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*Research Article*

# Evaluation of the Oil-Bearing Properties of Shale and Shale Oil Mobility in the Fengcheng Formation in the Mahu Sag, Junggar Basin, Northwest China: A Case Study of Well Maye-1

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Due to an increasing energy demand and the depletion of conventional oil, there is ever increasing demand for unconventional shale oil and gas resources. As the most hydrocarbon-rich sag in the Junggar Basin, the development prospects for shale oil in the Mahu Sag have become a focus of research. However, so far, there have been few studies of the oil-bearing properties of shale and shale oil mobility in the sag. This paper redresses this using a range of methods, such as pyrolysis and multi-temperature step pyrolysis. The results show that the Fengcheng Formation shales are generally good quality source rocks. The main body of the shale is low mature-mature, and the type of organic matter is mostly Type II kerogen. In the depth intervals at 4616.45~4640.30 m, 4661.25~4695.20 m, 4728.30~4759.80 m, 4787.60~4812.30 m, and 4876.70~4940.25 m, the oil-bearing properties of the shale and shale oil mobility are good, with an average $S_1$ of more than 1.5 mg/g, OSI of more than 100 mg/g.TOC$^{-1}$, a ratio of free/adsorbed oil $((S_{1-1}+S_{1-2})/S_{2-1})$ of more than 3, and a ratio of free/total oil $((S_{1-1}+S_{1-2})/(S_{1-1}+S_{1-2}+S_{2-1}))$ of more than 80%. The second member ($P_1f_2$) and the lower part of the first member ($P_1f_1$) of the formation offer the most promising commercial prospects. Shale oil mobility in the formation is greatly affected by the abundance of organic matter. The higher the TOC value, the greater the hydrocarbon generation capacity, and the better its adsorption capability in the shale. The Fengcheng Formation shale is mature, and shale oil mobility is good. Impacted by the main reservoir space, the felsic shale in the formation has optimal shale oil mobility, with the shale oil being characterized by self-generation and self-storage, and accumulation in adjacent layers.

## 1. Introduction

Evaluation of the oil bearing properties of shale systems is a fundamental requirement in shale oil exploration. It has a great impact on research into the mobility of residual hydrocarbons in shale strata [1]. However, there are no unified criteria for determining good oil-bearing properties. Shale series of strata contain both residual hydrocarbons and kerogen, with residual hydrocarbons including both light hydrocarbons (oil with carbon numbers less than 15, which can be effectively produced) and heavy hydrocarbons (carbon numbers greater than 15). According to the nature of the interaction between light hydrocarbon and media, the occurrence state of light hydrocarbons is divided into free state, dissolved state, physical adsorption state, chemical adsorption state, and a hydrated state. Free movable hydrocarbons are the principal contributors to shale oil productivity [2, 3]. However, there is no mature resource evaluation method for retained hydrocarbons. Common research methods use the pyrolysis parameter $S_1$ (free hydrocarbon) and the content of original chloroform bitumen "A" to calculate retained hydrocarbons, but there are obvious disadvantages in the amounts calculated by both methods. The amount of retained hydrocarbons calculated using $S_1$ is basically the content of free hydrocarbon released under rapid artificial heating to a constant temperature of 300 °C, and the carbon numbers of the hydrocarbon compounds are mainly between $C_{14}$ and $C_{18}$ [4]. Compared with crude oil in the field, there is light hydrocarbon loss and absent of heavy hydrocarbon, so the retained hydrocarbon content given will generally be lower than the actual content. The content of chloroform bitumen "A" represents free hydrocarbons, asphaltene, non-hydrocarbons, and adsorbed hydrocarbons which are soluble in organic solvents, with carbon numbers distributed between $C_6$ and $C_{38}$. The composition of chloroform bitumen "A" is similar to that of crude oil, but the content of macromolecular compounds is higher [4–7]. Analysis of $S_1$ and TOC data from the major pay zones in North America led Jarvie to believe that there is a characteristic threshold value for the flow of crude oil in shale strata [8, 9]. Excess hydrocarbons are only expelled once the hydrocarbons generated in shales exceed the adsorption and reservoir saturation. The oil saturation index (OSI) ($S_1$/TOC) is therefore included in the scope of oil-bearing property evaluation for shale. An OSI value of 100 mg/g.TOC is regarded as the threshold for movable hydrocarbons in shale oil. Chinese practice suggests that the movable hydrocarbon threshold for shale oil determined by Jarvie may not be applicable to lacustrine shale strata, which are prevalent in China's sedimentary basins, due to the differences in geological conditions. For example, the OSI values of intra-salt shale oil accumulations in the Qianjiang Sag can reach hundreds or even higher, but some formations with low $S_1$ contents have not achieved expected hydrocarbon production during exploration [10], so the theory needs to be combined with the actual situation to be applicable in practice. To accurately characterize shale oil-bearing property and mobility, new experimental methods, such as two-dimensional NMR and multi-temperature step pyrolysis, have also been applied to more accurately evaluate shale oil. Multi-temperature step pyrolysis has been widely used to evaluate shale oil-bearing properties and hydrocarbon mobility because of the comparative accuracy of the results and the low cost of application [4, 11]. The thermally released hydrocarbon peaks obtained under constant-rate heating can be used to define the occurrence characteristics of shale oil and evaluate their contents under various occurrence states. The thermally released hydrocarbon peak at a temperature of 200 °C indicates light hydrocarbons ($S_{1-1}$) and represents the actual amount of movable oil in the shale. When the temperature reaches 350 °C, the $S_{1-2}$ peak represents the medium-heavy component of thermally released free oil. The medium-heavy component is not completely movable. The sum of $S_{1-1}$ and $S_{1-2}$ represents the total amount of free oil in the shale (also known as the maximum movable oil). $S_{2-1}$ represents oil in an adsorbed-intermiscible or adsorbed state. The sum of these three parameters is the total generated oil and gas [4, 11].

The Mahu Sag is the richest of the petroliferous sags in the Junggar Basin. The lacustrine source rocks of the Lower Permian Fengcheng Formation in the Mahu Sag provide the material basis for the formation of two major oil provinces of enormous length in the northwest margin of the basin: the Karamay-Wuerhe and Mahu oil areas. [12–15]). Geological background analysis suggests that the high-quality middle-high mature alkaline lacustrine source rocks of the Fengcheng Formation in the northwest margin of the Mahu Sag [16, 17]) are the most likely to form in-source and outside-source oil and gas enrichment and whole petroleum system. Based on this understanding, the Xinjiang Oilfield deployed well Maye-1, the first shale oil risk exploration well in the basin. This well adopted the vertical well + multistage separate-layer fracturing process for the first time and obtained high and stable hydrocarbon flow. The reserves scale is preliminarily estimated at 600 million tons. Despite this success, there has still been little research on the oil-bearing properties and oil mobility characteristics of the shale in the Mahu Sag. This paper uses methods such as X-ray diffraction, pyrolysis, and multi-temperature step pyrolysis to study the cored interval of the Fengcheng Formation in well Maye-1. The mineral compositions, lithofacies classification, oil-bearing properties, and movable oil characteristics of various members of the Lower Permian Fengcheng Formation shale are described, and the characteristics of the source rocks in the formation analyzed. The main controlling factors affecting shale oil mobility are discussed, identifying the favorable lithofacies for the occurrence of movable shale oil and their reservoir-forming modes. This will provide data support for future shale oil development in the Fengcheng Formation.

## 2. Geological Settings

The Mahu Sag is located in the northwest of the Junggar Basin, between the Kebai-Wuxia fault zone and the western segment of the Luliang Uplift (Figure 1).

It is a Carboniferous-Quaternary sag with a sedimentary thickness of tens of thousands of meters developed on pre-Carboniferous basement. It is a hydrocarbon generating sag, with the highest degree of oil and gas enrichment in the Junggar Basin. There are four sets of effective source rocks: the Jiamuhe Formation, the Fengcheng Formation, the lower Wuerhe Formation, and the Carboniferous. The Fengcheng Formation source rocks are the most important [18, 19]). The Fengcheng Formation source rocks are considered to be the oldest high-quality alkaline lacustrine source rocks in the world. They were formed under semiarid conditions, with a humid, seasonal environment alternating with arid conditions [20]. From bottom to top, the sedimentary strata in the Mahu Sag consist of the Lower Permian Jiamuhe and Fengcheng Formations, the Middle Permian Xiazijie and Lower Wuerhe Formations, the Lower Triassic Baikouquan Formation, the Middle Triassic Karamay Formation, the Upper Triassic Baijiantan Formation, the Lower Jurassic Badaowan and Sangonghe Formations, the Middle Jurassic Xishanyao and Toutunhe Formations, the Upper Jurassic Qigu Formation, and the overlying Cretaceous strata (Figure 2).

The Fengcheng area is at the junction of the northwest of the Mahu Sag and the south of the Wuerhe-Xiazijie fault zone (the Wuxia fault zone) (Figure 1). It is an enrichment area for shale oil, with the lower Permian Fengcheng

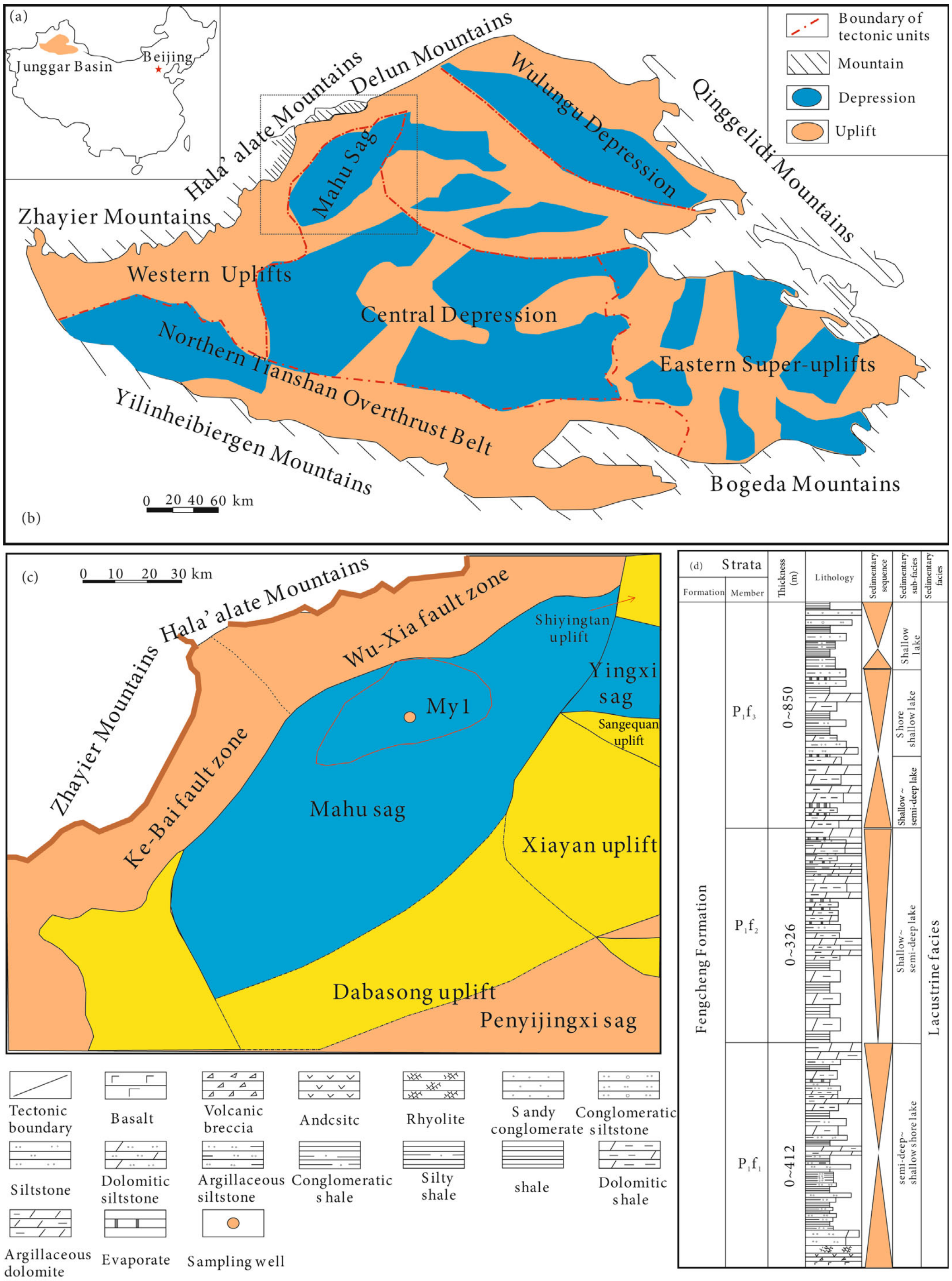


Figure 1: (a) Map of the Junggar Basin in China. (b) The division of tectonic units in the Junggar Basin and the location of the Mahu scheme. (c) The division of subtectonic units and thickness contour of Fengcheng Formation in Mahu Sag. (d) Lithology and sedimentary facies profile of the Fengcheng Formation in the Mahu Sag [22].

Formation providing good source rocks and reservoirs. The Fengcheng Formation is divided into three members: the first member ($P_1f_1$), the second member ($P_1f_2$), and the third member ($P_1f_3$), from bottom to top. It is basically a multi-source mixed fine-grained sedimentary formation deposited in a semi deep-deep alkaline lacustrine environment [21]. Mixed deposition of endogenetic chemical material generated in the arid and hot evaporation environment, volcanic material provided by peripheral volcanic activity, and near-source terrigenous debris formed by denudation of the nappe in the western margin, as well as endogenetic carbonate and other provenances, combined to create the complex mineral deposition characteristics and frequently interbedded structure of the formation, providing plentiful reservoir space for enrichment of oil and gas in the source rocks. In addition, due to its unique alkaline lacustrine deposition

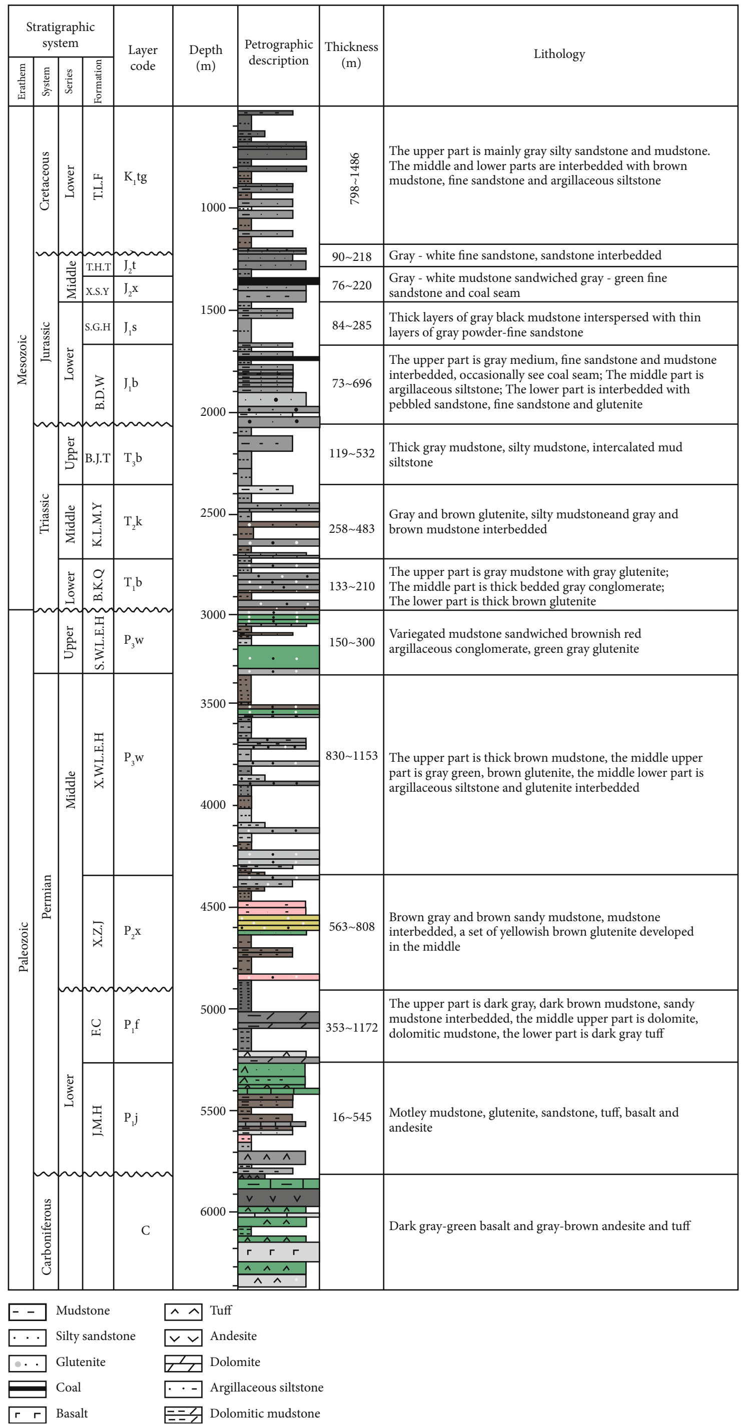


Figure 2: Comprehensive stratigraphic column of the Mahu Sag.

environment, the development process of the Mahu Sag was accompanied by episodes of alternate transgression and volcanism, which provided abundant nutrients for the propagation of microorganisms and algae on an enormous scale, providing luxuriant sapropelic parent material for hydrocarbons. This environment also meant that the source rocks of the Fengcheng Formation remained at the peak of oil generation in the high maturity ($R_o > 1.5\%$), so the oil generation stage was much longer than that of other high-quality lacustrine source rocks. The Fengcheng Formation source rocks are therefore characterized by more oil and less gas, high conversion rates, continuous hydrocarbon generation, multistage peaks, long oil generation windows, and light oil quality [18].

## 3. Samples and Methods

*3.1. Sample Collection.* Well Maye-1 lies in the Northern Slope of the Mahu Sag, with no discordogenic faults

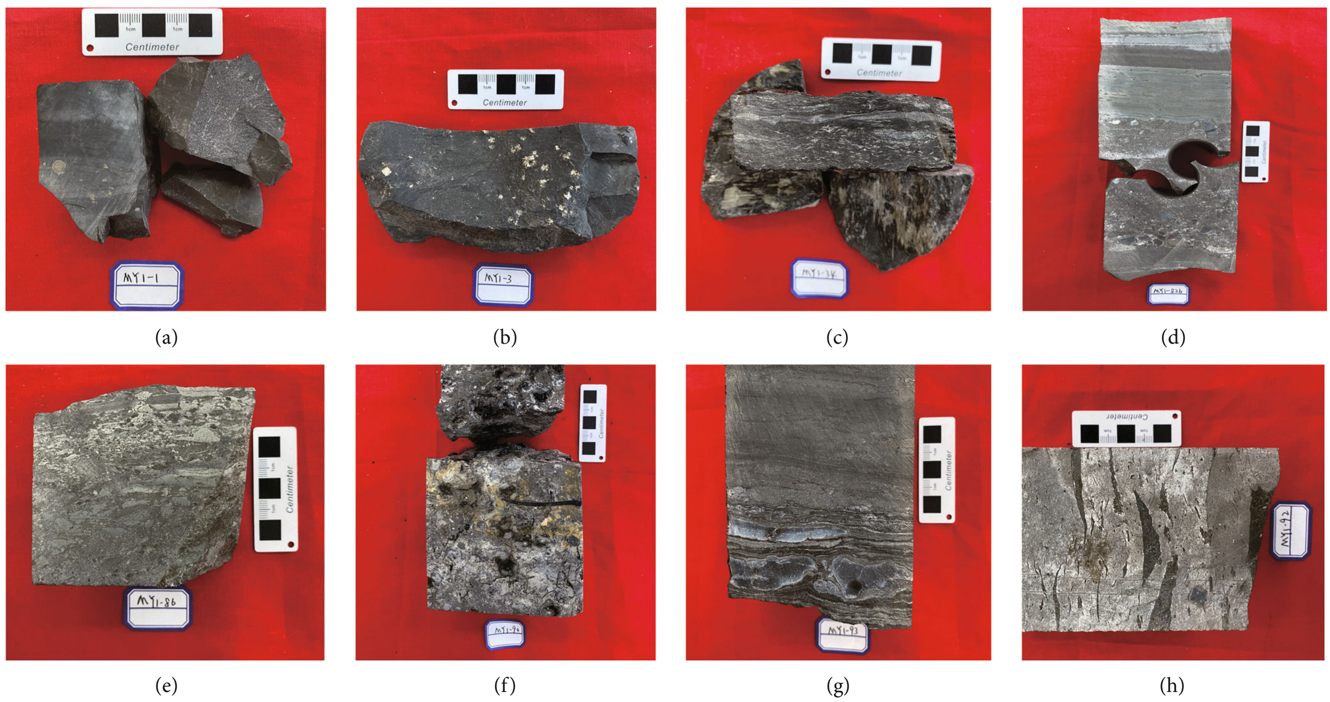


Figure 3: Cores of the Fengcheng Formation in the Mahu Sag. (a) Silty mudstone, $P_1f_3$, depth 4587.55 m; (b) argillaceous siltstone containing pyrite, $P_1f_3$, depth 4591.08 m; (c) mudstone intercalated with lime belts, $P_1f_2$, depth 4693.15 m; (d) alternate development of limerock, clastic rocks, siltstone, and argillaceous siltstone, $P_1f_1$, depth 4879.96 m; (e) hybrid sedimentary rock, chaotic mélange of terrigenous clast, $P_1f_1$, depth 4876.36 m; (f) ignimbrite, $P_1f_1$, depth 4912.92 m; (g) siltstone intercalated with lime lenticles, $P_1f_1$, depth 4917.6 m; (h) tuff, $P_1f_1$, depth 4916.43 m.

developed in the periphery, and the strata are relatively completely developed from the Paleozoic Carboniferous to the Cenozoic Quaternary. From base to top, the Permian is divided into the Lower Permian Jiamuhe Formation and Fengcheng Formation, the Middle Permian Xiazijie Formation, and Lower Wuerhe Formation, and the Upper Permian Upper Wuerhe Formation is absent. The evolution of the study area from the early Carboniferous to the Permian formed distinct alkaline lake deposition of Fengcheng Formation. Well Maye-1 is located at the edge of the alkali lake and mainly develops shore-shallow lacustrine sediment. The focus of this study is the Fengcheng Formation at sampling depths ranging from 4585 to 4940 m. The coring depths in $P_1f_3$, $P_1f_2$, and $P_1f_1$ are 4585~4595 m, 4607~4787 m, and 4790~4940 m, respectively. Core observation shows that the lithology of the cores of the formation includes silty mudstone, argillaceous dolomite, siltstone, tuff, terrigenous clastic rock, and pyroclastic rocks (Figure 3). There are apparent differences in lithologic assemblages between various members. $P_1f_1$ is mainly composed of dark gray-gray mudstone, tuffaceous mudstone intercalated with dolomitic sandstone, dolomite, tuffaceous dolomite, argillaceous dolomite, and tuff. Volcanic activity has been relatively intense, with pyroclastic rocks occurring, and the member is rich in salt rocks, shortite, and other distinctive alkaline minerals. $P_1f_2$ consists of dolomitic sandstone and gray mudstone intercalated with argillaceous dolomite, with a large number of alkaline minerals, primarily characterized by rhythmic, diverse thicknesses of layered alkaline minerals, and dark dolomitic mudstone. $P_1f_3$ comprises gray mudstone, argillaceous dolomite, and dolomitic mudstone, with relatively small contents of alkaline minerals.

*3.2. Experimental Method.* For X-ray diffraction analysis, a D8 AD-VANCE X-ray diffractometer from the Bruker Company, Germany, was used, with the sample broken down to about 0.1 mm particles. The test was carried out with reference to the standard SY/T 5163-2010 at a temperature of 25 °C and relative humidity of 50%. Test conditions were as follows: Cu target, X-ray tube voltage 40 kV, electric current 100 mA, scanning speed 4° ($2\theta$)/min, and scanning step width 0.02° ($2\theta$).

A Rock-Eval 6 pyrolysis machine was used for the pyrolysis and multi-temperature step pyrolysis tests, with different temperature programs for each. For the rock pyrolysis experiment, the temperature was first raised to 300 °C, then held for 3 min to measure the $S_1$ peak, and then increased at 25 °C/min to 650 °C, where it was maintained for 1 min to obtain the $S_2$ and $T_{max}$ values.

For the multi-temperature step pyrolysis experiment, the temperature was first kept at 200 °C for 1 min to measure $S_{1-1}$, then raised to 350°C at 25°C/min, where it was maintained for 1 minute to measure $S_{1-2}$, then raised again to 450 °C at 25 °C/min, where it was maintained for 1 min to measure $S_{2-1}$, and then finally raised to 650 °C at 25 °C/min to measure $S_{2-2}$. Both rock pyrolysis and multi-temperature pyrolysis required sample particles smaller than 0.1 mm.

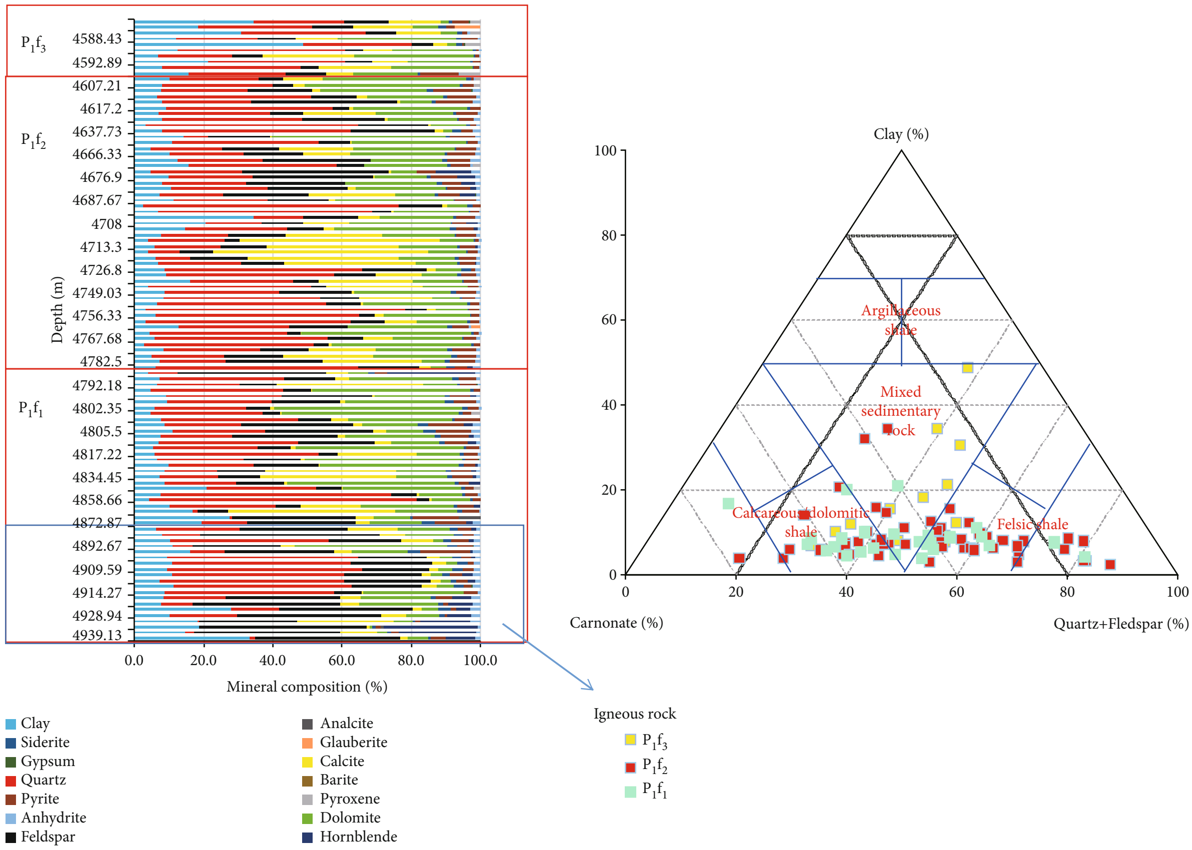


Figure 4: Mineral composition and lithofacies division of Fengcheng Formation shale.

X-ray diffraction analysis, pyrolysis, and multi-temperature step pyrolysis experiments were carried out in the Wuxi Research Institute of Petroleum Geology, Sinopec Petroleum Exploration, and Development Research Institute.

## 4. Results

*4.1. Mineral Composition and Lithofacies Division.* Figure 4 shows the basic mineral compositions of the cores from well Maye-1. It shows that the mineral composition of the Fengcheng Formation shale principally consists of three types of minerals: clay minerals, felsic minerals (quartz and feldspar), and carbonate minerals (dolomite and calcite). There are also smaller quantities of siderite, pyrite, and other sulfate minerals, as well as alkaline minerals such as gypsum, anhydrite, and glauberite. There are significant differences in the main mineral compositions of the three members of the formation. The content of clay minerals in the 48 cores from $P_1f_1$, 48 cores from $P_1f_2$, and 11 cores from $P_1f_3$ ranges from 4.0% to 37.5% (average 12.3%), 3.0% to 34.5% (average 9.0%) and 7.1% to 48.9% (average 20.9%). Correspondingly, the content of quartz ranges from 0.2% to 58.6% (average 26.8%), 7.0% to 73.7% (average 34.5%), and 21% to 48.7% (average 32.7%), respectively. Correspondingly, the content of feldspar ranges from 3.6% to 51.7% (average 22.8%), 4.0% to 42.3% (average 15.3%), and 5.1% to 12.8% (average 9.0%), respectively; the content of calcite ranges from 0.2% to 42.6% (average 8.1%), 0.1% to 62.2% (average 11.8%), and 4.3% to 26.3% (average 13.6%), respectively; the content of dolomite ranges from 0.8% to 54.4% (average 18.5%), 2.7% to 49.5% (average 22.1%), and 2.0% to 34.5% (average 16.9%), respectively. The cores from the lower part of $P_1f_1$ (4870~4940 m) are characterized by high feldspar and low quartz, which is quite different from the overall mineral characteristics of the formation, suggesting that the lower part of the Fengcheng Formation is composed of pyroclastic rocks.

The cores were divided on the basis of lithofacies, revealing a predominance of felsic shale facies, mixed sedimentary facies, and lime/dolomitic shale facies. There are discrepancies in the distributions of lithofacies in the various members. The $P_1f_1$ lithofacies is primarily lime/dolomitic shale facies and felsic shale facies. All three lithofacies are extensively distributed in $P_1f_2$. The $P_1f_3$ cores are basically hybrid sedimentary rock facies.

*4.2. Characteristics of Quality of Source Rocks.* Source rocks are the basis for oil generation. The quality of source rocks is a crucial factor affecting hydrocarbon accumulation quality. From an organic geochemical perspective, the hydrocarbon potential of source rocks depends on the abundance, type, and maturity of organic matter. These three factors complement each other. Source rocks with high abundance of organic matter and moderately mature Type I or Type II organic matter have great hydrocarbon potential. This

Table 1: Evaluation index of organic matter abundance of continental source rocks [26].

| Evaluation indicator | Lake salinity | Non-source | Poor | Fair | Good | Excellent |
|---|---|---|---|---|---|---|
| TOC (%) | Fresh-brackish | <0.4 | 0.4~0.6 | 0.6~1.0 | 1.0~2.0 | >2.0 |
| PG (mg/g) | | / | <2 | 2~6 | 6~20 | >20 |

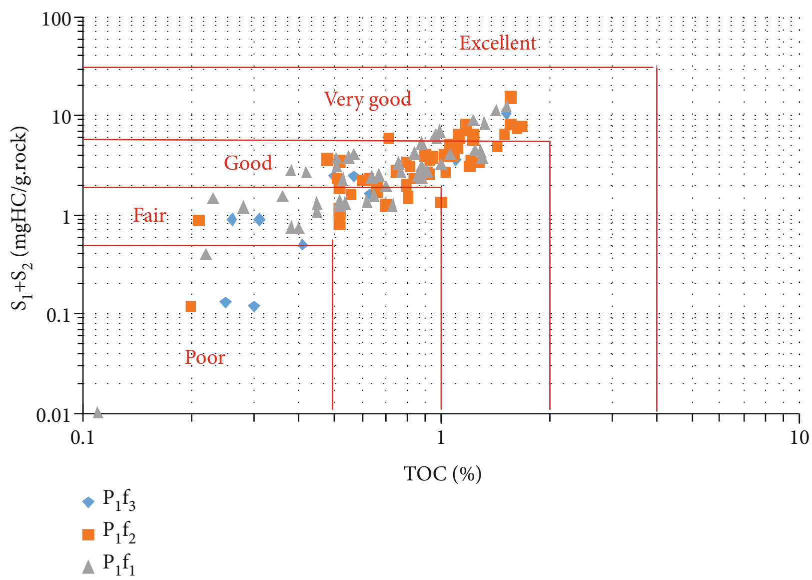


Figure 5: Quality classification of source rocks of the Fengcheng Formation shale in the Mahu Sag.

paper primarily evaluates three aspects of the Fengcheng Formation shale source rock: quality of the source rock, organic matter maturity, and organic matter type.

This paper uses hydrocarbon generation potential PG ($S_1 + S_2$) and TOC to classify the quality of continental source rocks [23, 24]. The current prevailing evaluation method for continental source rocks is mainly applicable to freshwater or brackish lakes [25, 26] (Table 1). The most appropriate evaluation criteria for alkaline lacustrine source rocks are still debated. Previous studies have shown that, compared with fresh water or brackish lacustrine source rocks, alkaline lacustrine source rocks have high hydrocarbon-generating transformation ratios and longer continuous hydrocarbon generation periods [18]. Hence, even if the TOC value is low, the hydrocarbon potential of a source rock may be high, so the application of traditional evaluation criteria may underestimate its resource potential. This is arguably true of the Fengcheng Formation. Tang et al. [27] combined the actual situation of the Mahu Sag with a large number of experimental results and classified the quality of the source rocks into five categories: nonhydrocarbon, fair, good, very good, and excellent, with (respectively) TOC < 0.3%, 0.3~0.5%, 0.5~0.7%, 0.7~1.4%, and > 1.4% and hydrocarbon potential PG ($S_1 + S_2$) < 0.5 mg/g, 0.5~1.5 mg/g, 1.5~3.0 mg/g, 3.0~7.0 mg/g, and > 7.0 mg/g. In this paper, the quality of source rocks in the study interval is determined according to this classification standard, and Figure 5 shows that the Fengcheng Formation shale is generally of good-excellent quality. The $P_1f_2$ source rock has the best quality but the main body of the formation also contains generally good-very good-excellent source rocks. The quality of some of the $P_1f_1$ source rocks is only fair, a few are poor, but the main body of the formation contains generally good-very good-excellent source rocks. The quality of source rocks in $P_1f_3$ is comparatively poor, and the rocks are of mixed quality, with some in every category.

The degree of thermal evolution is a vital factor for determining the resource potential of shale oil accumulations [28], and $T_{max}$ is one of the most commonly used parameters for evaluating the degree of thermal evolution [29]. Analysis of pyrolysis data $T_{max}$ (Figure 6) for the shale samples in the study area shows that the $T_{max}$ values are generally distributed in the range 410 to 460°C. However, the distributions of $T_{max}$ values in the various members are quite different. The deeper $P_1f_1$ cores generally have low $T_{max}$ values, mostly in the interval 415~445°C. The $T_{max}$ values of the $P_1f_2$ cores in the middle are relatively high, largely in the interval 430~445°C. The cores in the shallowest member, $P_1f_3$, have the highest thermal maturity, with $T_{max}$ values chiefly between 430 and 450°C. This apparent anomaly may indicate that $P_1f_1$ contains a proportion of oil that migrated from elsewhere. Figure 7 shows that the $S_1$ value in the lower part of $P_1f_1$ (4915~4940 m) is generally high, but the $S_2$ and HI values are low, showing typical reservoir characteristics. This strongly suggests that most of the oil and gas in $P_1f_1$ migrated into the member. The $T_{max}$ values decrease with increasing oil saturation, and the PI

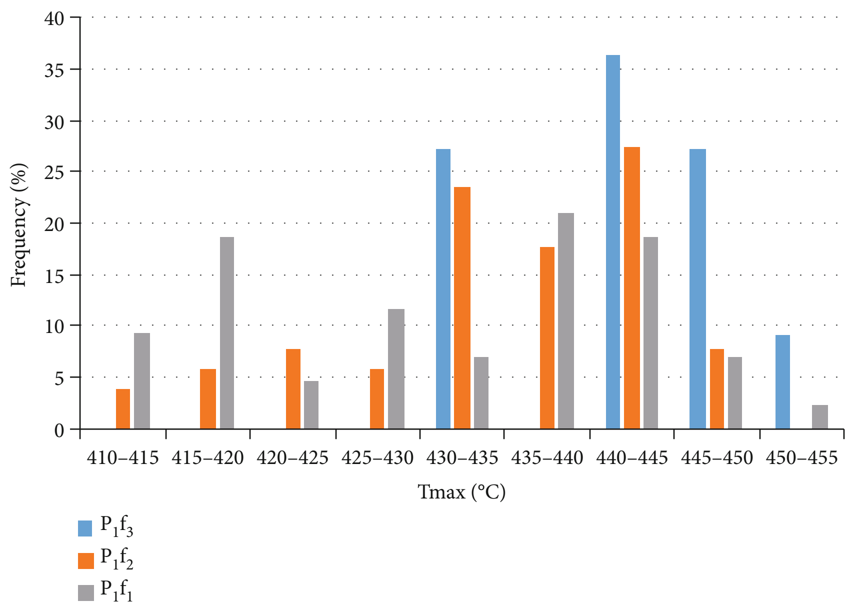


Figure 6: Maturity of shale in the Fengcheng Formation.

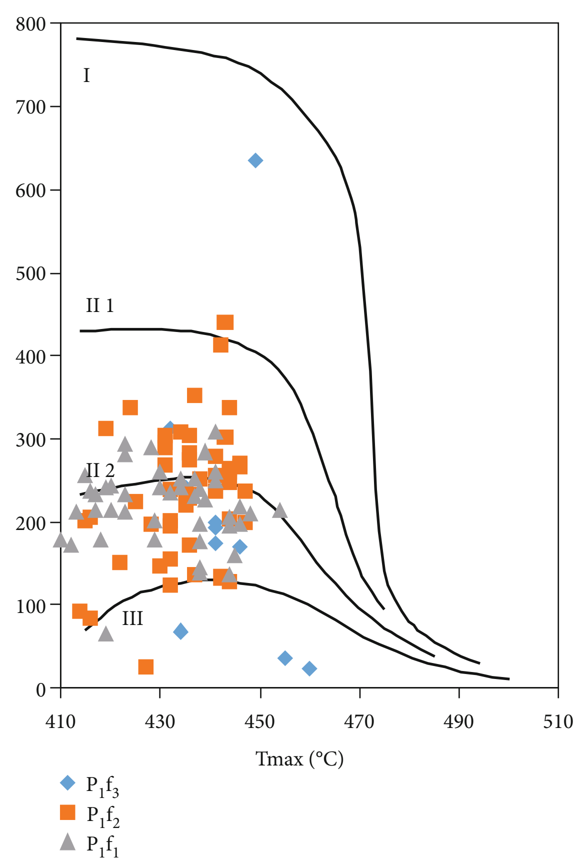


Figure 7: Classification of organic matter types in the Fengcheng Formation.

values increase significantly (Figure 8), which, again, signifies the presence of migrated oil in the area. This set of alkaline lacustrine dolomitic hybrid sedimentary rocks contains abundant residual hydrocarbons, resulting in a false low $T_{max}$ reading. The actual thermal evolution degree of the source rocks in the Fengcheng Formation is very likely to be higher [9]. The variation of $T_{max}$ values with depth shows that the $T_{max}$ values of the Fengcheng Formation shale are mostly between 440 °C and 450 °C, representing a mature stage. The change of vitrinite reflectance with depth

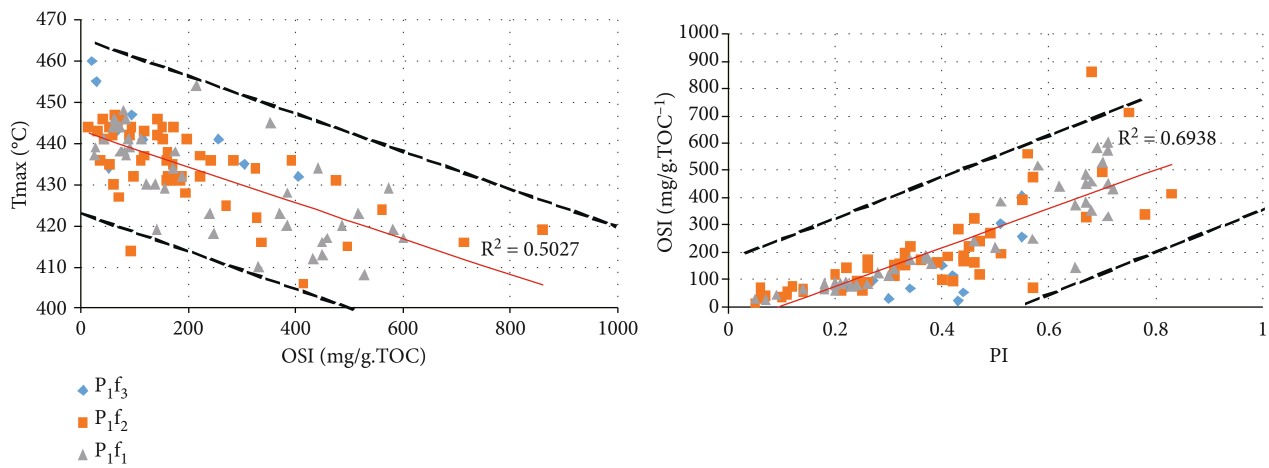


Figure 8: Variation of maturity with oil-bearing properties of the Fengcheng Formation shale and correlation between productivity and oil saturation indices (OSI).

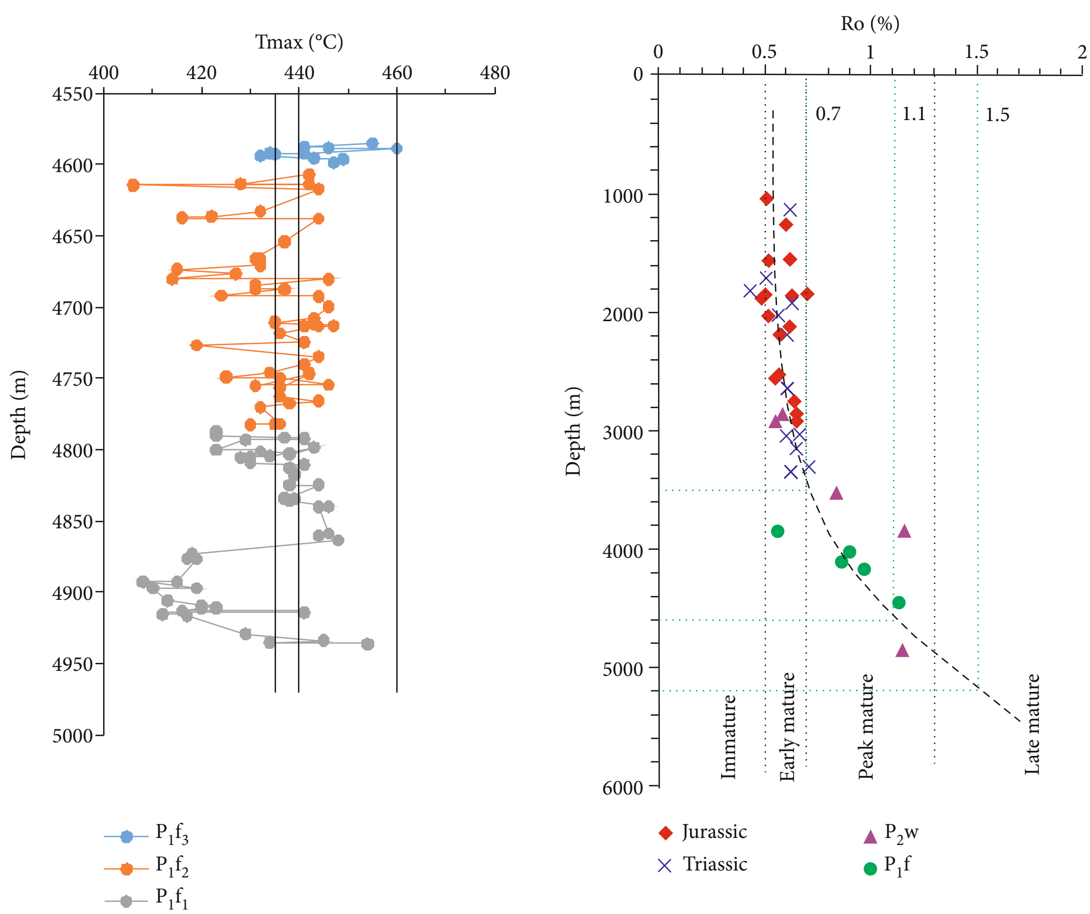


Figure 9: Change of $T_{max}$ value and vitrinite reflectance $R_o$ of the Fengcheng Formation shale with depth.

in the Mahu area indicates that the vitrinite reflectance of the Fengcheng Formation is mostly about 1.1%, which, again, represents a mature stage (Figure 9).

The hydrogen index ($HI = S_2/TOC$) and $T_{max}$ can be used together to determine the type of organic matter [30]. The results for the study area show that the HI range is 21.62-304.41 mg HC/g.TOC (average 164.96 mg HC/g.TOC). According to the resulting Van Krevelen diagram, the Fengcheng Formation shale is dominated by Type $II_1$ and Type $II_2$ kerogen, with little difference in the type of organic matter between the different members (Figure 9). Previous studies have identified the organic matter in the Fengcheng Formation shale in the Mahu Sag as mainly sapropelic organic matter derived from algae [9]. This is different from the results

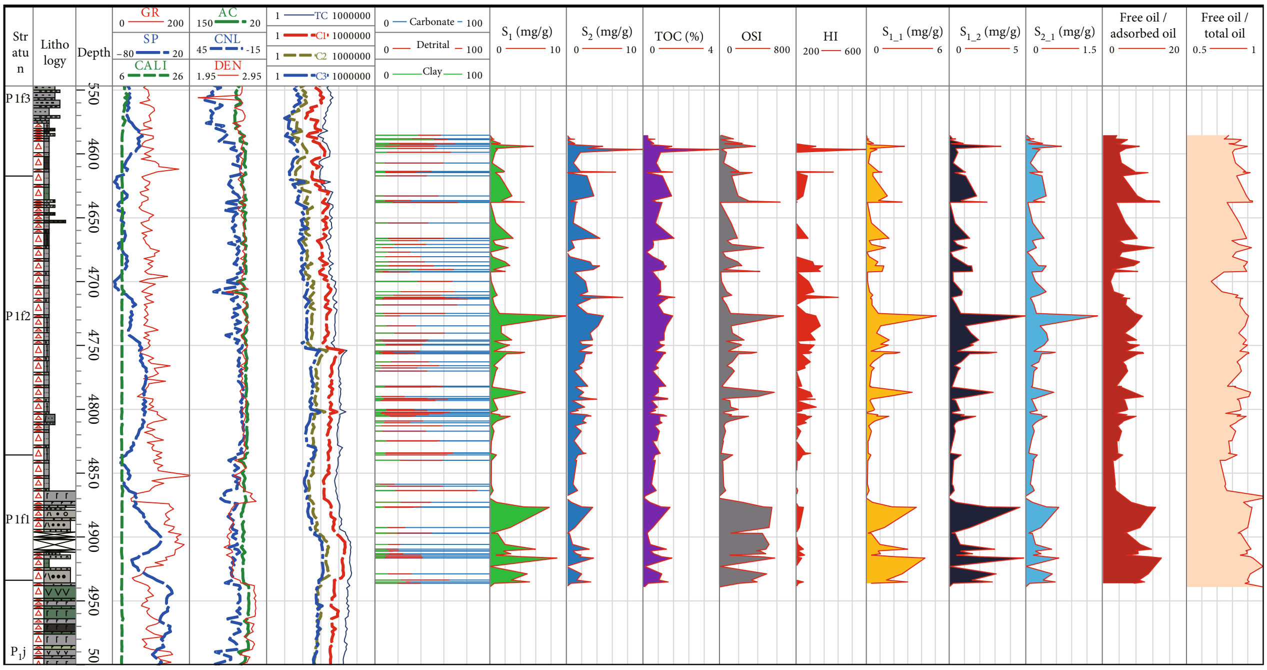


FIGURE 10: Oil-bearing property of the Fengcheng Formation shale and shale oil mobility characteristics in the Mahu Sag.

obtained in this paper. However, previous research results have assumed that the organic matter in the area has reached the mature stage, which may have led to low values for $S_2$ at the calculated $T_{max}$. The Van Krevelen diagram may therefore be inaccurate. Residual hydrocarbons in the samples may also have caused the low test value for $T_{max}$.

## 5. Discussion

*5.1. Evaluation of Oil-Bearing Properties.* Oil-bearing properties are crucial for determining whether a research interval has commercial potential. The parameters used in pyrolysis experiments include free hydrocarbon ($S_1$), pyrolyzed hydrocarbon (PHC) which reflects genetic potential ($S_2$), and residual organic carbon (TOC). These parameters are applied to determine the oil-bearing properties of the Fengcheng Formation in well Maye-1. Figure 10 shows that the distribution range of $S_1$, $S_2$, and the TOC content of the shale in the Fengcheng Formation are 0.04~10.46 mg/g, 0.07~26.49 mg/g, and 0.28~4.17%, respectively. In the $P_1f_1$ shale, $S_1$ is 0.04~5.71 mg/g (average 1.03 mg/g), $S_2$ is 0.07~26.49 mg/g (average 3.40 mg/g), and TOC content is 0.25~4.17% (average 0.91%). In the $P_1f_2$ shale, $S_1$ content is 0.07~10.46 mg/g (average 1.54 mg/g), $S_2$ is 0.05~7.37 mg/g (average 2.38 mg/g), and TOC content is 0.21~1.67% (average 0.93%). In the $P_1f_3$ shale, $S_1$ content is 0.15~9.26 mg/g (average 2.97 mg/g), $S_2$ content is 0.14~4.64 mg/g (average 1.79 mg/g), and TOC content is 0.28~1.81% (average 0.77%). Correlation between depth and oil-bearing properties indicates that the optimum oil-bearing properties of the Fengcheng Formation shale in well Maye-1 occur in the intervals at 4580.00~4600.00 m, 4616.45~4640.30 m, 4661.25~4695.20 m, 4728.30~4759.80 m, 4787.60~4812.30 m, and 4876.70~4940.25 m. The average values of $S_1$ at these depths are 1.03 mg/g, 2.01 mg/g, 1.55 mg/g, 2.97 mg/g, 1.25 mg/g, and 3.92 mg/g, respectively. The average values of $S_2$ are 3.40 mg/g, 1.71 mg/g, 2.19 mg./g, 3.05 mg/g, 2.07 mg/g, 1.92 mg/g, and 1.5 mg/g, respectively. The average TOC is 0.91%, 0.9%, 0.86%, 1.09%, 0.81%, and 0.86%. These six intervals are identified as "sweet spot" intervals with good oil-bearing properties.

In addition, OSI evaluation of the shale (Figure 11) shows that most core samples from $P_1f_2$ have high oil saturation, with OSI greater than 100 mg/g.TOC$^{-1}$, which indicates good commercial development potential. The OSI of the lower section of $P_1f_1$ is particularly high (Figures 10 and 11), with the OSI of some samples exceeding 400 mg/g.TOC$^{-1}$. This interval generally has good oil-bearing properties, with the OSI of some cores from $P_1f_3$ also surpassing 100 mg/g.TOC$^{-1}$. However, in this case, strata with good oil-bearing properties are frequently interbedded with poorer layers. Nevertheless, this represents a suitable target interval for future commercial development.

*5.2. Evaluation of Mobility.* Free movable hydrocarbons are the main contributors to shale oil productivity, so evaluation of shale oil mobility is recognized as a vital factor in evaluating the accumulation qualities of shales. Multi-temperature step pyrolysis has the advantage of accurately determining the amounts of oil in a variety of occurrence states in shales. The free hydrocarbon parameters include light hydrocarbons ($S_{1-1}$), heavy hydrocarbon ($S_{1-2}$), and adsorbed-miscible or adsorbed hydrocarbons ($S_{2-1}$). These parameters can be used to evaluate shale oil mobility. Figure 10 shows that the overall distribution ranges of $S_{1-1}$, $S_{1-2}$, and $S_{2-1}$ in the Fengcheng

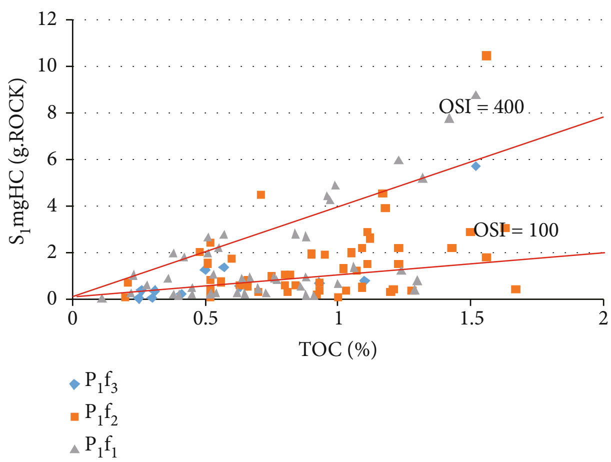


Figure 11: Oil saturation characteristics of the Fengcheng Formation shale in the Mahu Sag.

Formation shale of the Mahu sag are 0.1~5.09 mg/g, 0.18~8.33 mg/g, and 0.06~1.41 mg/g, respectively.

For the shale of the $P_1f_1$ member, $S_{1-1}$ content is 0.03~2.77 mg/g (average 0.47 mg/g), $S_{1-2}$ content is 0.04~3.39 mg/g (average 0.68 mg/g), and $S_{2-1}$ content is 0.01~0.70 mg/g (average 0.20 mg/g). For the $P_1f_2$ shale, $S_{1-1}$ content is 0.08~3.32 mg/g (average 0.88 mg/g), $S_{1-2}$ content is 0.05~3.11 mg/g (average 1.04 mg/g), and $S_{2-1}$ content is 0.03~1.41 mg/g (average 0.26 mg/g). For the $P_1f_3$ shale, $S_{1-1}$ content is 0.09~5.03 mg/g (average 0.99 mg/g), $S_{1-2}$ content is 0.08~5.53 mg/g (average 1.12 mg/g), and $S_{2-1}$ content is 0.06~0.89 mg/g (average 0.25 mg/g). In terms of identifying sweet spot layers, the Fengcheng Formation shale in well Maye-1 has high $S_{1-1}$ and $S_{1-2}$ contents at depths of 4580.00~4600.00 m, 4616.45~4640.30 m, 4661.25~4695.20 m, 4728.30~4759.80 m, 4787.60~4812.30 m and 4876.70~4940.25 m. In these intervals, the average values of $S_{1-1}$ are 0.47 mg/g, 1.33 mg/g, 0.83 mg/g, 1.6 mg/g, 0.8 mg/g and 1.85 mg/g, respectively, and the average values of $S_{1-2}$ are 0.68 mg/g, 1.39 mg/g, 0.91 mg/g, 2.16 mg/g, 0.83 mg/g and 2.03 mg/g, respectively. The oils in all of these intervals display good mobility, which is conducive to commercial shale oil development.

The free oil/adsorbed oil ratio $(S_{1-1}+S_{1-2})/S_{2-1}$ and the free oil/total oil ratio $(S_{1-1}+S_{1-2})/(S_{1-1}+S_{1-2}+S_{2-1})$ are considered to be important indicators for evaluating shale oil mobility. The values of $(S_{1-1}+S_{1-2})/S_{2-1}$ for the Fengcheng Formation shale in the Mahu Sag are almost all greater than 3 (the average is 6.63), and most of the values of $(S_{1-1}+S_{1-2})/(S_{1-1}+S_{1-2}+S_{2-1})$ exceed 80% (average 85%). The proportion of movable oil is therefore high. For shale oil exploration and development in North America, OSI ($S_1$/TOC ∗ 100) greater than 100 is regarded as a significant indicator of exploitability [8, 9]. However, as noted in that study, pyrolyzed $S_1$ is not all free oil. According to the more comprehensive free oil-bearing saturation index, $(S_{1-1}+S_{1-2})$/TOC) (Figure 12), most of the intervals in $P_1f_2$ have index values exceeding 100 mg/g.TOC$^{-1}$ and are therefore within the optimal range for movable oil.

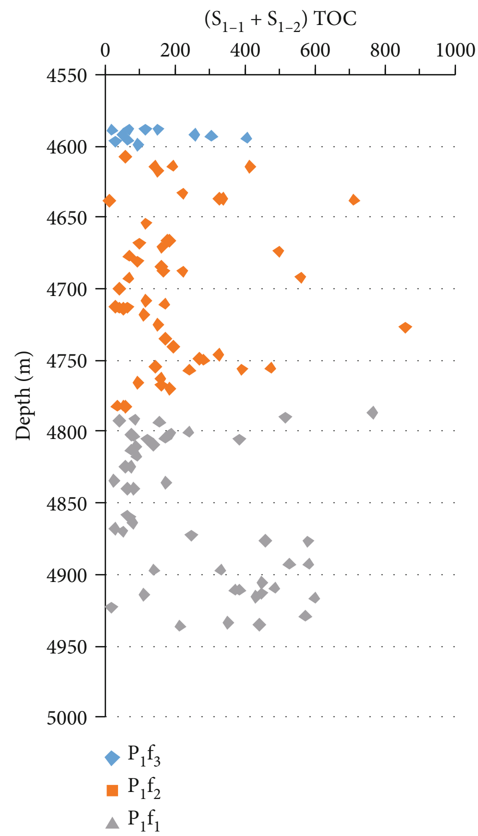


Figure 12: Variation of oil saturation with depth in the Fengcheng Formation shale.

### 5.3. Analysis of Factors Influencing Mobility

*5.3.1. Relationship between Free Oil, Adsorbed Oil, and Organic Matter.* Shale oil retained in shale systems is mostly in either free or adsorbed states. However, due to differences in mineral/kerogen surface wettability and molecular polarity, there are great variations in the conditions in which movable shale oils can be brought into production. Figure 13 reflects the relationship between adsorbed oil and free oil and TOC in the shale in the Mahu Sag. There is a very good positive correlation between adsorbed oil and TOC, indicating that the adsorbed oil is mainly related to kerogen. Physical simulation experiments have shown that the adsorption capacity of organic matter is nearly 10 times greater than that of minerals [31]. However, the correlation between free oil and TOC in the study area is poor. This is because, although increased amounts of kerogen result in increased hydrocarbon generation, the shale oil accumulations in this area are primarily sandwiched reservoirs, so the hydrocarbons generated in the source rocks are mostly stored in adjacent reservoirs, resulting in greatly reduced amounts of free hydrocarbons in the shales themselves [32].

*5.3.2. Relationship between Free Oil, Adsorbed Oil, and Maturity.* The content of adsorbed oil is related to the abundance of organic matter and also changes with variations in its thermal maturity. With increasing thermal maturity,

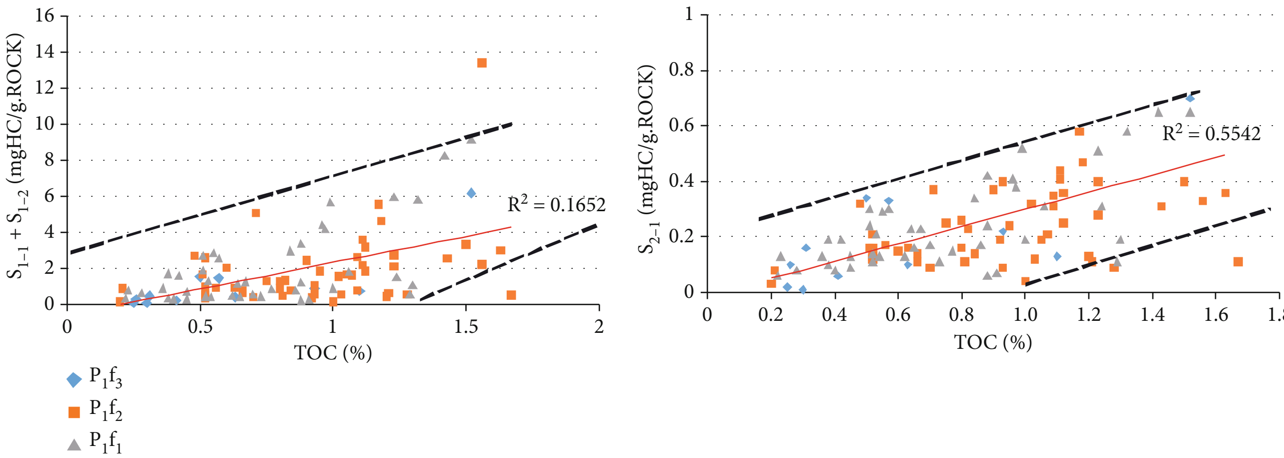


FIGURE 13: Relationship between free oil, adsorbed oil, and organic matter in the Fengcheng Formation shale.

disproportionation leads to removal of heteroatoms from solid organic matter, gradual aromatization of organic macromolecular structures, more stable chemical properties, and relatively reduced polarity. The generated hydrocarbons gradually become lighter and the relative content of polar molecules decreases, resulting in relative reduction of the adsorption capability and miscibility of the oil and kerogen in shales. Effective source rocks both generate and expel hydrocarbon. If the source rocks produce hydrocarbons but cannot expel them, they are not effective source rocks. Theoretically, generated oil and gas must first satisfy the source rock's own capacity for adsorption and pore filling, and only then can superfluous oil and gas be expelled. For $S_{2-1}$/TOC, the oil adsorption capacity of organic matter is far below that of kerogen in the early stage of kerogen evolution, so adsorption in the kerogen increases. Once the amount of generated oil and gas exceeds the adsorption capacity of the kerogen, hydrocarbon expulsion begins, reducing the amounts of movable hydrocarbons remaining in the source rocks [33, 34]. Because the depth range in the study formation is small and $T_{max}$ values are generally distributed at about 440°C, it is difficult to precisely determine the variations in free oil and adsorbed oil with maturity in the area. However, the previously established variation characteristics of $S_1$/TOC and chloroform asphalt "A"/TOC with burial depth (Figures 14(a) and 14(b)) showed a main peak of hydrocarbon generation at about 4600 m. With increasing depth, the ratios of $S_1$/TOC and chloroform asphalt "A"/TOC gradually decrease, the amount of gas generated increases, the gas-oil ratio increases, and mobility also increases (Figure 14(c)). In the main depth section studied in this paper (below 4600 m), the values of $(S_{1-1} + S_{1-2})/S_{2-1}$ are almost greater than 3, and the values of $(S_{1-1} + S_{1-2})/(S_{1-1} + S_{1-2} + S_{2-1})$ mostly exceed 70% (Figure 10), indicating good mobility.

*5.3.3. Relationship between Free and Adsorbed Oil and Mineral Composition, Lithology, and Lithofacies.* The mineral composition in the study area includes clay minerals, carbonate minerals, and detrital minerals. This paper establishes the ratios of free hydrocarbons to adsorbed hydrocarbons and to the various types of minerals and determines the available pore space for free hydrocarbons accordingly. Figure 15 shows that the ratio of free hydrocarbon to adsorbed hydrocarbon in the study area is positively correlated with detrital minerals. This indicates that the occurrence space for free hydrocarbons is mostly pores in detrital minerals. This accords with the known development of intergranular pores in feldspar and quartz in the area [32]. The ratio of free hydrocarbons to adsorbed hydrocarbons is negatively correlated with carbonate minerals. This is primarily because the carbonate minerals are lacustrine authigenic minerals with poorly developed pores, which cannot provide effective space for the occurrence of free hydrocarbons [32]. The ratio of free hydrocarbons to adsorbed hydrocarbons is also negatively correlated with clay minerals. This is largely because, due to their surface characteristics, clay minerals have good ability to adsorb hydrocarbons so that, when clay minerals increase, the content of adsorbed hydrocarbons increases. In addition, a handful of interlayer pores in clay provide the reservoir space for free oil [32], and hence the increase of clay minerals may also result in an increase in the amount of free hydrocarbons.

Figure 4 shows that the lithofacies in the Fengcheng Formation are generally of three types: hybrid sedimentary rock facies, lime/dolomitic shale facies, and felsic shale facies. Shale oil mobility and its geneses in the various lithofacies are explored within this context. Figure 16 shows the changes in the free oil $(S_{1-1} + S_{1-2})$, and free oil/adsorbed oil $(S_{1-1} + S_{1-2})/S_{2-1}$ ratios and TOC with depth in various depth sections in the formation (excluding the igneous facies in the lower section of $P_1f_1$). The lithofacies of $P_1f_1$ cores changes frequently, and the three lithofacies types are interbedded. Felsic shale facies show optimal shale oil mobility, followed by hybrid sedimentary rock facies. Shale oil mobility varies synchronously with TOC, indicating that the upper section of $P_1f_1$ is a self-generation and self-storage oil accumulation. The lithofacies in $P_1f_2$ is significantly different

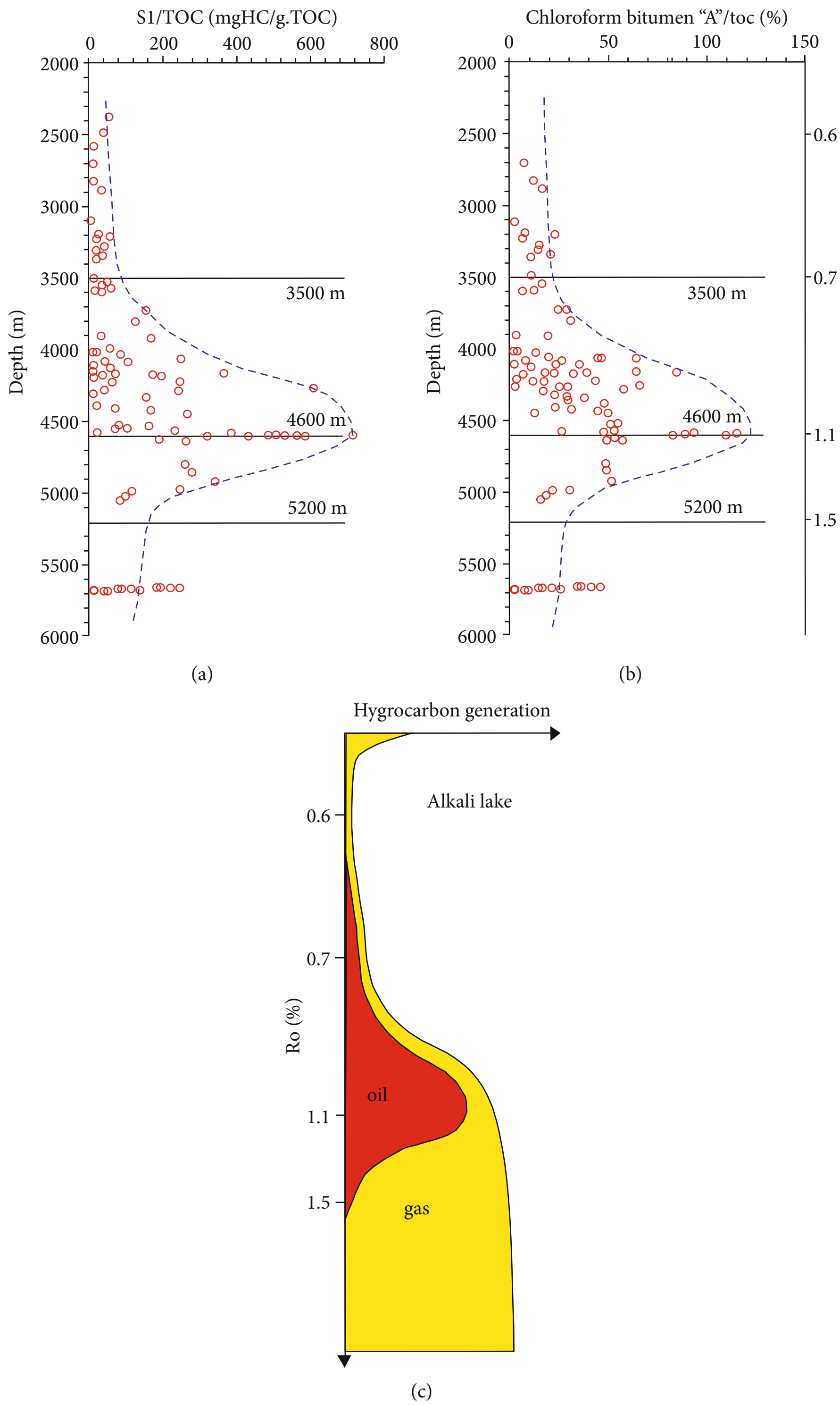


Figure 14: Relationships between hydrocarbon generation and burial depth in the Fengcheng Formation source rocks. (a) Main oil generation stage according to changes in $S_1$/TOC with depth and $R_O$. (b) Main stage of oil generation according to variations in chloroform asphalt "A"/TOC with depth and $R_O$. (c) Hydrocarbon generation model for source rocks [27].

from $P_1f_1$. In $P_1f_2$ the lithofacies is generally of a single type, with thin layers of other lithofacies occasionally intercalated in the predominant lithofacies. The lithofacies with optimal shale oil mobility in $P_1f_2$ cores is felsic shale facies, followed by lime/dolomitic shale facies. However, there are two types of oil and gas accumulation in $P_1f_2$, accumulation in adjacent intervals and self-generation/self-reservoir, and there is an obvious regularity. When hybrid sedimentary rock facies, lime/dolomitic shale facies, and felsic shale facies are contiguously developed, the TOC values of the hybrid

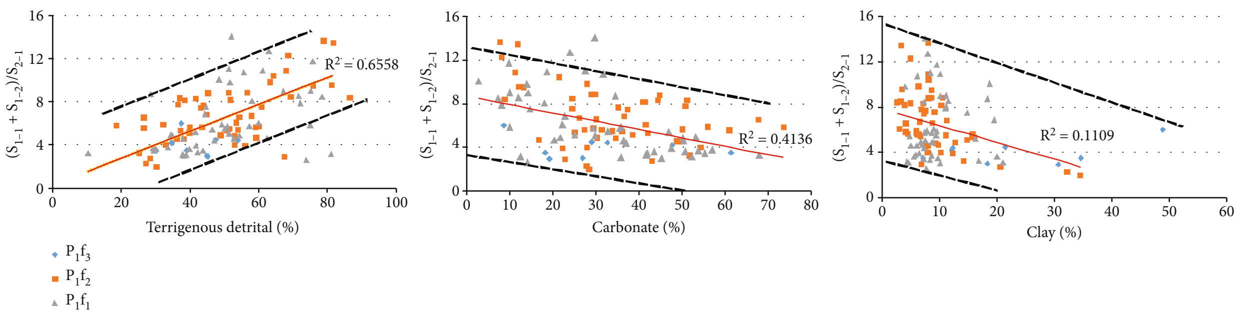


Figure 15: Relationship between free oil, adsorbed oil, and mineral composition in the Fengcheng Formation shale.

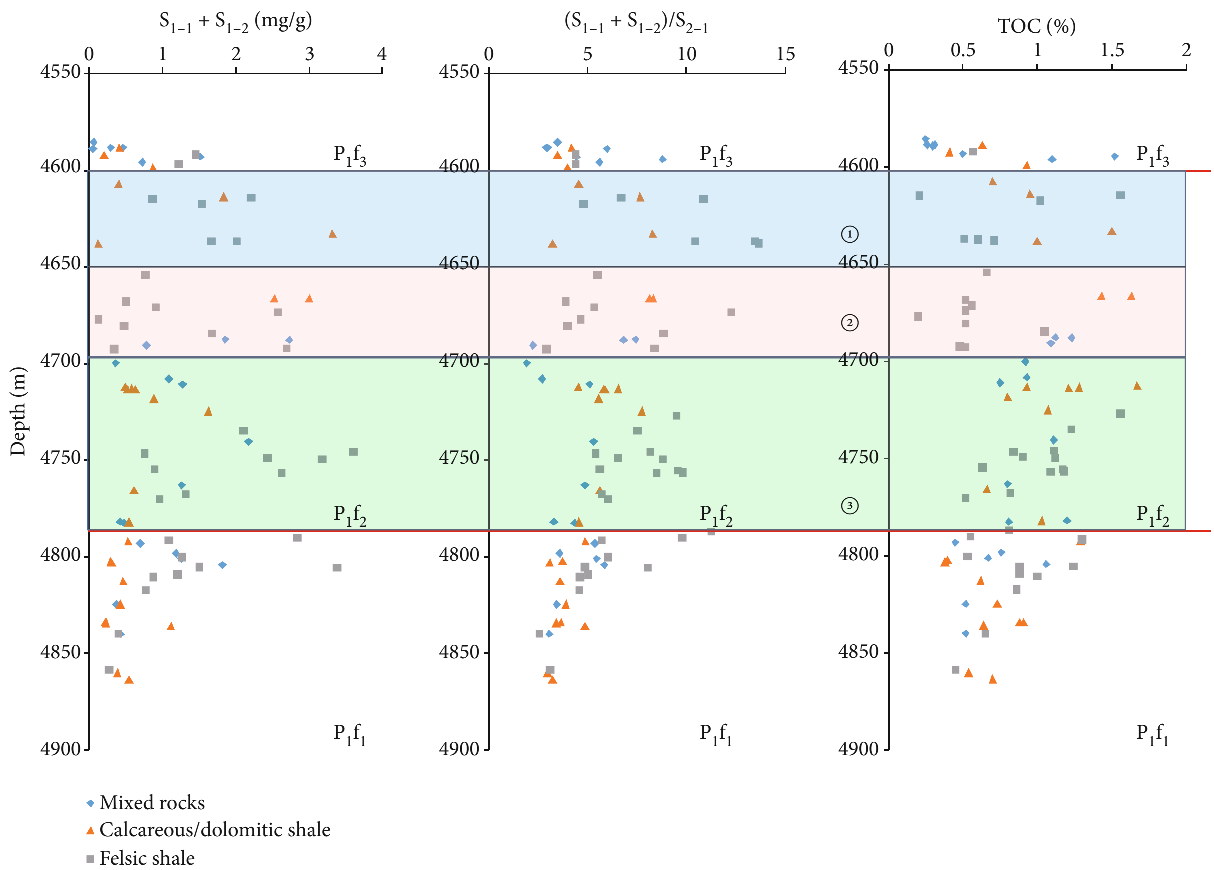


Figure 16: Shale oil mobility in different lithofacies in the Fengcheng Formation. (1) Interbedded development of lime/dolomitic shale facies and felsic shale facies; (2) continuous development of felsic shale facies intercalated with thin layers of lime/dolomitic shale facies; (3) continuous development of hybrid sedimentary rock facies, lime/dolomitic shale facies, and felsic shale facies.

sedimentary rock facies and lime/dolomitic shale facies are high, but the values of $(S_{1-1} + S_{1-2})$ and $(S_{1-1} + S_{1-2})/S_{2-1}$ are apparently low. The TOC content of the adjacent felsic shale facies is low, but the values of $(S_{1-1} + S_{1-2})$ and $(S_{1-1} + S_{1-2})/S_{2-1}$ are significantly higher, indicating that the oil and gas generated in the hybrid sedimentary rock facies and lime/dolomitic shale facies have migrated to the felsic shale facies. The same law applies to the interbedded development of lime/dolomitic shale facies and felsic shale. When continuously developed felsic shale facies is intercalated with a thin layer of lime/dolomitic shale facies, the lime/dolomitic shale becomes a self-generation/self-storage oil accumulation, and the values for TOC, $(S_{1-1} + S_{1-2})$, and $(S_{1-1} + S_{1-2})/S_{2-1}$ are correspondingly high. Similar to $P_1f_1$ cores, the three lithofacies are frequently interbedded in most $P_1f_3$ cores, but in $P_1f_3$, the lithofacies with optimal shale oil mobility are hybrid sedimentary rock facies and felsic shale facies.

## 6. Conclusions

(1) The mineral composition of the Fengcheng Formation shale in the Mahu Sag includes clay minerals, carbonate minerals (calcite, dolomite), and felsic minerals (quartz, feldspar), with some alkaline minerals. There are three basic lithofacies:

lime/dolomitic shale facies, felsic shale facies, and hybrid sedimentary rock facies. In $P_1f_1$, the main lithofacies are lime/dolomitic shale facies and felsic shale facies. In $P_1f_2$ and $P_1f_3$, the three lithofacies are all widely distributed, but the primary type is hybrid sedimentary rock facies. The quality of the source rocks in the Fengcheng Formation shale is mostly very good-excellent, low-mature, or mature, and the organic matter is mostly Type II kerogen

(2) The oil-bearing properties and shale oil mobility of the Fengcheng Formation shale are good. The depth ranges with the best oil-bearing properties are at 4616.45~4640.30 m, 4661.25~4695.20 m, 4728.30~4759.80 m, 4787.60~4812.30 m, and 4876.70~4940.25 m. $S_1$ is generally greater than 1.5 mg/g, OSI is greater than 100 mg/g.TOC$^{-1}$, and the free oil/adsorbed oil ratio $(S_{1-1} + S_{1-2})/S_{2-1}$ is greater than 3. The free oil/total oil ratio $(S_{1-1} + S_{1-2})/(S_{1-1} + S_{1-2} + S_{2-1})$ exceeds 80%. $P_1f_2$ and the lower section of $P_1f_1$ are the preferred intervals for commercial development

(3) Shale oil mobility in the Fengcheng Formation is related to the adsorption of organic matter, the level of maturity, and the available pore space in inorganic minerals. The higher the TOC, the better the adsorption capacity for shale oil, and consequently the worse the mobility. With increasing maturity, shale oil mobility begins to increase once the ability of the kerogen to adsorb shale oil has reached saturation. Shale oil mobility in pore spaces formed by terrigenous debris is particularly good

(4) Shale oil occurrence in the Fengcheng Formation is characterized by self-generation and self-reservoir and by accumulation in adjacent intervals. The upper section of $P_1f_1$ is primarily self-generation and self-storage oil accumulation, and the felsic shale facies have optimal shale oil mobility. $P_1f_2$ is characterized by self-generation and self-reservoir and by accumulation in adjacent intervals. Shale oil mobility is high in both the predominant felsic shale facies and in the intercalated lime/dolomitic shale facies. $P_1f_3$ is also essentially a self-generation/self-storage oil accumulation, with the hybrid sedimentary rock facies and felsic shale facies offering the optimum shale oil mobility

## Data Availability

The figures and tables used to support the findings of this study are included in the article.

## Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

## Authors' Contributions

The evaluation of oil content was completed by Wenjun He, the division of sweet spots was completed by Menhui Qian and Zhifeng Yang, the data analysis was completed by Zhongliang Sun, the text modification was completed by Zhiming Li, and the evaluation of hydrocarbon generation was completed by Junying Leng.

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