Research Article

Geological and Geochemical Characteristics of the First Member of the Cretaceous Qingshankou Formation in the Qijia Sag, Northern Songliao Basin, Northeast China: Implication for Its Shale Oil Enrichment

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The Qijia Sag, a secondary tectonic unit in the northern Songliao Basin, developed plentiful shale oil resources in the first member of the Cretaceous Qingshankou Formation (K2qn1) as its main target layer. However, the systematic study on the geological and geochemical characteristics of K2qn1 in the sag has not been carried out. Taking the core samples from the SYY1 well covering the whole K2qn1 as the main study object and concerning some relevant intervals from the SYY1HF well and other earlier wells, petrologic features, organic geochemical characteristics, oil-bearing property, and reservoir characteristics of K2qn1 were analyzed in detail. The results show that the lithology of K2qn1 is mainly dark mudstone genera accounting for more than 90% of the formation thickness with few macrostructural fractures, indicating that K2qn1 developing in deep to semideep lacustrine facies of the Qijia Sag belongs to the typical matrix reservoirs for shale oil. According to lithology features and logging curves, K2qn1 can be divided into three submembers consisting of K2qn11, K2qn12, and K2qn13 from above to below. Compared to the K2qn11 submember, the K2qn12 and K2qn13 submembers obviously are more enriched in shale oil, which is supported by the following three aspects: (i) the average TOC (total organic carbon) values of K2qn11, K2qn12, and K2qn13 are 1.96%, 2.42%, and 2.72%, respectively. The organic matter types of K2qn12 and K2qn13 are mainly type I and type II1, while those of K2qn11 are mainly type II1 and type II2. K2qn1 is at the end of the oil window with a R0 (vitrinite reflectance) average of 1.26%, and the maturity of K2qn12 and K2qn13 is slightly higher than that of K2qn11. (ii) The average OSI (oil saturation index) values of K2qn11, K2qn12, and K2qn13 are 110.54 mg/g, 171.74 mg/g, and 150.87 mg/g, respectively, which all reach the zone of oil crossover. The saturated hydrocarbon of EOM (extractable organic matter) in K2qn12 and K2qn13 is of higher content than that in K2qn11, while it is the opposite for the aromatic hydrocarbon, nonhydrocarbon, and asphaltene, indicating better oil mobility for K2qn12 and K2qn13. The average oil saturation values of K2qn11, K2qn12, and K2qn13 are 24.77%, 32.86%, and 35.54%, respectively. (iii) The intragranular dissolution pores and organic pores in K2qn12 and K2qn13 are more developed than those in K2qn11. The average effective porosity values of K2qn11, K2qn12, and K2qn13 interpreted from NMR logging are 4.88%, 6.26%, and 5.86%, respectively. Based on the above-mentioned analyses, the lower K2qn11 and the upper K2qn13 are determined as the best intervals of shale oil enrichment for K2qn1 vertically in the Qijia Sag. There is a certain horizontal heterogeneity of TOC, S1, and effective porosity in the drilling horizontal section of K2qn1 of the SYY1HF well. Therefore, the lower K2qn12 and the upper K2qn13 in the area with relatively weak horizontal reservoir heterogeneity of the study area should be selected as the preferential targets for shale oil exploration.
1. Introduction

As the commercial development of shale oil was achieved in North America, shale oil/reservoir has been one of the hottest fields for petroleum exploration and geological study. Shale oil is defined as the generated and unexpended residual petroleum occurring in organic-rich shale strata series with three occurrence states of free, adsorbed, and dissolved oils, in which the free oil is the main potential recoverable part under the widely used exploitation technology of hydraulic fracturing [1, 2]. According to the report from EIA (U.S. Energy Information Administration), Russia, U.S., and China occupy the top three of the technically recoverable shale oil resources in the world [3]. Through the shale revolution, U.S. took the lead in successively achieving the commercial development of shale gas and shale oil, which has attracted great attention from many petroleum companies and explorers of other countries. China began to carry out shale gas exploration works since 2005 [4], and the commercial development of marine shale gas in the southern China was realized in 2015 [5]. However, the exploration of shale oil, especially for the oil reserved in the nano-micron pores and microfractures of the shale matrix rather than in nonshale interlayers and macrofractures, is still in the initial stage. Unlike shale oils in the U.S., which mainly occur in marine shale strata series, shale oils in China are mainly distributed in the lacustrine shale strata series of the petroliferous basins such as Songliao, Bohai Bay, Ordos, Sichuan, Juggar, and Jianghan [6–12]. Due to different characteristics of water environment, sediment sources, biotic input, and buried history from the marine shale strata series in the U.S., the lacustrine shale strata series in China are generally characterized by stronger lithofacies heterogeneity and lower maturity [4, 6, 12–15], which makes reservoir fracturing and shale oil extraction more challenging.

The Songliao Basin is a large lacustrine basin in the northeast China (Figure 1(a)) with 11.5 billion barrels of technically recoverable shale oil [3]. The Upper Cretaceous Qingshankou Formation (K2qn), the main hydrocarbon generation strata in the Songliao Basin, is also the main target of the second-third member in the upper (K2qn2+3) (Figure 2). According to the report from EIA (U.S. Energy Information Administration), Russia, U.S., and China occupy the top three of the technically recoverable shale oil resources in the world [3]. Through the shale revolution, U.S. took the lead in successively achieving the commercial development of shale gas and shale oil, which has attracted great attention from many petroleum companies and explorers of other countries. China began to carry out shale gas exploration works since 2005 [4], and the commercial development of marine shale gas in the southern China was realized in 2015 [5]. However, the exploration of shale oil, especially for the oil reserved in the nano-micron pores and microfractures of the shale matrix rather than in nonshale interlayers and macrofractures, is still in the initial stage. Unlike shale oils in the U.S., which mainly occur in marine shale strata series, shale oils in China are mainly distributed in the lacustrine shale strata series of the petroliferous basins such as Songliao, Bohai Bay, Ordos, Sichuan, Juggar, and Jianghan [6–12]. Due to different characteristics of water environment, sediment sources, biotic input, and buried history from the marine shale strata series in the U.S., the lacustrine shale strata series in China are generally characterized by stronger lithofacies heterogeneity and lower maturity [4, 6, 12–15], which makes reservoir fracturing and shale oil extraction more challenging.

The Songliao Basin is a large lacustrine basin in the northeast China (Figure 1(a)) with 11.5 billion barrels of technically recoverable shale oil [3]. The Upper Cretaceous Qingshankou Formation (K2qn), the main hydrocarbon generation strata in the Songliao Basin, is also the main target of the second-third member in the upper (K2qn2+3) (Figure 2). The northern Songliao Basin belongs to the main exploration area of the Daqing Oilfield, and its shale oil exploration of the Qingshankou Formation has roughly experienced three stages. During the first stage, the exploration of shale oil accumulating in mudstone fractured reservoirs started in 1981, aimed at the lower K2qn2+3 and the upper K2qn1 in the Gulong Sag, and industrial oil flows were approached in the Y12, Y18, H16, and GP1 wells [18, 19]. As the significant continuous shale oil productions were not realized in the above wells, i.e., the low yield and rapid oil yield decay, the relative exploration works were slowed down. During the second stage, the exploration of shale oil in sandstone interbedded reservoirs started in 2011, aimed at the delta outer front facies of the lower K2qn2+3 in the Qijia Sag, and high production industrial oil flows were discovered in several horizontal wells including the QP1 and QP1-1 wells [20, 21]. The resource of desert areas for this kind of shale oil was estimated to be 1.5 × 1015 t in the Qijia Sag [22]. Recently for the third stage, the exploration of shale oil in the K2qn1 shale reservoirs started in 2016. Cooperating with the Daqing Oilfield, the China Geological Survey deployed and implemented several shale oil parameter wells, including the SYY1 and SYY1HF wells in the Qijia Sag and the SYY2 and SYY2HF wells in the Gulong Sag. Industrial oil flows were achieved in the SYY1 and SYY2 wells, and high production industrial oil flows were achieved in the SYY1HF and SYY2HF wells. Good results have been approached through the producing tests of the SYY1HF and SYY2HF wells, which indicates huge resource potential for shale oil in the K2qn1 shale reservoirs [23]. The K2qn1 in the Qijia and Gulong sags was regarded as the most promising exploration field of shale oil in the northern Songliao Basin [24, 25].

The previous geological and geochemical studies of shale oil in the northern Songliao Basin were focused on the Gulong Sag [6, 26–30], less involving in the Qijia Sag. Moreover, all these studies were based on the incomplete core data, which cannot represent the detailed profile characteristics of K2qn1. A full-section coring of K2qn1 was performed on the SYY-1 well, which lays a good foundation for the further detailed study in the Qijia Sag. Therefore, the SYY1 well as the main object combining other well data including the newly drilled SYY1HF well in the study area created very good conditions for this study. This paper is aimed at comprehensively analyzing the geological and geochemical characteristics of K2qn1 in detail through the analytical test, mud logging, and logging data and thus determining the shale oil enrichment regularity of K2qn1 in the Qijia Sag.

2. Geological Setting

The Songliao Basin located in the northeastern China (Figure 1(a)) is a Mesozoic-Cenozoic continental petroliferous basin superimposing on the Hercynian fold basement. It is about 750 km long and 350 km wide with an area of 2.6 × 106 km2 [31], and the long axis direction of the basin is northeast-southwest (Figure 1(b)). According to the development characteristics of strata and faults during the depression period, the Songliao Basin can be divided into six first-order structural units, including the Central Depression, the Northern Plunge, the Northeastern Uplift, the Southern Uplift, the Southwestern Uplift, and the Western Slope [16]. Taking the central line of the basin as a boundary, the exploration area to the north of the boundary (the northern Songliao Basin) mainly belongs to the Daqing Oilfield of PetroChina, while the exploration area to the south of the boundary (the southern Songliao Basin) mainly belongs to the Jilin Oilfield of PetroChina and the Northeast Petroleum Bureau of Sinopec (Figure 1(b)). The Qijia Sag as the study area of this paper is one of the second-order structural units of the Central Depression, adjacent to the north of the Gulong Sag (Figure 1(c)). The area of the Qijia Sag is about 2225 km2.

According to the regional tectonic setting, tectonic style, sedimentary evolution, volcanic activity, and thermal history, the formation and development of the Songliao Basin
Figure 1: Location of the study area and structural unit division of the Songliao Basin (modified from [16]).
experienced three evolution periods of fault basin, depression basin, and structural inversion (Figure 2) since the Cretaceous [31–33]. The Cretaceous strata, the main hydrocarbon-bearing series developed in the basin, consist of the Lower Cretaceous Huoshiling, Shahezi, Yingcheng, Denglouku, and Quantou formations and the Upper Cretaceous Qingshankou, Yaojia, Nenjiang, Sifangtai, and Mingshui formations from below to above (Figure 2). The oil and gas in the Songliao Basin are mainly distributed in the Daqing Placanticline, the Qijia Sag, the Sanzhao Sag, and the Changling Sag of the Central Depression (Figure 1(c)).

The SYY1 well located in the southern Qijia Sag is a vertical parametric well for shale oil exploration, and the SYY1HF well is the horizontal well adjusted from the SYY1 well with an azimuth of 10.97 degrees (Figure 1(c)). It must be pointed out that vertical well hydraulic fracturing was conducted on the K2qn1 and the bottom of K2qn2+3 of the SYY1 well before the drilling of the SYY1HF well.

### Table: Comprehensive Stratigraphic Column of the Songliao Basin

| System       | Series | Formation | Member | Thickness (m) | Lithologic section | Sedimentary environment | Structure evolution          |
|--------------|--------|-----------|--------|---------------|---------------------|--------------------------|----------------------------|
| Quaternary   |        |           |        | 140           |                     |                          |                            |
| Neogene      | Pliocene| Taikang   | N1j    | 0.165         |                     |                          |                            |
|              |        | Duan      | N1d    | 0.123         |                     |                          |                            |
| Palaeogene   | Eocene-Oligocene | Yian | K2y1~K2y4 | 0.260         |                     |                          |                            |
|              |        | Mingshui  | K1m1   | 0.576         |                     | Meandering river delta, shallow lacustrine | Period of depression basin |
|              |        | K1m2      | K1m3   | 0.320         |                     |                          |                            |
|              |        | Sifangtai | K1s    | 100-470       |                     | Delta, deep and semi-deep lacustrine | Period of structural inversion |
|              | Upper  | Nenjiang  | K1n1   | 80-210        |                     |                          |                            |
|              |        | Yaojia    | K1y1~K1y2 | 260-500     |                     |                          |                            |
|              | Upper  | Qingshankou | K2qn1+3 | 550-1200     |                     | Meandering river delta, shallow lacustrine | Period of depression basin |
|              | Lower  | Quantou   | K2qn1  | 500-1000      |                     | Braided river, delta, lacustrine | Period of depression basin |
|              | Lower  | Denglouku | K2qn2+3 | 400-1500     |                     | Alluvial fan, fan delta, delta, lacustrine bog | Period of depression basin |
|              | Lower  | Yingcheng | K2qn3+4 | 500-1600     |                     | Shore shallow lacustrine, volcanic facies | Period of depression basin |
|              | Lower  | Shangzi   | K2qn5   | 500-1000      |                     |                          |                            |
|              | Basement | Mingshui | K1sh1+2  | 140           |                     | Alluvial fan, flood plain |                            |
|              | Basement | Huoshiling| K1sh3+4 | 0-165         |                     |                          |                            |
|              | Basement | Shahezi   | K1h     | 0-123         |                     |                          |                            |
|              | Basement | Yingcheng| N1d     | 0-260         |                     |                          |                            |
|              | Basement | Nenjiang  | N2t     | 0-123         |                     |                          |                            |

**Figure 2:** Comprehensive stratigraphic column of the Songliao Basin.
3. Data and Methods

3.1. Petrographic Description. Coring operation was conducted on the whole K2qn1 section of the SYY1 well in the Qijia Sag at the depth from 2357.00 m to 2448.00 m, and the characteristics of lithology, fossils, and sedimentary structure of the cores were described in detail with a scale of 1:10. Meanwhile, a few pictures of typical geological phenomena of cores were taken and collected. Based on that, the vertical petrographic distribution of K2qn1 in the Qijia Sag can be analyzed. Because there was no coring in the SYY1HF well, the lithologic description data of K2qn1 rock debris collected from the mud logging were adopted to study the horizontal lithology distribution of K2qn1.

3.2. Mineral and Reservoir Analyses

3.2.1. X-Ray Diffraction Mineral Analysis. A total of 21 core samples from K2qn1 of the SYY1 well were analyzed by means of the German Brook D8A A25 X-ray Diffractive Instrument in order to obtain the percentage composition of whole rock minerals and clay minerals. For the SYY1HF well, the percentage composition data of whole rock minerals of 214 K2qn1 core debris samples were collected from the X-ray diffraction mud logging.

3.2.2. Effective Porosity Analysis. The effective porosity of 15 core samples from K2qn1 of the SYY1 well was conducted on the PoroPDP-200 Instrument from the American Core Lab Company. In order to solve the problem of a small number of measured data, the high-resolution effective porosity data of the SYY1 and SYY1HF wells were obtained through the nuclear magnetic resonance (NMR) logging interpretation calibrated by the measured data.

3.2.3. NMR Laboratory Analysis. A total of 37 core samples from K2qn1 of the SYY1 well were analyzed at room temperature by means of the MR Core-XX NMR Analyzer from the American Core Lab Company in order to obtain the oil saturation data.

3.2.4. Argon Ion Polishing-Scanning Electron Microscopy. Considering lithology and depth distribution, 14 core samples were selected from K2qn1 of the SYY1 well. The samples were cut into suitable blocks (10 mm × 10 mm × 3 mm), and the block samples were manually polished using the sandpapers with various degree of roughness. Then, the samples were polished for 6 hours at 4 kV voltage with high-energy argon ion beam on the IlionII 697C Polisher from the American Gatan Company. Finally, the microscopic pore structures of the samples were observed on the Quanta 450 Scanning Electron Microscopy from the American FEI Company.

3.3. Organic Geochemical Analyses

3.3.1. Total Organic Carbon (TOC) and Rock Pyrolysis. A total of 81 core samples from the K2qn1 of the SYY1 well were selected according to the lithofacies. TOC and rock pyrolysis tests of those samples were performed on the American LECO CS Analyzer and French VINCI Rock-Eval 6 Analyzer, respectively. The commonly used geochemical parameters including pyrolysed hydrocarbon (S1), kerogen pyrolytic hydrocarbon (S2), and maximum pyrolysis peak temperature (Tmax) were approached by rock pyrolysis.

3.3.2. Microscopic Examination of Kerogen. The microscopic observation of kerogen macerals of 7 core samples from K2qn1 of the SYY1 well was conducted on the German Leica-DM4500 Microscope. Before the microscopic observation, the samples were made into polished sections according to petroleum and natural gas industry standard of the People’s Republic of China (SY/T 6414-2014). The composition of kerogen macerals including sapropelite, exinite, vitrinite, and inertinite was counted and recorded.

3.3.3. Vitrinite Reflectance ($R_0$). The reflectance of vitrinite of 5 core samples from the K2qn1 of the SYY1 well was tested using oil-immersed objective lens by means of the German Leica DM4500P Polarizing Microscope and American CRAIC Microphotometer. Before the microscopic observation, the samples were made into polished sections according to the petroleum and natural gas industry standard of the People’s Republic of China (SY/T 5124-2012). In order to ensure the testing accuracy of the results, the number of measuring points should not be less than 30 for each sample.

3.3.4. Extraction and Column Chromatography of Soluble Organic Matter. A total of 21 core samples from the K2qn1 of the SYY1 well were selected, and Soxhlet extraction and column chromatographic separation were performed on these samples. First, the samples were crushed into 100 mesh and extracted for 24 h with dichloromethane, and the content of extractable organic matter (EOM) was confirmed. Then, asphaltenes in the EOM were removed and measured by n-hexane precipitation. After that, the deasphalted EOM were separated by silica gel and alumina column chromatography, and saturated and aromatic hydrocarbon fractions were obtained by the flushing of n-hexane and the mixture of n-hexane and dichloromethane (volume ratio 2:1), respectively. Finally, nonhydrocarbon was obtained by the flushing of chloroform.

4. Results and Discussion

4.1. Petrologic Features and Submember Division

4.1.1. Petrologic Features. The lithology of K2qn1 in the SYY1 well consists of mainly gray-black/black mudstone, gray/gray-black silty mudstone, and black Ostracoda-bearing mudstone, locally interbedded with gray-black argillaceous siltstone, gray siltstone, and gray/gray-black Ostracoda layers (Figure 3, Table 1). In addition, black-gray marl and gray-white tuffite can be found sporadically. Pyrite aggregates, carbonaceous fragments, plant fossil fragments, Ostracoda, Eoestheria fossils, and horizontal beddings were generally observed throughout the cores (Figure 3, Table 1). From the geological mud logging data, the lithology of K2qn1 in the SYY1HF well consists of black-gray silty mudstone and gray-black mudstone. The all above evidences suggest that K2qn1 was deposited in the deep and semideep lacustrine...
environment with volcanic activities around the lacustrine water. The thickness of mudstone genera is 86.12 m, accounting for 94.64% of the K2qn1 thickness in the SYY1 well (Table 1), and the macrostructural fractures were not developed in the cores, indicating that K2qn1 belongs to the typical matrix reservoirs for shale oil. Thus, the reservoir spaces of K2qn1 may be mainly matrix pores and microfractures of mudstones.

Minerals in K2qn1 of the SYY1 well are mainly composed of clay minerals, quartz, and plagioclase, containing a small amount of calcite and pyrite with dolomite, K-feldspar, ankerite, and siderite in some parts (Figure 4). The content of clay minerals ranges from 7.80% to 45.20% (36.37% on average), while the content of quartz and plagioclase ranges from 27.20% to 42.0% (35.20% on average) and from 7.50% to 50.80% (18.50% on average), respectively. It indicates that siliceous minerals are the dominant component in K2qn1 core samples. The content of calcite ranges from 0.70% to 27.10% (5.85% on average). The high abundances of carbonate minerals at the depths of 2378.83 m and 2402.67 m (Figure 4) are related to ostracod biodeposition. Based on the mineral compositions, Allix and Burnham divided the shale/mudstone into five types including siliceous mudstone, argillaceous mudstone (traditional shale), siliceous marlstone, argillaceous marlstone, and calcareous or dolomitic mudstone [34]. From Figure 5, most of the K2qn1 samples of SYY1 and SYY1HF wells are mainly siliceous mudstones, and a few are argillaceous mudstones, which are similar to the Lower Marcellus and Bakken shales in North America (Figure 5).

4.1.2. Submember Division of K2qn1. Based on the lithology features and logging curves, the connected well profile of K2qn1 crossing the X81, SYY1, X91, and X83 wells in the Qijia Sag was drawn, and K2qn1 in the study area can be divided into three submembers including K2qn1<sup>1</sup>, K2qn1<sup>2</sup>, and K2qn1<sup>3</sup> from above to below (Figure 6). The K2qn1<sup>1</sup> submember is characterized by developing nonmudstone thin
intercalations in the whole submember, low-medium natural gamma, and low-medium resistivity, corresponding to the depth from 2357.00 m to 2390.00 m in the SYY1 well. The K_{2}qn_{1}^{2} submember is characterized by developing nonmudstone thin intercalations mainly in the middle-upper submember, medium natural gamma, and medium-high resistivity, corresponding to the depth from 2390.00 m to 2418.50 m in the SYY1 well. The K_{2}qn_{1}^{3} submember is

| Genera | Color                | Lithology                  | Thickness (m) | Percentage (%) |
|--------|----------------------|----------------------------|---------------|----------------|
|        |                      |                            | Single value  | Subtotal value |
|        |                      |                            | Single value  | Subtotal value |
| Mudstone | Gray-black/black     | Mudstone                   | 73.50         | 80.77          |
|        | Gray-gray-black      | Silty mudstone             | 7.93          | 8.72           |
|        | Black                | Ostracoda-bearing mudstone | 3.97          | 4.36           |
|        | Black/gray-black     | Ostracoda-bearing silty mudstone | 0.64 | 0.70 |
|        | Gray-black           | Calcereous mudstone        | 0.08          | 0.09           |
|        | Gray-black           | Argillaceous siltstone     | 1.65          | 1.81           |
| Siltstone | Gray/gray-black     | Siltstone                  | 1.63          | 1.79           |
|        | Black-gray           | Calcareous siltstone       | 0.60          | 0.66           |
|        | Gray-black           | Ostracoda-bearing siltstone | 0.18 | 0.19 |
|        | Gray-black           | Ostracoda-bearing siltstone | 0.15 | 0.17 |
| Ostracoda layer | Gray/gray-black    | Ostracoda layer            | 0.54          | 0.60           |
| Marlstone | Black-gray          | Marlstone                  | 0.08          | 0.09           |
| Tuffite | Gray-white           | Tuffite                    | 0.05          | 0.05           |
| Total value |                      |                            | 91.00         | 100.00         |

Figure 4: Diagram of mineral composition of the K_{2}qn_{1} core samples in the SYY1 well, Qijia Sag, northern Songliao Basin.
characterized by developing nonmudstone thin intercalations mainly in the middle-lower submember, high natural gamma, and medium-high resistivity, corresponding to the depth from 2418.50 m to 2448.00 m in the SYY1 well. The target layer of the SYY1HF well corresponds to the upper K2qn1 submember at the depth from 2419 m to 2429 m in the SYY1 well (Figure 6).

4.2. Organic Geochemical Characteristics

4.2.1. Organic Matter Abundance. Total organic carbon (TOC) and \( S_1 + S_2 \) are two commonly used parameters for the evaluation of organic matter abundance in shale/mudstone [35–37]. Both the parameters show that the organic matter abundance of K2qn1 in the SYY1 well is generally high, and most of the TOC and \( S_1 + S_2 \) values are greater than 2.0% and 6.0 mg/g, respectively. Both the two parameters increase first and then decrease with the increase in buried depth (Figure 7). From the perspective of three submembers, the TOC values of K2qn1, K2qn2, and K2qn3 range from 1.30% to 2.68% (1.96% on average), from 0.87% to 3.73% (2.42% on average), and from 1.12% to 5.04% (2.72% on average), respectively (Figure 7(a)), and the \( S_1 + S_2 \) values of K2qn1, K2qn2, and K2qn3 range from 3.27 mg/g to 10.02 mg/g (6.39 mg/g on average), from 4.86 mg/g to 23.77 mg/g (13.03 mg/g on average), and from 3.96 mg/g to 25.33 mg/g (13.06 mg/g on average), respectively (Figure 7(b)). It indicates that K2qn1, K2qn2, and K2qn3 are of higher organic matter abundance than K2qn1, and the lower K2qn1 and the upper K2qn3 have the highest organic matter abundance (Figure 7). Shale oil is characterized by in situ retention and enrichment [38], so the high organic matter abundance in the lower K2qn1 and the upper K2qn3 created a very good hydrocarbon-generating material base for their shale oil enrichment.

From the TOC variation characteristics of well logging interpretation of K2qn1 in the SYY1HF well, the overall trend of TOC value increasing from top boundary depth of K2qn1 to the depth of target A (drilling inclined section of K2qn1) can be observed (Figures 8(a) and 8(b)), which is consistent with the results from the SYY1 well (Figure 7(a)). The TOC values at the drilling inclined section of K2qn1 in the SYY1HF well range from 0.64% to 4.09% with an average of 2.06%, while the TOC values at the drilling horizontal section of K2qn1 range from 0.62% to 5.69% with an average of 2.45% (Figures 8(a) and 8(b)). Furthermore, the TOC values at the drilling horizontal section fluctuated greatly, and the TOC values near target A are distinctly higher than those near target C (Figures 8(a) and 8(b)), which indicates that the abundance of organic matter in K2qn1 is highly heterogeneous horizontally.

4.2.2. Organic Matter Type. Whether shale as source rock is oil-prone or gas-prone mainly depends on organic matter types, which are generally classified into four categories including type I, type II, type II, and type III. Among them, the type I and type II kerogens are oil-prone with high hydrocarbon generation potential, while the type II and type III kerogens are gas-prone with low hydrocarbon generation potential [39, 40]. The HI-\( T_{\text{max}} \) discriminant chart and the

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**Figure 5:** Ternary diagram showing the mineral compositions of the K2qn1 samples in the SYY1 and SYY1HF wells and the samples from some typical shale oil basins of North America (sample data of the typical shale oil basins of North America are from Reference [34]).

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**Figure 6:** Shale oil basins of North America (sample data of the typical shale oil basins of North America are from Reference [34]).
kerogen maceral analysis are two commonly used methods for determining organic matter types. The HI-$T_{\text{max}}$ discriminant chart shows that the organic matter types of the K2qn1 core samples in the SYY1 well are mainly type I and type II1 with a small number of type II2 (Figure 9), indicating the oil-prone feature for K2qn1 organic matter. The K2qn1 kerogen maceral groups from the SYY1 well are mostly oil-prone sapropelite, followed by gas-prone inertinite and vitrinite with little exinite (Figure 10), which also proves that K2qn1 is oil-prone generally. However, K2qn12 and K2qn13 have better organic matter types than K2qn11. The organic matter types of K2qn12 and K2qn13 submembers are mainly type I and type II1 with a small number of type II2, while those of the K2qn11 submember are mainly type II1 and type II2.
without type I (Figure 9), indicating better oil generation potential for the K2qn1
and K2qn3 submembers.

4.2.3. Organic Matter Maturity. The maturity of organic matter reflects the degree of transformation from organic matter to oil and gas, and the products of organic matter are varied in different stages of thermal evolution [35, 37, 39]. Therefore, the amount of retained oil in shale and its mobility are closely related to the maturity of organic matter, and only the shale oil with medium-high maturity can be effectively exploited by hydraulic fracturing technology at present [4].

RO and Tmax are two commonly used parameters to evaluate the maturity of organic matter. However, relevant studies have shown that Tmax is greatly affected by organic matter types and is more suitable for the maturity assessment of gas-prone organic matter of type III and type II2 [39, 41]. As mentioned above, the organic matter types of the studied samples are mainly oil-prone type I and type II2, so RO is adopted here to evaluate the sample maturity. The measured RO values of five K2qn1 samples in the SYY1 well range from 1.21% to 1.28% with an average of 1.26% (Table 2), indicating that those samples are at the end of the oil window. Such high maturity indicates that crude oil has been produced in large quantities and, if not expelled, can remain and accumulate in shale/mudstone. In addition, shale oil at this stage of thermal evolution can be of better fluidity and better recoverability because of having more light components. The RO values increase slightly with the increase in depth (Table 2), indicating that the maturity of the lower part of K2qn1 is slightly higher than that of the upper part of that. From the plane, deep to semideep lacustrine facies in the Qijia Sag is usually located in the central sag with large burial depth, so the maturity is generally high, which can create a good thermal evolution condition for shale oil enrichment.

![Diagram](image-url)
K₂qn₁³ in the SYY1 well range from 1.32 mg/g to 2.91 mg/g (2.16 mg/g on average), from 1.65 mg/g to 7.25 mg/g (4.11 mg/g on average), and from 1.93 mg/g to 7.71 mg/g (4.25 mg/g on average), respectively (Figure 11(a)). It indicates that K₂qn₁² and K₂qn₁³ are of higher oil content than K₂qn₁¹. Furthermore, the lower K₂qn₁² and the upper K₂qn₁³ obviously have the best oil content (Figure 11(a)). The S₁ values from well logging interpretation at the drilling horizontal section of the SYY1HF well fluctuated greatly, and the S₁ values near target A are distinctly greater than those near target C (Figures 8(a) and 8(c)), which indicates that the oil-bearing content of K₂qn₁ is highly heterogeneous horizontally.

According to the results of Jarvie’s study [42], there is a certain threshold for free oil flowing in shale, and the OSI parameter (oil saturation index, S₁ × 100/TOC) is required to exceed 100 mg/g, which is considered the oil crossover effect. The OSI values for most of the K₂qn₁ samples in the SYY1 well are greater than 100 mg/g (Figure 11(b)), indicating that K₂qn₁ generally is of high oil content with good oil mobility. From the perspective of three submembers, the OSI values of K₂qn₁¹, K₂qn₁², and K₂qn₁³ in the SYY1 well range from 72.73 mg/g to 145.83 mg/g (110.54 mg/g on average), from 77.61 mg/g to 233.16 mg/g (171.74 mg/g on average), and from 63.25 mg/g to 213.76 mg/g (150.87 mg/g on average), respectively (Figure 11(b)). It indicates that K₂qn₁² and K₂qn₁³ can have more producible oils than K₂qn₁¹, and the lower K₂qn₁² and the upper K₂qn₁³ obviously have the highest oil content with the best oil mobility.

### 4.3. Oil-Bearing Property

#### 4.3.1. Pyrolysis S₁ and OSI

Pyrolysis S₁ represents that relatively light liquid hydrocarbons exist in rocks before heating to 300°C in the Rock-Eval analysis and is used as a common oil-bearing parameter to characterize the content of free hydrocarbon in shales [42, 43]. The S₁ values of K₂qn₁¹,

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**Figure 9**: HI-Tₘₐₓ discriminant chart showing the organic matter types of K₂qn₁ core samples in the SYY1 well, Qijia Sag, northern Songliao Basin.

**Figure 10**: Kerogen maceral pictures of the typical K₂qn₁ core samples in the SYY1 well, Qijia Sag, northern Songliao Basin.

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nonhydrocarbon, and asphaltene decreased (Figures 12(b)–12(e)), so the lower part of K$_2$qn$_1$ has better shale oil mobility than the upper part of that. In particular for K$_2$qn$_1$$^3$, the contents of saturated hydrocarbon are the highest of the three submembers, while the contents of aromatic hydrocarbon, nonhydrocarbon, and asphaltene are all the lowest. That can be related to the maximum burial depth and the highest maturity of the K$_2$qn$_1$$^3$ submember. Therefore, there are more small molecules with lower polar in the composition of shale oil of the K$_2$qn$_1$$^3$ submember, which has better oil mobility.

4.3. Oil Saturation. Oil saturation reflects the volume proportion occupied by oil in the reservoir space and directly represents the content of potentially recoverable free oil and dissolved oil in the shale. The oil saturations of K$_2$qn$_1$ samples in the SYY1 well range from 12.54% to 39.83% (24.77% on average); the oil saturations of K$_2$qn$_1$$^2$ range from 13.77% to 54.32% (32.86% on average); the oil saturations of K$_2$qn$_1$$^3$ range from 26.86% to 42.53% (35.54% on average) (Figure 13). On the whole, K$_2$qn$_1$$^2$ and K$_2$qn$_1$$^3$ have higher oil saturation and better oil content.

4.4. Reservoir Characteristics

4.4.1. Reservoir Space. The reservoir space of K$_2$qn$_1$ samples in the SYY1 well mainly consists of intergranular micropores and microfractures, intercrystal micropores and microfractures, and intragranular dissolution pores, with organic pores found locally (Figure 14). The composition of clastic grains is mainly quartz and feldspar, and clay minerals are mostly filled between grains in the form of squama shape. The spherical pyrite crystals are developed in the form of star-shaped, patchy, or band-like distribution (Figures 14(a), 14(i), and 14(o)), and the crystals of calcite and rutile can be seen (Figures 14(e), 14(g), 14(i), and 14(n)). The intergranular
micropores and microfractures consist of the primary intergranular micropores and microfractures and the clastic grain edge microfractures. The intercrystal micropores and microfractures consist of intercrystalline micropores and microfractures of clay minerals (Figures 14(d) and 14(o)), intercrystalline pores of pyrites (Figures 14(a) and 14(o)), cleavage cracks of mineral crystals (Figures 14(i) and 14(m)), and intercrystalline microfractures. The intragranular dissolution pores are distributed mainly in the clastic grains of quartz and feldspar (Figures 14(b), 14(h), and 14(l)), followed by calcite grains (Figures 14(g) and 14(i)), and also developed in mineral crystals such as rutiles (Figures 14(e) and 14(n)).

Interestingly, it seems that the intragranular dissolution pores in the lower part are more developed than those in the upper part, which is reflected in the number of dissolution pores increasing and the pore size becoming bigger gradually from above to below (Figure 14). Coincidentally, it shows a similar trend for the distribution characteristics of organic pores. In the K$_2$qn$_1^1$ submember and the upper K$_2$qn$_1^2$ submember, the organic pores are hard to be found (Figures 14(c) and 14(f)). However, in the lower K$_2$qn$_1^2$ submember and the K$_2$qn$_1^3$ submember, the organic pores are much developed. They are distributed in clusters, and the pore size can reach hundreds of nanometers (Figures 14(j), 14(k), and 14(p)). The related studies show that the development degree of organic pores increases with the increase in maturity, and organic pores develop in a large number only when $R_o$ exceeds a certain critical value [44, 45]. Therefore, maturity is one of the important reasons for the difference in the development of organic pores of K$_2$qn$_1$. According to the distribution characteristics and the sample maturities as mentioned above, we infer that there may be a maturity

![Figure 12: Graphs of EOM (a), saturated hydrocarbon (b), aromatic hydrocarbon (c), nonhydrocarbon (d), and asphaltene (e) variation with the depth of K$_2$qn$_1$ core samples in the SY1 well, Qijia Sag, northern Songliao Basin.](image)

![Figure 13: Graph of oil saturation with the depth of K$_2$qn$_1$ core samples in the SY1 well, Qijia Sag, northern Songliao Basin.](image)
Intercrystalline pores of pyrites

Intragranular dissolution pores of quartz

Band-shaped organic matter without organic pores

Intercrystalline micropores and microfractures of clay minerals

Intercrystalline pores of rutiles

Block-shaped organic matter without organic pores

Intragranular dissolution pores of calcite

Intragranular dissolution pores of feldspar

Figure 14: Continued.
Intragranular dissolution pores of calcite
Spherical pyrite crystals in the form of band-like distribution
Cleavage cracks of calcite
Bead-shaped organic matter with organic pores
Band-shaped organic matter with organic pores
Organic pores
Intercrystalline pores of rutiles
Intercrystalline micropores and microfractures of clay minerals
Faveolate organic pores

Figure 14: Argon ion polishing-scanning electron microscopy pictures showing the typical reservoir space of the K2qn1 core samples in the SYY1 well, Qijia Sag, northern Songliao Basin.
Table 3: Percentage content data table of clay minerals of K_{2}q_{n1} cores in the SYY1 well, Qijia Sag, northern Songliao Basin.

| Depth (m) | Submembers | Illite | Chlorite | Illite/smectite mixed layer mineral (I/S) | Chlorite/smectite mixed layer mineral (C/S) | Composition of I/S (%) | Smectite in I/S | Illite in I/S |
|-----------|-------------|--------|----------|------------------------------------------|---------------------------------------------|------------------------|----------------|--------------|
| 2357.85   | K_{2}q_{n1}^{1} | 40     | 9        | 49                                        | 2                                           | 15                     | 85             |
| 2365.30   | K_{2}q_{n1}^{1} | 33     | 31       | 15                                        | 21                                          | 25                     | 75             |
| 2373.40   | K_{2}q_{n1}^{1} | 87     | 6        | 7                                         | /                                           | 15                     | 85             |
| 2378.83   | K_{2}q_{n1}^{1} | 41     | 20       | 36                                        | 3                                           | 15                     | 85             |
| 2384.19   | K_{2}q_{n1}^{1} | 78     | 10       | 12                                        | /                                           | 15                     | 85             |
| 2386.81   | K_{2}q_{n1}^{1} | 88     | 4        | 8                                         | /                                           | 15                     | 85             |
| 2394.50   | K_{2}q_{n1}^{2} | 89     | 5        | 6                                         | /                                           | 15                     | 85             |
| 2400.69   | K_{2}q_{n1}^{2} | 83     | 5        | 8                                         | 4                                           | 15                     | 85             |
| 2402.67   | K_{2}q_{n1}^{2} | 56     | 25       | 9                                         | 10                                          | 15                     | 85             |
| 2406.68   | K_{2}q_{n1}^{2} | 74     | 13       | 13                                        | /                                           | 15                     | 85             |
| 2407.71   | K_{2}q_{n1}^{2} | 54     | 8        | 37                                        | 1                                           | 15                     | 85             |
| 2409.61   | K_{2}q_{n1}^{2} | 41     | 8        | 48                                        | 3                                           | 15                     | 85             |
| 2418.03   | K_{2}q_{n1}^{2} | 83     | 10       | 7                                         | /                                           | 20                     | 80             |
| 2422.48   | K_{2}q_{n1}^{3} | 65     | 14       | 21                                        | /                                           | 15                     | 85             |
| 2428.57   | K_{2}q_{n1}^{3} | 78     | 10       | 12                                        | /                                           | 15                     | 85             |
| 2433.54   | K_{2}q_{n1}^{3} | 74     | 10       | 14                                        | 2                                           | 15                     | 85             |
| 2435.13   | K_{2}q_{n1}^{3} | 73     | 16       | 11                                        | /                                           | 25                     | 75             |
| 2439.51   | K_{2}q_{n1}^{3} | 76     | 13       | 11                                        | /                                           | 15                     | 85             |
| 2441.75   | K_{2}q_{n1}^{3} | 43     | 13       | 40                                        | 4                                           | 15                     | 85             |
| 2445.12   | K_{2}q_{n1}^{3} | 72     | 12       | 11                                        | 5                                           | 15                     | 85             |
| 2447.51   | K_{2}q_{n1}^{3} | 64     | 22       | 14                                        | /                                           | 15                     | 85             |

**Figure 15:** Diagenetic evolution diagram showing the diagenetic stage of K_{2}q_{n1} in the SYY1 well, Qijia Sag, northern Songliao Basin (modified from the petroleum and natural gas industry standard of the People’s Republic of China (SY/T 5477-2003)).
4.4.2 Diagenetic Stages and Effective Porosity

The average $R_o$ of K$_2$qn$_1$ in the SYY1 well is 1.26% (Table 2), which is at the late mature stage. The content of clay minerals is mainly illite, which ranges from 33% to 89% with an average of 66%, followed by chlorite and I/S (Table 3). The content of smectite in I/S is low between 15% and 25% with an average of 16% (Table 3). The reservoir space contains plenty of quartz, feldspar, and calcite dissolution pores as mentioned above (Figure 14). The above evidences indicate that K$_2$qn$_1$ in the SYY1 well is in the late period of Middle Diagenesis A (Figure 15). The primary pores can be retained, and the release of organic acids leads to the increase in dissolution pores of mineral grains and meanwhile the formation of more organic pores during this stage.

As the effective porosity measurements are limited, we obtained more effective porosity data via interpreting the high-resolution NMR logging in the SYY1 well calibrated by the measured data. The results show that the effective porosity of K$_2$qn$_1^1$ is 3.06%-6.22% with an average of 4.88%; that of the K$_2$qn$_1^2$ submember is 4.47%-6.26% with an average of 6.26%; that of the K$_2$qn$_1^3$ submember is 3.10%-8.50% with an average of 5.86% (Figure 16). Obviously, the effective porosity of K$_2$qn$_1^2$ and K$_2$qn$_1^3$ is better than that of K$_2$qn$_1^1$. On the whole, there are two high-porosity value zones, distributed in the middle-lower part of the K$_2$qn$_1^2$ submember and the upper part of the K$_2$qn$_1^3$ submember, respectively (Figure 16), which exactly correspond to the high-value zones of organic matter abundance and oil content (Figure 17). Those indicate that these two high values of physical properties are related to the development of secondary dissolution pores and organic pores.

Relative to the TOC and $S_t$ values (Figures 8(a), 8(b), and 8(c)), the effective porosity values obtained from well logging interpretation at the drilling horizontal section of the SYY1 well fluctuated slightly, and the effective porosity values near target A are greater than those near target C (Figures 8(a) and 8(d)). However, this difference in effective porosity can be related to the previous vertical fracturing of the SYY1 well in K$_2$qn$_1$ and K$_2$qn$_2+3$, which greatly improved the physical properties of K$_2$qn$_1$ near the wellbore trajectory of the SYY1 well. That is to say, the present effective porosity cannot reflect the original porosity characteristics of K$_2$qn$_1$ close to target A at the drilling horizontal section and also at the drilling inclined section, while the effective porosity of K$_2$qn$_1$ close to target C is similar to the real value at the drilling horizontal section.

4.5 Enrichment Regularity of Shale Oil

Based on the above analysis, the enrichment of shale oil in K$_2$qn$_1^2$ and K$_2$qn$_1^3$ of the SYY1 well is significantly better than that in K$_2$qn$_1^1$ (Figure 17). In terms of organic geochemical characteristics, K$_2$qn$_1^2$ and K$_2$qn$_1^3$ have the higher abundance, better types, and slightly higher maturity of organic matter than K$_2$qn$_1^1$, so the oil generation capacity of K$_2$qn$_1^2$ and K$_2$qn$_1^3$ is better than that of K$_2$qn$_1^1$, which develops a good material basis for shale oil enrichment in K$_2$qn$_1^2$ and K$_2$qn$_1^3$. In terms of oil-bearing property, $S_t$, OSI, EOM, and oil saturation of K$_2$qn$_1^2$ and K$_2$qn$_1^3$ are generally higher than those of K$_2$qn$_1^1$, and additionally, saturated hydrocarbon content in EOM is relatively higher, which indicates that K$_2$qn$_1^2$ and K$_2$qn$_1^3$ not only have better oil content but also contain more movable oil. In terms of reservoir characteristics, dissolution pores in mineral grains and organic pores in K$_2$qn$_1^2$ and K$_2$qn$_1^3$ are more developed, and the effective porosity of K$_2$qn$_1^2$ and K$_2$qn$_1^3$ is also significantly bigger than that of K$_2$qn$_1^1$, which provides better occurrence spaces for the shale oil enrichment of K$_2$qn$_1^2$ and K$_2$qn$_1^3$. It was found that the intervals with good organic geochemical properties also are good in oil content and reservoir characteristics (Figure 17), which indicates that the shale oil of deep to semideep lacustrine facies of K$_2$qn$_1$ in the study area is formed mainly by in situ retention of residual oil.

Furthermore, it was found that the lower part of the K$_2$qn$_1^2$ submember and the upper part of the K$_2$qn$_1^3$ submember contain more proportion of mudstones with less nonshale...
interlayers, and their parameters relative to organic matter geochemical characteristics, oil-bearing property, and reservoir characteristics are generally better than those of the remaining part of K2qn12 and K2qn13 (Figure 17). Therefore, the lower part of the K2qn12 submember and the upper part of the K2qn13 submember are determined as the best intervals of shale oil enrichment for K2qn1 vertically and should be the first target layer choice for shale oil exploration in the study area.

Based on the TOC, S1, and effective porosity interpreted from the logging data of the SYY1HF well, it was found that there is a certain degree of horizontal heterogeneity in K2qn1. Compared with the effective porosity, the horizontal heterogeneity of TOC and S1 is stronger (Figure 8). Therefore, in the exploration of continental lacustrine matrix shale oil, it is necessary to predict the horizontal geological and geochemical parameters of the target layer accurately and to select the area with relatively weak heterogeneity for horizontal well drilling, so as to obtain a higher shale oil yield.

### 5. Conclusions

The lithology of K2qn1 deposited in deep to semideep lacustrine facies of the Qijia Sag is mainly dark mudstone with few macrostructural fractures and belongs to the typical matrix reservoirs for shale oil. On the basis of lithology features and logging curves, K2qn1 can be divided into three submembers including K2qn11, K2qn12, and K2qn13 from above to below.

On the whole, the conditions for shale oil enrichment in K2qn1 are good in the Qijia Sag. Among the three submembers, shale oil in K2qn12 and K2qn13 is more enriched than that in K2qn11 for the following reasons. First, K2qn12 and K2qn13 have better oil generation capacity with the higher abundance, better types, and slightly higher maturity of organic matter than K2qn11. Second, K2qn12 and K2qn13 are of higher oil content and more movable oil than K2qn11, which was supported by larger values in the parameters of S1, OSI, EOM, oil saturation, and saturated hydrocarbon.
content in EOM for $K_2qn_1$ and $K_2qn_3$. Third, $K_2qn_1$ and $K_2qn_3$ with more intragranular dissolution pores and organic pores are of higher effective porosity than $K_2qn_1$.

By integrating all kinds of parameters including organic geochemical characteristics, oil-bearing property, and reservoir characteristics, the lower $K_2qn_1$ and the upper $K_2qn_3$ are regarded as the best intervals of shale oil enrichment in $K_2qn_1$. From the TOC, $S_1$, and effective porosity in the drilling horizontal section of the SYY1HF well, there is a certain horizontal heterogeneity in the $K_2qn_1$ shale oil reservoir. Therefore, the lower $K_2qn_1$ and the upper $K_2qn_3$ in the area with relatively weak horizontal reservoir heterogeneity should be selected as the preferential targets for shale oil exploration in the Qijia Sag.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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