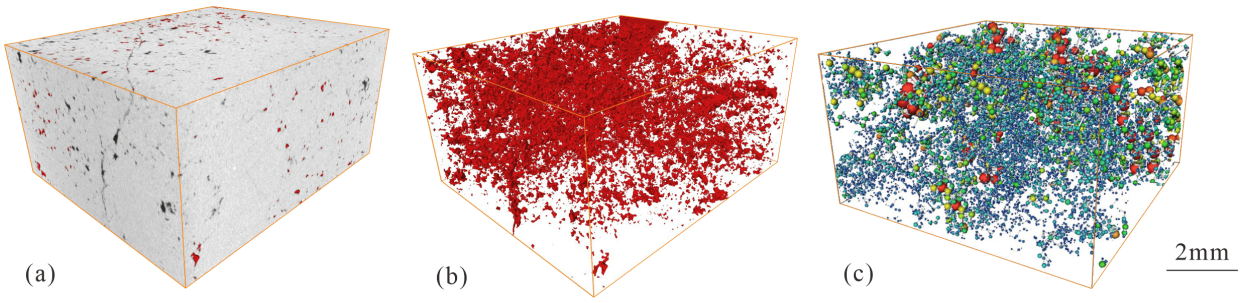

Fig. 2. Digital core reconstruction and pore system simulation of YX3. (a) Digital core body reconstructed by imaging, (b) spatial distribution of pore skeleton, (c) pore network model.

extremely low permeability compared to that in pore systems dominated by dissolution pores.

For the dissolution pore system, the simulated results indicated that dissolution processes have great degrees of improvement effect on the permeable capability of the original matrix pore, and both the radius and specific surface area of the pore-throat system show a certain increase. Guo et al. (2019)'s study on the characteristics and formation mechanism of carbonate rocks of E_3^2 in the Yingxi area provides theoretical support for our experimental findings, which suggests that the diagenetic environment of sedimentary-penecontemporaneous period controls the development of matrix pores, forming the material basis for the formation of high-quality reservoirs. At the same time, the substantial discharge of organic acids and CO_2 during the peak period of oil generation exerts a significant solubilization effect on the widely developed intercrystalline pores, which can effectively optimize the pore-throat structure and improve the connectivity of intercrystalline pores.

5. Conclusions

Based on digital core technology, the pore systems of fine-grained carbonate rocks in the Xiaganchaigou Formation were characterized in this study by the combination of high-resolution visualization and digitization. The main conclusions and insights gained can be summarized as follows:

1) Fine-grained carbonate rocks from the Xiaganchaigou Formation predominantly exhibit two types of pores: intercrystalline pores and dissolution pores.
2) The intercrystalline pore system with high porosity and extremely low permeability is primarily developed in bedded dolostones. The elevated dolomite content provides the material basis for the development of intercrystalline pores, while the extremely small throat radius constrains the fluidity of this pore system.
3) Dissolution greatly promotes the permeable capability of the original matrix pore system, achieved by increased pore-throat radius and specific surface area.

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Conflict of interest

The authors declare no competing interest.

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