



Digital characterization and fractal quantification of the pore structures of tight sandstone at multiple scales

Wei Lin^{1,2} · Zhenkai Wu^{3,4} · Xizhe Li⁴ · Zhengming Yang⁴ · Mingyi Hu¹ · Denglin Han^{1,2} · Chenchen Wang² · Jizhen Zhang²

Received: 24 October 2021 / Accepted: 11 April 2022 / Published online: 8 May 2022
© The Author(s) 2022

Abstract

Pore structures determine reservoir storage capacity, control rock transportation characteristics and represent microscopic properties of the rock. Therefore, the characterization and quantification of the pore structures of tight oil and gas reservoir are of primary importance for quality evaluation and the successful production of these unconventional resources. In this study, we obtained X-CT images with two resolutions of the same tight sandstone and studied the pore structures and heterogeneity of tight sandstone using digital rock technology combined with fractal theory. In traditional Euclidean space, digital image analysis shows that the pore structure of tight sandstone is mainly flat, isolated pores that occupy a large number ratio in high-resolution images and a large volume ratio in low-resolution images. Most seepage channels are mainly composed of large pores. The porosity analysis of 2D and 3D suggests that the representative elementary volume of low-resolution digital rock is 300 voxels, and the axial heterogeneity of tight sandstone is stronger than the bulk heterogeneity. In non-Euclidean space, fractal characterization parameters indicate that the fractal dimension (FD) of low-resolution digital rock is 2.6548, that of high-resolution digital rock is 2.6194, and the FD of tight sandstone is insensitive to imaging resolution. The lacunarity of high-resolution digital rock is obviously larger than that of low-resolution digital rock, which suggests that lacunarity can be used to analyze the heterogeneous structures with similar FD of tight sandstone precisely.

Keywords Tight sandstone · Pore structure · X-CT · Heterogeneity · Fractal dimension · Lacunarity

Introduction

With the rapid advances of horizontal drilling and hydraulic fracturing, tight oil and gas, as a major alternative to conventional hydrocarbon resources, have received significant

attention all around the world (Zhao et al. 2015; Li et al. 2020a, 2020b; Liu et al. 2017; Shen et al. 2019). Unlike conventional reservoirs, however, given the characteristics of tight reservoirs, there are many challenges that need to be addressed (Radwan et al. 2022, 2021). For instance, tight oil and gas generally have no natural industrial productivity, and their present output mainly relies on large-scale hydraulic fracturing, which has the features of high initial production, rapid production decline, and low recovery (7–8%) (Yu et al. 2019; Li et al. 2021; Lin et al. 2020; Zhao et al. 2021). In the development of oil and gas, some physical properties of the reservoir, such as porosity, permeability, and capillary pressure, are mainly controlled by its microstructure, that is, the physical properties and phenomena usually only contribute to the appearance, while the microstructure is what is fundamental. Consequently, a comprehensive understanding of microcontrol is required to improve reservoir performance.

In China, tight petroleum reservoirs are usually characterized by extremely low porosity of less than 10% and ultra-low permeability of less than 1.0 mD or 0.1 mD in

Wei Lin and Zhenkai Wu have been contributed equally to this work.

✉ Xizhe Li
lxz69@petrochina.com.cn

¹ School of Geosciences, Yangtze University, Wuhan 430100, China

² Laboratory of Reservoir Microstructure Evolution and Digital Characterization, School of Geosciences, Yangtze University, Wuhan 430100, China

³ Institute of Porous Flow and Fluid Mechanics, University of Chinese Academy of Sciences, Langfang 065007, China

⁴ Research Institute of Petroleum Exploration & Development, PetroChina Company Limited, Beijing 100083, China

the subsurface. Tight petroleum reservoirs have a highly complicated pore geometry and heterogeneity and show a wide pore size distribution, ranging from several nanometers to several hundred micrometers (Zhao et al. 2015; Lin et al. 2021; Zhang et al. 2016; Zhao et al. 2019). In particular, the pore structure determines reservoir storage capacity, controls rock transport properties, and represents the microscopic characteristics of the rock. Therefore, the characterization and quantification of pore structure of tight oil and gas reservoirs are of primary importance for the quality evaluation and successful production of these unconventional resources (Solano et al. 2013). Existing pore structure characterization techniques in tight reservoirs include X-ray computed tomography (X-CT), focused ion beam-scanning electron microscopy (FIB-SEM), mercury injection porosimetry (MIP), N_2 gas adsorption (N_2 GA), nuclear magnetic resonance (NMR), etc. There is an extensive literature on these various techniques, Bai et al. (2013) implemented multiscale (nano-to-micro) three-dimensional CT imaging to characterize the distribution and texture of microscale pore throats in tight sandstone reservoirs of the Triassic Yanchang Formation, Ordos Basin. Zhao and Zhou et al. (Zhao and Zhou 2021, 2020; Zhao et al. 2020; Zhou and Zhao 2020) conducted some interesting works on the pore structure, fractal dimension and multi-scale analyses of geomaterials using X-ray CT, they employed X-ray u-CT to study the microscopic heterogeneity of sandstone (Zhao and Zhou 2021), investigate the permeability and fracture characteristics for predicting the hydraulic properties of porous geomaterials (Zhao et al. 2020), study the pore-scale effect on the hydrate variation and flow behaviors in microstructures (Zhao and Zhou 2020), and establish fractural models to propose 3D spatial fracture-pore fractal dimensions for predicting shale permeability and their effects on fluid flow behaviors (Zhou and Zhao 2020). Li et al. (2016) constructed a digital rock and pore network model of tight sandstone samples from the Fuyu oil layer in Daan Oilfield of Songliao basin using micro-CT. Wang et al. (2020) and Zhao et al. (2015) employed SEM to determine the pore space types and simultaneously integrated pressure-controlled porosimetry (PCP) and rate-controlled porosimetry (RCP) to obtain the full-range pore size distribution in tight sandstones from the Ordos Basin, China. Peng et al. (2018) utilized image processing and multifractal analyses to classify the pore structure of tight sandstone in the Kepingtage Formation in the Shuntuoguole low uplift, Tarim Basin. Zhang et al. (2016) combined SEM, N_2 GA, PCP, and RCP to investigate the pore systems of five tight sandstone samples of Yanchang Formation in Upper Triassic Ordos Basin China, the pore throat types and shapes were qualitatively identified and classified, and the pore size distribution was calculated. Using NMR and MIP, Wang et al. (2018a) presented an advanced fractal analysis of the pore structures

and petrophysical properties of the tight sandstones from Yanchang Formation, Ordos Basin, China, their studies demonstrate that the combination of NMR and MIP can improve the accuracy of pore structure characterization and fractal dimensions calculated from NMR T_2 spectrum are effective for a petrophysical properties analysis. Nevertheless, there is no standardized method to characterize pore space so far, all of the aforementioned techniques have some limitations in characterizing the pore structure of tight reservoirs (Yang et al. 2019).

Nowadays, image analysis is a robust visual method to quantify pore information from a porous rock. X-CT has been one of the most useful tools to study the pore microstructures of tight rocks because it can provide detailed topological information. The difference between the solid matrices and pores due to the different gray level pixels can be used to study the pore structures (Li et al. 2020a; Jouini et al. 2011; Risovića et al. 2008). However, previous studies have paid more attention to the integrated characterization of pore size distribution combined with MIP, N_2 GA, and NMR. The studies on the heterogeneity and pore structure based on digital image analysis were weakened, and the reflection of digital image information, especially including the insights from different scales and non-Euclidean spaces, needs to be enhanced (Peng et al. 2018). In this work, by imaging the same tight sandstone sample using two-resolution X-CT, we constructed digital rocks to analyze the heterogeneity and pore structure of rocks from different scales. Further, combining with fractal theory, we revealed the information behind the CT images from non-Euclidean space and obtained the rock fractal dimension (FD) and lacunarity quantifying rock heterogeneity. Moreover, we compared the changes of these fractal quantitative characterization parameters in images of different resolution.

Samples and experiments

The tight sandstone specimen was collected from the fourth member of the Quantou Formation, southern Songliao Basin, Jilin oilfield, China, and its petrophysical parameters are shown in Table 1. The porosity and permeability were measured using conventional gas measurement with nitrogen. The throat parameters were measured by an ASPE 730 rate-controlled mercury intrusion instrument manufactured by the US company CoreTest, the mercury-injection pressure was 0–1000 psi (about 7 MPa), mercury penetration speed was 0.00005 mL/min, contact angle was 140° , and interfacial tension was 0.485 N/m (Lin et al. 2019).

To analyze the characteristics of a multiscale pore structure, we employed an Xradia UltraXRM-L200 CT scanner to scan the tight sandstone with two resolutions, and the machine was produced by Xradia company of America,

Table 1 Physical properties of tight sandstone

Porosity (%)	Gas permeability (mD)	Maximum throat radius (μm)	Average throat radius (μm)	Variance	Relative sorting coefficient	Uniformity coefficient
10.42	0.107	0.60	0.42	0.08	0.20	0.68

whose highest resolution reached 50 nm per pixel. The process of building 3-D digital rocks with the X-ray CT scanning method can be divided into six steps (Zhou et al. 2020):

- (1) Sample preparation. In order that the specimen cylinder has the proper size.
- (2) Sample X-ray CT scanning. After reasonable selection of scanning resolution, the 3-D gray images of the cores are built through the scanning experiment.
- (3) Gray image filtering. To eliminate 3-D gray image noise by median filtering method and so on.
- (4) Binarization of gray image. For two-phase system of rock skeleton and pore space, the image segmentation technique is adopted to convert the gray image into binary image.
- (5) Smoothing processing of binary image. To eliminate isolated rock skeletons.
- (6) Representative volume element analysis. To select the best size of 3-D digital cores.

Specifically, we imaged a cylinder approximately 8.0 mm in diameter and 8.0 mm in length with the resolution of 7.6 μm and constructed a three-dimensional (3D) digital rock model to analyze the pore structure characteristics of the sample at low resolution; the workflow is shown in Fig. 1. Likewise, to characterize the more microscopic pore structure, a smaller cylinder approximately 1.0 mm in

diameter and 1.0 mm in length was drilled from the cylinder mentioned above for CT scanning with a resolution of 0.6 μm , and the microscopic pore structure characteristics of the sample were analyzed at high resolution using the same method.

Results and discussion

Pore structure analysis of tight sandstone digital rock

The working principle of CT is that when X-rays penetrate through the sample, the energy will be attenuated differently. In CT grayscale images, the areas with high gray values generally correspond to high-density components, whereas low-density components exhibit low gray values on CT images. As can be seen from Fig. 2, the image background is black, the dark part is the pore, and the light part is the rock matrix. Because the pores of tight sandstone are extremely small, the shape and distribution of the macropores can be only roughly identified on the low-resolution CT image (Fig. 2a). From the high-resolution CT image (Fig. 2b), it can be seen that there are still relatively coarse and complex filamentous or lamellar solid components in the macropores, which are often identified as the pore phase in low-resolution CT images. On the high-resolution CT image, it is evident

Fig. 1 CT image processing flow

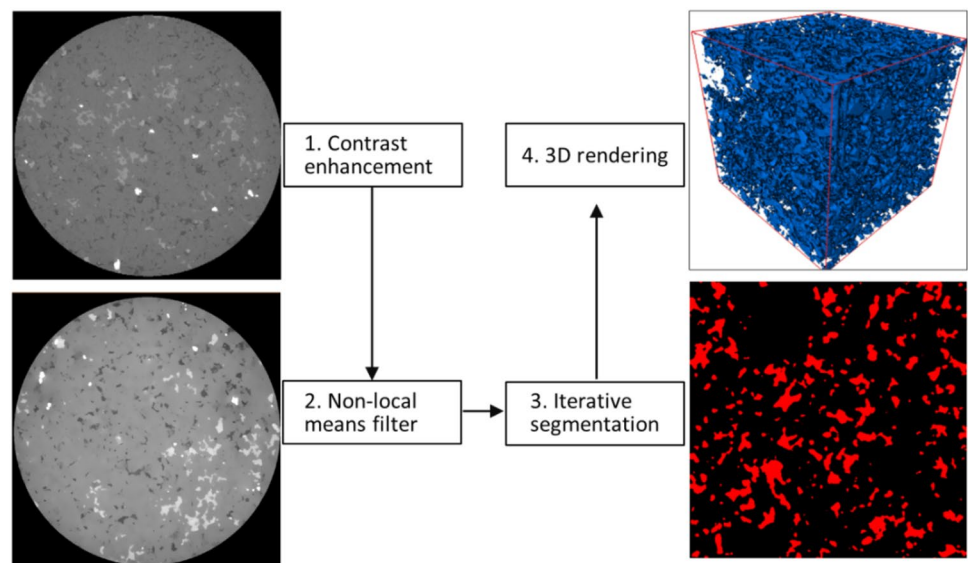
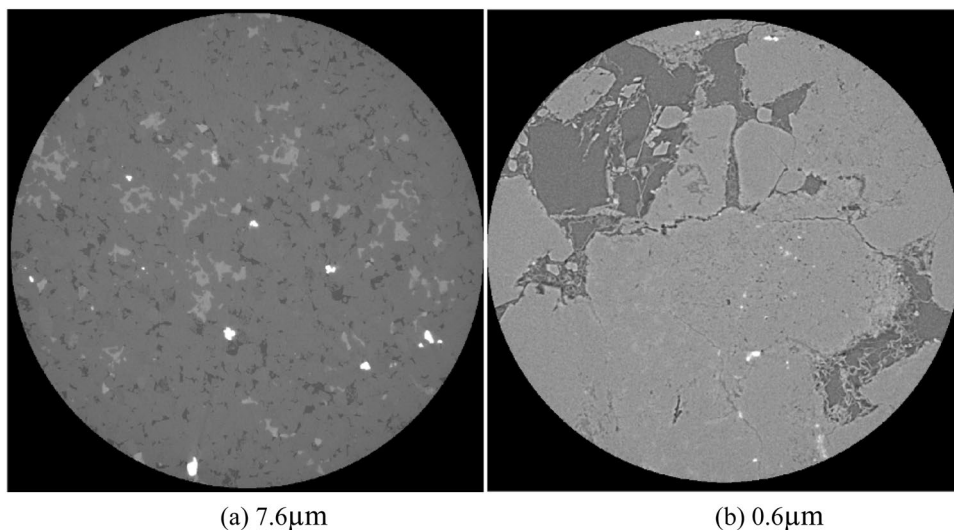


Fig. 2 CT grayscale images of tight sandstone sample at different resolutions



that there are narrow microcracks between the rock particles around the macropores. Combined with the qualitative analysis of low- and high-resolution CT images, it can be concluded that the pore size of tight sandstone has a large range of variation and that there are micropore throats and cracks.

Figure 3 shows 3D digital rock models of CT scan results at two resolutions in full view (left—7.6 μm, right—0.6 μm; gray—rock matrix, multicolor—pore space). The reconstructed 3D digital model basically reflects the characteristics of the rock skeleton and pore

structure. In order to avoid the interference of the scanning environment and the sample edge on the analysis of the scan results, a subcube volume of $512 \times 512 \times 512$ voxels with a porosity of 0.1244 was extracted from the low-resolution CT dataset for subsequent analysis, and the extracted subcube digital rock model is shown in Fig. 4. Due to the small scanning volume of the high-resolution CT scan, only part of the macroporous structure is included in the high-resolution digital rock. In order to maximize the use of the scanning results at this resolution, the cylindrical dataset, after removing the scanning

Fig. 3 3D digital models of CT scan results at two resolutions in full view (left—7.6 μm, right—0.6 μm; gray—rock matrix, multicolor—pore space; the models were constructed by Avizo 2019)

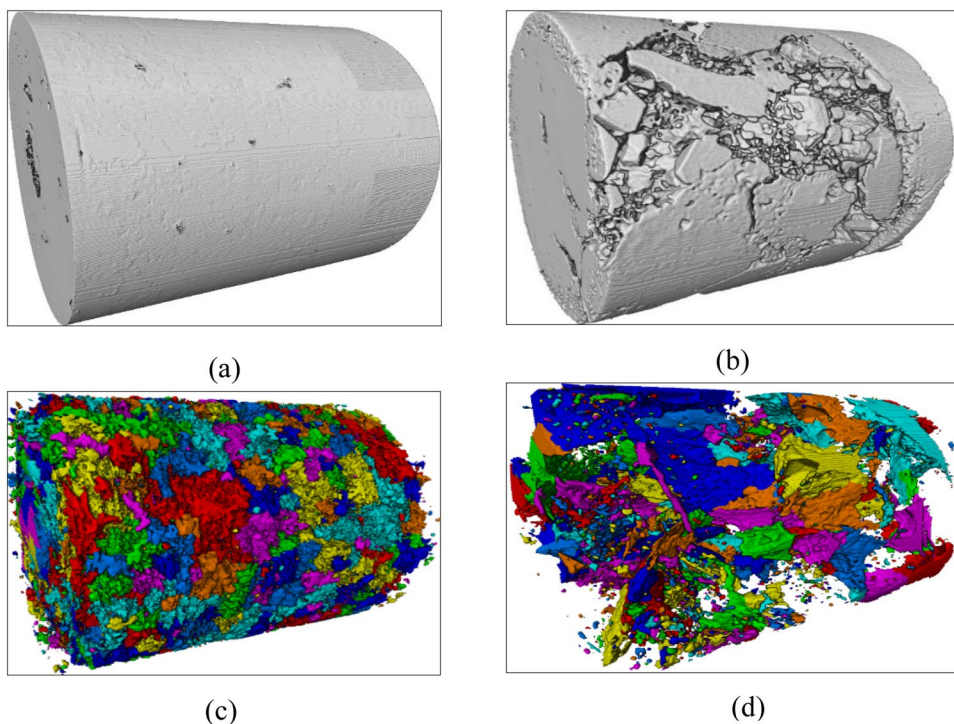
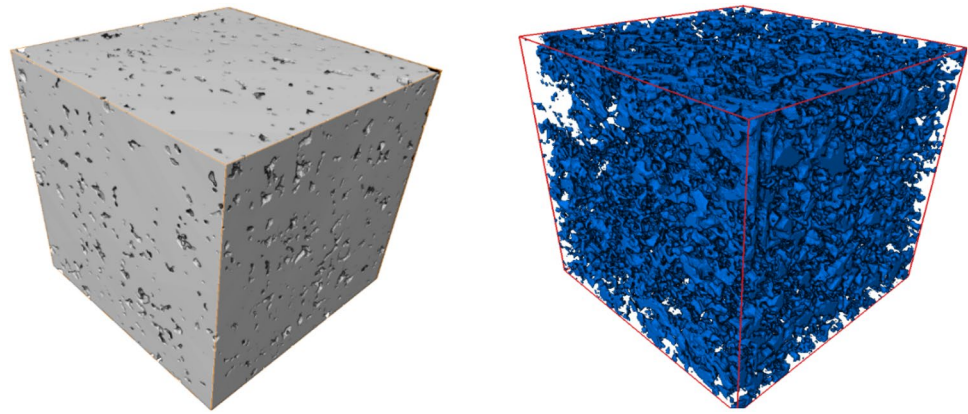


Fig. 4 Subvolume of digital rock model of 512^3 pixels (gray—rock matrix, blue—pore space)



background and edge voxels, is used directly for analysis, as shown in Fig. 3b,d.

Based on the reconstructed 3D digital models at two resolutions, the distribution and morphological characteristics of a pore throat of tight sandstone were analyzed with a multiscale approach. The qualitative descriptions of three-dimensional pore throat shape, distribution, and connectivity at low and high resolution are summarized in Table 2. From Fig. 3 and Table 2, we can see that the low-resolution digital rock model can characterize most macropore groups with relatively large sizes, and to a certain extent shows the morphological characteristics and spatial distribution of the macropore groups. In the high-resolution digital rock model, the micropore groups around the macropore are identified, and these microstructures usually cannot be identified in low-resolution CT scans. However, the actual size of the sample corresponding to the high-resolution CT scan results is small, and the reconstructed 3D digital model is not representative for studying the macrophysical properties of the rock sample,

so it is only used to qualitatively analyze the microscale pore throat structure of tight sandstone.

Quantitative heterogeneity of tight sandstone digital rock

The heterogeneity of the tight sandstone digital rock was quantitatively analyzed by the representative elementary volume (REV) (Singh et al. 2020; Jackson et al. 2020) and axial change of image porosity. Due to the small volume of high-resolution digital rock, only the low-resolution digital rock (as shown in Fig. 4) was used to analyze the heterogeneity of the tight sandstone sample.

Representative elementary volume analysis

The REV analysis based on digital rock is of great significance for understanding the bulk heterogeneous pore structure characteristics of the tight sandstone sample. The REV contains the unity of opposites between micro and

Table 2 Qualitative description of three-dimensional pore throat features at two resolutions

	Pore throat structure characteristics	Qualitative description
Low-resolution digital rock	Morphology	The overall pores are developed in flat sheets; Small pores are distributed in isolation in 3D space; Relatively large pores are flat in 3D space;
	Distribution	The micropore throats are unevenly distributed in all directions, and the minority is obviously layered; The large pore throats are flat and surrounded by a large number of isolated pores;
	Connectivity	Small size pore throats are not connected and are isolated; Large flat pores constitute the main connecting channel;
High-resolution digital rock	Morphology	The overall pores are developed in short flat sheets; There are many small-sized pores, distributed in isolation in 3D space;
	Distribution	The distribution is extremely uneven in all directions; There are a large number of isolated pores scattered around the large pores;
	Connectivity	Small size pore throats are not connected and are isolated; Large flat pores constitute the main connecting channel;

macro, discrete and continuous, and random and certainty. Therefore, in order to understand the spatial characteristics of the pore structure of the tight sandstone, it is necessary to analyze the REV of the low-resolution digital rock. REV is the smallest subset of the pore space that shows similar volume-averaged properties (here, the porosity) as larger subsets.

Two strategies were applied to determine the REV of the tight sandstone digital rock. The first is to randomly select subvolumes at any position in the low-resolution digital rock; the side lengths of these subvolumes have an interval of 50 voxels, and the porosity of each subvolume is counted. The results are shown in Fig. 5. The second is to take a subvolume of 50 voxels in the center of the low-resolution digital rock and then gradually increase the side length of the

subvolume at intervals of one voxel. The porosity of these subvolumes is counted and the results are shown in Fig. 6.

From the analysis of the scattered point data in Fig. 5, the porosity of randomly selected subvolumes with different side lengths fluctuates around the absolute porosity value of the low-resolution digital rock (0.1244), showing that the larger the subvolumes, the closer the distribution of the porosity values, and the smaller the subvolumes, the more scattered the distribution of the porosity values. Although the porosity of small subvolumes fluctuates greatly, the average porosity of all these small subvolumes of the same volume is close to the absolute porosity of the low-resolution digital rock. When the side length of the subvolume is greater than 300 voxels, the porosity value still fluctuates, but it is basically close to the absolute porosity of the low-resolution digital

Fig. 5 Statistical porosity changes using stochastic sub-volume method

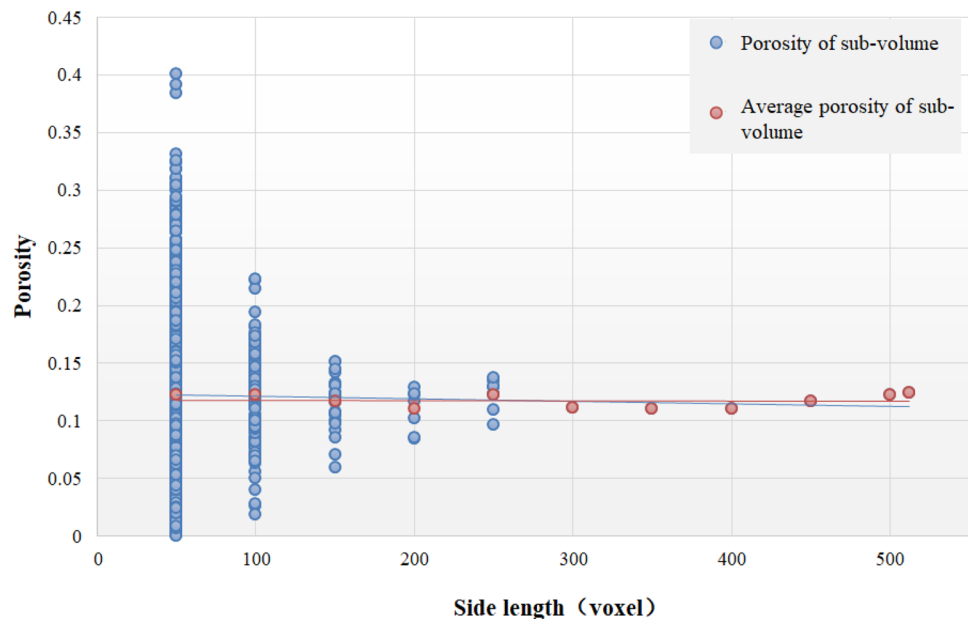
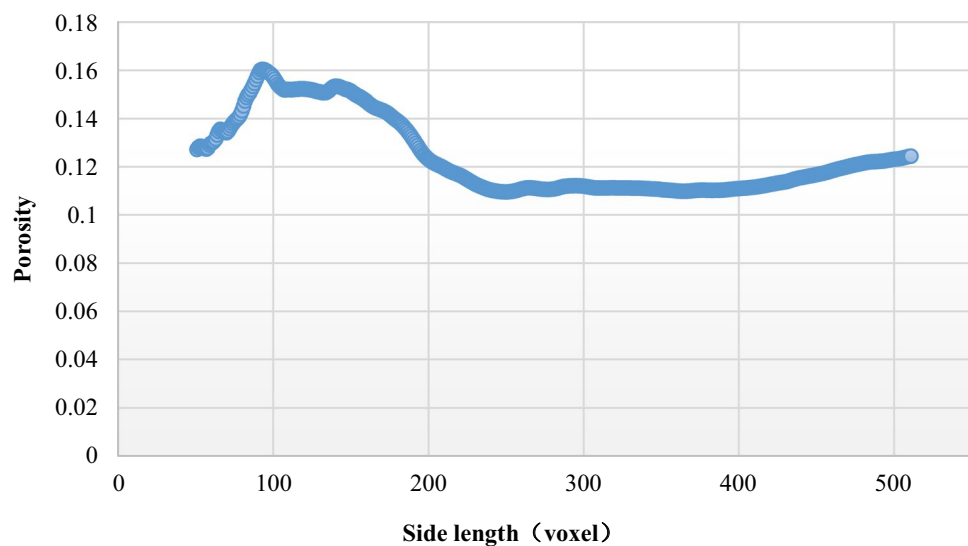


Fig. 6 Statistical porosity changes with continuous sub-volume method



rock, indicating that the messy and complex pore structure shows a relatively stable trend after the volume reaches a certain level.

From Fig. 6 we can see that when the side length of the central subvolume gradually increases by one voxel, the porosity of the subvolumes gradually stabilizes from extensive oscillations and then there is a slight fluctuation with the same general trend as in Fig. 5. The porosity at relatively stable intervals is about 0.1100, the maximum porosity of subvolume is 0.1243, and the difference between the two is 0.0143, which accounts for about 13.7% of the experimental porosity of the sample (0.1042), indicating that the tight sandstone has a certain degree of heterogeneity. Combining Figs. 5 and 6, it can be seen that when the subvolume size extracted by the two methods is greater than 300 voxels, the subvolume porosity tends to be stable.

Axial change of image porosity

The low-resolution digital rock includes a total of 512 two-dimensional scan images. By counting the porosity of these images, the axial heterogeneity degree of the tight sandstone sample can be quantitatively characterized. Specifically, based on the segmented binary CT images, the rock skeleton pixel was labeled with 1 and the pore pixel was labeled with 0. We counted the ratio of pixels labeled with 0 versus the total pixels labeled with 0 and 1, and the porosity of a single CT image was obtained. Figure 7 shows the axial change of the porosity of a single CT image.

The porosity of the single CT image of the tight sandstone fluctuates between 0.097 and 0.171 axially, and the difference between the maximum and minimum porosity reaches 0.074. Compared with the absolute porosity of the low-resolution digital rock (0.1244), this fluctuation is distinct. Moreover, the porosity of the images numbered between

429 and 512 has a large jump, which implies that the tight sandstone sample has a strong degree of axial heterogeneity.

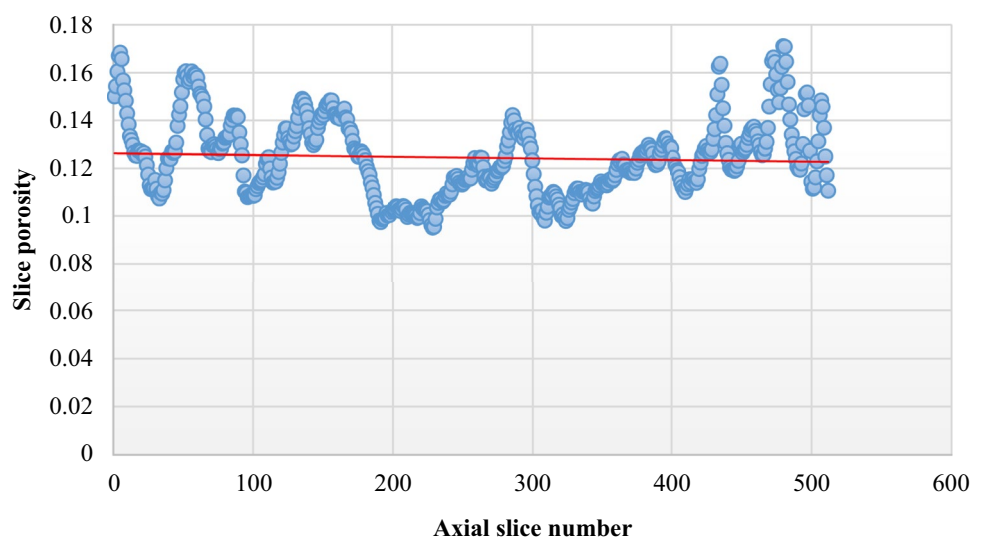
Fractal characterization of pore space of tight sandstone digital rock

The transport and storage capacity of porous media (rocks, manmade materials, tissues, organs, etc.) depend on the microstructures, including the volume, shape, distribution, and connectivity of their pores. Traditional Euclidean geometry cannot accurately characterize the complexity of the pore structure and heterogeneity, but the fractal is an effective means to describe the morphology, complexity, and irregularity of the microscopic pore structure of porous media (Zhang et al. 2021, 2020; Wang et al. 2018b; Huang et al. 2021; Cai and Yu 2010; Qin et al. 2019; Li et al. 2020c; Sheng et al. 2019). The book *Fractal Theory in Porous Media and Its Application*, edited by Cai and Hu (2015), provides a systematic introduction to the basic fractal theory of porous media from different perspectives, as well as the latest international research results of applying fractal theory to study the transmission characteristics of porous media. The fractal characterization parameters of porous media mainly include fractal dimension (FD), lacunarity, etc. The FD is used to measure how much space an object occupies and can calibrate the complexity of the microstructure of the porous media. The lacunarity characterizes the distribution of gaps or cracks in the porous media and calibrates the heterogeneity of the porous media.

Fractal dimension of tight sandstone

As the basic parameter of fractal quantitative characterization, FD is a fixed value; its mathematical meaning is that there is a power exponential relationship between the size of the object

Fig. 7 Axial variation of porosity in 2D CT images



and the scale, and the exponent is defined as the FD. The FD breaks the limitation that the traditional Euclidean geometric dimension must be an integer; it is believed that the spatial dimension of an object can be a fraction in fractal theory. As long as the two objects have the same FD, the two objects are similar. In the field of rock analysis, FD mainly represents the complexity of the measured target, and there are multiple types of fractal dimensions that can be distinguished according to different definitions. For the rock pores, the main association between the pore accumulation number and the pore size is as follows:

$$M(\varepsilon) \propto \varepsilon^D, \quad (1)$$

where D is the FD that characterizes the complexity of rock pores, which is called the FD of pore distribution (Zhao and Yu 2011).

The FD of pore distribution can be obtained by three methods: image processing, experimental measurement, and theoretical calculation. Among them, the box-counting method (Liu et al. 2020; Lin et al. 2018; Panigrahy et al. 2019) is the most commonly used and is an accurate method to obtain the FD by processing images. Assuming that the image is covered with boxes of different scales r , and the number of boxes covering the fractal is N , then

$$N = r^{-D}, \quad (2)$$

where D is the FD calculated by the box-counting method. The interval in which Eq. (2) holds is $r_{\min} < r < r_{\max}$, where r_{\min} and r_{\max} are the lower and upper limits of the fractal self-similar interval, respectively. The slope of the linear fit of the double logarithmic plot of the box number and the scale in the self-similar interval is the FD (Liu et al. 2020; Lin et al. 2018).

Table 3 shows the 3D fractal dimensions calculated from low- and high-resolution tight sandstone digital rocks. The value of FD characterizes a complex feature of the overall pore shape, which is greatly affected by porosity. Generally speaking, the greater the porosity, the greater the FD, and when the difference in porosity is small, the larger the FD, the weaker the heterogeneity, and the more complex the pore morphology. Based on this, it can be seen from Table 3 that the low-resolution digital rock shows a higher FD than the high-resolution digital rock, but overall is at the same level, which also shows that the FD characterizes the overall distribution characteristics of the pore space and is less affected by microscopic isolated pores. Therefore, more microscopic pore throat details being

identified in the high-resolution scanning results cannot effectively increase the complexity of the pore space distribution.

Lacunarity of tight sandstone

Lacunarity has become a very popular tool for analyzing fractal microstructures in recent years. It can be used to quantitatively analyze the clustering degree of fractals and characterize the changes in natural images and can distinguish different structures with the same fractal dimension. It has characteristics that characterize the heterogeneity of rock structure (Cai and Hu 2015; Theiler 1988; Sijlmassi et al. 2020; Dong 2000).

The lacunarity, Λ , is related to the correlation dimension D_q of the multifractal. Lacunarity analysis can be used to identify grayscale images with the same D_q but different cluster scales and correlation degrees. In most physical processes, FD is used as a measure of irregularity to characterize the geometric properties of the structure. In the case of similar sets, the FD can describe the “quality” of the elements in the set. Sets of different structures may have the same FD, and the lacunarity has the characteristic of spatial translation invariance, so it can be used to distinguish these sets of different structures.

At present, the gliding box algorithm (Charles et al. 2008; Backes 2013) is a common method for calculating lacunarity and has a wide range of applications. Similar to the box-counting method, the gliding box algorithm for calculating 3D lacunarity uses a cube grid of scale r to glide on the 3D image. Compared with the 2D lacunarity that characterizes the clustering characteristics of pore distribution, the 3D lacunarity can better characterize whether the pores are concentrated in the 3D space. Therefore, in this study, we used 3D lacunarity to characterize the structural properties of the CT scan images of tight sandstone and analyzed the relationship between the structure and the physical properties.

Table 4 shows the 3D lacunarity calculated from digital rocks of two resolutions at different scales. The maximum and minimum values of the upper and lower boundaries of the lacunarity are $\Lambda_{\max} = \Lambda(1) = 1/\phi$ and $\Lambda_{\min} = \Lambda(l) = 1$, respectively, which indicates that different porosity values will change the maximum value of the lacunarity. In order to avoid the influence of porosity, the lacunarity calculated from the gliding box algorithm is normalized by the following equation:

$$\Lambda^*(r) = \frac{\Lambda(r) - \Lambda_{\min}}{\Lambda_{\max} - \Lambda_{\min}} = \phi \frac{\Lambda(r) - 1}{1 - \phi}. \quad (3)$$

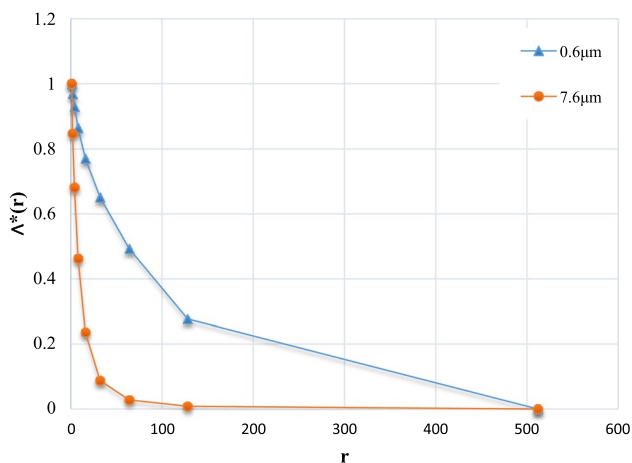
In order to observe the size of the lacunarity of different digital rocks, the normalized values of the lacunarity at different scales are shown in Fig. 8. It can be seen that, since the high-resolution digital rock contains fewer pore

Table 3 3D fractal dimension of tight sandstone digital rocks

Characterization parameters	High resolution	Low resolution
3D fractal dimension	2.6194	2.6548

Table 4 Calculated values of 3D Lacunarity of digital rocks in tight sandstone at different scales (r is the scale value-voxel)

Lacunarity	High-resolution data	Low-resolution data
$r=1$	6.983179784	8.036871794
$r=2$	6.794265435	6.96258277
$r=4$	6.561312358	5.794522957
$r=8$	6.173402722	4.254820938
$r=16$	5.610737259	2.661378822
$r=32$	4.896480834	1.617056646
$r=64$	3.950686802	1.196570251
$r=128$	2.656693509	1.059055075
$r=512$	1	1

**Fig. 8** Normalized curves of Lacunarity for high- and low-resolution digital rock models

structures compared with the low-resolution digital rock, it shows stronger heterogeneity—that is, the degree of aggregation of pore spaces is higher than that of low-resolution digital rock.

Conclusions

By constructing digital rocks of two resolutions, this study qualitatively and quantitatively analyzed the pore structure characteristics and heterogeneity of tight sandstone sample at multiple scales and dimensions. Our conclusions are as follows:

- (1) Tight sandstone has low permeability and narrow storage spaces, and microscopic pore throat characteristics have different patterns at different scales. In low-resolution CT images, it mainly has sheet-like nonuniform distribution and is accompanied by a larger volume of isolated pore space. In high-resolution CT images, the

number of isolated pores accounts for a large proportion; the pore geometry is mostly in short flat sheets, distributed inside and on the surface of mineral particles, and the main connecting channels are still composed of relatively larger pores.

- (2) Using low-resolution CT scan data, combined with REV and axial porosity distribution, the 3D and 2D porosity changes were quantitatively analyzed to investigate the degree of heterogeneity of tight sandstone. The results show that the degree of heterogeneity of the tight sandstone sample is strong in axial (2D), the sample has a certain degree of bulk heterogeneity, and the REV of low-resolution digital rock is 300 voxels.
- (3) The complexity and heterogeneity of the pore structure distribution in the tight sandstone were analyzed through fractal geometric parameters such as fractal dimension and lacunarity. The fractal dimension of the CT images of the two resolutions shows very little difference, but the difference in lacunarity values is notable. The microscopic pore details identified in the high-resolution CT images have a certain impact on the spatial distribution of the overall pore throat structure of tight sandstone, but the overall fractal dimension is not sensitive to changes in the microstructure; the lacunarity analysis shows that the tight sandstone has distinct heterogeneous characteristics, and the lacunarity value of high-resolution digital rock is obviously larger than that of low-resolution digital rock.

Funding The work was financially supported by the National Science and Technology Major Project of China [Grant Nos. 2017ZX05013-001 and 2017ZX05008003-050] and the Hubei Provincial Natural Science Foundation of China [Grant No. 2021CFB182].

Data availability The data used to support the findings of this study are available from the corresponding author upon request.

Declarations

Conflict of interest All authors declare that there is no conflict of interest in this article.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Backes A (2013) A new approach to estimate lacunarity of texture images[J]. *Pattern Recogn Lett* 34(13):1455–1461
- Bai B, Zhu R, Wu S et al (2013) Multi-scale method of Nano(Micro)-CT study on microscopic pore structure of tight sandstone of Yanchang Formation, Ordos Basin[J]. *Pet Explor Dev* 40(3):354–358
- Cai J, Hu X (2015) *Fractal theory in porous media and its application*[M]. Science Press, Beijing
- Cai J, Yu B (2010) Prediction of maximum pore size of porous media based on fractal geometry[J]. *Fractals* 18(4):417–423
- Charles R, Timothy R, David J et al (2008) An efficient implementation of the gliding box lacunarity algorithm[J]. *Physica D* 237(3):306–315
- Dong P (2000) Test of a new lacunarity estimation method for image texture analysis[J]. *Int J Remote Sens* 21(17):3369–3373
- Huang L, Sheng G, Li S et al (2021) A review of flow mechanism and inversion methods of fracture network in shale gas reservoirs [J]. *Geofluids* 2021:6689698
- Jackson S, Lin Q, Krevor S (2020) Representative elementary volumes, hysteresis, and heterogeneity in multiphase flow from the pore to continuum scale[J]. *Water Resour Res* 56(6):e2019WR026396
- Jouini M, Vega S, Mokhtar E (2011) Multiscale characterization of pore spaces using multifractals analysis of scanning electronic microscopy images of carbonates[J]. *Nonlin Processes Geophys* 18(6):941–953
- Li Y, Zhang Y, Cong L et al (2016) Application of X-CT scanning technique in the characterization of micro pore structure of tight sandstone reservoir: an example from Fuyu oil layer in Daan oilfield[J]. *J Jilin Univ (earth Sci Edn)* 46(2):379–387
- Li HB, Liu XG, Yang ZM et al (2020a) Quantitative analysis method of oil occurrences in tight reservoir [J]. *Energy Rep* 6:1067–1072
- Li X, Guo Z, Hu Y et al (2020b) High-quality development of ultra-deep large gas fields in China: challenges, strategies and proposals [J]. *Nat Gas Ind* 40(2):75–82
- Li K, Kong S, Xia P et al (2020c) Microstructural characterisation of organic matter pores in coal-measure shale[J]. *Advances in Geo-Energy Research* 4(4):372–391
- Li X, Yang Z, Li S et al (2021) Reservoir characteristics and effective development technology in typical low-permeability to ultralow-permeability reservoirs of China National Petroleum Corporation[J]. *Energy Explor Exploit*. <https://doi.org/10.1177/01445987211005212>
- Lin W, Li X, Yang Z et al (2018) A new improved threshold segmentation method for scanning images of reservoir rocks considering pore fractal characteristics[J]. *Fractals* 26(2):1840003
- Lin W, Li X, Yang Z et al (2019) Multiscale digital porous rock reconstruction using template matching[J]. *Water Resour Res* 55(8):6911–6922
- Lin L, Lin W, Xiong S et al (2020) Supplementary energy development boundaries of staged fracturing horizontal wells in tight oil reservoirs[J]. *Energy Explor Exploit* 38(6):2217–2230
- Lin W, Xiong S, Liu Y et al (2021) Spontaneous imbibition in tight porous media with different wettability: pore-scale simulation [J]. *Phys Fluids* 33(3):032013
- Liu X, Wang J, Ge L et al (2017) Pore-scale characterization of tight sandstone in Yanchang Formation Ordos Basin China using micro-CT and SEM imaging from nm- to cm-scale. *Fuel* 209:254–264
- Liu Y, Xiao B, Yu B et al (2020) Fractal analysis of digit rock cores[J]. *Fractals* 28(6):2050144
- Panigrahy C, Seal A, Mahato N et al (2019) Differential box counting methods for estimating fractal dimension of gray-scale images: a survey [J]. *Chaos, Solitons Fractals* 126:178–202
- Peng J, Han H, Xia Q et al (2018) Evaluation of the pore structure of tight sandstone reservoirs based on multifractal analysis: a case study from the Kepingtage formation in the Shuntuoguole uplift, Tarim Basin, NW China[J]. *J Geophys Eng* 15(4):1122–1136
- Qin X, Zhou Y, Sasmito A (2019) An effective thermal conductivity model for fractal porous media with rough surfaces[J]. *Adv Geo-Energy Res* 3(2):149–155
- Radwan AE, Trippetta F, Kassem AA et al (2021) Multi-scale characterization of unconventional tight carbonate reservoir: Insights from October oil field, Gulf of Suez rift basin, Egypt[J]. *J Petrol Sci Eng* 197:107968
- Radwan AE, Wood DA, Mahmoud M et al (2022) Chapter Twelve— Gas adsorption and reserve estimation for conventional and unconventional gas resources[M]. *Sustain Geosci Natural Gas Subsurface Syst* 2:345–382. <https://doi.org/10.1016/B978-0-323-85465-8.00004-2>
- Risovića D, Mahović PS, Furić K et al (2008) Inferring fractal dimension of rough/porous surfaces—a comparison of SEM image analysis and electrochemical impedance spectroscopy methods[J]. *Appl Surf Sci* 255(5):3063–3070
- Shen W, Song F, Hu X et al (2019) Experimental study on flow characteristics of gas transport in micro- and nanoscale pores[J]. *Sci Rep* 9:10196
- Sheng G, Su Y, Wang W (2019) A new fractal approach for describing induced-fracture porosity/permeability/compressibility in stimulated unconventional reservoirs[J]. *J Petrol Sci Eng* 179:855–866
- Sijilmassi O, Alonso J, Sevilla A et al (2020) Multifractal analysis of embryonic eye structures from female mice with dietary folic acid deficiency. Part I: fractal dimension, lacunarity, divergence, and multifractal spectrum [J]. *Chaos Solitons Fract* 138:109885
- Singh A, Regenauer-Lieb K, Walsh S et al (2020) On Representative elementary volumes of grayscale micro-CT images of porous media[J]. *Geophys Res Lett* 47(15):e2020GL88594
- Solano N, Clarkson C, Krause F et al (2013) On the characterization of unconventional oil reservoirs[J]. *Recorder* 38:42–47
- Theiler J (1988) Lacunarity in a best estimator of fractal dimension[J]. *Phys Lett A* 133(4–5):195–200
- Wang F, Yang K, Cai J (2018a) Fractal characterization of tight oil reservoir pore structure using nuclear magnetic resonance and mercury intrusion porosimetry[J]. *Fractals* 26(2):1840017
- Wang X, Hou J, Song S et al (2018b) Combining pressure-controlled porosimetry and rate-controlled porosimetry to investigate the fractal characteristics of full-range pores in tight oil reservoirs[J]. *J Petrol Sci Eng* 171:353–361
- Wang W, Yu C, Zhao L et al (2020) Combining SEM and mercury intrusion capillary pressure in the characterization of pore-throat distribution in tight sandstone and its modification by diagenesis: a case study in the Yanchang Formation, Ordos Basin, China[J]. *Earth Sci Res J* 24(1):19–28
- Yang Z, Zhao X, Xiong S et al (2019) Research progress on microstructure characterization of pore throat for tight oil reservoirs[J]. *Sci Technol Rev* 37(5):89–98
- Yu H, Yang Z, Luo L et al (2019) Application of cumulative-in-situ-injection-production technology to supplement hydrocarbon recovery among fractured tight oil reservoirs: a case study in Changqing Oilfield, China[J]. *Fuel* 242:804–818
- Zhang Z, Shi Y, Li H et al (2016) Experimental study on the pore structure characteristics of tight sandstone reservoirs in Upper Triassic Ordos Basin China[J]. *Energy Explor Exploit* 34(3):418–439
- Zhang L, Ba J, Carcione JM et al (2020) Differential poroelasticity model for wave dissipation in self-similar rocks[J]. *Int J Rock Mech Min Sci* 128:104281
- Zhang L, Ba J, Carcione J (2021) Wave Propagation in Infinite-Porosity Media[J]. *J Geophys Res Solid Earth* 126(4):e2020JB021266

- Zhao M, Yu B (2011) The fractal characterization of pore structure for some numerical rocks and prediction of permeabilities[J]. *J Chongqing Univ* 34(4):88–94
- Zhao Z, Zhou XP (2020) Pore-scale effect on the hydrate variation and flow behaviors in microstructures using X-ray CT imaging[J]. *J Hydrol* 584:124678
- Zhao Z, Zhou XP (2021) Microscopic characterizations of heterogeneous pores, ITZs, multiple-solids, and their impacts on damage property of sandstone by low-high resolution 3D reconstruction[J]. *Geophys Res Lett* 48(19):e2021GL95001
- Zhao H, Ning Z, Wang Q et al (2015) Petrophysical characterization of tight oil reservoirs using pressure-controlled porosimetry combined with rate-controlled porosimetry[J]. *Fuel* 154:233–242
- Zhao X, Yang Z, Lin W et al (2019) Study on pore structures of tight sandstone reservoirs based on nitrogen adsorption, high-pressure mercury intrusion, and rate-controlled mercury intrusion[J]. *J Energy Resour Technol Trans ASME* 141(11):112903
- Zhao Z, Zhou XP, Qian QH (2020) Fracture characterization and permeability prediction by pore scale variables extracted from X-ray CT images of porous geomaterials[J]. *Sci China Technol Sci* 63(5):755–767
- Zhao X, Liu X, Yang Z et al (2021) Experimental study on physical modeling of flow mechanism in volumetric fracturing of tight oil reservoir [J]. *Phys Fluids* 33(10):107118
- Zhou XP, Zhao Z (2020) Digital evaluation of nanoscale-pore shale fractal dimension with microstructural insights into shale permeability[J]. *J Natural Gas Sci Eng* 75:103137
- Zhou XP, Zhao Z, Liu Y (2020) Digital spatial cracking behaviors of fine-grained sandstone with precracks under uniaxial compression[J]. *Int J Numer Anal Meth Geomech* 44(13):1770–1787

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.