Research Article

Enrichment Factors and Resource Potential Evaluation of Qingshankou Formation Lacustrine Shale Oil in the Southern Songliao Basin, NE China

Long Luo, Dongping Tan, Xiaojun Zha, Xianfeng Tan, Jing Bai, Cong Zhang, Jia Wang, Lei Zhang, and Xuanbo Gao

1The Key Laboratory of Unconventional Oil & Gas Geology, CGS, Beijing 100083, China
2Shandong Provincial Key Laboratory of Depositional Mineralization & Sedimentary Minerals, Qingdao 266590, China
3College of Petroleum and Gas Engineering, Chongqing University of Science and Technology, Chongqing 401331, China
4Chongqing Key Laboratory of Complex Oil and Gas Exploration and Development, Chongqing 401331, China

Correspondence should be addressed to Xianfeng Tan; xianfengtan8299@163.com

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China shale oil, which is preserved in lacustrine shale with strong heterogeneity and relatively low maturity, has been a research hotspot of unconventional resources. However, controlling factors of shale oil enrichment and resource potential evaluation restricted efficient exploration and development of lacustrine shale oil. On the basis of well logging data, TOC content, Rock-Eval pyrolysis values, thermal maturity, oil saturation data, and pressure coefficient, the core observation, X-ray diffraction analysis, physical property analysis, scanning electron microscopy, CT scan, well logging interpretation, and volumetric genesis method depending on three-dimensional geological modeling were used to determine enrichment factors and evaluate the resource potential of Qingshankou Formation shale oil in the Southern Songliao Basin. Shale oil was mainly enriched in the semideep and deep lake shale of K2qn1, with the high capacity of hydrocarbon generation and favorable petrological and mineralogical characteristics, pore space characteristics, and physical properties in the low structural part of the Southern Songliao Basin. The three-dimensional geological resource model of Qingshankou Formation lacustrine shale oil was determined by the key parameters (Ro, TOC, and S1) of shale oil in the favorable zone of the Southern Songliao Basin, northeast China. The geological resource of shale oil, which was calculated by two grid computing methods (F1 and F2), was, respectively, 1.713 × 10\(^{12}\) kg and 1.654 × 10\(^{12}\) kg. The great shale oil resource indicates a promising future in the exploration and development of Qingshankou Formation shale oil of the Southern Songliao Basin.

1. Introduction

Shale oil, which has been successfully and effectively developed in North America, is currently a research hotspot of unconventional hydrocarbon resources [1–5]. Shale oil is mainly developed in Mesozoic and Cenozoic lacustrine shale strata in the continental basins of China [2, 6–9]. Lacustrine shale oil has a lot of potential to fill and even replace the decreasing conventional oil resources in China [2, 7, 10–13]. Besides, the controlling factors and quantitative evaluation methods of oil content are crucial for understanding the resource potential of shale oil [6, 9, 14–16]. However, controlling factors and resource potential evaluation of lacustrine shale oil have not been well determined [9, 17–21].

The assessment methods of shale oil include dynamic and static methods. On the basis of dynamic data during the development of shale oil, dynamic methods try to quantitatively calculate the shale oil resource by means of a mathematical model. Static methods can be divided into the statistical method, analogy method, and genetic method [22]. The statistical method, which needs a large number of typical examples, is generally applied in the medium-high degree of the exploration process. The analogy method, which needs a similar calibration area, is generally applied...
in the low degree of the exploration process [23]. The genetic method, which belongs to deterministic evaluation and depends on the material balance approach, can be applied in every stage of basin exploration. The geological model-based simulation method was also used to evaluate the resource potential of shale oil in Upper Cretaceous Cardium Formation, Western Canada sedimentary basin [24]. The evaluation standard and methods of American marine shale oil cannot be directly used in the lacustrine shale oil evaluation of China because of the limited exploration well of shale oil, strong heterogeneity, many pore types, and relatively low maturity of lacustrine shale [22]. On the basis of a three-dimensional (3D) geological model, the volumetric genesis method is the most common and effective evaluation method for lacustrine shale oil of China [25–27]. This paper is aimed at determining the controlling factors and resource potential evaluation of Qingshankou Formation lacustrine shale oil in the Southern Songliao Basin, northeast China, by means of the volumetric genesis method depending on the geological model.

2. Geological Setting

2.1. Basin Structural Characteristics. The Songliao Basin is a Mesozoic-Cenozoic superimposed continental sedimentary basin in Northeastern China (Figure 1(a)). The Songliao Basin has mainly undergone five structural evolution stages, including the early mantle uplift stage, initial extrusion stage, rifting stage, depression stage, and equilibrium shrinkage [28]. The Songliao Basin can be divided into six first-order structural units, including the Northern Plunge, Northeastern Uplift, Central Depression, Southwestern Uplift, and Western Slope (Figure 1(b)) [29]. The Southern Songliao Basin mainly comprises the Southern Central Depression, east part of Western Slope, and west part of Southwestern Uplift (Figures 1(b) and 1(c)) [29]. The Central Depression of the Southern Songliao Basin mainly consists of Changling Sag, Huazijing terrace, Fuxin uplift, and Honggang terrace (Figure 1(c)).

2.2. Stratigraphic and Sedimentary Characteristics. Qingshankou Formation mainly comprises three members from bottom to top [5]. The first member of Qingshankou Formation (K2qn1) mainly consists of gray-black/dark-gray mudstone and shale, which were deposited in the semideep and deep lakes (Figure 2). The second member of Qingshankou Formation (K2qn2) mainly consists of gray and dark-gray shale/mudstone, which was deposited in the semideep and shallow lake (Figure 2). The third member of Qingshankou Formation (K2qn3) consists of gray shale/mudstone with
| Series | Form        | Member | Age (Ma) | Thickness (m) | Sedimentary facies               | Sea level |
|--------|-------------|--------|----------|---------------|----------------------------------|-----------|
|        | Sifangtai   | K₂ₚ₈  | 73       | 600           | Delta                           | High      |
|        |             | K₂ₚ₇  |          |               |                                 | Low       |
|        |             | K₂ₚ₆  |          |               |                                 |           |
|        |             | K₂ₚ₅  |          |               |                                 |           |
|        | Nejiagou    | E₂ₚ₂  | 80       | 800           | Semi-deep lake                  | High      |
|        |             | E₂ₚ₁  |          |               |                                 | Low       |
|        |             | E₂ₚ₀  |          |               |                                 |           |
|        |             | E₂ₚ₋₁| 84       | 1200         | Deep lake                       | High      |
|        |             | K₃ₚ₂  |          |               |                                 | Low       |
|        |             | K₃ₚ₁  | 88.5     | 1400         | Delta                           |           |
|        | Yanjiagou   | E₂ₚ₋₂ | 97       | 1600         | Shore-shallow lake              | High      |
|        |             | E₂ₚ₋₃ |          |               |                                 | Low       |
|        | Qingshankou | E₂ₚ₁  | 100      | 1800         | Semi-deep lake                  | High      |
|        |             | E₂ₚ₀  |          |               |                                 | Low       |
|        |             | E₂ₚ₋₁| 102      | 2000         | Deep lake                       | High      |
|        |             | K₃ₚ₀  |          | 2200         |                                 | Low       |

**Figure 2:** Stratigraphic and sedimentary characteristics of Qingshankou Formation (K₂ₚ) in the Southern Songliao Basin [5, 29].

**Figure 3:** Sedimentary facies distribution of the first member of Qingshankou Formation (K₂ₚ₁) in the Southern Songliao Basin.
some interlayers of gray-green silty mudstone or siltstone, which were deposited in the shore-shallow and delta lakes (Figure 2). Qingshankou Formation was mainly deposited in the fluvial delta lake system, especially the deep lake, semi-deep lake, and shallow lake [30]. The gray-black/dark-gray mudstone and shale, which were mainly deposited in the
lacustrine facies, were the main source rock in the Southern Songliao Basin [30].

3. Data and Methods

Two hundred twenty exploration wells have been drilled in Qingshankou Formation of the Southern Songliao Basin. Well logging data (220 wells), TOC content (718 data points), Rock-Eval pyrolysis values (325 $S_1$, $S_2$, and $T_{max}$ data points), thermal maturity (156 Ro data), 100 oil saturation data (So), and pressure coefficient were provided by the Key Laboratory of Unconventional Oil & Gas Geology, CGS. Core observation, physical property analysis, scanning electron microscopy (SEM), X-ray diffraction (XRD) analysis, and CT scan were performed on the shale and mudstone for determining reservoir characteristics of Qingshankou Formation in the Key Laboratory of Unconventional Oil & Gas Geology, CGS. The geological model was established by Petrel software depending on the main parameters, including structure, shale thickness, TOC, thermal maturity (Ro), porosity, and $S_1$. Geological resources of Qingshankou Formation shale oil will be calculated by the volumetric genesis method depending on the geological model.

4. Results

4.1. Sedimentary Facies and Shale Distribution. The first member of Qingshankou Formation ($K_{2qn1}$) mainly consists of gray-black/dark-gray mudstone and shale, which were deposited in the semideep and deep lakes (Figure 2). The semideep and deep lakes were mainly distributed in the northeastern study area (Figure 3). Some delta and shore-shallow lakes were distributed in the southwestern study area (Figure 3). The shale/mudstone thickness of $K_{2qn1}$ generally varies from 40 to 100 m (Figure 4). The black/dark-gray shale of $K_{2qn1}$ was mainly distributed in the DaAn-QianAn area and $Qn1$-$Q217$ well area (Figure 4).

4.2. Reservoir Characteristics of Qingshankou Formation

4.2.1. Petrological and Mineralogical Characteristics. Qingshankou Formation ($K_{2qn}$) mainly consists of gray-black/dark-gray mudstone and shale, gray and dark-gray shale/mudstone, gray-green silty mudstone, and siltstone. The first member of Qingshankou Formation ($K_{2qn1}$) comprises gray-black/dark-gray shale and some interbedded layers of mudstone and siltstone in the Southern Songliao Basin (Figure 5). The lamellation density of shale varies from 2 to 5 layers/cm, and a single layer varies from 2 to 5 mm (Figure 5).

$K_{2qn1}$ shale minerals mainly consist of quartz, plagioclase, potassium, calcite, dolomite, pyrite, and clay minerals (Figure 6). Brittle mineral content of $K_{2qn1}$ shale mainly varies from 40% to 60%, including quartz, plagioclase, potassium, minor calcite, dolomite, and little pyrite (Figure 6). Clay mineral content mainly varies from 30% to 40%, which mainly consists of illite (Figure 6). The brittleness index (brittle minerals/(brittle minerals + clay mineral)) mainly ranges from 40 to 60%.

Figure 5: Petrological characteristics of the first member of Qingshankou Formation ($K_{2qn1}$) in the Southern Songliao Basin. (a) D86, $K_{2qn1}$, 2035.88-2039.46 m, shale. (b) C34-7, $K_{2qn1}$, 2349.20-2352.10 m, shale interbedded with mudstone. (c) X381, $K_{2qn1}$, 1482.95-1486.70 m, shale interbedded with mudstone. (d) He101, $K_{2qn1}$, 2412.2-2415.6 m, siltstone interbedded with shale.
Figure 6: Continued.
The mineralogical lithofacies of K2qn1 can be divided into feldspar-quartz shale facies with high content of organic matter (TOC > 3%) (SFHOM), feldspar-quartz shale facies with middle content of organic matter (TOC: 1-3%) (SFMOM), silt-fine sandstone facies with low content of organic matter (TOC < 1%) (DFLOM), massive feldspar-quartz mudstone facies with middle content of organic matter (TOC: 1-3%) (MFMOM), and feldspar-quartz mudstone facies with low content of organic matter (TOC < 1%) (MFLOM).

4.2.2. Reservoir Spaces. The pore space of the shale oil reservoir comprises the organic pore, inorganic pore, and microfracture (Figure 7). Inorganic pores include the intergranular pore of minerals, intragranular pore of minerals, intercrystalline pore, and intracrystalline pore (Figure 7). Organic pores mainly consist of primary and dissolved organic pores (Figure 7). The pore diameter of the shale reservoir ranges from 10 to 40 nm. The pore diameter of the massive mudstone reservoir ranges from 5 to 10 nm. The pore net of shale mainly occurred as a flake and was distributed in the lamellation surfaces; the pore connectivity of shale is better than that of mudstone (Figure 8).

4.2.3. Reservoir Porosity and Permeability. The core porosity of K2qn1 shale varies from 2% to 6%, and the core permeability...
is characterized by $0-0.1 \times 10^{-3} \mu m^2$ and more than $0.2 \times 10^{-3} \mu m^2$ (Figure 9). Logging porosity of K$_2$qn$^1$ shale mainly ranges from 2%-6% to 8%-14%; logging permeability of K$_2$qn$^1$ shale is generally less than $0.05 \times 10^{-3} \mu m^2$ (Figure 9).

The BET multipoint specific surface area of SFHOM, SFMOM, and DFLOM lithofacies mainly varies from 0 to 2 m$^2$/g (TOC > 0.7) (Figure 10). The total mesoporous volume of SFHOM, SFMOM, and DFLOM lithofacies mainly ranges from 3 to 6 m$^2$/g (Figure 10). Pore diameters were mainly distributed in 5-20 nm and 30-40 nm in the SFHOM, SFMOM, and DFLOM lithofacies (Figure 10).

The BET multipoint specific surface area of MFMOM lithofacies mainly varies from 3 to 7 m$^2$/g (Figure 10). The total mesoporous volume of MFMOM lithofacies mainly ranges from 6 to 18 m$^2$/g (Figure 10). Pore diameters were mainly distributed in 2-10 nm in the MFMOM lithofacies (Figure 10).

The BET multipoint specific surface area of MFLOM lithofacies is generally more than 10 m$^2$/g (Figure 10). The total mesoporous volume of MFLOM lithofacies mainly ranges from 12 to 21 m$^2$/g (Figure 10). Pore diameters were mainly distributed in 0.5 nm in the MFLOM lithofacies (Figure 10).

4.3. Types and Hydrocarbon Generation Ability of Shale

4.3.1. Types of Organic Matter. Kerogen types can be divided into I, II$_1$, II$_2$, and III, depending on HI and Tmax [31, 32]. The organic matter types of K$_2$qn$^1$ and K$_2$qn$^2$ mainly consist of type I and type IIa (Figures 11(a) and 11(b)). The HI ($S_2$/TOC) of K$_2$qn$^1$ organic matter mainly varies from 150 to 800 mg/g, and the Tmax of K$_2$qn$^1$ organic matter varies from 440 to 460°C (Figure 11(a)). The HI ($S_2$/TOC) of K$_2$qn$^2$ organic matter mainly varies from 150 to 700 mg/g, and the Tmax of K$_2$qn$^2$ organic matter varies from 440 to 450°C (Figure 11(b)).
Figure 8: Continued.
4.3.2. Total Organic Carbon (TOC). The TOC of K2qn1 organic matter ranges from 1 to 4%, and the TOC of K2qn2 varies from 0 to 2% (Figures 12(a) and 12(b)). The TOC of K2qn1 organic matter is mainly distributed in the Songyuan area (3%-5%), DaAn area (2%-2.5%), QianAn area (1.5%-2.5%), and well He100-YZ2 area (1.5%-2%) in the Southern Songliao Basin (Figure 13). The high TOC was mainly distributed in the deep lake environment of Fuxin terrace and the shore-shallow lake of Changling Sag (Figures 1, 3, and 13).

4.3.3. Vitrinite Reflectance (Ro). The Ro of K2qn1 and K2qn2 organic matter mainly ranges from 0.5% to 1.35% (Figures 11(a) and 11(b)). The Ro of K2qn1 mainly focuses on the DaAn area (0.8-1.0%), QianAn area (0.8-1.0%), and well He55-He100-He43 area (0.7-1.1%) (Figure 14). The K2qn1 shale with a high Ro value was mainly centered in Changling Sag (Figures 1 and 14).

4.4. Oiliness of Qingshankou Formation Shale. There are about 45 wells with core oil-gas display wells and 130 gas logging display wells, which were mainly distributed in the Central Depression (Figure 1). Good oil and gas production was found in K2qn1 of the 8 wells, including X380, X381, D86, X389, He238, C34-7, and C70 (Figure 1). Besides, the good industrial oil flow was produced in the K2qn1 of the He197 (Figure 1). The oil measured peak values of K2qn1 were mainly centered in the Central Depression, which were obviously higher than those in the east part (Figure 17).

5. Discussion

5.1. Main Controlling Factors of Shale Oil Enrichment

5.1.1. Sedimentary Characteristics. The gray-black/dark-gray shale was developed in the semideep and deep lakes of K2qn1 with high lake levels (Figures 2–4) because the gray-black/dark-gray shale was generally deposited in the quiet deepwater environment [33, 34]. The quiet deepwater anoxic environment was favorable for the preservation of organic matter [33, 34]. Therefore, the gray-black/dark-gray shale was rich in organic matter (Figures 3 and 12). The organic-rich shale of Qingshankou Formation was deposited during the third global anoxic event [30]. The three sets of gray-black shale were steadily developed in the region due to the sedimentary cycle and lake-level change. Therefore, the sedimentary characteristics are the material basis of gray-black/dark-gray shale.

5.1.2. Structural Characteristics. The structural characteristics were one of key factors of shale oil and gas [35]. The Ro of K2qn1 and K2qn2 organic matter mainly ranges from 0.5% to 1.35% (Figures 11(a) and 11(b)). The high Ro value of K2qn1 was mainly distributed in Changling Sag, which indicates the obvious structural controls on organic maturity of K2qn1 shale (Figures 1 and 14).
Figure 9: Continued.
Western Slope and west part of Southwestern Uplift (Figures 1(b), 1(c), and 16). This indicates that the low structural part was favorable for the evolution and hydrocarbon generation of K2qn1 oil shale. The deep burial can accelerate the thermal evolution of K2qn1 shale due to low structural characteristics.

5.1.3. Capacity of Hydrocarbon Generation. The generation capacity and composition of hydrocarbon are determined by the organic matter type of source rock [31]. The type I and II kerogens generally generate liquid hydrocarbons. Type II and III kerogens, which are mainly composed of woody materials, are more susceptible to generate gas [36]. Thermal maturation of source rock can be divided into immature, mature (early, peak, and late), and postmature (Table 1) [36].

The organic matter types (type I and type IIa) of K2qn1 and K2qn2 indicate that the organic matter of K2qn1 shale...
can produce a large amount of oil and gas (Figures 11(a) and 11(b)). The TOC of K2qn1 and K2qn2 suggests that K2qn1 shale has abundant organic matter for hydrocarbon generation (Figures 12 and 13). The Ro of K2qn1 and K2qn2 organic matter mainly ranges from 0.5% to 1.35% (Figures 11(a) and 11(b)), and the Tmax (440-460°C) suggests that K2qn1 and K2qn2 organic matter was mainly in mature, which means mature enough to generate oil, especially the organic matter of K2qn1 shale (Figures 11 and 14, Table 1). The S1 values, abnormally high pressure, and gas measured peak values of the K2qn1 indicate that abundant oil was generated and preserved in the K2qn1 shale of the Southern Songliao Basin (Figures 16–18). Therefore, the high capacity of hydrocarbon generation was crucial to the formation of shale oil.

5.1.4. Reservoir Quality of Shale Oil. The shale oil was mainly preserved in the pore space, including the organic pore, inorganic pore, and minor microfracture (Figure 7). The

Figure 11: Scatter plot of Tmax and HI of Qingshankou Formation shale. (a) First member. (b) Second member.

Figure 12: TOC histogram of the first and second members of Qingshankou Formation shale (a) and mudstone (b) in the Southern Basin.
Multipoint specific surface area and total pore volume of feldspar-quartz organic-rich shale (SFHOM and SFMOM) were less than those of mudstone (MFMOM and MFLOM), but the feldspar-quartz organic-rich shale (SFHOM and SFMOM) has more large pores than the mudstone (MFMOM and MFLOM). Besides, the porosity, permeability, and better pore connectivity of K2qn1 shale were favorable for the accumulation and development of shale oil (Figures 8 and 9).

5.2. Resource Potential of Qingshankou Formation Shale Oil. The favorable zone and three-dimensional (3D) geological resource model of Qingshankou Formation lacustrine shale oil were determined by the main controlling factors in the
Southern Songliao Basin, northeast China [37, 38]. At first, the structural model was established depending on the structural top and bottom surfaces and well logging data. The structural model was divided into 30897600 3D grids with the 100 m $\times$ 100 m $\times$ 2 m grid density. The parameters, including experimental data and log interpretation data, were discretized to establish resource parameter models [39].

According to the relationship between parameters and shale oil production display, the lower limiting values of Ro, TOC, and $S_1$ for the favorable zone and resource model of shale oil were, respectively, 0.7%, 1.8%, and 1 mg/g. The effective grids were determined by the lower limiting values of the resource parameter. The geological resource of shale oil was calculated by two grid computing methods based on effective grids of the three-dimensional (3D) geological
model of K2qn1 shale ($F_1$ and $F_2$) in the favorable zone of the Southern Songliao Basin. The geological resource of shale oil ($Q_1$) of K2qn1 shale calculated by $F_1$ is $1.713 \times 10^{12}$ kg, and the $Q_2$ of K2qn1 shale calculated by $F_2$ is $1.654 \times 10^{12}$ kg. The geological resource of shale oil of two methods is abundant with a 3.5% deviation.

\[
Q_1 = \sum_{i=1}^{n} (Ai \times Hi \times \rho \times S_1 i), \quad F_1, \\
Q_2 = \sum_{i=1}^{n} (Ai \times Hi \times \Phi i \times Soi \times \rho o), \quad F_2,
\]

where $Q$ is the geological resource of shale oil; $Ai$ is the grid area of shale; $Hi$ is the thickness of grid shale; $\rho$ is the density of shale, 2.35 g/cm$^3$; $S_1$ is the residual liquid hydrocarbon of grid shale; $\Phi$ is the porosity of shale; $Soi$ is the oil saturation of grid shale; $\rho o$ is the density of shale oil, 0.85 g/cm$^3$.

Free hydrocarbon ($S_1$) generally was less than the oiliness of shale oil due to heavy hydrocarbon loss [6, 40, 41]. However, $F_1$ was a sample, and it was easy to calculate the geological resource of shale oil because the $S_1$ was easy to be determined by log data. The second grid computing method ($F_2$) was constrained by oil saturation (So) and porosity ($\Phi$). Oil saturation (So) and porosity ($\Phi$) can reflect much information on the reservoir and occurrence characteristics of shale oil. However, the So and $\Phi$ were

![Figure 15: So (a) and $S_1$ (b) histogram of the K2qn1 shale and mudstone in the Southern Basin.](image)
Figure 16: $S_i$ isogram of the first member of Qingshankou Formation (K\textsubscript{2}qn\textsuperscript{1}) in the Southern Songliao Basin.

Figure 17: Pressure coefficient isogram of the first member of Qingshankou Formation (K\textsubscript{2}qn\textsuperscript{1}) in the Southern Songliao Basin.
characterized by strong heterogeneity because the oil saturation \((S_o)\) was controlled by the complex pore structure and porosity \((\Phi)\). Therefore, the first grid computing method \((F_1)\) is more favorable to the resource calculation of lacustrine shale oil than the second grid computing method \((F_2)\).

6. Conclusions

We determined the main enrichment factors and resource potential evaluation of Qingshankou Formation lacustrine shale oil in the Southern Songliao Basin, NE China. The deepwater anoxic environment, low structural part, high capacity of hydrocarbon generation, and high-quality shale reservoir are the main enrichment factors of lacustrine shale oil. The grid computing volumetric method with the 3D geological model is an available and effective evaluation method for lacustrine shale oil of China.

The gray-black/dark-gray shale, which was the main source rock of shale oil, was mainly developed in the semi-deep and deep lakes of \(k_{qn1}\) with high lake levels. The low structural part was favorable for the evolution and

Table 1: Geochemical parameters of thermal maturation of source rock (modified from Peters and Cassa [36]).

| Stage of thermal maturity for oil | Maturation | Ro (%) | Tmax (°C) |
|----------------------------------|------------|--------|-----------|
| Immature                         |            | 0.2-0.6| <435      |
| Mature                           | Early      | 0.6-0.65| 435-445  |
|                                  | Peak       | 0.65-0.9| 445-450  |
|                                  | Late       | 0.9-1.35| 450-470  |
| Postmature                       |            | >1.35  | >470      |

Figure 18: Gas measured peak isogram of \(k_{qn1}\) shale and mudstone of \(k_{qn1}\) in the Southern Songliao Basin.
hydrocarbon generation of K2qn1 oil shale. The high capacity of hydrocarbon generation provided an abundant oil source for the accumulation of shale oil. Petrological and mineralogical characteristics, pore space characteristics, physical properties of shale were favorable for the accumulation and development of shale oil.

The favorable zone and geological model of Qingshankou Formation lacustrine shale oil were determined by the main controlling factors in the Southern Songliao Basin, northeast China. The geological resource of shale oil, which was calculated by two grid computing methods (F1 and F2), was, respectively, $1.713 \times 10^{12}$ kg and $1.654 \times 10^{12}$ kg.

The great shale oil resource indicates a promising future in the exploration and development of Qingshankou Formation shale oil of the Southern Songliao Basin. The first grid computing method (F1) is more favorable to the resource calculation of lacustrine shale oil than the second grid computing method (F2).

Data Availability

If readers want to access the data, they can get the original data by contacting the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] J. A. Breyer, “Shale reservoirs: giant resources for the 21st century,” AAPG Memoir, vol. 97, pp. 1–451, 2012.
[2] C. Zou, Z. Yang, J. Cui et al., “Formation mechanism, geological characteristics and development strategy of nonmarine shale oil in China,” Petroleum Exploration and Development, vol. 40, no. 1, pp. 14–26, 2013.
[3] S. A. Holditch, “Unconventional oil and gas resource development – let’s do it right,” Journal of Unconventional Oil and Gas Resources, vol. 1-2, pp. 2–8, 2013.
[4] R. J. Davies, S. Almond, R. S. Ward et al., “Oil and gas wells and their integrity: implications for shale and unconventional resource exploitation,” Marine and Petroleum Geology, vol. 56, pp. 239–254, 2014.
[5] Z. Huo, S. Hao, B. Liu et al., “Geochemical characteristics and hydrocarbon expulsion of source rocks in the first member of the Qingshankou Formation in the Qijia-Gulong Sag, Songliao Basin, Northeast China: evaluation of shale oil resource potential,” Energy Science & Engineering, vol. 8, no. 5, pp. 1450–1467, 2020.
[6] S. Lu, W. Huang, F. Chen et al., “Classification and evaluation criteria of shale oil and gas resources: discussion and application,” Petroleum Exploration and Development, vol. 39, no. 2, pp. 249–256, 2012.
[7] J. Zhang, L. Lin, Y. Li et al., “Classification and evaluation of shale oil,” Earth Science Frontiers, vol. 19, no. 5, pp. 322–331, 2012.
[8] J. L. Song, R. Little, P. Weniger, C. Ostertag-Henning, and S. Nelskamp, “Shale oil potential and thermal maturity of the Lower Toarcian Posidonia Shale in NW Europe,” International Journal of Coal Geology, vol. 150-151, pp. 127–153, 2015.
[9] Z. Yang, C. Zou, S. Wu et al., “Formation, distribution and resource potential of the “sweet areas (sections)” of continental shale oil in China,” Marine and Petroleum Geology, vol. 102, pp. 48–60, 2019.
[10] L. Cao, Y. Cao, Z. Jiang, J. Wu, G. Song, and Y. Wang, “Shale oil potential of lacustrine black shale in the Eocene Dongying depression: implications for geochemistry and reservoir characteristics,” American Association of Petroleum Geologists Bulletin, vol. 101, pp. 1835–1858, 2017.
[11] M. Li, Z. Chen, T. Cao et al., “Expelled oils and their impacts on Rock-Eval data interpretation, Eocene Qianjiang Formation in Jianghan Basin, China,” International Journal of Coal Geology, vol. 191, pp. 37–48, 2018.
[12] M. Li, Z. Chen, X. Ma, T. Cao, Z. Li, and Q. Jiang, “A numerical method for calculating total oil yield using a single routine Rock-Eval program: a case study of the Eocene Shahejie formation in Dongying depression, Bohai Bay Basin, China,” International Journal of Coal Geology, vol. 191, pp. 49–65, 2018.
[13] M. Li, Z. Chen, X. Ma et al., “Shale oil resource potential and oil mobility characteristics of the Eocene-Oligocene Shahejie Formation, Jiyang Super-Depression, Bohai Bay Basin of China,” International Journal of Coal Geology, vol. 204, pp. 130–143, 2019.
[14] D. M. Jarvie, “Shale resource systems for oil and gas: part 2–shaleoil resource systems. In: Breyer JA, ed., Shale Reservoirs-Giant Resources for the 21st Century,” AAPG Memoir, vol. 97, pp. 89–119, 2012.
[15] H. T. Lee, “Analysis of relationships between geochemical parameters of petroleum potential in related source and carbonaceous materials,” Environmental Earth Sciences, vol. 69, pp. 2257–2274, 2012.
[16] M. H. Hakimi and W. H. Abdullah, “Organic geochemical characteristics and oil generating potential of the Upper Jurassic Safer shale sediments in the Marib-Shabowah Basin, western Yemen,” Organic Geochemistry, vol. 54, pp. 115–124, 2013.
[17] B. Liu, Y. Liu, R. Zhao, X. Guo, and Y. Shen, “Formation overpressure and shale oil enrichment in the shale system of Luaogou Formation, Malang Sag, Santanghu Basin, NW China,” Petroleum Exploration and Development, vol. 39, no. 6, pp. 744–750, 2012.
[18] D. M. Jarvie, “Components and processes affecting producibility and commerciality of shale resource systems,” Geologica Acta, vol. 12, pp. 307–325, 2014.
[19] B. Katz and F. Lin, "Lacustrine basin unconventional resource plays: key differences," *Marine and Petroleum Geology*, vol. 56, pp. 255–265, 2014.

[20] J. Li, Y. Shi, X. Zhang et al., "Control factors of enrichment and producibility of shale oil: a case study of Biyang depression," *Earth Science Reviews*, vol. 39, pp. 848–857, 2014.

[21] S. Wu, R. Zhu, J. Cui et al., "Characteristics of lacustrine shale porosity evolution, Triassic Chang 7 Member, Ordos Basin, NW China," *Petroleum Exploration and Development*, vol. 42, no. 2, pp. 167–176, 2015.

[22] R. Zhu, L. Zhang, Z. Li, R. Wang, S. Zhang, and L. Zhang, "Evaluation of shale oil resource potential in continental rift basin: a case study of Lower Es3 Member in Dongying Sag," *Petroleum Geology and Recovery Efficiency*, vol. 26, no. 1, pp. 129–136, 2019.

[23] Q. Guo, S. Wang, and X. Chen, "Assessment on tight oil resources in major basins in China," *Journal of Asian Earth Sciences*, vol. 178, pp. 52–63, 2019.

[24] Z. Chen and G. O. Kirk, "An assessment of tight oil resource potential in Upper Cretaceous Cardium Formation, Western Canada Sedimentary Basin," *Petroleum Exploration and Development*, vol. 40, no. 3, pp. 344–353, 2013.

[25] D. A. White and H. M. Gehman, "Methods of estimating oil and gas resources," *AAPG Bulletin*, vol. 63, no. 12, pp. 2183–2192, 1979.

[26] J. N. Seshadri and L. Mattar, "Comparison of power law and modified hyperbolic decline methods," in *Paper presented at the Canadian Unconventional Resources and International Petroleum Conference*, Calgary, Alberta, Canada, 2010.

[27] L. Kegang and H. Jun, "Theoretical bases of Arps empirical decline curves," in *Paper presented at the Abu Dhabi International Petroleum Conference and Exhibition*, Abu Dhabi, UAE, 2012.

[28] J. Yao, "Fracture distribution characteristics and comprehensive evaluation of shale reservoir in Southern Songliao Basin," Master theses, Northeast Petroleum University, 2019.

[29] S. Deng, J. Fan, and Y. Wang, "The geological conditions, resource potential,and exploration direction of oil of middle-shallow layers in the southern Songliao Basin," *Marin Origin Petroleum Geology*, vol. 24, no. 2, pp. 33–42, 2019.

[30] P. Sun, "Environmental dynamics of organic accumulation in the oil shale bearing layers in the Upper Cretaceous, Southeast Songliao Basin (NE China)," Doctor theses, Jilin University, 2013.

[31] B. P. Tissot and D. H. Welte, *Petroleum Formation and Occurrence*, Springer-Verlag, Berlin, 2nd edition, 1984.

[32] Z. Xu, L. Liu, B. Liu et al., "Geochemical characteristics of the Triassic Chang 7 lacustrine source rocks, Ordos Basin, China: implications for paleoenvironment, petroleum potential and tight oil occurrence," *Journal of Asian Earth Sciences*, vol. 178, pp. 112–138, 2019.

[33] T. J. Algeo and R. J. Twitchett, "Anomalous Early Triassic sediment fluxes due to elevated weathering rates and their biological consequences," *Geology*, vol. 38, no. 11, pp. 1023–1026, 2010.

[34] M. Tan, X. Zhu, M. Geng, S. Zhu, and W. Liu, "The occurrence and transformation of lacustrine sediment gravity flow related to depositional variation and paleoclimatic in the Lower Cretaceous Prosopis Formation of the Bongor Basin, Chad," *Journal of African Earth Sciences*, vol. 134, pp. 134–148, 2017.

[35] K. Zhang, C. Jia, and Y. Song, "Analysis of Lower Cambrian shale gas composition, source and accumulation pattern in different tectonic backgrounds: a case study of Weiyuan Block in the Upper Yangtze region and Xiuwu Basin in the Lower Yangtze region," *Fuel*, vol. 263, article 115978, 2020.

[36] K. E. Peters and M. R. Casa, "Applied source rock geochemistry," in *The Petroleum System: From Source to Trap*, L. B. Magoon and W. G. Dow, Eds., pp. 93–120, American Association of Petroleum Geologists, Tulsa, 1994.

[37] C. Jia, C. Zou, J. Li, D. Li, and M. Zheng, "Assessment criteria, main types, basic features and resource prospects of the tight oil in China," *Acta Petrolei Sinica*, vol. 33, no. 3, pp. 343–350, 2012.

[38] X. Wu, B. Gao, X. Ye, R. Bian, H. Nie, and F. Lu, "Shale oil accumulation conditions and exploration potential of faulted basins in the east of China," *Oil & Gas Geology*, vol. 34, no. 4, pp. 455–462, 2013.

[39] B. Liu, "Technique and application of recognizing oil shale effectively using logging data-the example from the area in southern Songliao Basin," Master theses, Jilin University, 2010.

[40] J. Li, "Selection and correction of key parameters in quantitative evaluation of shale oil resources," Master theses, China University of Petroleum (East China), 2017.

[41] H. Xue, S. Tian, S. Lu, W. Zhang, T. Du, and G. Mu, "Selection and verification of key parameters in the quantitative evaluation of shale oil: a case study at the Qingshankou Formation, Northern Songliao Basin," *Bulletin of Mineralogy, Petrology and Geochemistry*, vol. 34, no. 1, pp. 70–78, 2015.