Classification of the tight oil reservoir storage space in the Raoyang Sag of the Jizhong Depression in the Bohai Bay Basin, China

Fangwen Chen1,2 | Qiang Zheng1,2 | Shuangfang Lu1,2 | Xue Ding1,2 | Yiwen Ju3 | Hongqin Zhao1,2

1Key Laboratory of Deep Oil and Gas, China University of Petroleum (East China), Qingdao, China
2School of Geosciences, China University of Petroleum (East China), Qingdao, China
3College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing, China

Abstract

To improve the precision of predicting sweet spots in tight oil reservoirs, the classification of tight oil reservoir storage space is necessary. The tight oil reservoir in the lower submember of the first member of Shahejie Formation (Es1L) of the Raoyang Sag of the Jizhong Depression in the Bohai Bay Basin was selected as a case study for testing a new method of classifying tight oil reservoir storage space based on the results of porosity, permeability, and mercury intrusion porosimetry measurements. The pore-throat size ranges were classified according to pore-throat fractal characteristics and were divided into three groups: <100 nm, 100–1000 nm, and >1000 nm. The oil-bearing property of tight oil reservoir samples is closely related to the median and maximum pore-throat radii. The inflection and intersection points in the trend lines of the pore volume percentages connected by different pore-throat widths (<100 nm, 100–1000 nm, and >1000 nm) vs the porosity and permeability values (which represent the relationship between the pore volume connectivity characteristics and porosity/permeability) were used as the basis for classifying the tight oil reservoir storage space. The tight oil reservoir storage space in the Es1L formation of the Raoyang Sag was divided into three categories, namely classes of III, II, and I. The porosity ranges of the three tight reservoir storage space classes are <5%, 5%–8%, and 8%–11%, respectively, and their permeability ranges are <0.04 mD, 0.04–0.15 mD, and 0.15–0.8 mD, respectively.

Key Words

classification, connected pore volume, fractal, pore-throat size, tight oil reservoir

1 | INTRODUCTION

Tight oil reservoirs exist widely in oil- and gas-bearing basins of the world and have recently been one focus of unconventional oil and gas (including coalbed methane, tight oil, tight gas, shale oil, and shale gas) exploration in many countries.
source rocks, large-scale reservoirs with nanoscale pore systems and local sweet spots. The sweet spot area evaluation of tight oil reservoirs focuses on six features, namely the source property, lithology, reservoir quality, brittleness (closely related to Young’s modulus and Poisson’s ratio), oil-bearing property, and stress anisotropy. The source property includes the abundance, type and maturity of organic matter and characteristics of source rock distribution. The lithology of tight oil reservoirs includes the tight sandstone, tight sandy gravel, tight carbonate, tight peperite, and tight sedimentary tuff. The reservoir quality mainly contains the parameters of porosity and permeability, which largely reflect storage space and fluid seepage of tight oil reservoirs. Brittleness is an important parameter used to characterize the fracturing behavior of a rock mass. One of the most important parameters for evaluating a tight oil reservoir is the oil-bearing property, which largely reflects the resources and productivity level of a tight oil reservoir. The stress anisotropy mainly contains and involves the four important research aspects during the development of tight oil: (a) the varying of stress in the reservoir; (b) the deformation and fracturing mechanisms of the rock; (c) the optimization of the horizontal well trajectory; and (d) the hydraulic fracturing design. The oil-bearing property of a tight oil reservoir has strong heterogeneity. How to improve the efficiency of selecting sweet spots in tight oil reservoirs has become a key research area in the exploration and development of tight oil.

Many scholars have been conducting research on the six features of tight oil reservoirs to predict sweet spots. The source rocks for tight oil reservoirs are classified using the relationship between the total organic carbon content and residual oil content. They are categorized into three classes of resource enrichment, namely scattered (ineffective), low effective, and enriched resources. The relationships between the source rocks and the tight oil reservoirs were determined, classified, and compared. The relationships of between-source, interbedded-source, and in-source mud-subordinated rocks are major targets for tight oil development with high production. The classes of source rocks and the matching relation of source and reservoir rocks were used as evidence to optimize the sweet spots of tight oil reservoirs. There are four main lithologic types of tight oil reservoirs based on the sedimentary environment: salty lacustrine carbonate, shallow lake beach-bar sandstone, delta-front-sandstone, and deep lake gravity-flow-sandstone. Tight oil reservoirs were classified according to the empirical statistics between flow characteristics and porosity values and divided into three classes using porosity ranges of <4%, 4%-7%, and 7%-10%, which is very useful at the early stage of tight oil exploration. The brittleness sensitivity of the elastic parameters in an anisotropic medium was analyzed, and a new brittleness index was established to evaluate the brittleness of tight oil reservoirs. The geologic resources and recoverable reserves of tight oil reservoirs were calculated using the resource abundance analogy. The classification of tight oil reservoir storage space is one of the key indicators for forecasting and evaluating sweet spots in tight oil reservoirs. Pore volumes connected by pore throats with different sizes (or fractal characteristics) have significant effects on oil-bearing properties and fluid flow characteristics. However, these characteristics have rarely been used in the classification of tight oil reservoir storage space. In addition, the previous classification of tight oil reservoir storage space is lacking.

For the purpose of improving the precision of predicting sweet spots in tight oil reservoirs, a new method for classifying tight oil reservoir storage space is introduced. This study uses the tight oil reservoir from the lower submember of the First Member of the Shahejie Formation (EsIL) in the Raoyang Sag as an example. The pore-throat size ranges are classified according to pore-throat fractal characteristics, and then, the tight oil reservoir storage space is classified according to the relationships between the reservoir quality and the pore volume percentage connected by pore throats with different fractal characteristics.

2 | GEOLOGICAL SETTING

The Raoyang Sag is a secondary tectonic unit located in the southwest of the Jizhong Depression in the Bohai Bay Basin, China (Figure 1A). The Raoyang Sag, which is a hydrocarbon-rich sag, has an area of approximately 5300 km² and consists of the Lixian Slope, Hejian subbasin, Renxi subbasin, Renqiu buried buried-hill and Maxi subbasin (Figure 1B). The Raoyang Sag is filled mainly with thick Paleogene sediments comprising the Kongdian Formation (Ek), Shahejie Formation (Es), and Dongying Formation (Ed). The Shahejie Formation includes four members named E1, E2, E3, and E4, from bottom to top (Figure 2). E1 is further divided into a lower submember (EsIL) and an upper submember (EsILU). The lower part of EsIL is derived from sedimentary environments of littoral lakes and river deltas with shallow lake beach-bar sandstone-type tight oil reservoirs. The upper part of EsIL is derived from sedimentary environments of deep lakes and semi-deep lakes with organic-rich muddy shale as the source rock and regional cap rock (Figure 2). The lower and upper parts of EsIL form a good association of reservoir and cap rock. From the center sag to the edge, as well as from the bottom to the top, the reservoir quality gradually worsens and transitions from a conventional reservoir to a tight reservoir, which is one of the key targets of tight oil exploration in recent years. Therefore, the EsIL formation of the Raoyang Sag was selected as a case study to introduce the new method for classifying tight oil reservoir storage space.
3 | SAMPLES AND EXPERIMENTS

3.1| Samples

A total of 30 sandstone reservoir samples from the Es₁L were selected from 14 wells located in the Lixian Slope of the Raoyang Sag. The source rock (including abundance, type, and maturity of organic matter) and stress anisotropy (containing directions and magnitudes of the minimum and maximum principal stresses) conditions of the samples are the same or similar, and the source-reservoir configuration of the samples is “upper generation and lower storage.” In addition, these samples belong to the shallow lake beach-bar sandstone. All samples were cylindrical core plug samples with a diameter of 25 mm and a length of approximately 40 mm; they were collected from core material, and the plug samples were drilled parallel to the bedding.

The lithology and the main minerals of the samples are listed in Table 1. Before the experiments, the cylindrical core plug samples were cleaned using the distillation extraction method. Hot dichloromethane solvents were evaporated and flowed through the core plug samples for at least 60 hours, removing oil in the pores. Then, the solvents condensed and evaporated again in a continuous closed system. After cleaning with hot solvents, the core plug samples were dried in a vacuum drying oven at 90°C for 10 hours to drive off physically absorbed fluid.

3.2| Porosity and permeability

After the pretreatment, the porosity values of the cylindrical core plug samples were measured at laboratory temperature and without overburden pressure conditions based on the bulk and grain volumes. The bulk volumes were measured with a caliper, and the grain volumes were measured by a gas (He) porosity test instrument (KX-90F) according to Boyle’s law. Then, the permeability value of each sample was measured by a gas permeation test instrument (GDS-90F) using the helium pressure drop method at laboratory temperature. The detailed operations for measuring the porosity and permeability were introduced in the practices for core analysis of the oil and gas industry standards, China (SY/T 5336-2006).

3.3| Mercury intrusion porosimetry

The mercury intrusion porosimetry (MIP) experiments were performed using a Micromeritics’ AutoPore IV 9505. The
cumulative intrusion and extrusion mercury volumes were recorded under related pressures during the process of increasing the pressure up to approximately 120 MPa and decreasing the pressure stepwise. The pressures were converted to the equivalent pore radii by Equation (1). The pore volume percentages connected by pore throats of different sizes were obtained from the incremental intrusion mercury saturations under different pressures using Equation (2). At the same time, the median and maximum pore‐throat radii of the samples were acquired. The median pore‐throat radius corresponds to the median pressure when the cumulative intrusion mercury saturation is equal to 50%. The maximum pore‐throat radius corresponds to the displacement pressure when the incremental intrusion mercury saturation is 1%.

\[ P_c = \frac{2\sigma \cos \theta}{r} \]  
\[ S_{Hg-i} = \frac{V_{Hg-i}}{V \cdot \Phi} \times 100\% \]

where \( r \) is the pore radius (μm); \( P_c \) is the capillary pressure (MPa); \( \sigma \) is the interfacial tension of mercury, which is 0.48 J/m²; \( \theta \) is the contact angle between the mercury and pore surface, which is 140° in the MIP experiment; \( S_{Hg-i} \) is the incremental intrusion mercury saturation under the \( i \)th pressure range (%); \( V_{Hg-i} \) is the incremental intrusion mercury volume under the \( i \)th pressure range (cm³); \( V \) is the bulk volume of the sample (cm³); and \( \Phi \) is the porosity value of the sample (%).

### METHODS

#### 4.1 Method for classifying pore‐throat sizes

According to the pore classification of IUPAC, the pore widths of <2 nm, 2-50 nm, and >50 nm are defined as micropore, mesopore, and macropore, respectively. This classification has been widely used in materials science field, as well as in the microscopic pore structure evaluation of...
unconventional tight reservoirs such as coalbed gas, shale gas, and shale oil. For coalbed methane and shale gas reservoirs, a considerable proportion of natural gas exists as adsorbed state in micropores, mesopores, and small macropores, and can be mined under the existing technical conditions. However, the fluidity of crude oil in tight oil reservoirs (containing shale oil and tight sandstone oil) is much lower than that of natural gas in shale gas and coalbed reservoirs. Due to the effect of water film bound at pore throat, the tight oil in the pores connected by pore-throat widths <100 nm can hardly be mined under existing technical conditions. Many scholars believe that pore-throat width of 100 nm is the significant boundary where the characteristics of fluid flowing obviously change. Therefore, the pore classification of IUPAC has some limitations in classification and optimization of tight oil reservoirs storage space.

Pore throats of different sizes have unique self-affinities, which can be quantitatively evaluated by a power-law function (Equation 3).

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

where \( r \) is the radius of a unit chosen to fill the fractal object; \( D_f \) is the fractal dimension; and \( N(r) \) is the number of units required to fill the entire fractal object, which can be expressed as Equation (4) according to the capillary tube model.

\[ N(r) = \frac{V_{Hg}}{\pi r^2 l} \]  

TABLE 1 The lithology and the main minerals of the samples from Es1L in the Raoyang Sag

| Sample no. | Well   | Depth (m) | Lithology                                 | Quartz | Feldspar | Calcite | Dolomite | Clay |
|------------|--------|-----------|-------------------------------------------|--------|----------|---------|----------|------|
| 1          | Gao105 | 2448.80   | Calcareous argillaceous siltstone         | 38.9   | 14.2     | 5.8     | 1.9      | 39.2 |
| 2          | Gao45  | 2939.30   | Calcareous argillaceous siltstone         | 39.6   | 13.5     | 6.2     | 1.8      | 38.9 |
| 3          | Rao2   | 3263.85   | Calcareous argillaceous siltstone         | 40.3   | 14.4     | 5.7     | 2.1      | 37.5 |
| 4          | Gao37  | 2575.10   | Calcareous argillaceous siltstone         | 40.7   | 16.3     | 5.3     | 2.6      | 25.1 |
| 5          | Xiliu102| 3390.32   | Muddy calcareous siltstone                | 37.3   | 27.4     | 17.8    | 3.3      | 14.2 |
| 6          | Ning55 | 3473.10   | Muddy calcareous siltstone                | 42.5   | 29.3     | 12.7    | 3.2      | 12.3 |
| 7          | Xiliu102| 3378.90   | Muddy calcareous siltstone                | 49.6   | 28.1     | 13.2    | 1.3      | 7.8  |
| 8          | Gao104 | 2617.50   | Calcareous muddy siltstone                | 51.7   | 29.6     | 8.4     | 0        | 10.3 |
| 9          | Gao44  | 2382.44   | Calcareous muddy siltstone                | 49.2   | 23.7     | 11.4    | 1.1      | 14.6 |
| 10         | Gao118 | 2337.15   | Calcareous muddy siltstone                | 58.6   | 24.4     | 5.4     | 1.7      | 9.9  |
| 11         | Gao118 | 2338.05   | Calcareous muddy siltstone                | 61.1   | 21.6     | 6.6     | 1.4      | 9.3  |
| 12         | Gao64  | 2343.85   | Calcareous muddy siltstone                | 45.3   | 25.5     | 9.8     | 2.1      | 17.3 |
| 13         | Gao44  | 2379.64   | Muddy calcareous siltstone                | 49.6   | 24.7     | 15.1    | 1.3      | 9.3  |
| 14         | Gao105 | 2447.50   | Calcareous muddy siltstone                | 66.4   | 19.6     | 5.7     | 0        | 8.3  |
| 15         | Gao105 | 2456.26   | Calcareous muddy siltstone                | 57.5   | 24.3     | 5.3     | 0        | 12.9 |
| 16         | Gao37  | 2570.10   | Calcareous muddy siltstone                | 55.2   | 25.6     | 8.8     | 1.3      | 9.1  |
| 17         | Gao37  | 2570.90   | Calcareous muddy siltstone                | 58.5   | 24.1     | 6.3     | 1.2      | 9.9  |
| 18         | Gao26  | 2572.05   | Muddy calcareous siltstone                | 70.7   | 18.3     | 5.7     | 0        | 5.3  |
| 19         | Gao26  | 2572.80   | Calcareous muddy siltstone                | 62.4   | 22.6     | 6.8     | 0        | 8.2  |
| 20         | Gao26  | 2573.55   | Calcareous muddy siltstone                | 61.8   | 21.2     | 6.7     | 1.2      | 9.1  |
| 21         | Gao104 | 2613.09   | Calcareous muddy siltstone                | 54.4   | 20.1     | 9.9     | 2.4      | 13.2 |
| 22         | Gao104 | 2615.19   | Calcareous siltstone                     | 71.6   | 17.2     | 6.4     | 0        | 4.8  |
| 23         | Gao45  | 2944.30   | Calcareous muddy siltstone                | 47.4   | 26.4     | 10.4    | 0        | 15.8 |
| 24         | Xiliu5 | 3275.88   | Calcareous muddy siltstone                | 50.1   | 25.7     | 8.3     | 1.8      | 14.1 |
| 25         | Xiliu5 | 3282.57   | Calcareous muddy siltstone                | 49.6   | 26.9     | 6.4     | 2.6      | 14.5 |
| 26         | Xiliu5 | 3362.00   | Calcareous muddy siltstone                | 42.4   | 33.3     | 5.3     | 3.2      | 15.8 |
| 27         | Xiliu102| 3378.20   | Calcareous muddy siltstone                | 55.7   | 27.8     | 5.4     | 1.4      | 9.7  |
| 28         | Xiliu102| 3359.82   | Calcareous muddy siltstone                | 56.4   | 24.2     | 6.1     | 1.5      | 11.8 |
| 29         | Xiliu8 | 3483.64   | Calcareous muddy siltstone                | 49.4   | 27.7     | 6.9     | 2.3      | 13.7 |
| 30         | Xiliu8 | 3483.85   | Calcareous muddy siltstone                | 47.6   | 24.3     | 7.8     | 2.7      | 17.6 |
where $l$ is the length of a capillary tube and $V_{Hg}$ is the stage cumulative mercury volume intruded in or extruded from the sample according to the pore throat of $r$ during the MIP experiment. By combining Equation (3) and Equation (4), Equation (5) is obtained.

$$V_{Hg} \propto r^{2-D_f} \tag{5}$$

Substituting Equation (1) and Equation (2) into Equation (5) gives:

$$S_{Hg} = aP_c^{-(2-D_f)} \tag{6}$$

where $a$ is a constant in a similar equation. Equation (6) shows that there is a linear relationship between the mercury saturation ($S_{Hg}$) vs capillary pressure ($P_c$) on a log-log plot for each self-affinity pore-throat range. Namely, each self-affinity pore-throat range has its own fractal dimension. In this paper, the pore-throat sizes were classified according to the relationship between $Lg(S_{Hg})$ and $Lg(P_c)$ based on the results of the MIP experiment.

### 4.2 Method for classifying the tight oil reservoir storage space

The pore volumes connected by pore throats with different fractal dimensions control the permeability of a tight oil reservoir. For tight oil reservoirs, a larger pore volume percentage connected by large pore throats corresponds to a higher permeability value. However, a larger pore volume percentage connected by small pore throats corresponds to a lower permeability value. There are inflection and intersection points between the trend lines of the pore volume percentages connected by pore throats with different size ranges vs permeability values, which represent the relationship between the pore volume connected characteristics and permeability. The inflection points indicate that the pore volume proportion connected by the pore-throat range will change. The intersection points suggest that the pore volume proportions connected by the two corresponding pore-throat ranges are the same, namely the contributions of the two pore-throat ranges on the connected pore volume are equal. Therefore, the permeability values corresponding to the inflection and intersection points are the permeability boundaries that classify the tight oil reservoir storage space. Because there is a good relationship between porosity and permeability values of tight oil reservoirs, the porosity boundaries of different classes of tight oil reservoir storage space can also be determined. The key issue is how to obtain the trend lines of the pore volume percentages connected by pore throats of different size ranges vs porosity/permeability values. The values of the trend lines were calculated by the sliding average method according to Equation (7).

$$V_{i-1} = \left( \sum_{k=i-4/2}^{i+1/2} V_{ik} \right) / x \tag{7}$$

where $V_{ik}$ is the pore volume percentage connected by the pore throats of the $i$th width range in the sample with the $i$th porosity/permeability value (%); $V_{i-1}$ is the sliding average value that corresponds to $V_i$ (%); $x$ is the step size of the sliding average method, which is 5 in this study; $i = 1, 2, \ldots, m$, which represents the tag number of the pore-throat range; and $j = 1, 2, \ldots$, which represents the tag number of tight oil samples according to the ascending order of the porosity/permeability value.

### 5 RESULTS

#### 5.1 Porosity and permeability

The porosity and permeability values of the samples, as well as the oil-bearing characteristics, are listed in Table 2. The porosity and permeability values ranged from 3.66%-33.90% and 0.02-450 mD, with average values of 14.06% and 26.49 mD, respectively.

#### 5.2 MIP

The intruded and extruded mercury saturation curves of the nine samples (samples 1-9), including the low, medium, and high porosity samples, are shown in Figure 3. The relationships between the maximum volume of mercury intruded and the reservoir quality are shown in Figure 4. The maximum volumes of mercury intruded increased with increasing porosity and permeability values, and the mercury was more easily intruded into the samples with higher porosity and permeability values. The median and maximum pore-throat radii of these samples from the MIP method are also listed in Table 2 and Figure 5. The median and maximum pore-throat radii of these samples were in the ranges of 20-60 700 nm and 110-735 000 nm, with average values of 690 nm and 66 000 nm, respectively. Both the median and maximum pore-throat radii of the samples increased with increasing porosity and permeability values. These results indicate that there is a close relationship between the microscopic pore structure and the reservoir quality (porosity and permeability). If the relationship between the pore volumes connected by different pore-throat sizes and the reservoir quality can be determined, the classification standard of tight oil reservoir storage space may be established.

#### 5.3 Classification of the pore-throat size ranges

The pore-throat fractal characteristics of the nine samples from the intruded mercury saturation experiments are listed in Figure 6. For the low porosity samples (samples 1, 2, and 3), there was an obvious pore-throat width boundary of approximately 100 nm dividing the pore-throat width...
ranges into <100 nm and >100 nm according to the pore-throat fractal characteristics (Figure 6A-C). For the medium and high porosity samples (samples 4-9), there were two pore-throat width boundaries of approximately 100 nm and 1000 nm dividing the pore-throat width ranges into <100 nm, 100-1000 nm, and >1000 nm according to the pore-throat fractal characteristics (Figure 6D-I). The boundary of 100 nm was more obvious in the medium porosity samples, whereas the boundary of 1000 nm was more obvious in the high porosity samples.

For all of the samples, the pore-throat size ranges were divided into <100 nm, 100-1000 nm, and >1000 nm according to the pore-throat fractal characteristics based on the relationship between \( \log(S_{He}) \) and \( \log(P_c) \) from the MIP experiments. The three size ranges of pore throats had their self-affinities and controlled the fluid flow characteristics. In oil and gas fields, the pore-throat widths of <100 nm, 100-1000 nm, and >1000 nm relate to microtransition pores, mesopores, and macropores, respectively, which are different from the definitions supplied by the International Union of Pure and Applied Chemistry (IUPAC). The pore volumes connected by pore-throat widths of <100 nm, 100-1000 nm, and >1000 nm represent the adsorbed, seeped, and well-seeped channels, respectively.

### Table 2

The characteristics of the samples from Es1L in the Raoyang Sag

| Sample no. | Well    | Depth (m) | Oil-bearing status | Porosity (%) | Permeability (mD) | Median pore-throat radius (nm) | Maximum pore-throat radius (nm) | Pore volume connected by pore throats (%) |<100 nm | 100-1000 nm | >1000 nm |
|------------|---------|-----------|--------------------|--------------|-------------------|-------------------------------|---------------------------------|---------------------------------------|---------|-------------|-----------|
| 1          | Gao105  | 2448.80   | Oil-free           | 3.66         | 0.04              | 40                            | 370                             | 21.26                                 | 0.36    |
| 2          | Gao45   | 2939.30   | Oil-free           | 3.91         | 0.02              | 20                            | 180                             | 36.57                                 | 30.31   | 1.37        |
| 3          | Rao2    | 3263.85   | Oil-free           | 4.20         | 0.03              | 5.92                          | 40                              | 2450                                 | 30.34   | 1.64        |
| 4          | Gao37   | 2575.10   | Oil-free           | 5.92         | 0.04              | 8.04                          | 770                             | 46.44                                 | 23.91   |
| 5          | Xiliu102| 3390.32   | Oil immersion     | 5.84         | 0.09              | 100                           | 770                             | 14.67                                 | 23.91   |
| 6          | Ning55  | 3473.10   | Oil-free           | 7.09         | 0.08              | 20                            | 1230                            | 23.02                                 | 40.41   | 2.61        |
| 7          | Xiliu102| 3738.90   | Oil immersion     | 13.09        | 1.03              | 240                           | 3680                            | 14.67                                 | 46.44   | 23.91       |
| 8          | Gao104  | 2617.50   | Oil-free           | 15.21        | 1.22              | 170                           | 1230                            | 23.02                                 | 40.41   | 2.61        |
| 9          | Gao44   | 2382.44   | Oil-free           | 3.48         | 3.60              | 80                            | 3680                            | 14.67                                 | 46.44   | 23.91       |
| 10         | Gao118  | 2337.15   | Oil patch          | 26.00        | 120.00            | 2660                          | 7500                            | 2.91                                  | 27.83   | 40.28       |
| 11         | Gao118  | 2338.05   | Oil-free           | 26.22        | 57.63             | 110                           | 1470                            | 9.66                                  | 25.31   | 39.02       |
| 12         | Gao64   | 2343.85   | Oil-free           | 7.90         | 0.99              | 130                           | 490                             | 12.52                                 | 48.04   | 16.81       |
| 13         | Gao44   | 2379.64   | Oil-free           | 13.21        | 0.84              | 50                            | 490                             | 13.81                                 | 42.49   | 12.34       |
| 14         | Gao105  | 2447.50   | Oil patch          | 24.60        | 8.73              | 280                           | 4680                            | 6.91                                  | 26.95   | 37.12       |
| 15         | Gao105  | 2456.26   | Oil-free           | 9.65         | 0.19              | 30                            | 490                             | 16.68                                 | 44.79   | 4.34        |
| 16         | Gao37   | 2570.10   | Oil-free           | 15.59        | 1.94              | 470                           | 6190                            | 9.50                                  | 33.32   | 41.75       |
| 17         | Gao37   | 2570.90   | Oil-free           | 17.79        | 4.90              | 310                           | 3680                            | 5.55                                  | 25.92   | 42.50       |
| 18         | Gao26   | 2572.05   | Oil patch          | 32.69        | 123.00            | 300                           | 5700                            | 6.40                                  | 28.24   | 41.24       |
| 19         | Gao26   | 2572.80   | Oil-free           | 20.68        | 2.54              | 240                           | 2450                            | 5.91                                  | 25.82   | 37.85       |
| 20         | Gao26   | 2573.55   | Oil-free           | 19.43        | 3.26              | 170                           | 920                             | 3.71                                  | 37.80   | 39.46       |
| 21         | Gao104  | 2613.09   | Oil patch          | 16.04        | 3.52              | 1050                          | 5500                            | 6.35                                  | 25.02   | 42.11       |
| 22         | Gao104  | 2615.19   | Oil-rich           | 33.90        | 450.00            | 6070                          | 73 500                          | 4.95                                  | 27.50   | 42.22       |
| 23         | Gao45   | 2944.30   | Oil immersion     | 9.31         | 0.38              | 370                           | 1470                            | 12.90                                 | 57.48   | 9.19        |
| 24         | Xiliu3  | 3275.88   | Oil immersion     | 11.59        | 0.48              | 1120                          | 7350                            | 10.19                                 | 51.59   | 10.23       |
| 25         | Xiliu3  | 3282.57   | Oil-free           | 10.05        | 0.29              | 90                            | 490                             | 13.04                                 | 48.11   | 10.65       |
| 26         | Xiliu5  | 3362.00   | Oil-free           | 7.78         | 0.13              | /                             | 120                             | 19.69                                 | 47.04   | 2.27        |
| 27         | Xiliu102| 3378.20   | Oil-rich           | 16.94        | 4.83              | 3230                          | 10 500                          | 2.36                                  | 29.85   | 43.85       |
| 28         | Xiliu102| 3359.82   | Oil immersion     | 15.10        | 3.80              | 1500                          | 7350                            | 10.86                                 | 25.82   | 46.25       |
| 29         | Xiliu8  | 3483.64   | Oil immersion     | 8.37         | 0.15              | 170                           | 36 750                          | 12.65                                 | 58.75   | 3.72        |
| 30         | Xiliu8  | 3483.85   | Oil-free           | 6.51         | 0.11              | 20                            | 490                             | 26.25                                 | 44.99   | 1.46        |

*The symbol ‘/’ represents without data.*
5.4 Classification of the sandstone oil reservoir storage space

5.4.1 Trend lines of the connected pore volumes vs the porosity and permeability

The trend lines of the pore volume percentages connected by pore-throat widths of <100 nm, 100-1000 nm, and >1000 nm vs the porosity and permeability values are shown in Figure 7. The trend lines of the pore volume percentages connected by pore-throat widths of <100 nm decreased with increasing porosity and permeability values and tended to be stable when the porosity and permeability values were larger than 18% and 5 mD, respectively. There were two inflection points in the trend lines, and the porosity and permeability values related to the two inflection points were 11% and 0.15 mD and 18% and 5 mD, respectively. The trend lines of the pore volume percentages connected by pore-throat widths of 100-1000 nm initially increased with increasing porosity and permeability values, then decreased, and finally tended to remain stable. The porosity and permeability values related to the three intersection points were 5%, 11%, and 15%, and their permeability values were 0.04 mD, 0.8 mD, and 18% and 5 mD, respectively. The trend lines of the pore volume percentages connected by pore-throat widths >1000 nm initially tended to be stable with increasing porosity and permeability values, then increased, and finally tended to remain stable again. The porosity and permeability values related to the two inflection points were 8% and 0.15 mD and 18% and 5 mD, respectively.

The three trend lines of the pore volume percentages connected by pore-throat widths of <100 nm, 100-1000 nm, and >1000 nm vs the porosity and permeability values exhibited three intersection points, which indicated that the pore volumes connected by the corresponding pore throats had the same contribution to the porosity/permeability of the samples. The porosity values of the three intersection points were 5%, 11%, and 15%, and their permeability values were 0.04 mD, 0.8 mD, and 2 mD, respectively.

5.4.2 Classification standard of the tight oil reservoir storage space

The sandstone reservoirs were classified according to the inflection and intersection points of the trend lines of the pore volumes.
volume percentages connected by pore throats with different sizes vs the porosity and permeability values as introduced in Sections 3.2 and 5.4.1. As shown in Figure 7, the plateau of the trend lines found toward the right of the graphs corresponded to the conventional sandstone reservoir class I. The intersection point in the trend lines of the pore volume percentages connected by pore-throat widths of 100-1000 nm and >1000 nm vs the porosity and permeability values corresponded to the lower limit of the conventional sandstone reservoir class II. The intersection point in the trend lines of the pore volume percentages connected by pore-throat widths of <100 nm and >1000 nm corresponded to the lower limit of the conventional sandstone reservoir class III. In addition, this latter intersection point is also the boundary between tight and conventional sandstone reservoirs. The first inflection point in the trend lines of the pore volume percentages connected by pore-throat widths of 100-1000 nm and >1000 nm corresponded to the lower limit of tight reservoir class I. The intersection point in the trend lines of the pore volume percentages connected by pore-throat widths of <100 nm and 100-1000 nm corresponded to the lower limit of tight reservoir class II and the upper limit of tight reservoir class III.

The porosity and permeability values related to the classification of sandstone reservoir storage space from the Es1L formation in the Raoyang Sag are listed in Table 3. The porosity ranges of the tight oil reservoir classes III, II, and I are <5%, 5%-8%, and 8%-11%, respectively, and the permeability ranges of the three classes are <0.04 mD, 0.04-0.15 mD, and 0.15-0.8 mD, respectively.

![Figure 4](image1.png)  
**Figure 4** The relationship between the maximum volume of mercury intruded and the reservoir quality. A, Maximum volume of mercury intruded vs porosity. B, Maximum volume of mercury intruded vs permeability.

![Figure 5](image2.png)  
**Figure 5** The relationship between the reservoir quality and the pore-throat size. A, Porosity vs throat radius. B, Permeability vs throat radius.
6 | DISCUSSION

6.1 | Relationship between the pore-throat and oil-bearing properties

The relationship between the reservoir quality and pore-throat size (including the median and maximum pore-throat radius) for sandstone samples of different oil-bearing characteristics showed that there were both oily and nonoily samples that belonged to high porosity-high permeability and low porosity-low permeability sandstone classes. The porosity and permeability were not particularly significant in affecting the oil-bearing property of reservoirs. In the case of porosity and permeability values that were the same or similar, the sample with a larger pore-throat size (both the median and maximum pore-throat radius) had better oil-bearing properties (Figure 4). Compared with the porosity and permeability, the pore-throat size, namely the median and maximum pore-throat radii of the sample, played a more significant role in the oil-bearing characteristics of the reservoir samples. The tight reservoirs with larger pore-throat sizes were filled by oil to a greater extent during the process of secondary hydrocarbon migration and were the sweet spots in tight oil reservoirs. Therefore, the classification of tight oil reservoirs according to the relationships between the reservoir quality and the pore volume percentage connected by pore throats with different fractal characteristics not only reflects the reservoir space level but also the oil-bearing property to a certain extent.

6.2 | Pore connectivity controls the classes of reservoir storage space

The percentages of pore volumes connected by pore throats with different fractal characteristics controlled the classes
of sandstone oil reservoir storage space. From tight reservoir class III to conventional sandstone reservoir class I (which equates to the values of porosity and permeability increasing), the percentages of pore volumes connected by pore-throat widths of <100 nm decreased, and the percentages of pore volumes connected by pore-throat widths of >1000 nm increased (Figure 8). At the same time, the percentages of pore volumes connected by pore-throat widths of 100-1000 nm first increased and then decreased. The maximum value of the latter pore-throat width range was found in tight reservoir class I (Figure 8). The larger the percentages of pore volumes connected by large pore throats, the higher the porosity and permeability values of the reservoir, and vice versa. Therefore, the classification of the tight oil reservoir storage space was based on the variation in characteristics of the pore volume percentages connected by pore throats of different fractal dimensions vs the porosity and permeability values.

### 6.3 Relationship between reservoir storage space class and test oil production

Figure 9 shows the relationship between test oil production (without fracturing) and per unit length of reservoir from different classifications of reservoir storage space. Although there are many factors that influence oil production, such as source rock, source-storage configuration, reservoir pressure, ground stress, data of test oil production were selected from three adjacent wells to evaluate the effect of reservoir storage space on test oil production. The test oil productions from various reservoir storage space classes have obvious discrepancy, which increase from tight reservoir class III to conventional sandstone reservoir class I. As discussed in Section 5.2, the percentages of pore volume connected by large pore throats increase from tight reservoir class III to conventional sandstone reservoir class I, and the capacity of reservoir storage gradually gets better. The crude oil accumulated in the
better reservoir flows easier into the wellbore and forms a higher oil flow. Therefore, it is necessary to classify the reservoir storage space for the purpose of predicting and optimizing sweet spots of tight oil reservoirs.

6.4 Comparison with the classification of other methods

Compared with the previous classification for tight oil reservoirs, the porosity ranges of tight oil reservoir classes III, II, and I from the Raoyang Sag were similar to the results from previous studies (Table 3). Jia et al (2012) proposed a classification for tight oil reservoirs, which defined the porosity ranges of tight oil reservoir classes III, II, and I as <4%, 4%-7%, and 8%-10%, respectively, and defined the upper limit permeability value of a tight oil reservoir (without overburden pressure conditions) as 1 mD. The previous classification of tight oil reservoir storage space was based on empirical statistics from several basins. It was proposed that when the porosity value of an oil reservoir
was larger than 7%, the light crude oil flowed according to Darcy’s law in the oil reservoir without water. Otherwise, the light crude oil did not flow according to Darcy’s law in the actual oil reservoir with water. The nanoscale pores make up the majority of pores in a tight reservoir with a porosity value smaller than 4%. The previous classification is very useful at the early stage of tight oil exploration. However, almost all tight oil reservoirs contain pore water, and the flow characteristics are different for tight oil reservoirs in different basins, specifically a tight oil reservoir with microfractures. In addition, using one standard to classify different tight reservoirs in multiple basins is not ideal, because each tight reservoir has its own characteristics. Moreover, the previous studies provided porosity boundaries to classify tight reservoirs without permeability boundaries. Compared with the previous classification method, the method introduced in this paper has the following advantages: (a) the classification of tight oil reservoirs is based on pore-throat fractal characteristics and levels of connectivity, which is credible and practical; (b) the method is more targeted because it uses formation samples from a specific study area rather than data from several formations or several study areas; and (c) the classification results not only contain porosity boundaries but also include permeability boundaries. The classification of tight oil reservoir storage space used in this study is useful to improve the precision of predicting sweet spots in tight oil reservoirs.

7 | CONCLUSIONS

For the sandstone oil reservoir samples from the Es\textsuperscript{1L} formation of the Raoyang Sag, the pore-throat size ranges were divided into <100 nm, 100-1000 nm, and >1000 nm according to the pore-throat fractal characteristics based on the relationship between Lg\(S_{Hg}\) and Lg\(P_{t}\) from the MIP experiments.

Compared with the porosity and permeability, the pore-throat size, namely the median and maximum pore-throat radii, plays a more significant role in affecting the oil-bearing property of the reservoir samples. In the case of the porosity and permeability values that are the same or similar, the sample with a larger throat size (both in terms of the median and maximum pore-throat radius) has better oil-bearing properties.

The inflection and intersection points in the trend lines of the pore volume percentages connected by pore-throat widths of <100 nm, 100-1000 nm and >1000 nm vs porosity and permeability values can be used to classify the tight oil reservoir storage space. The tight oil reservoir of the Es\textsuperscript{1L} formation in the Raoyang Sag is divided into three categories, namely tight reservoir classes III, II, and I. The porosity ranges of the three tight reservoir classes are <5%, 5%–8%, and 8%–11%, respectively, and their permeability ranges are <0.04 mD, 0.04–0.15 mD, and 0.15–0.8 mD, respectively. It is useful to classify the reservoir storage space for the purpose of predicting and optimizing sweet spots of tight oil reservoirs.

ACKNOWLEDGMENTS

We would like to thank the Natural Science Foundation of China (41972136, 41530315 and 41922015), the Natural Science Foundation of Shandong Province (ZR2019MD003) and the Fundamental Research Funds for the Central Universities (18CX02071A) for financially supporting this project.

ORCID

Fangwen Chen https://orcid.org/0000-0002-6200-1506
Qiang Zheng https://orcid.org/0000-0003-1489-3412
Shuangfang Lu https://orcid.org/0000-0002-5555-8170
Xue Ding https://orcid.org/0000-0003-1648-1817
Yiwen Ju https://orcid.org/0000-0001-5534-7392
Hongqin Zhao https://orcid.org/0000-0002-9785-2888

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How to cite this article: Chen F, Zheng Q, Lu S, Ding X, Ju Y, Zhao H. Classification of the tight oil reservoir storage space in the Raoyang Sag of the Jizhong Depression in the Bohai Bay Basin, China. Energy Sci Eng. 2020;8:74–88. https://doi.org/10.1002/ese3.510