Nanoscale pore structure and fractal characteristics of the continental Yanchang Formation Chang 7 shale in the southwestern Ordos Basin, central China

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Abstract
Shales from the Yanchang Formation Chang 7 Member in the Ordos Basin are among the most important shale reservoirs in China and have been investigated due to their great potential. Knowledge of pore structure is important for understanding the storage capacity and flow mechanism in shale reservoirs. In this study, eight shale samples were collected from the Yanchang Formation Chang 7 Member in the southwestern Ordos Basin, and their geochemistry, mineral compositions, pore structure, and fractal characteristics were investigated based on X-ray diffraction (XRD) analysis, total organic carbon (TOC) analysis, low-pressure adsorption/desorption analysis, thermal maturity analysis, and fractal analysis. The results indicated that the TOC content ranged between 0.48% and 2.37%, and the Ro values varied from 0.826% to 1.217%. The major mineral compositions were quartz and clay minerals. Nitrogen adsorption/desorption analysis indicated that the isotherms were similar for all collected shale samples from the Chang 7 Member and resembled the type IV isotherm. Narrow slit-like pore was the dominant pore type, and the pore size distribution appeared to be unimodal with its peak mainly around 40 nm. Investigation of factors for pore structures showed that the TOC content was the controlling factor for the Chang 7 shales. The Frenkel-Halsey-Hill (FHH) method was applied to determine fractal dimensions, which were calculated as the D1 (relative pressure >0.96), D2 (0.96 >relative pressure >0.45), and D3 (0.45 >relative pressure) values, ranging in the intervals of 2.788–2.854, 2.547–2.688, and 2.410–2.567, respectively. The relatively high fractal dimensions indicated that pore structures were complicated, and the higher D1 values suggested that pores with larger sizes showed a rougher pore surface and more complex pore structure. Fractal dimensions showed positive correlations with the contents of TOC and clay minerals, and a negative relationship with the quartz contents.

KEYWORDS
continental shale, fractal dimension, nitrogen adsorption/desorption analysis, Ordos Basin, pore structure, Yanchang Formation Chang 7 Member
With increasing depletion of conventional hydrocarbon reserves, attention has been focused on unconventional resources, for example, shale gas, tight sandstone gas, and coalbed methane. Hydrocarbons within shales are important and realistic alternative unconventional resources, and commonly, they are featured by self-generation, self-reservoir, and self-seal. Organic-rich shales generally show low porosity and permeability; therefore, measures are necessary for production. The successful development of shale gas has broken through the lower limit of the conventional reservoir and the traditional concept of trap accumulation and reinvested the geological theory of petroleum and gas with new connotations. In addition, fortunately, recent advancements in methods of horizontal drilling and hydraulic fracturing have significantly increased the recovery. Until now, in the United States of America, more than 20 shale gas basins, including the Appalachian Basin, Michigan Basin, and Illinois Basin, have been successfully put into commercial exploitation, and the production has grown swiftly.

China has great hydrocarbon resources within shales, including 1115 trillion cubic feet (TCF) technically recoverable shale gas resources and 32 billion barrels technically recoverable shale oil resources based on EIA/ARI World Shale Gas and Shale Oil Resource Assessment (Advanced Resources International, Inc., 2013). Currently, the majority of China’s shale gas exploration and development are focused on the marine shales in and around Sichuan Basin, southwestern China. The marine Longmaxi shale is estimated to have the highest risked recoverable shale gas. However, the shale reservoirs from the Upper Triassic Yanchang Formation in the Ordos Basin are distinguished from those marine shale reservoirs both in southwestern China and in abroad, because they are generated within continental shales. Actually, in the Ordos Basin of central China, the geological reserve for shale gas is estimated to be approximately $1.99 \times 10^{12}$ m$^3$ based on the Ministry of Land and Resources of China. Moreover, studies have indicated that, in the Ordos Basin, hydrocarbons from continental shales within the Upper Triassic Yanchang Formation show a great development potential.

Shale is a heterogeneous porous medium. Schettler and Parmely indicated that about 50% of the gas in Devonian shale is associated with and stored in the open porosity of the rock. Pore size in shales indicates a large range, varying from nanometers to meters. In the Ordos Basin, numerous nanometer-size pores are in the Upper Triassic Yanchang shales, which may significantly influence the adsorption behavior. Pore structure in shales is complex, which serves as an important parameter for understanding the adsorption, desorption, diffusion, and percolation, and is vital for the assessment of shale reservoirs. Generally, pore shapes and size distributions can be determined based on experiments and methods including low-pressure gas adsorption analysis, mercury injection capillary pressure, nuclear magnetic resonance, and field-emission environmental scanning electron microscopy (FE-SEM). Among them, low-pressure nitrogen adsorption analysis has been proven to be an effective approach to characterize pore structures in shales. If applied over a wide range of relative pressure, nitrogen adsorption isotherms can provide information on size distribution in the micro-, meso-, and macro-porosity range (approximately between 0.5 nm and 200 nm). However, generally, only pores with a diameter ranging from 1.5 nm and 200 nm can be measured effectively due to the limitations from instrument accuracy and experimental operation difficulty.

In this study, the objective was to investigate the pore structure and fractal characteristics within the Upper Triassic Yanchang Chang 7 shale in the southwestern Ordos Basin utilizing low-pressure nitrogen adsorption/desorption and fractal analysis. The relationships between mineralogical compositions, TOC content, and pore structure parameters were studied. This study results can provide geological references for exploring continental shale reservoirs in the southwestern Ordos Basin of central China.

The Ordos Basin, located in central China, is a large multicycle superimposed sedimentary basin with abundant energy resources. This basin underwent a series of tectonic episodes, and currently, it is internally stable with a simple structure and surrounded by several deformed belts, Lyuliang Mountains in the east, Liupan and Helan Mountain Ranges in the west, Qinling Mountain Ranges in the south, and Lang-Daqing Mountains in the north (Figure 1: Refs [24-26]) The strata within this basin gently dip (<2°) to the west based on regional seismic surveys.

The Ordos Basin underwent a transition during the Permian from marine to a nonmarine depositional environment. The Paleozoic marine and Mesozoic continental sedimentary rocks are petroliferous. The Mesozoic Ordos Basin is a large intra-continent basin characterized by a thick, undeformed stratigraphic succession over a wide region. Within this basin, the Upper Triassic Yanchang Formation has large volumes of unconventional hydrocarbon resources, which are generated in a lake-delta sedimentary system (Figure 2A: Refs [23,27,28]).

The Yanchang Formation consists of 10 members, known as the Chang 10 Member to Chang 1 Member from bottom to top (Figure 2A). Among them, the Chang 7 Member consists of shales, black mudstones together with thin beds of fine-grained sandstone and siltstone, which serves as the most important layer for shale gas production. The Chang 7 shale is characterized by wide distribution and great thickness (Figure 2B), and represents the maximum transgressive stage across the whole basin.
3 | SAMPLES AND EXPERIMENTS

In this study, eight Yanchang Formation Chang 7 Member shale samples were collected from wells Z-125, Z-308, Z-388, X-195, G-71, G-73, G-167, and G-204 in the southwestern Ordos Basin to describe the mineralogical, geochemical, and pore structure characteristics. A series of experiments were conducted including low-pressure nitrogen adsorption/desorption analysis, thermal maturity analysis, TOC content analysis, X-ray diffraction (XRD) analysis, and pore structure observation with field-emission scanning electron microscope (FE-SEM).
The low-pressure nitrogen adsorption/desorption experiments were conducted utilizing the TriStar 3020 analyzer, following Chinese National Standard GB/T 21650.2-2008. Prior to adsorption measurement, shale samples were degassed for at least 4 hours at 573 K within a vacuum oven to remove moisture and volatile in the sample pores. For all samples, nitrogen adsorption and desorption isotherms were obtained at 77 K under relative pressure ranging between 0.01 and 0.995. The pore structure parameters, including total pore volume, specific surface area, and pore size distribution, were calculated from the nitrogen adsorption/desorption data. The specific surface area was calculated by the multipoint Brunauer-Emmet-Teller (BET) method from the nitrogen adsorption data under the relative pressure ranging from 0.05 to 0.30.\textsuperscript{31} Pore size distributions were determined based on the Barrett-Joyner-Halenda (BJH) method from the adsorption/desorption isotherms.\textsuperscript{32} The BJH model, based on Kelvin equation and corrected for multilayer adsorptions, is most widely used for calculations of pore size distribution over the mesopore and part of the macropore range.\textsuperscript{21,32}

The TOC content was obtained from the LECO CS230 carbon-sulfur analyzer following Chinese National Standard GB/T 19145-2003. The mineral composition data were obtained utilizing the X’Pert Pro MPD XRD instrument following Chinese Professional Standard SY/T 5163-2010. The thermal maturity analysis can be usually determined from the optical, chemical, and spectral methods. In this study, the Scope.Al microphotometer was used to measure the optical vitrinite reflectance (Ro, %) values following Chinese Professional Standard SY/T 5124-2012. The random reflectance was measured in oil immersion (n = 1.518) at 546 nm, and the Ro values are reported using an average of more than 20 measurements. All the above experiments were conducted in the Laboratory of Coalfield Geology Bureau of Guizhou Province, China.
Observation of pore structure was carried out utilizing the HITACHI SU8220 FE-SEM with the maximum acceleration voltage 30KV in China University of Mining and Technology. The samples should be within 20 × 20 × 10 mm in dimensions, and the produced images can reach the lowest pixel resolution of 0.8 nm.

4 | RESULTS

4.1 | Organic geochemistry and mineral compositions

Experimental results indicated that the TOC content ranged between 0.48% and 2.37% with an average of 1.10%. The measured Ro values generally varied from 0.826% to 1.217%, suggesting a late mature (0.90%-1.35%) level (Table 1).

Mineral compositions of the Chang 7 Member shale samples were determined based on the XRD analysis (Table 2). The mineral contents indicated significant differences in samples with dominated quartz and clay minerals. The quartz content varied between 40.67% and 49.48% with an average of 44.65%, and clay minerals ranged from 14.79% to 35.72% with an average of 28.25%. In the Chang 7 Member shales, clay minerals included illite, mixed layer illite-smectite, kaolinite, and chlorite, and the illite took up the largest proportion. In addition, minerals of plagioclase, potash feldspar, calcite, dolomite, pyrite, and siderite were also identified with relatively small amounts.

4.2 | Nitrogen adsorption/desorption isotherms

Nitrogen adsorption/desorption isotherms (Figure 3) are useful for determining pore characteristics within samples. The nitrogen adsorption/desorption isotherms were similar for all Chang 7 Member shale samples, which resembled the type IV isotherm according to the International Union of Pure and Applied Chemistry (IUPAC) classification (Figure 4A; Refs [33,34]). Generally, when the relative pressure was low, the adsorbed amount was low and increased slowly, whereas the adsorbed amount was high and increased swiftly in the relatively high-pressure zone (approximately 0.900 to 0.995 for the Chang 7 Member shale samples; Figure 3). At relative pressure higher 0.900, capillary condensation of nitrogen occurred in larger mesopores and macropores, resulting in the remarkable adsorption. Moreover, another characteristic feature of this type was the hysteresis loop,34 which commonly indicated that there were mesopores and macropores within shale samples. The hysteresis loop was closed at low relative pressure (approximately 0.45) for nearly all the Chang 7 Member shale samples, which was generally resulted from the tensile strength effect.21,33

In general, the hysteresis loop shape can reflect pore structures in shales.19,20,34 Based on the IUPAC classification,33 the hysteresis loop of the nitrogen adsorption/desorption isotherms for the Chang 7 shale samples was similar to Type H4 (Figure 4B), which was usually associated with narrow slit-like pores.17 The results were in accordance with pore characteristics in FE-SEM images.

Based on the observations from FE-SEM, the Yanchang Formation Chang 7 shales were overall tight and the pores were primarily at the nanoscale with a few at microscale. Those slit-like pores were along grain rims with their shapes indicating irregular elongated lines (Figure 5).

4.3 | Pore size distribution

Pore structure parameters obtained from the nitrogen adsorption/desorption isotherms are listed in Table 3. In the southwestern Ordos Basin, the results indicated that the BET specific surface area, BJH total pore volume, and average pore diameter for the Chang 7 Member shale samples varied in the range of 2.2744 m²/g~7.3463 m²/g (average: 4.1381 m²/g). 0.0074 cm³/g~0.0146 cm³/g (average: 0.0108 cm³/g), and 11.1126 nm~13.8970 nm, respectively (Table 3).

Pore size distribution may be represented by the cumulative pore volume, incremental pore volume, differential pore volume, and surface area versus pore diameter, from which, information on pore size range, dominant pore size, and pore size distribution peak can be obtained.15 As demonstrated by previous studies, for example, Groen et al.,21 the adsorption branch is highly preferred for the calculation of pore size

| Sample number | Well name | Depth (m) | TOC (%) | Ro (%) |
|---------------|-----------|-----------|---------|--------|
| YcS-1         | X-195     | 2093.77   | 1.71    | 1.217  |
| YcS-2         | Z-308     | 1854.75   | 0.51    | 0.826  |
| YcS-3         | G-167     | 1832.70   | 1.34    | 1.139  |
| YcS-4         | G-71      | 1913.50   | 0.48    | 1.167  |
| YcS-5         | Z-125     | 2326.10   | 2.37    | /      |
| YcS-6         | G-73      | 1559.15   | 0.73    | /      |
| YcS-7         | G-204     | 1800.27   | 0.83    | /      |
| YcS-8         | Z-388     | 2074.67   | 0.83    | /      |

TABLE 1 The basic properties, TOC content, and Ro data for the Chang 7 Member shale samples in the southwestern Ordos Basin, central China
distribution and can be hardly affected by the tensile strength effect.\textsuperscript{35} Therefore, in the present study, the BJH method and the adsorption branch of nitrogen adsorption/desorption isotherms were utilized to investigate pore size distributions within the Yanchang Formation Chang 7 Member shale samples of southwestern Ordos Basin.

The plot of incremental pore volume versus pore diameter illustrated that pore sizes in the Chang 7 Member shale samples were in the range from 1.73 nm to 201.42 nm. The pore size distribution appeared to be unimodal with its peak lying mainly around 40 nm (Figure 6). Generally, the Chang 7 Member shales were dominated by nanopores (from 1 nm to less than 1 μm) based on the pore size classification for mudrock pores from Loucks et al\textsuperscript{14}

### 4.4 Fractal characteristics

#### 4.4.1 Theory and methods

Fractal analysis is an important approach to describe the geometric and structural properties of solid surfaces.\textsuperscript{29,36} In general, fractal dimension $D$, defined as an index of surface roughness or structural irregularity, is used to quantitatively evaluate the fractal geometry.\textsuperscript{4,29,37,38} Based on the nitrogen adsorption data, the fractal dimension can be determined by the Frenkel-Halsey-Hill (FHH) model expressed as Equation (1),\textsuperscript{37,39} which is commonly considered as the most effective and widely used model for characterizing the pore structure within porous materials.

$$\ln(V) = (D - 3)\ln(\ln(p_0/p)) + \text{constant} \quad (1)$$

where $V$ is the adsorbed nitrogen volume, $p$ is the gas vapor pressure, $p_0$ is the saturation pressure of nitrogen, and $D$ is the fractal dimension, varying between 2 (perfectly smooth surface) and 3 (totally rough surface).

Hence, based on the FHH Equation (1), the plot of $\ln(V)$ versus $\ln(\ln(p_0/p))$ indicates a linear relationship, and the slope is determined to calculate the fractal dimension.

#### 4.4.2 Fractal dimensions from nitrogen adsorption isotherms

According to the fractal FHH equation, the plots of $\ln(V)$ versus $\ln(\ln(p_0/p))$ for all the Chang 7 Member shale samples in the southwestern Ordos Basin are shown in Figure 7. Obviously, within these plots, there were three distinct linear segments. The fractal dimensions D1, D2, and D3 were calculated based on Equation (1) with D1 from the first segment (high relative pressure, $p/p_0$ higher than 0.96) and D3 from the third segment (low relative pressure; $p/p_0$ lower than 0.45; Table 4). The D1 values ranged from 2.788 to 2.854 with an average of 2.815, the D2 values varied between 2.547 and 2.688 with an average of 2.614, and the D3 values ranged between 2.410 and 2.567.
with an average of 2.492 (Table 4). All these fractal dimensions indicated relatively complex pore structures within the Cheng 7 Member shale samples, southwestern Ordos Basin.

In addition, the functional relationship between relative pressure and pore size (diameter) can be established by the classical Kelvin equation shown as Equation (2) and Halsey equation

**FIGURE 3** Nitrogen adsorption/desorption isotherms of the Chang 7 Member shale samples in the southwestern Ordos Basin. In Figure 3, $p$ is the gas vapor pressure and $p_0$ is the saturation pressure of nitrogen.

**FIGURE 4** Types of physisorption isotherms (A) and types of hysteresis loops (B) (after ref. 34)
Hence, the boundary relative pressures of approximately 0.45 and 0.96 were observed and calculated among the straight-line segments at different relative pressure range. As the Kelvin equation was not suitable for micropores, the pores within the Chang 7 Member shale samples were divided into three zones, 2.0~3.7 nm (segment III), 3.7~50 nm (segment II), and larger than 50 nm (segment I). The fractal dimensions showed the relationship D1 > D2 > D3, and the higher D1 values suggested that pores with larger sizes showed a rougher pore surface and more complex pore structure.

$$r_K = -\frac{2\gamma V_{mol}\cos\theta}{rT\ln\left(\frac{p}{p_0}\right)}$$  \hspace{1cm} (2)

$$t = 0.354\left[-5\ln\left(\frac{p}{p_0}\right)\right]^{1/3}$$  \hspace{1cm} (3)

$$d = 2(r_K + t)$$  \hspace{1cm} (4)

where $r_K$ is the radius of the pore in which the condensation occurs, $\gamma$ is the surface tension of the liquid adsorbate, $T$ is the temperature, $r$ is the gas constant, $V_{mol}$ is the volume occupied by one mole of condensate at $T$, $\theta$ is the contact angle between the liquid and pore wall, $p$ is the pressure of condensation inside the pore, $p_0$ is the saturation pressure of the bulk fluid, $t$ is the multilayer thickness, and $d$ is the pore size (diameter).

### DISCUSSIONS

#### 5.1 Factors controlling pore structure

Previous analysis suggested that mineral compositions and the TOC content indicated significant effects on pore structure parameters both in marine and in continental shales. However, the applied analysis manner showed questions. The relationships between total pore volume (or specific surface area) and mineral compositions

| Sample number | Well name | Depth (m) | BET specific surface area (m²/g) | BJH total pore volume (cm³/g) | Average pore diameter (nm) |
|---------------|-----------|-----------|---------------------------------|-----------------------------|--------------------------|
| YcS-1         | X-195     | 2093.77   | 5.5689                          | 0.0124                      | 11.1126                  |
| YcS-2         | Z-308     | 1854.75   | 2.2744                          | 0.0074                      | 13.4727                  |
| YcS-3         | G-167     | 1832.70   | 2.5142                          | 0.0090                      | 13.3669                  |
| YcS-4         | G-71      | 1913.50   | 3.0597                          | 0.0086                      | 13.8970                  |
| YcS-5         | Z-125     | 2326.10   | 7.3463                          | 0.0146                      | 11.2077                  |
| YcS-6         | G-73      | 1559.15   | 4.1631                          | 0.0125                      | 12.7737                  |
| YcS-7         | G-204     | 1800.27   | 5.3028                          | 0.0121                      | 11.5630                  |
| YcS-8         | Z-388     | 2074.67   | 2.8756                          | 0.0097                      | 13.4302                  |
and the TOC content were obtained under different conditions. However, all factors were put together during previous analysis; hence, one could not figure out the contribution of each single factor to the final result. Therefore, in this study, the fitting relationship between the total pore volume (or specific surface area) and different factors including mineral compositions and the TOC content was separately established first. Then, in each analysis step, only a single factor varied and the rest parameters were fixed to obtain a total pore volume (or specific surface area). The controlling factor for pore structures within shale samples was hence determined by comparing the corresponding coefficient.

As the Ro values were tested only in four samples, the factors of TOC content, quartz content, and clay mineral content were analyzed. A normalization was first carried out to change all factors into the same dimensionless standard, and the Max-Min normalization method was utilized in this study.

Let $s_k$ $(k = 1, 2, 3, ..., n)$ represent the original data, then the Max-Min normalization can be formulated as Equation (5):\[^{32,43}\]

$$s_k = \frac{s_k - s_{\min}}{s_{\max} - s_{\min}}$$

where $S_k$ represents the normalized datum, $s_k$ represents the original datum, and $s_{\min}$ and $s_{\max}$ are the minimum and maximum one of the original data, respectively.

In the following, the multivariate regression analysis was carried out, and the fitting relationships between total pore structure.
volume and the TOC content, quartz content, and clay mineral content, and between specific surface area and the TOC content, quartz content, and clay mineral content were established as Equation (6) and Equation (7), respectively, with the normalized data.

\[ \text{TPV} = 0.3634x_c + 0.3876x_q + 0.8216x_T - 0.3108(R^2 = 0.6246) \]  
(6)

\[ \text{SSA} = 0.4493x_c + 0.4251x_q + 0.7303x_T - 0.2520(R^2 = 0.5596) \]  
(7)

where TPV is the normalized total pore volume, SSA is the normalized specific surface area, \( x_c \), \( x_q \), and \( x_T \) are the normalized clay mineral content, quartz content, and TOC content, respectively, and \( R \) is the correlation coefficient.

The TOC content, quartz content, and clay mineral content influenced pore structures within the Chang 7 Member shale samples could be analyzed based on Equation (6) and Equation (7) above, and obviously, the TOC content was the controlling factor for pore structures because it indicated the largest coefficient comparing with those of the quartz content and clay minerals.

### 5.2 Fractal dimensions and shale compositions

The relationships between fractal dimensions (D1, D2, and D3) and the quartz content, clay mineral content and TOC content were analyzed and plotted in Figure 8. The results indicated that the quartz content showed a slightly negative correlation with fractal dimensions (Figure 8A), which might be resulted from the smooth quartz grain surface, reducing the heterogeneity of shale pore structures. Fractal dimensions, to some extent, positively correlated with the clay mineral content (Figure 8B), which might be related to the types of clay minerals within the Chang 7 Member shales. Generally, different types of clay minerals indicated different effects on the fractal dimension, with the illite and chlorite presenting a good correlation with fractal dimensions.44 In this study, the illite was the dominant clay mineral (Table 2), resulting in the positive relationship between fractal dimensions and clay mineral content. Fractal dimensions showed positive relationships with the TOC content (Figure 8C). Shales with a higher TOC content tend to have more micropores and mesopores due to the kerogen deformation during thermal maturation,14,16 resulting in a complex pore system; therefore, the fractal dimensions are relatively larger.

### 5.3 Fractal dimensions and pore structure parameters

The relationships between fractal dimensions and pore structure parameters were analyzed and illustrated in Figure 9. The results showed that fractal dimensions indicated positive
correlations with total pore volume (Figure 9A) and specific surface area (Figure 9B), suggesting that higher total pore volume or specific surface area might have larger fractal dimensions. Fractal dimensions showed negative linear correlations with the average pore size (Figure 9C). Smaller pore sizes would result in higher fractal dimensions, namely complex pore structures.

6 | CONCLUSIONS

In this study, nanoscale pore structure and fractal characteristics of the Yanchang Formation Chang 7 Member shales in the southwestern Ordos Basin are investigated with low-pressure nitrogen adsorption/desorption analysis.

1. The major mineral compositions are quartz and clay minerals. The TOC content ranges between 0.48% and 2.37% with an average of 1.10%, and the Ro values vary from 0.826% to 1.217%.

2. The BET specific surface area, BJH total pore volume, and average pore size vary in the range of 2.2744 m$^2$/g–7.3463 m$^2$/g, 0.0074 cm$^3$/g–0.0146 cm$^3$/g, and 11.1126 nm–13.8970 nm, respectively. The narrow slit-like pore is the dominant pore type. The pore size distribution appears to be unimodal with its peak mainly around 40 nm.

3. The TOC content is the controlling factor for pore structures based on the multivariate regression analysis.

4. Three fractal dimensions are obtained with the FHH method. The D1, D2, and D3 values range in the intervals of 2.788–2.854, 2.547–2.688, and 2.410–2.567, respectively, indicating that pore structures are complicated. The higher D1 values suggest that pores with larger sizes show a rougher pore surface and more complex pore structure.

5. Fractal dimensions become larger with the increased total pore volume and specific surface area, and the decreased average pore size. Fractal dimensions show positive correlations with the TOC and clay mineral contents, and negative relationships with the quartz content.

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REFERENCES

1. Zou CN, Zhu RK, Chen ZQ, et al. Organic-matter-rich shales of China. Earth Sci Rev. 2019;189:51-78.
2. Jarvie DM, Hill RJ, Ruble TE, Pollastro RM. Unconventional shale-gas systems: the Mississippian Barnett Shale of north-central Texas as one model for thermogenic shale-gas assessment. *AAPG Bulletin* 2007;91(4):475-499.

3. Ju W, Wang JL, Fang HH, Sun WF. Paleotectonic stress field modeling and prediction of natural fractures in the Lower Silurian Longmaxi shale reservoirs, Nanchuan region, South China. *Mar Pet Geol*. 2019;100:20-30.

4. Liu XJ, Xiong J, Liang LX. Investigation of pore structure and fractal characteristics of organic-rich Yanchang formation shale in central China by nitrogen adsorption/desorption analysis. *J Nat Gas Sci Eng*. 2015;22:62-72.

5. Färe R, Alavi SA, Ghassemi MR, Shaban A. Analysis of natural fractures and effect of deformation intensity on fracture density in Garau formation for shale gas development within two anticlines of Zagros fold and thrust belt, Iran. *J Petrol Sci Eng*. 2015;125:162-180.

6. Jarvie DM, Hill RJ, Pollastro RM. Assessment of the gas potential and yields from shales: the Barnett Shale model. In: Cardot BJ, ed. *Unconventional energy resources in the Southern Midcontinent (2004 Symposium)*. 110. Oklahoma City: Oklahoma Geological Survey Circular, 2005:37-50.

7. Bowker KA. Barnett shale gas production, Fort Worth Basin: issues and discussion. *AAPG Bulletin*. 2007;91(4):523-533.

8. Ma YS, Cai XY, Zhao PR. China's shale gas exploration and petroleum development: understanding and practice. *Pet Explor Dev*. 2007;91(4):523-533.

9. Soeder DJ. The successful development of gas and oil resources from shales in North America. *J Petrol Sci Eng*. 2012;163:399-420.

10. Ju W, Wang JL, Fang HH, Gong YP, Zhang SJ. Paleostress reconstruction and stress regimes in the Nanchuan region of Sichuan Basin, South China: implications for hydrocarbon exploration. *Geosci J*. 2017;21(4):553-564.

11. Zhang JC, Jiang SL, Tang X, Zhang PX, Tang Y, Jing TY. Accumulation types and resources characteristics of shale gas in China. *Nat Gas Ind*. 2009;29:109-114. (in Chinese with English abstract).

12. Wang Y, Zhu YM, Wang HY, Feng GJ. Nanoscale pore morphology and distribution of lacustrine shale reservoirs: examples from the Upper Triassic Yanchang Formation, Ordos Basin. *J Energy Chem*. 2015;24:512-519.

13. Schettler PD, Parmely CR. Contributions to total storage capacity in Devonian shales. *Soc. Petro. Eng*. 1991;23422:77-88.

14. Loucks RG, Reed RM, Ruppel SC. Hames U. Spectrum of pore types and networks in mudrocks and a descriptive classification for matrix-related mudrock pores. *AAPG Bulletin*. 2012;96(6):1071-1098.

15. Clarkson CR, Solano N, Bustin RM, et al. Pore structure characterization of North American shale gas reservoirs using USANS/SANS, gas adsorption, and mercury intrusion. *Fuel*. 2013;103:606-616.

16. Ross DJK, Bustin RM. The importance of shale composition and pore structure upon gas storage potential of shale gas reservoirs. *Mar Pet Geol*. 2009;26:916-927.

17. Anowitz LM, Cole DR. Characterization and analysis of porosity and pore structures. *Rev Mineral Geochem*. 2015;80:61-164.

18. Lai J, Wang GW, Wang ZY, et al. A review on pore structure characterization in tight sandstones. *Earth Sci Rev*. 2018;177:436-457.

19. Chalmers GRL, Bustin RM, Power IM. Characterization of gas shale pore systems by porosimetry, pycnometry, surface area, and field emission scanning electron microscopy/transmission electron microscopy image analyses: examples from the Barnett, Woodford, Haynesville, Marcellus, and Diog units. *AAPG Bulletin*. 2012;96(6):1099-1119.

20. Shao XH, Pang XQ, Li QW, et al. Pore structure and fractal characteristics of organic-rich shales: a case study of the lower Silurian Longmaxi shales in the Sichuan Basin, SW China. *Mar Pet Geol*. 2017;80:192-202.

21. Groen JC, Peffer LAA, Perez-Ramirez J. Pore size distribution in modified micro- and mesoporous materials: Piferrals and limitations in gas adsorption data analysis. *Microporous Mesoporous Mater*. 2003;60(1-3):1-17.

22. Li WJ, Wang CC, Shi ZJ, Wei Y, Zhou HL, Deng K. The description of shale reservoir pore structure based on method of moments estimation. *PLoS ONE*. 2016;11(3):e0151631.

23. Ju W, Sun WF, Hou GT. Insights into the tectonic fractures in the Yanchang Formation interbedded sandstone-mudstone of the Ordos Basin based on core data and Geomechanical models. *Acta Geol Sin (Eng Ed)* 2015;89(6):1986-1997.

24. Liu CY, Zhao HG, Gui XJ, Yue LP, Zhao JF, Wang JQ. Space-time coordinate of the evolution and reformation and mineralization response in Ordos Basin. *Acta Geol Sin*. 2006;80(5):617-638. (in Chinese with English abstract).

25. Lin SH, Yuan XJ, Tao SZ, Yang Z, Wu ST. Geochemical characteristics of the source rocks in Mesozoic Yanchang Formation, central Ordos Basin. *J Earth Sci*. 2013;24(5):804-814.

26. Ritts BD, Weislogel A, Graham SA, Darby BJ. Mesozoic tectonics and sedimentation of the giant polyphase nonmarine intraplatch Ordos Basin, western North China Block. *Int Geol Rev*. 2009;51(2):95-115.

27. Yang RC, Jin ZJ, van Loon AJ, Han ZZ, Fan AP. Climatic and tectonic controls of lacustrine hyperpycnite origination in the late Triassic Ordos Basin, central China: implications for unconventional petroleum development. *AAPG Bulletin*. 2017;101(1):95-117.

28. Zeng LB, Li XY. Fractures in sandstone reservoirs with ultra-low permeability: a case study of the Upper Triassic Yanchang Formation in the Ordos Basin, China. *AAPG Bulletin*. 2009;93(4):461-477.

29. Lai J, Wang GW, Fan ZY, et al. Insight into the pore structure of tight sandstone using NMR and HPMI measurements. *Energy Fuels*. 2016;30(12):10200-10214.

30. Lai J, Wang GW, Ran Y, Zhou ZL, Cui YF. Impact of diagenesis on the reservoir quality of tight oil sandstones: the case of Upper Triassic Yanchang Formation Chang 7 oil layers in Ordos Basin, China. *J Petrol Sci Eng*. 2016b;145:54-65.

31. Brunauer S, Emmett PH, Teller E. Adsorption of gases in multimolecular layers. *J Am Chem Soc*. 1938;60(2):309-319.

32. Barrett EP, Joyner LG, Halenda PP. The determination of pore volume and area distributions in porous substances. I. Computations from nitrogen isotherms. *J Am Chem Soc*, 1951;73(1):373.

33. Gregg SJ, Sing KSW. *Adsorption, Surface Area, and Porosity (second edition).* London: Academic Press; 1982:303.

34. Sing KSW, Everett DH, Haul RAW, et al. Reporting physiosorption data for gas/solid systems with special reference to the determination of surface area and porosity. *Pure Appl Chem*. 1985;57(4):603-619.

35. Bertier P, Schweinar K, Stanjek H, et al. On the use and abuse of N2 physiosorption for the characterization of the pore structure
of shales. *The Clay Minerals Society Workshop Lectures Series*. 2016;21:151-161.

36. Mandelbrot BB. *The Fractal Geometry of Nature*. New York: W.H. Freeman and Company, 1982: 480.

37. Pfeifer P, Avnir D. Chemistry in noninteger dimensions between two and three. I. Fractal theory of heterogeneous surfaces. *J Chem Phys* 1983;79(7):3558.

38. Schluter EM, Zimmerman RW, Witherspoon PA, Cook NGW. The fractal dimension of pores in sedimentary rocks and its influence on permeability. *Eng Geol*. 1997;48(3):199-215.

39. Avnir D, Jaroniec M. An isotherm equation for adsorption on fractal surfaces of heterogeneous porous materials. *Langmuir*. 1989;5:1412-1433.

40. Skinner LM, Sambles JR. The Kelvin equation-A review. *J Aerosol Sci*. 1972;3(3):199-210.

41. Halsey G. Physical adsorption on non-uniform surfaces. *J Chem Phys*. 1948;16(10):931-937.

42. Ju W, Hou GT, Zhang B. Insights into the damage zones in fault-bend folds from geomechanical models and field data. *Technophysics*. 2014;610:182-194.

43. Wang YJ, Zhang R, Guan L, Venetsanopoulos AN. Kernel fusion of audio and visual information for emotion recognition. In: Kamel M, Campilho A, eds. *Image Analysis and Recognition*. Heidelberg: Springer; 2011:140-150.

44. Gu Y, Ding WL, Yin M, et al. Nanoscale pore characteristics and fractal characteristics of organic-rich shale: an example from the lower Cambrian Niutitang Formation in the Fenggang block in northern Guizhou Province, South China. *Energy Explor Exploit*. 2019;37(1):273-295.

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