Classifications of the Reservoir Space of Tight Sandstone Based on Pore Structure, Connectivity, and Fractal Character: A Case Study from the Chang 7 Member of the Triassic Yanchang Formation in the Ordos Basin, China

Wei Wang,* Weizhen Li, and Shuang Xu

ABSTRACT: Pore structure characteristics of tight sandstones, including pore types, connectivity, and morphological features, provides a basis for selecting the “sweet spot” in tight sandstone reservoirs. A variety of research methods, high-pressure mercury intrusion porosimetry, cast thin sections, scanning electron microscopy, and fractal theory were integrated to explore these parameters of tight sandstones from the Chang 7 member of the Triassic Yanchang Formation in the Ordos Basin, China. Results indicate that tight sandstones are defined by three pore types with distinct fractal dimensions and corresponding pore structure, which are combined pores, isolated grain pores, and clay-dominated pores. The pore spaces of the three types gradually evolve from the microscale to the nanoscale. Combined pores were formed by dissolution pores connected to the surrounding pores and have been distinguished by their irregular shape. Their connected paths are multidirectional, resulting in better connectivity. Isolated grain pores have a small number of poorly connected paths, which causes weak connectivity. Clay-dominated pores have narrow and complex connected paths, resulting in poor connectivity. From the combined pore to the clay-dominated pore, the fractal dimensions of pore spaces decrease, indicating that the heterogeneity of pore spaces is gradually weakened whereas the heterogeneity of the flow characteristics is gradually enhanced. On the basis of the proportions of the three pore types, the tight sandstones can be genetically classified into a combined pore type, an isolated grain pore type, and a clay-dominated pore type. The differences in pore space and heterogeneity affect the distribution of tight oil; therefore, sand bodies located near the source rock, characterized by strong dissolution and dominated by the combined pore type, are favorable zones for tight sandstone reservoirs.

1. INTRODUCTION

With the development of exploration technologies and the depletion of conventional oil reserves, tight sandstone reservoirs have become the focus of global oil and gas exploration.1–3 The main factors influencing a well’s performance in tight sandstone are the pore structures and the connectivity.4,5 Because tight sandstone is affected by diagenesis, its pore structure is characterized by a complex and irregular pore shape, various connectivities, and strong heterogeneity, thus the identification of reservoir space types and heterogeneity and the quantification of their contribution to the storage capacity are the bases for predicting the enrichment and development of tight sandstone reservoirs.6–8

Pore structures of tight sandstone have been measured by many methods, and the parameters of the pore throat, such as the pore radius, pore size distribution, and sorting coefficient, were obtained. Although these parameters clarified the pore structure of tight sandstone, they ignored the evolution of the reservoir pore space and the corresponding change in heterogeneity and did not quantify the contribution of different types of reservoir space to the physical properties. The study of reservoir space evolution (including pore type and size) is not only helpful for evaluating the storage and connectivity of tight reservoirs but also can effectively guide the prediction of favorable areas for tight sandstone reservoirs. However, traditional experimental methods and parameters are not able to comprehensively measure the heterogeneity and pore structure.9,10 Therefore, a more modern approach is necessary to understand the microscopic pore structure, specifically by combining the theoretical methods with the experimental ones.

During the past few years, several techniques have been used to characterize the pore structure of tight sandstone, including...
X-ray-computed tomography, nuclear magnetic resonance, rate-controlled porosimetry, low-pressure gas adsorption (LPGA), and small-angle and ultrasmall-angle neutron scattering (SANS/USANS). Although these methods play an important role in exploring the pore structures, all of these techniques have limitations to the experimental method or are too expensive for routine use. However, high-pressure mercury intrusion porosimetry (HMIP) can identify microscale and nanoscale pores and is widely used to measure the pore size distribution in rocks because of its high injection pressure.

Fractal theory is an effective method of nonlinear mathematics that can characterize intricate phenomena, and it is used to explicate system characteristics of irregular, unstable, and complex structures. The fractal dimension \(D\) is the expression of fractal characteristics and contributes to the quantitative measurement of the irregularity of pore structures. It builds a link between morphological features and physical properties. Many scholars have successfully applied fractal theory to investigate the pore structure of coal and sandstone. The increase in the fractal dimension indicates rough surfaces and complex structure of the pore space, and the decreasing in the fractal dimension indicates a regular shape and a smooth pore surface.

In this study, we used HMIP, cast thin sections, scanning electron microscopy (SEM), and fractal methods to investigate the pore space evolution, heterogeneity, and effects on physical properties of tight sandstone from the Triassic Yanchang Formation in the Ordos Basin, China. Pore types and corresponding pore structures in the tight sandstones have been identified. The contributions of different pore types to the physical properties were quantified. The pore structure and connectivity characteristics of different tight sandstone types were discussed. The obtained results provide insights regarding oil migration and distribution in tight sandstone.

2. MATERIALS AND METHODS

2.1. Sampling and Sample Preparation. For this study, tight sandstone samples were collected from the Chang 7 Member of the Triassic Yanchang Formation in the Ordos Basin, China (Figure 1A). The Chang 7 subsection is a semideep and deep lake deposit with tight sandstone that developed adjacent to the source rocks (Figure 1B). The acid fluid from the source rock migrated into the Chang 7 tight
sandstone, resulting in the extensive dissolution of the tight sandstone.38
Ten 2.5-cm-diameter cylindrical core plugs were drilled parallel to the bedding surface of the tight sandstone. Residuals were removed from all of the samples, after which they were dried under vacuum at 105 °C for 24 h. Each core plug was then analyzed using helium porosity and nitrogen permeability tests and then divided into three parts for thin-section, SEM, and HMIP analyses to determine the microscopic and fractal characteristics of the pore space of the tight sandstones.

2.2. Experimental Methods. 2.2.1. Thin-Section Analysis. Thin sections were impregnated with red epoxy resins and then analyzed to determine their petrological characteristics and pore origin. Petrographic images were captured using a Leica DLC-420 microscope camera system.

2.2.2. Scanning Electron Microscopy (SEM). An FEI Quanta 400 FEG SEM was used to examine the pore structure of broken fragments from samples with fresh surfaces. Samples were coated with gold and used for secondary electron imaging (SE), backscattering electron imaging (BSE), and energy-dispersive spectroscopy (EDS) mineral identification. The accelerating voltage and SEM resolution were 30 kV and 1.2 nm, respectively.

2.2.3. High-Pressure Mercury Intrusion Porosimetry (HMIP). The HMIP is a pore-size measurement technique that uses the penetration of a nonwetting liquid (in this case, mercury) to measure the size and volume of pores in porous solids (in this case, sandstone). When mercury is injected into the porous sample, capillary pressure prevents the mercury from invading the pore space. Therefore, the injection pressure is required to overcome the capillary resistance, and each injection pressure of mercury corresponds to the capillary pressure of the pore with the corresponding size. The volume of mercury represents the volume of the connected pore space.

An Autopore 9420 mercury porosimeter was used to perform HMIP on the collected samples. Using a maximum displacement pressure of 200 MPa, the HMIP analysis determined the capillary pressure curves of the sandstone samples during mercury intrusion. After reaching the maximum pressure, the displacement pressure is gradually decreased to allow for mercury extrusion from the samples. The intrusion and extrusion mercury curves are obtained on the basis of pressure data and corresponding mercury saturation. Because the pore size and pore connectivity control the capillary pressure, the capillary pressure curve can reflect the pore structure. The pore diameter was evaluated using the Washburn equation as seen in eq 1, with an air/mercury surface tension of 480 dyn/cm and a contact angle of 140°. These HMIP measurements can identify pore sizes larger than 3.6 nm

\[ P_c = \frac{2\sigma \cos \theta}{r} \]  
(1)

where \( P_c \) is the capillary pressure in MPa, \( \theta \) is the contact angle in degrees, \( \sigma \) is the air/mercury surface tension in N/m, and \( r \) is the pore radius in \( \mu \text{m} \).

2.3. Fractal Method. If the pore space has fractal characteristics, then the number of pores \( N(r) \) with a radius greater than \( r \) can be mathematically expressed according to fractal theory as the function

\[ N(r) \propto r^{-D} \]  
(2)

where \( r \) is the pore radius and \( D \) is the fractal dimension. For mercury porosimetry, eq 2 can be inferred as follows

\[ V_{Hg} \propto P_c^{-(3-D)} \]  
(3)

where \( V_{Hg} \) is the mercury intrusion saturation corresponding to the capillary pressure \( (P_c) \). We combined eqs 3 and 4 to obtain the fractal dimension, \( D \) (eq 5), as follows

\[ \frac{dV_{Hg}}{dP_c} \propto P_c^{D-4} \]  
(4)

\[ D = 4 + K \]  
(5)

where \( K \) is the line slope for plotting the double logarithm of \( dV_{Hg}/dP_c \) versus \( P_c \).

3. RESULTS AND DISCUSSION

3.1. Petrophysical Characteristics. Table 1 shows the mineral compositions of the samples. The tight sandstone of the Chang 7 subsection is dominated by feldspathic lithic sandstone (Figure 2A). The rock components mainly consist of feldspar and quartz, followed by rock fragments. The cement is mainly authigenic clay minerals (chlorite, kaolinite, and illite) and carbonate (Figure 2B,C).

On the basis of the origin of the Chang 7 tight sandstone, its pores are predominately intergranular, dissolution, and clay. Intergranular pores are formed by primary pores that remain after compaction and cementing of the clastic particles, and they are polygon-shaped with straight edges (Figure 2D). Dissolution pores formed as a result of the corrosion by acidic fluid within the particles, and they have an ink bottle shape (Figure 2D). Dissolution pores can connect with the surrounding pores to form combined pores with irregular shapes and large radii (Figure 2E). Authentic clay that occurs in the intergranular pores and dissolution pores form clay-dominated pores (Figure 2F).

The porosity values of the samples range from 7.2 to 11.5%, with an average of 9.9%. The permeability values of the samples range from 0.13 × 10⁻³ to 0.27 × 10⁻³ μm², with an average of 0.20 × 10⁻³ μm² (Table 1). An increase in porosity has a corresponding increase in permeability (Figure 3). This correlation between porosity and permeability indicates good
pore connectivity, and a few microfractures also exist in the tight sandstone.

3.2. Characteristics of Mercury Curves from HMIP.

The HMIP is an effective method for obtaining pore connectivity, which directly influences the fluid flow in porous materials. Figure 4 shows the HMIP curves of the eight samples. The mercury intrusion saturation increased rapidly when the pressure was low. This indicates that a large amount of mercury enters the large pores and that the connectivity of the large pores is good. As the pressure is further increased ($P_c > 40$ MPa), the mercury intrusion saturation increases slowly, indicating that the connectivity of the small pores is poor. The characteristics of the mercury curves indicate that there was significant variation in the pore structure of the tight sandstone.

The pore sizes of the sample can be calculated and the pore size distribution (PSD) can be obtained by combining the mercury intrusion curves. The pore size distributions of the tight sandstone in this study mainly range from 3.6 nm to 0.6 μm (Figure 5), and the pore distribution ranges from the microscale to the nanoscale. The PSD curves show evident fluctuations, which means that the pore throat distribution is highly heterogeneous.

3.3. Pore Type Identification Based on Fractal Dimensions.

Fractal dimensions can be used to characterize the heterogeneity of space. The larger the fractal dimensions, the more heterogeneous the space. Fractal dimensions can
specifcally be used to distinguish the pore space of the tight sandstones.

The log(dVp/dP)−log(P) plots that have been obtained from the HMIP curves of the eight samples have two obvious turning points, which divided the plots into three stages (Figure 6). Fractal dimensions $D_1$, $D_2$, and $D_3$ are derived from three stages with all $p$ values being less than 0.05 (Table 2), indicating that the pores of the Chang 7 samples have three...
Table 2. Fractal Dimension Value and Related Parameters for Three Stages of MICP

| samples | \( D^1 \) | \( D^2 \) | \( D^3 \) | \( K^1 \) | \( K^2 \) | \( K^3 \) | \( P^1 \) | \( P^2 \) | \( P^3 \) |
|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| G1      | 5.5635  | 2.3897  | 1.9333  | 1.5635  | −1.6103 | −2.0667 | 0.0017  | 0.0001  | 0.0450  |
| G2      | 7.3749  | 2.8372  | 1.8713  | 3.3749  | −1.1628 | −2.1287 | 0.0094  | 0.0001  | 0.0001  |
| G3      | 6.6017  | 2.5354  | 1.8366  | 2.6017  | −1.4646 | −2.1634 | 0.0007  | 0.0001  | 0.0001  |
| G4      | 5.3937  | 2.7591  | 1.7851  | 1.3937  | −1.2409 | −2.2169 | 0.0050  | 0.0001  | 0.0146  |
| G5      | 6.1417  | 2.8054  | 1.6038  | 2.4147  | −1.1946 | −2.3962 | 0.0220  | 0.0001  | 0.0006  |
| G6      | 5.4113  | 2.6618  | 1.9802  | 1.4113  | −1.3382 | −2.0198 | 0.0043  | 0.0001  | 0.0047  |
| G7      | 6.4210  | 2.8177  | 1.5796  | 2.4210  | −1.1823 | −2.4204 | 0.0347  | 0.0001  | 0.0050  |
| G8      | 4.9335  | 2.8785  | 1.6002  | 0.9335  | −1.1215 | −2.3998 | 0.0030  | 0.0001  | 0.0005  |

*Fractal dimension of stage A. *Fractal dimension of stage C. *Slope of the fitted line of stage A. *Slope of the fitted line of stage B. *Slope of the fitted line of stage C. *P value in the linear regression analysis of stage A. *P value in the linear regression analysis of stage B. *P value in the linear regression analysis of stage C.

**Figure 7.** Schematic diagrams of pore connectivity. (A) Connectivity and pore structure of combined pores (CP) and isolated grain pores (IGP) in sample G2. (B) Clay-dominated pores within the intergranular space of chlorite aggregations in sample G4. (C) Clay-dominated pores within the intergranular space of kaolinite aggregations in sample G3.

Types of fractal features which can be identified by calculating the principle fractal dimensions. The related values of the fractal dimensions are shown in Table 2.

The \( D^1 \) value of the samples ranges from 4.9335 to 7.3749 with an average of 6.0143, with \( D^1 \) being larger than 3. Any \( D > 3 \) has no geometrical meaning for pore spaces in fractal theory. According to previous studies, \( D > 3 \) can be attributed to many factors, such as compression and rupture of the matrix, microfracturing, and oversimplification of the pore space and skin effects. For the Chang 7 tight sandstone, the pressure corresponding to stage A is low, the microfractures are not developed, and the \( P \) values of the linear regression analysis corresponding to stage A are less than 0.05. This indicates that pores with large reservoir spaces are present and that the strong heterogeneity can be represented by the fractal characteristics.

On the basis of the thin section and SEM analyses, we found that the dissolution pores connect with the surrounding pores, forming combined pores with a large, complex storage space (Figure 7A). The radius of the combined pores is large, and the fluid can easily flow into these large combined pore spaces, resulting in a rapid increase in mercury saturation at low pressures, and high values of \( \log(dVp/dP)/\log(P) \). Stage A corresponds to mercury filling the combined pores, which have irregular bottleneck shapes and are significantly heterogeneous, resulting in high fractal dimensions (\( D > 3.0 \)).

\( D^2 \) of the samples ranges from 2.3897 to 2.8785 with an average of 2.7106. Fractal dimensions of between 2 and 3 represent the dissolution pores due to their volume-filling shapes. Diagenesis caused heavy deformation of the intergranular pores of the Chang 7 tight sandstone (Figure 7A). These pores show heterogeneity and fractal dimensions similar to those of dissolution pores.

The intergranular pores and the isolated dissolution pores have a few connection paths, and these two pore types can be identified as isolated grain pores as a result of their poor connectivity. Stage B therefore corresponds to filling isolated grain pores, which have medium heterogeneity and fractal dimensions, with mercury.

\( D^3 \) of the samples ranges from 1.5796 to 1.9302, with an average of 1.7735. Fractal dimensions of between 1 and 2 indicate that mercury is invading the intergranular voids during stage C. The corresponding pressure of stage C is greater than 11 MPa, whereas the size of corresponding stage C is less than 0.06 nm, which is associated with clay-dominated pores. 1 < \( D^3 < 2 \) indicates limited compressibility of the clay in the tight sandstone. The clay-dominated pores originate from the intergranular space of clay aggregations with regular shapes (Figure 7B, C). The radii of the clay-dominated pores are small, and fluid flows into the pores only under high pressure. Stage C therefore corresponds to the mercury filling of clay-dominated pores, which have simple intergranular fill shapes, poor heterogeneity, and low fractal dimensions.
The reservoir space of tight sandstone is defined by combined pores, isolated grain pores, and clay-dominated pores (Figure 8). The fractal dimensions decrease from combined pores to clay-dominated pores, indicating that the heterogeneity of the pore space decreases from the microscale to the nanoscale.

Figure 8. Schematic diagram of the pore types of the tight sandstone: (A) combined pore, (B) isolated grain pore, and (C) clay-dominated pore.

The fractal characteristics of HMIP results show three distinct fractal dimensions (D1, D2, and D3), mainly ranging from 1.8 to 6.5 and corresponding to different pore types. These results are obviously different from the fractal dimensions calculated with SANS/USANS and LPGA results (ranging mostly between 2.6 and 2.8). The differences in fractal dimensions from HMIP, LPGA, and SANS/USANS techniques may be partially attributed to the following: (1) LPGA and SANS/USANS obtain only a narrow range of pore structure, mostly concerning nanoscale pores. The small range of pores shows only one fractal metric. (2) Mercury can enter only the connected pores, and the accessibility at lower relative pressures to the complex pore by probe molecules (N2 and CO2) is limited. (3) Different pore geometry is assumed in the analysis data from different techniques.

3.4. Effect of Pores on Physical Properties. 3.4.1. Effect of Pores on Porosity. The proportion of different pore types among the total reservoir spaces can be used to calculate the mercury saturation in each type of pore relative to the total mercury saturation (Table 3 and Figure 9). The proportions of combined pores, isolated grain pores, and clay-dominated pores range from 18.23 to 43.83% (average 27.22%), 39.52 to 58.02% (average 46.28%), and 3.74 to 426.91% (average 15.24%), respectively, and proportions of three types of pores show variability between samples. Combined pores and isolated grain pores form the two main pore types in the sandstone samples of this study, of which isolated grain pores are the majorit.

3.4.2. Effect of Pores on Permeability. The bundle of tubes model can be used to calculate the contributions of the different pore throats to the permeability (Ki).

\[ K_i = \frac{dS_{Hg} \cdot r_i^2}{\sum_i (dS_{Hg} \cdot r_i^2)} \]  

where \(dS_{Hg}\) is the increment of the total mercury intrusion corresponding to pore throats with a radius of \(r_i\).

On the basis of the distribution ranges of three pore types, the contributions of the different pore types to the permeability were calculated and are shown in Table 3. Combined pores contribute 83.43–92.85% (average 86.71%) to the permeability, indicating that the main pore type contributing to permeability is combined pores. The contribution of isolated grain pores to permeability ranges from 7.14 to 16.56% (average 13.27%), while the contribution of clay-dominated pores is 0.11%, indicating that the contribution of isolated grain pores and clay-dominated pores to the permeability is low.

The porosity permeability contribution ratio (PPCR) is the ratio of the contribution of permeability to the proportion of the porosity and can reflect the connectivity of pores. The PPCR values of the combined pores, dissolution pores, and clay-dominated pores range from 2.118 to 5.005 (average 3.584), 0.180 to 0.360 (average 0.286), and 0.001 to 0.003 (average 0.001), respectively (Table 3). The storage capacity and connectivity decrease from combined pores to clay-dominated pores, which is inconsistent with the heterogeneity of the pore space.

3.5. Effect of Diagenesis on the Pore Structure and Connectivity Characteristics of the Pores. Diagenesis has an important influence on the morphological structure and connectivity of pores, which are in turn closely related to the fractal dimensions and the connectivity of the tight sand-

Table 3. Petrophysical Properties Related to Various Types of Pores in Eight Tight Sandstone Samples

| samples | proportion of porosity (%) | contribution to permeability (%) | porosity permeability contribution ratio |
|---------|----------------------------|----------------------------------|----------------------------------------|
|         | combined pores | isolated pores | clay-dominated pores | combined pores | isolated pores | clay-dominated pores | combined pores | isolated pores | clay-dominated pores |
| G1      | 43.83         | 39.64           | 3.74                  | 92.85         | 7.14           | 0.01               | 2.118         | 0.180           | 0.003               |
| G2      | 24.35         | 47.99           | 17.88                 | 86.34         | 13.65          | 0.01               | 3.546         | 0.284           | 0.001               |
| G3      | 32.66         | 40.89           | 17.21                 | 85.27         | 14.72          | 0.01               | 2.611         | 0.360           | 0.001               |
| G4      | 22.12         | 58.02           | 10.03                 | 86.33         | 13.66          | 0.01               | 3.903         | 0.235           | 0.001               |
| G5      | 25.81         | 46.75           | 16.99                 | 84.73         | 15.26          | 0.01               | 3.160         | 0.326           | 0.001               |
| G6      | 23.57         | 50.71           | 9.80                  | 83.54         | 16.45          | 0.01               | 3.154         | 0.324           | 0.001               |
| G7      | 26.19         | 46.72           | 19.17                 | 83.43         | 16.56          | 0.01               | 3.186         | 0.354           | 0.001               |
| G8      | 18.23         | 39.52           | 26.91                 | 91.25         | 8.74           | 0.01               | 5.005         | 0.221           | 0.001               |
Figure 10. Typical pores that occur in the tight sandstones samples. (A) Intergranular pores with closed connection paths in sample G6. (B) Dissolution pores in the interior of clastic particles in sample G8. (C) Combined pores in sample G2. (D) Clay-dominated pores of clay aggregates in sample G3.

Figure 11. Classification and flow characteristics of the tight sandstone, where G1, G4, and G8 represent the combined pore (CP) type, the isolated grain pore (IGP) type, and the clay-dominated pore (CDP) type, respectively. (1) Comparison of different pore contents. (2) Comparison of the mercury intrusion saturation. (3) Schematic diagrams of flow characteristics in the different tight sandstone types.
stone.\textsuperscript{50} Compaction reduces the intergranular space and causes the clastic particles to be in close contact with each other. Intergranular pores, therefore, develop in isolation and connect with other pores via a narrow necking throat (Figure 10A).

Dissolution is the main diagenesis that increases the storage space in tight sandstone. Dissolution mainly occurs in the interior of particles to form dissolution pores (Figure 10B). The dissolution pores mainly connect with the dissolution pore-shrinking throats, thus the connection paths of the intergranular pores and dissolution pores are relatively isolated.

With increased dissolution, most of the particles dissolved and the dissolution pores started to extend outward and connect with surrounding pore spaces to form combined pores with large storage spaces. Multiple and broad connection paths of combined pores occur in the samples (Figure 10C).

Aggregates of authigenic clay minerals fill the pores and segment the primary intergranular pores into clay-dominated pores, which connect with cluster throats (Figure 10D).

In summary, combined pores formed via dissolution pores connecting with the surrounding pores. The pore spaces of the combined pores is large and extremely irregular, and the connectivity of these pores is good. Isolated grain pores include intergranular pores and dissolution pores. Their pore spaces are slightly irregular and they have moderate connectivity. Clay-dominated pores originated from the intergranular space between clay aggregates. Their pore spaces are regular and homogeneous, and their connectivity is poor. A clear correlation exists between connectivity and pore type. The connected path reveals the mismatch of heterogeneity of pore spaces and connectivity.

3.6. Pore Structures and Flow Characteristics of Tight Sandstone. The storage capacity, connectivity, and heterogeneity of the reservoir space have an important impact on the accumulation and development of tight sandstone reservoirs.

On the basis of the proportions of the three pore types in the tight sandstone, the tight sandstone can be genetically classified into a combined pore type, an isolated grain pore type, and a clay-dominated pore type. The pore structures and flow characteristics of the various types of tight sandstone are distinct. These three genetic classifications are discussed below.

(1) Combined pore type (samples G1). This tight sandstone type was strongly affected by dissolution. The combined pore content is high (more than 30%), while the isolated pore content is relatively low, with the clay-dominated pore content being the lowest (Figure 11A). This tight sandstone has a large storage space (with a porosity higher than 11%) and a strong connectivity (with a permeability larger than 0.25 $\times 10^{-3}$ $\mu m^2$). The speed of mercury intrusion into this sandstone type is fast, indicating that the fluid can quickly enter the pore spaces of this tight sandstone type (Figure 11B).

Because of the multidirectional connected paths, the heterogeneity of the seepage process is low (Figure 11C). The oil uniformly migrated through these multiple paths and into the pore spaces and was well distributed within the pore spaces of the tight sandstone, leading to large areas with high oil saturation within the sand bodies.\textsuperscript{31}

(2) Isolated pore type (samples G2–G7). This tight sandstone was affected by compaction and cementation, which led to a higher isolated pore content compared to the other pore types. This tight sandstone has moderate storage space (with an average porosity of 10.1%), and a moderate connectivity (with an average permeability of 0.19 $\times 10^{-3}$ $\mu m^2$). The initial speed of mercury intrusion was slow but increased rapidly as the pressure increased (Figure 11). This means that fluid first migrated into a small number of combined pores, after which it migrated into a large number of isolated grain pores.

The flow characteristics of these tight sandstones are controlled by the isolated grain pores, which have fewer connected paths (Figure 11). In this tight sandstone type, the oil migrated via a few obvious and dominant flow paths, and the oil intrusion and saturation of the isolated pore type of tight sandstone is moderate.

(3) Clay-dominated pore type (sample G8). These tight sands are predominately affected by clay cementation and have a high clay content (larger than 20%). The clay fills the pores and lowers the availability of combined pores and isolated grain pores (Tables 1 and 3 and Figure 11A). The storage space of this tight sandstone type is low (porosity 7.2%), and the connectivity is poor (permeability $0.12 \times 10^{-3}$ $\mu m^2$), indicating that clay minerals occupy the intergranular space and separate the connected paths. The initial speed at which the fluid entered this sandstone is slow, indicating that a large amount of fluid filled the clay-dominated pores (Figure 11B).

The clay-dominated pores are mainly connected with combined pores because of a lack of isolated grain pores and form a short-radial-flow characteristic (Figure 11C). The movement of the oil front is not uniform, and the oil and gas are mainly located in the clay-dominated pores, resulting in a small area within the sand bodies that have a low saturation.

Combined pores greatly improve the storage and connectivity of the tight sandstones. The combined pores predominantly form by dissolution via the acids from the hydrocarbon source rocks. The sand bodies that are close to the hydrocarbon source rock are therefore favorable tight sandstone reservoir areas. In areas located far from the hydrocarbon source rock, the tight sandstone dominated by isolated grain pores should be the favorable area for a tight reservoir. This research is useful for the exploration and development of tight sandstone reservoirs.

4. CONCLUSIONS

In this article, thin sections, SEM, HMIP, and fractal theory were used to examine the pore structure, connectivity, and fractal characteristics of eight tight sandstone samples of the Upper Triassic Yanchang Formation from the Ordos Basin. The following conclusions are relevant:

(1) Diagenesis causes the evolution of reservoir space size from the microscale to the nanoscale. Accordingly, a relevant pore type evolved from combined pores and isolated grain pores to clay-dominated pores, with each corresponding to a distinct pore structure. The changes in the type and size of reservoir spaces not only cause the differences in storage capacity and connectivity but also lead to the fractal features of pore spaces evolving from high ($D_1 > 3$) to low ($1 < D_3 < 3$) values.

(2) From the combined pore to the clay-dominated pore, the storage capacity and connectivity decrease and the heterogeneity of pore spaces is gradually weakened, whereas that of the flow process is gradually enhanced.

https://doi.org/10.1021/acsomega.2c00252
ACS Omega 2022, 7, 10627–10637
The connected paths reveal the mismatch of the heterogeneity of the pore space and flow characteristics. (3) The tight sandstone can be classified into three pore types: the combined pore type, the isolated grain pore type, and the clay-dominated pore type, with each having distinct pore structures and flow characteristics. All of these changes in reservoir spaces influence the distribution of tight oil. The sandstone dominated by the combined pore type has a uniform flow process and large areas available for oil ingress, which results in high saturated sand bodies. The sand bodies that are located close to the hydrocarbon source rock are therefore favorable tight sandstone reservoirs. In areas located far from the hydrocarbon source rock, the tight sandstone dominated by isolated grain pores should be the favorable area for the tight reservoir.

AUTHOR INFORMATION

Corresponding Author
Weil Wang — College of Chemistry and Chemical Engineering, Yulin University, Yulin 719000 Shaanxi, P. R. China; orcid.org/0000-0001-7565-6969; Phone: +86(0912) 3891144; Email: wangwei_1988@yulinu.edu.cn

Authors
Weizhen Li — Oil Production Plant No. 1, Petrochina
Changqing Oilfeld Company, Yan’an 716000 Shaanxi, P. R. China
Shuang Xu — Oil Production Plant No. 1, Petrochina
Changqing Oilfeld Company, Yan’an 716000 Shaanxi, P. R. China

Complete contact information is available at:
https://pubs.acs.org/10.1021/acsomega.2c00252

Notes
The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This research was financially supported by the National Natural Science Foundation of China (nos. 41904128 and 42062011), the Initial Scientific Research Fund of High Level Talents in Yulin University (18GK22), and the Department of Science and Technology of Shaanxi Province (2021SF-495).

REFERENCES

(1) Ghanizadeh, A.; Clarkson, C.; Aquino, S.; Ardakani, O. H.; Sanei, H. Petrophysical and geomechanical characteristics of Canadian tight oil and liquid-rich gas reservoirs: II. Geomechanical property estimation. Fuel 2015, 153 (1), 682–691.
(2) Li, Y.; Tang, D.; Wu, P.; Niu, X.; Wang, K.; Qiao, P.; Wang, Z. Continuous unconventional natural gas accumulations of Carboniferous-Permian coal-bearing strata in the Linxing area, northeastern Ordos basin, China. J. Nat. Gas Sci. Eng. 2016, 36, 314–327.
(3) Li, Y.; Yang, J.; Pan, Z.; Meng, S.; Wang, K.; Niu, X. Unconventional Natural Gas Accumulations in Stacked Deposits: A Discussion of Upper Paleozoic Coal-Bearing Strata in the East Margin of the Ordos Basin, China. Acta Geol. Sin. (Engl. Ed.) 2019, 93 (1), 111–129.
(4) Shao, X. H.; Pang, X. Q.; Li, H.; Zhang, X. Fractal Analysis of Pore Network in Tight Gas Sandstones Using NMR Method: A Case Study from the Ordos Basin, China. Energy Fuels 2017, 31 (10), 10358–10368.
(5) Zhang, J. Y.; Liu, G. D.; Torsaeter, O.; Tao, S. Z.; Jiang, M. Y.; Li, G. H.; Zhang, S. X. Pore-throat structure characteristics and its effect on flow behavior in Gaotaiji tight siltstone reservoir, northern Songliao Basin. Mar. Pet. Geol. 2020, 122, 104651.
(6) Morad, S.; Al-Ramadan, K.; Keterz, J. M.; De Ros, L. F. The impact of diag enesis on the heterogeneity of sandstone reservoirs: A review of the role of depositional facies and sequence stratigraphy. AAPG Bull. 2010, 94 (8), 1267–1309.
(7) Wang, W.; Yu, C. L.; Zhao, L.; Xu, S.; Gao, L. 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. Earth Sci. Res. J. 2020, 24 (1), 19–28.
(8) Li, Y.; Xu, W.; Wu, P.; Meng, S. Dissolution versus cementation and its role in determining tight sandstone quality: A case study from the Upper Paleozoic in northeastern Ordos Basin, China. J. Nat. Gas Sci. Eng. 2020, 78, 103324.
(9) Yang, Q. L.; Xue, J. H.; Li, W.; Du, X. H.; Ma, Q.; Zhan, K. L.; Chen, Z. H. Comprehensive evaluation and interpretation of mercury intrusion porosimetry data of coals based on fractal theory, Tait equation and matrix compressibility. Fuel 2021, 298, 120823.
(10) Zhang, K.; Lai, J.; Bai, G.; Pang, X.; Ma, X.; Qin, Z.; Zhang, X.; Fan, X. Comparison of fractal models using NMR and CT analysis in low permeability sandstones. Mar. Pet. Geol. 2020, 112, 104069.
(11) Li, Y.; Yang, J.; Pan, Z.; Tong, W. Nanoscale pore structure and mechanical property analysis of coal: An insight combining AFM and SEM images. Fuel 2020, 260, 116352.
(12) Hazra, B.; Varma, A. K.; Bandopadhyay, A. K.; Chakravarty, S.; Buragohain, J.; Samad, S. K.; Prasad, A. K. FTIR, XRF, XRD and SEM characteristics of Permainian shales, India. J. Nat. Gas Sci. Eng. 2016, 32, 239–255.
(13) Zhu, X.; Cai, J.; Wang, X.; Zhang, J.; Xu, J. Effects of organic components on the relationships between specific surface areas and organic matter in mudrocks. Int. J. Coal Geol. 2014, 133, 24–34.
(14) Vishal, V.; Chandra, D.; Bahadur, J.; Sen, D.; Hazra, B.; Mahanta, B.; Mani, D. Interpreting Pore Dimensions in Gas Shales Using a Combination of SEM Imaging, Small-Angle Neutron Scattering, and Low-Pressure Gas Adsorption. Energy Fuels 2019, 33 (6), 4835–4848.
(15) Zhang, L.; Zhou, F.; Zhang, S.; Wang, Y.; Wang, J.; wang, J. Investigation of Water-Sensitivity Damage for Tight Low-Permeability Sandstone Reservoirs. ACS Omega 2019, 4 (6), 11197–11204.
(16) Clarkson, C. R.; Solano, N.; Bustin, R. M.; Bustin, A. M.; Chalmers, G. R.; He, L.; Melinchenko, Y. B.; Radlinski, A. P.; Blach, T. P. Pore structure characterization of North American shale gas reservoirs using USANS/SANS, gas adsorption, and mercury intrusion. Fuel 2013, 103, 606–616.
(17) Yao, Y.; Liu, D. Comparison of low-field NMR and mercury intrusion porosimetry in characterizing pore size distributions of coals. Fuel 2012, 95, 152–158.
(18) Zhao, H. W.; Ning, Z. F.; Wang, Q.; Zhang, R.; Zhao, T. Y.; Niu, T. F.; Zeng, Y. Petrophysical characterization of tight oil reservoirs using pressure-controlled porosimetry combined with rate-controlled porosimetry. Fuel 2015, 154, 233–242.
(19) Yang, F.; Ning, Z.; Liu, H. Fractal characteristics of shales from a shale gas reservoir in the Sichuan Basin, China. Fuel 2014, 115, 378–384.
(20) Su, Y.; Zha, M.; Jiang, L.; Ding, X.; Qu, J.; Jiehua, J.; Iglaure, S. Pore structure and fluid distribution of tight sandstone by the combined use of SEM, MICP and X-ray micro-CT. J. Pet. Sci. Eng. 2022, 208, 109241.
(21) Lai, J.; Wang, G. W. Fractal analysis of tight gas sandstones using high-pressure mercury intrusion techniques. J. Nat. Gas Sci. Eng. 2015, 24, 185–196.
(22) Mandelbrot, B. B.; Passoja, D. E.; Paullay, A. J. Fractal Character of Fracture Surfaces of Metal. Nature 1984, 308, 721–722.
(23) Schlutier, E. M.; Zimmerman, R. W.; Witherspoon, P. A.; Cook, N. The fractal dimension of pores in sedimentary rocks and its influence on permeability. Eng. Geol. 1997, 48 (3), 199–215.
(24) Li, Y.; Wang, Z.; Pan, Z.; Niu, X.; Yu, Y.; Meng, S. Pore structure and its fractal dimensions of transitional shale: A cross-

ACS Omega http://pubs.acs.org/journal/acsofdf Article

10636 https://doi.org/10.1021/acsomega.2c00252 ACS Omega 2022, 7, 10627–10637
section from east margin of the Ordos Basin, China. *Fuel* 2019, **241** (1), 417–431.

(25) Li, C. Y.; Dai, W. H.; Luo, B. F.; Pi, J.; Liu, Y. S.; Zhang, Y. New fractal-dimension-based relation model for estimating absolute permeability through capillary pressure curves. *J. Pet. Sci. Eng.* 2021, **196**, 107672.

(26) Zhang, X.; Wu, C.; Li, T. Comparison analysis of fractal characteristics for tight sandstones using different calculation methods. *J. Geophys. Eng.* 2017, **14** (1), 120–131.

(27) Bahadur, J.; Ralildins, A. P.; Melnikchenko, Y. B.; Mastalterz, M.; Schimmelmann, A. Small-Angle and Ultrasall-Angle Neutron Scattering (SANS/USANS) Study of New Albany Shale: A Treatise on Microporosity. *Energy Fuels* 2015, **29** (2), S67–S76.

(28) Hazra, B.; Wood, D. A.; Vishal, V.; Varma, A. K.; Sarkha, D.; Singh, A. K. Porosity controls and fractal disposition of organic-rich Permian shales using low-pressure adsorption techniques. *Fuel* 2018, **220**, 837–848.

(29) Friesen, W. I.; Mikula, R. J. Mercury porosimetry of coalsPore volume distribution and compressibility. *Fuel* 1988, **67** (11), 1516–1520.

(30) Zhang, J.; Hu, Y. Comparative Evaluation of Pore Structure in Low-Permeability Tight Sandstones Using Different Fractal Models Based on NMR Technology: A Case Study of Benxi Formation in the Central Ordos Basin. *Energy Fuels* 2020, **34** (11), 13924–13942.

(31) Huang, W.; Lu, S.; Hersi, O. S.; Wang, M.; Deng, S.; Lu, R. Reservoir spaces in tight sandstones: Classification, fractal characters, and heterogeneity. *J. Nat. Gas Sci. Eng.* 2017, **46**, 80–92.

(32) Li, P.; Zheng, M.; Bi, H.; Wu, S. T.; Wang, X. R. Pore throat structure and fractal characteristics of tight oil sandstone: A case study in the Ordos Basin, China. *J. Pet. Sci. Eng.* 2017, **149**, 665–674.

(33) Liu, C.; Sang, S.; Zhang, K.; Song, F.; Wang, H.; Fan, X. Effects of temperature and pressure on pore morphology of different rank coals: Implications for CO2 geological storage. *J. CO2 Util.* 2019, **34**, 343–352.

(34) Liu, C.; Wang, G.; Sang, S.; Gilani, W.; Rudolph, V. Fractal analysis in pore structure of coal under conditions of CO2 sequestration process. *Fuel* 2015, **139**, 125–132.

(35) Liu, S.; Ma, J.; Sang, S.; Wang, T.; Du, Y.; Fang, H. The effects of supercritical CO2 on mesopore and macropore structure in bituminous and anthracite coals. *Fuel* 2018, **223**, 32–43.

(36) Wang, H.; Yu, L.; Song, Y.; Zhao, Y.; Zhao, J.; Wang, D. Fractal analysis and its impact factors on pore structure of artificial cores based on the images obtained using magnetic resonance imaging. *J. Appl. Geophys.* 2012, **86**, 70–81.

(37) Zhang, W.; Yang, H.; Li, J.; Ma, J. Leading effect of high-class source rock of Chang 7 in Ordos Basin on enrichment of low permeability oil-gas accumulation—Hydrocarbon generation and expulsion mechanism. *Pet. Explor. Dev.* 2006, **33** (3), 289–293.

(38) Yang, H.; Deng, X. Deposition of Yanchang Formation deep-water sandstone under the control of tectonic events in the Ordos Basin. *Pet. Explor. Dev.* 2013, **40** (5), 549–557.

(39) Friesen, W. I.; Mikula, R. J. Fractal dimensions of coal particles. *J. Colloid Interface Sci.* 1987, **120** (1), 263–271.

(40) Pfeifer, P.; Avnir, D. Chemistry in noninteger dimensions between two and three. I. Fractal theory of heterogeneous surfaces. *J. Chem. Phys.* 1983, **79** (7), 3558–3565.

(41) Jullien, M.; Raynal, J.; Kohler, E.; Bildstein, O. Physicochemical Reactivity in Clay-Rich Materials: Tools for Safety Assessment. *Oil Gas Sci. Technol.* 2005, **60** (60), 107–120.

(42) Xiao, D.; Jiang, S.; Thul, D.; Lu, S.; Zhang, L.; Li, B. Impacts of clay on pore structure, storage and percolation of tight sandstones from the Songliao Basin, China: Implications for genetic classification of tight sandstone reservoirs. *Fuel* 2018, **211**, 390–404.

(43) Li, K.; Horne, R. N. Fractal modeling of capillary pressure curves for The Geysers rocks. *Geothermics* 2006, **35** (2), 198–207.

(44) Li, Y.; Lu, G.; Rudolph, V. Compressibility and fractal dimension of fine coal particles in relation to pore structure characterisation using mercury porosimetry. *Part. Part. Syst. Charact.* 1999, **16** (1), 25–31.

(45) Li, K. Analytical derivation of Brooks—Corey type capillary pressure models using fractal geometry and evaluation of rock heterogeneity. *Journal of Petroleum Science & Engineering* 2010, **73** (1–2), 20–26.

(46) Yu, Y.; Luo, X.; Wang, Z.; Cheng, M.; Lei, Y.; Zhang, L.; Yin, J. A new correction method for mercury injection capillary pressure (MICP) to characterize the pore structure of shale. *J. Nat. Gas Sci. Eng.* 2019, **68**, 102896.

(47) Clarkson, C. R.; Freeman, M.; He, L.; Agamalian, M.; Melnikchenko, Y. B.; Mastalerz, M.; Bustin, R. M.; Ralidlns, A. P.; Blach, T. P. Characterization of tight gas reservoir pore structure using USANS/SANS and gas adsorption analysis. *Fuel* 2012, **95**, 371–385.

(48) Chandra, D.; Vishal, V.; Bahadur, J.; Agrawal, A. K.; Das, A.; Hazra, B.; Sen, D. Nano-scale physicochemical attributes and their impact on pore heterogeneity in shale. *Fuel* 2022, **314**, 123070.

(49) Purcell, W. R. Capillary Pressures - Their Measurement Using Mercury and the Calculation of Permeability Therefrom. *Trans. AIME* 1949, **186** (2), 39–48.

(50) Li, Y.; Gao, X.; Meng, S.; Wu, P.; Niu, X.; Qiao, P.; Elsworth, D. Diagenetic sequences of continuously deposited tight sandstones in various environments: A case study from upper Paleozoic sandstones in the Linxing area, eastern Ordos basin, China. *AAPG Bull.* 2019, **103** (11), 2757–2783.

(51) Wang, W.; Li, Y.; Chen, X. Microscope dynamic characterization of oil charging in tight sandstone using a physical simulation experiment. *J. Pet. Sci. Eng.* 2021, **200**, 108379.