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Geochemical Characteristics and Development Model of the Coal-Measure Source Rock in the Kuqa Depression of Tarim Basin

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Abstract: The development model of the coal-measure source rock may be different from that of the lacustrine source rock. The depositional environment of the coal-measure source rock is dominated by weak oxidation and weak reduction, and the majority of the organic material originates from terrestrial higher plants. Taking the Jurassic coal-measure source rock in the Kuqa Depression as the research object, the geochemical characteristics of the source rock are comprehensively analyzed, the primary controlling elements of source rock development are made clear, and the development model of the coal-measure source rock is established. This study contributes to the field of source rock prediction and oil and gas exploration. The lithology of the coal-measure source rock in the Kuqa Depression is mainly mudstone, carbonaceous mudstone, and coal, which are medium- to good-quality source rocks, and the organic matter type is mainly II_2 and III. Terrestrial organic matter is a key factor in controlling the formation of coal-measure source rocks, and the sedimentation rate also has a certain influence. The redox degree of the depositional environment, water salinity, and clay mineral content has little influence on the development of coal-measure source rocks. By integrating the main control factors, the development model of the coal-measure source rock is established. It is considered that the development model and distribution characteristics of the coal-measure source rock are different from the traditional understanding of lacustrine source rocks, and it is pointed out that the coal-measure source rock in the gentle slope zone is more developed than the sag area.

Keywords: coal-measure source rock; input of terrestrial organic matter; depositional environment; sedimentary rate; Jurassic system; Kuqa Depression

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1. Introduction

The study on the development of source rocks is of great significance to predict the distribution of source rocks and hydrocarbon accumulation. With regard to the distribution and development of lacustrine source rocks, the source rock of the large depression-type lake basin is mainly distributed in the deep and semi-deep lacustrine facies in the center of the lake basin [1], whereas the source rock of the faulted lake basin is mainly distributed in the steep side belt with a larger thickness and a bigger water depth [2,3].

As for the development of source rocks, researchers have studied the controlling effects of different lake types on the formation of source rocks under macroscopic conditions. Carroll and Bohacs (1999, 2001), through the comparative study of the sediments of modern lakes and ancient lakes, divided lakes into three categories: underfilled, balanced fill, and overfilled, and concluded that balanced fill lakes are most conducive to the development of source rock, underfilled lakes are in the middle, and overfilled lakes are the least conducive to the development of source rocks [4,5]. These three simple types cannot solve the problem of source rock heterogeneity in the basin, which is a critical problem in petroleum exploration.

Most scholars believe that productivity and preservation conditions are the main factors controlling the development of source rocks. Some scholars believe that the input of rich nutrients causes productivity to flourish, thus promoting the development of source rocks [6,7]. Some scholars also pointed out that the proportion of organic matter preserved in modern marine sediments in the world is less than 0.5% of the original organic matter, and most of the organic matter has been degraded [8,9]. The strongly reducing depositional environment of the underwater environment is the key factor in promoting the preservation of organic matter and the development of the source rock [10]. Coal-measure source rocks are mainly deposited in delta swamps [11], delta plains and tidal flat lakes [12], river delta systems, and other sedimentary environments with shallow water, gentle terrain, and high input of terrestrial organic matter [13–16]. Compared with marine source rock and lacustrine source rock, the coal-measure source rock lacks a strong reduction environment, and the depositional environment is dominated by weak oxidation and weak reduction. The main source of organic matter is terrestrial higher plants, and its development mechanism is different from the traditional understanding of the marine source rock and lacustrine source rock. Taking the Jurassic coal-measure source rock in the Kuqa Depression as the research object, the geochemical characteristics of the coal-measure source rock are comprehensively analyzed. The control of terrigenous organic matter input, depositional environment, and sedimentation rate on the development of coal-measure source rocks is discussed. The primary controlling factors of the coal-measure source rock development are identified, a coal-measure source rock development model is developed, and the source rock development mechanism is improved. In addition, relevant research can guide the distribution prediction of coal-measure source rocks and facilitate oil and gas exploration. This study may be useful in the analysis of hydrogeological processes [17–19].

2. Geological Setting

The Kuqa Depression is located at the northern edge of Tarim Basin and is usually divided into four tectonic zones and three sags. From north to south, the four structural belts are the Northern Structural Belt, Kelasu Structural Belt, Qiulitag Structural Belt, and Front Uplift Belt. From west to east, the three sags are Wushi Sag, Baicheng Sag, and Yangxia Sag, as shown in Figure 1. In recent years, the Dibei gas reservoir, Tuzi gas reservoir, and other tight sandstone gas reservoirs have been successively discovered in the Jurassic system in the northern structural belt of the Kuqa Depression, which has become an important area for natural gas exploration of the Tarim Basin [20,21].

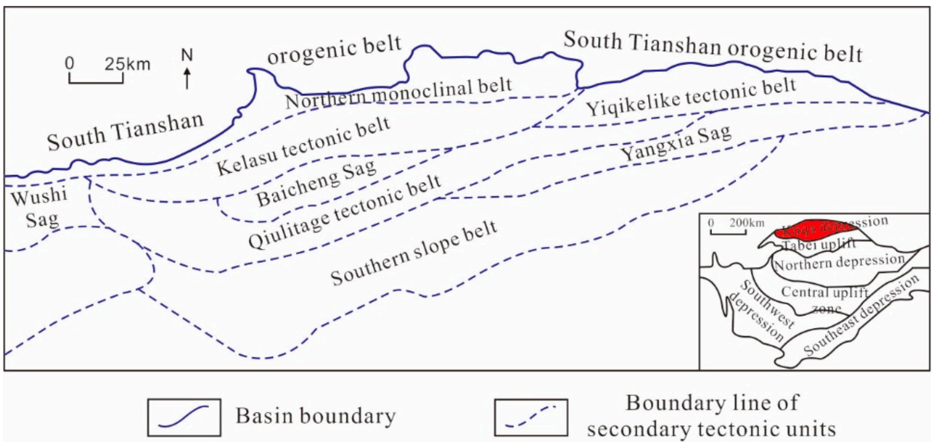

Figure 1. Geographical location of the northern tectonic belt in the Kuqa Depression (Wang et al., 2021 [18]).

The source rock in the Kuqa Depression is mainly developed in the Triassic and Jurassic systems. Five sets of hydrocarbon source rocks are developed from bottom to top, including the Upper Triassic Huangshanjie Formation (T_3h) and Tariqike Formation (T_3t), the Lower Jurassic Yangxia Formation (J_1y), the Middle Jurassic Kezilenuer Formation (J_2kz), and the Qiakemake Formation (J_2q). The Triassic source rock is mainly lacustrine mudstone, and the Jurassic source rock is mainly coal-measure mudstone, as shown in Figure 2.

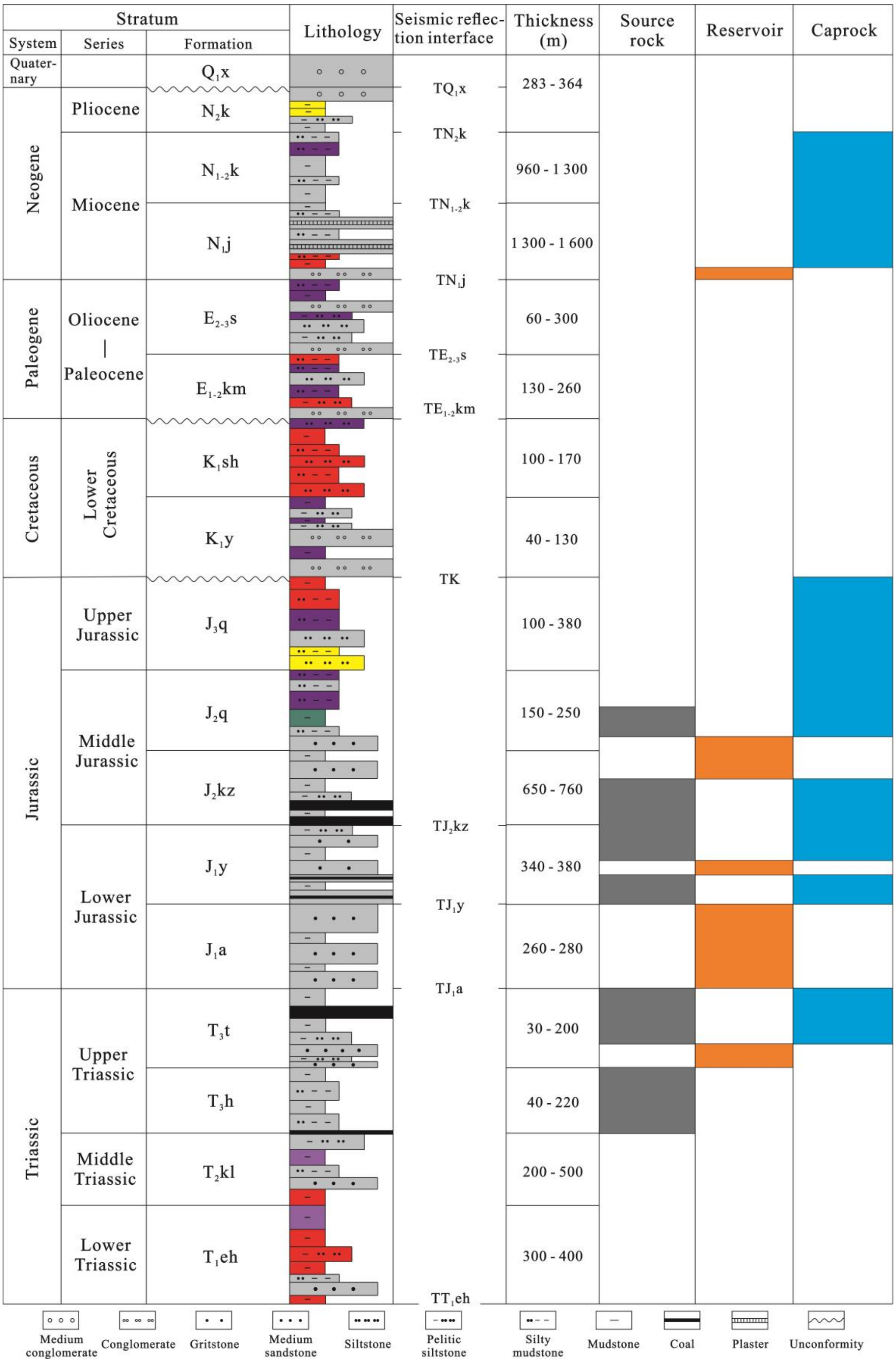

Figure 2. Mesozoic-Cenozoic stratigraphic system in the northern tectonic belt of the Kuqa Depression (Wang et al., 2021 [18]).

3. Samples and Analytical Methods

3.1. Samples

The Jurassic source rock samples, including mudstone samples, carbonaceous mudstone samples, and coal samples, were collected from J_2kz and J_1y strata in the northern tectonic belt.

3.2. Analytical Methods

The total organic carbon content (TOC), total hydrocarbon content (HC), rock pyrolysis hydrocarbon generation potential (S_1 + S_2), hydrogen index (HI), and pyrolysis hydrocarbon peak temperature (T_{max}) samples from the Kuqa Depression were analyzed at the Key Laboratory of Deep Oil and Gas of the China University of Petroleum (East China) using a Rock-Eval 7 analyzer. The vitrinite reflectance (R_O) was determined using a Leica DM4500P polarizing microscope with an MPS200 photometer at the State Key Laboratory of Heavy Oil, China University of Petroleum (Beijing).

The samples of source rocks used the Soxhlet extraction method to extract chloroform asphalt, and the chloroform asphalt was divided into saturated and aromatic hydrocarbons (the separation standard was SY/T 5119-2008). The saturated and aromatic hydrocarbons were finally tested by GC-MS. GC-MS uses the gas chromatography–mass spectrometer manufactured by Agilent, and the GC model is Agilent 9000.

4. Results and Discussion

4.1. Geochemical Characteristics

4.1.1. Abundance of Organic Matter

The abundance of organic matter reflects the relative content of organic matter in the source rocks and is one of the main factors controlling hydrocarbon generation potential. At present, the commonly used indicators of organic matter abundance mainly include total organic carbon content (TOC), chloroform asphalt "A", total hydrocarbon content (HC), and rock pyrolysis hydrocarbon generation potential (S_1 + S_2). Among them, organic carbon content (TOC) and pyrolysis hydrocarbon generation potential (S_1 + S_2) are commonly used indicators to evaluate organic matter abundance.

The coal-measure source rock in the Kuqa Depression is mainly divided into three lithologies: mudstone, carbonaceous mudstone, and coal. The ratings for organic matter abundance in mudstone, carbonaceous mudstone, and coal vary significantly. The TOC of mudstone is mostly less than 6%, whereas the TOC distribution range of carbonaceous mudstone is mainly between 6% and 40%, while that of coal is generally greater than 40%. The TOC distribution range of coal-measure mudstone is about 0.1~8%, and the S_1 + S_2 distribution range is about 0.2~20 mg/g. The distribution range of TOC in carbonaceous mudstone is about 6~40%, and the distribution range of S_1 + S_2 is about 10–90 mg/g. The distribution range of coal TOC is about 40~90%, and the distribution range of S_1 + S_2 is about 30~200 mg/g, as shown in Figure 3. According to the evaluation criteria for organic matter abundance of coal-measure source rock [22], the organic matter abundance of coal-measure mudstone in the Kuqa Depression varies greatly, and the non-source rock (TOC < 0.75%, S_1 + S_2 < 0.5 mg), poor source rock (0.75% < TOC < 1.5%, 0.5 mg/g < S_1 + S_2 < 2.0 mg/g), medium source rock (1.5% < TOC < 3.0%, 2.0 mg/g < S_1 + S_2 < 6.0 mg/g) and good source rock (TOC > 3.0%, S_1 + S_2 > 6.0 mg/g) are all developed. Carbonaceous mudstone is mainly a medium source rock (10% < TOC < 18%, 35 mg/g < S_1 + S_2 < 70 mg/g) or a good source rock (18% < TOC < 35%, 70 mg/g < S_1 + S_2 < 120 mg/g). Coal is mainly a poor source rock (100 mg/g < S_1 + S_2 < 200 mg/g) or a non-source rock (S_1 + S_2 < 100 mg/g). It should be pointed out that although coal and carbonaceous mudstone may not meet the standard of a good source rock according to the previous standards, the hydrocarbon generation potential (S_1 + S_2) of coal and carbonaceous mudstone is significantly greater than that of the mudstone, with a relatively higher hydrocarbon generation potential.

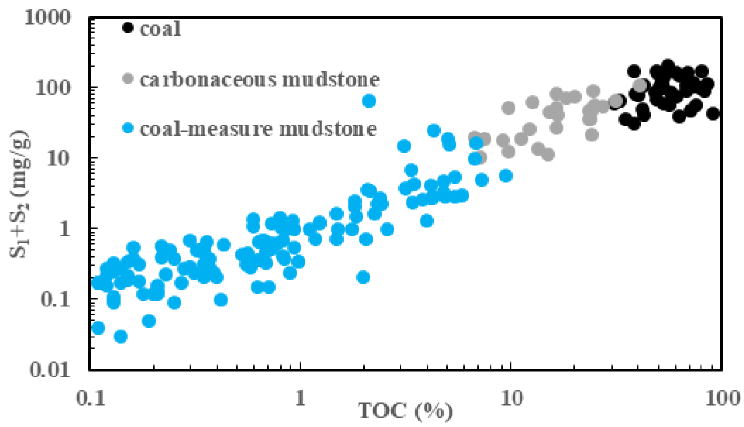

Figure 3. Crossplot of TOC and $S_1 + S_2$ of the Jurassic coal-measure source rocks.

4.1.2. Type of Organic Matter

The $S_1 + S_2$ is not only affected by the organic matter abundance but is also related to the organic matter type. The most popular technique for identifying the type of organic matter is the graphical analysis of kerogen elements. Type I kerogen typically has the largest potential for oil production, a high original hydrogen content, and a low oxygen content. The original hydrogen content of type II kerogen is relatively high, but slightly lower than that of type I kerogen, with a moderate oil generation potential. Type III kerogen has a low original hydrogen content and a high oxygen content, and it does not have the ability to generate oil, relying mainly on gas generation.

The hydrogen index (HI) distribution range of Jurassic coal-measure mudstone is about 50~400 mg/g·TOC, with most of it being less than 200 mg/g·TOC. The organic matter types are mainly II_2 and III types. The difference between HI in the distribution range of carbonaceous mudstone and coal is relatively small, mainly ranging from 100 to 500, and the organic matter type is mainly type II, as shown in Figure 4.

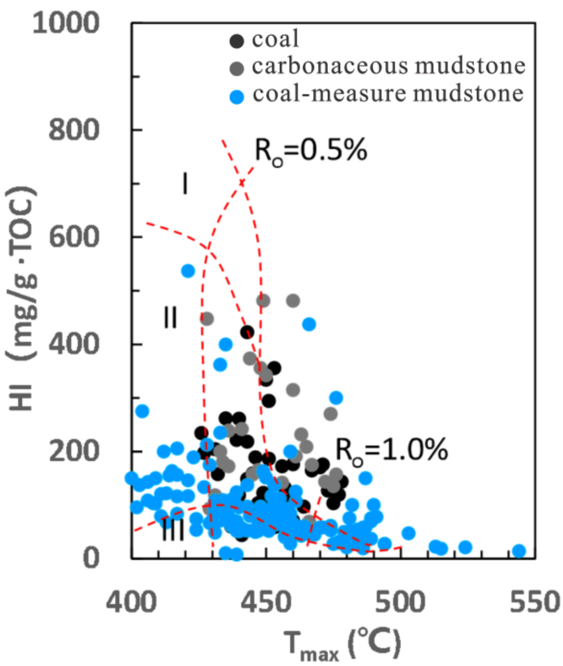

Figure 4. Organic matter types of the Jurassic coal-measure source rocks.

4.1.3. Maturity of Organic Matter

In addition to the abundance and type of organic matter, the degree of thermal evolution of organic matter is also closely related to the hydrocarbon generation capacity of source rocks. There are currently many indicators for determining the maturity of organic matter, such as vitrinite reflectance (R_o), rock pyrolysis peak temperature (T_{max}), kerogen H/C atomic ratio, and biomarker parameters. Among them, R_o is currently the most common method for determining the maturity of organic matter.

The R_o of Jurassic coal-measure source rock is 0.4~1.3%, and the organic matter evolution is mainly in the mature stage. R_o gradually increases with the increase in depth and enters the mature stage when R_o is more than 0.5% at a depth of about 1000 m, as shown in Figure 5.

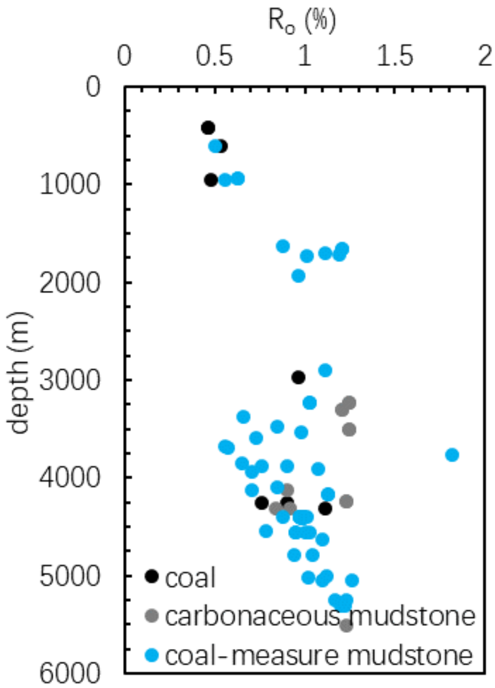

Figure 5. Kerogen types of the Jurassic coal-measure source rocks.

4.2. Main Control Factors of Coal-Measure Source Rock Development

The development of source rock is a process of organic matter enrichment. The organic matter in the lake basin mainly comes from aquatic organisms and terrestrial higher plants. Organic matter slowly settles to the bottom of the lake and is degraded during the long process of burial. The remaining organic matter enters the sediment and is preserved in the rock via diagenesis. Researchers have carried out systematic research on the effects of productivity, redox environment, sedimentation rate, and other factors on the development of source rocks [23–26], and believe that organic matter supply, organic matter preservation, and organic matter dilution are the main factors controlling the development of source rocks [27–29]. The input of terrestrial organic matter and the paleoproductivity of water bodies determine the supply of organic matter. It is generally believed that the greater the supply of organic matter, the better the development of source rocks. Organic matter preservation refers to the process of preserving the organic matter at the bottom of a lake basin via degradation. When the organic matter is well preserved, it suffers less degradation, and the proportion of preserved organic matter is high, which is conducive to the development of source rocks. The dilution of organic matter means that the input of non-organic terrigenous detritus will dilute the organic matter and reduce the abundance of organic matter, which is not conducive to the development of source rocks.

4.2.1. Organic Matter Supply

Biomarkers are commonly used parameters for studying the source of organic matter, the depositional environment (redox degree and salinity), the maturity of organic matter, and biodegradation [30]. The relative abundance of regular steroids is commonly used to identify the source of the organic matter. It is generally believed that C_{27} regular steroids mainly come from aquatic organic matter, whereas C_{29} regular steroids mainly come from terrestrial organic matter [31]. The content of C_{27} regular steranes in the coal-measure source rock in the Kuqa Depression is about 5~45%, mainly distributed in 5~30%, and the content of coal and carbonaceous mudstone is lower than that of the mudstone. There is a negative correlation between C_{27} regular sterane and TOC. As the content of C_{27} regular sterane increases, TOC shows a significant downward trend, as shown in Figure 6a. The content of C_{29} regular sterane in the coal-measure source rock is generally greater than 35%, and the content of C_{29} regular sterane in carbonaceous mudstone and coal is significantly higher than that of the mudstone. The C_{29} regular sterane content shows a positive correlation with TOC. As the C_{29} regular sterane content increases, TOC shows a gradually increasing trend, as shown in Figure 6b. Tricyclic terpenes are ubiquitous in source rock extracts, and the carbon number can extend from C_{19} to C_{45} [32,33]. Usually, lacustrine terrestrial organic matter is characterized by a high content of C_{21} tricyclic terpenoids (C_{21}TT), nearshore sediments are mainly characterized by C_{19} tricyclic terpenoids (C_{19}TT) and C_{20} tricyclic terpenoids (C_{20T}T), whereas the shale facies is characterized by a high content of C_{23} tricyclic terpenoids (C_{23}TT) [34]. It is believed that the higher the C_{19}TT/C_{23}TT and C_{21}TT/C_{23}TT ratios, the more terrestrial organic matter input [35,36]. The distribution range of C_{19}TT/C_{23}TT of coal-measure source rocks in the Kuqa Depression is about 0~15. Among them, the ratio of C_{19}TT/C_{23}TT of coals is the highest, that of carbonaceous mudstone is in the middle, and that of mudstone is the lowest. The TOC of the source rock shows an obvious positive correlation with C_{19}TT/C_{23}TT, as shown in Figure 6c. The distribution range of C_{21}TT/C_{23}TT in the coal-measure source rock is about 0~5, which also shows the characteristics of the highest ratio of coal, the middle ratio of carbonaceous mudstone, and the lowest ratio of mudstone. The positive correlation between TOC and C_{21}TT/C_{23}TT in the source rock is good, as shown in Figure 6d. These indicate that the greater the input of terrestrial organic matter, the higher the TOC of the source rock.

In conclusion, the input of terrigenous organic matter has obvious control over the development of coal-measure source rocks. The proportion of terrigenous organic matter in coal is the highest, followed by carbonaceous mudstone, and mudstone is the lowest. The more terrestrial organic matter input, the higher the organic matter abundance of coal-measure source rocks.

4.2.2. Organic Matter Preservation

There are many factors affecting organic matter preservation. It is generally believed that the redox degree [9], water salinity [37], and clay minerals [38] have obvious effects on organic matter preservation. Strong reducing environments have low oxygen concentrations and poor oxidative destruction of organic matter, which favors the preservation of organic matter and the formation of source rock [39–41]. High water salinity promotes the development of stable stratification, hypoxia in the bottom water body, and the preservation of organic matter by reducing the rate at which organic matter is oxidized by oxygen [42,43]. Clay minerals are highly effective in absorbing organic materials. Some organic matter can also enter the clay minerals to prevent oxygen degradation. A high concentration of clay minerals is thought to favor the preservation of organic materials and the formation of source rocks [44].

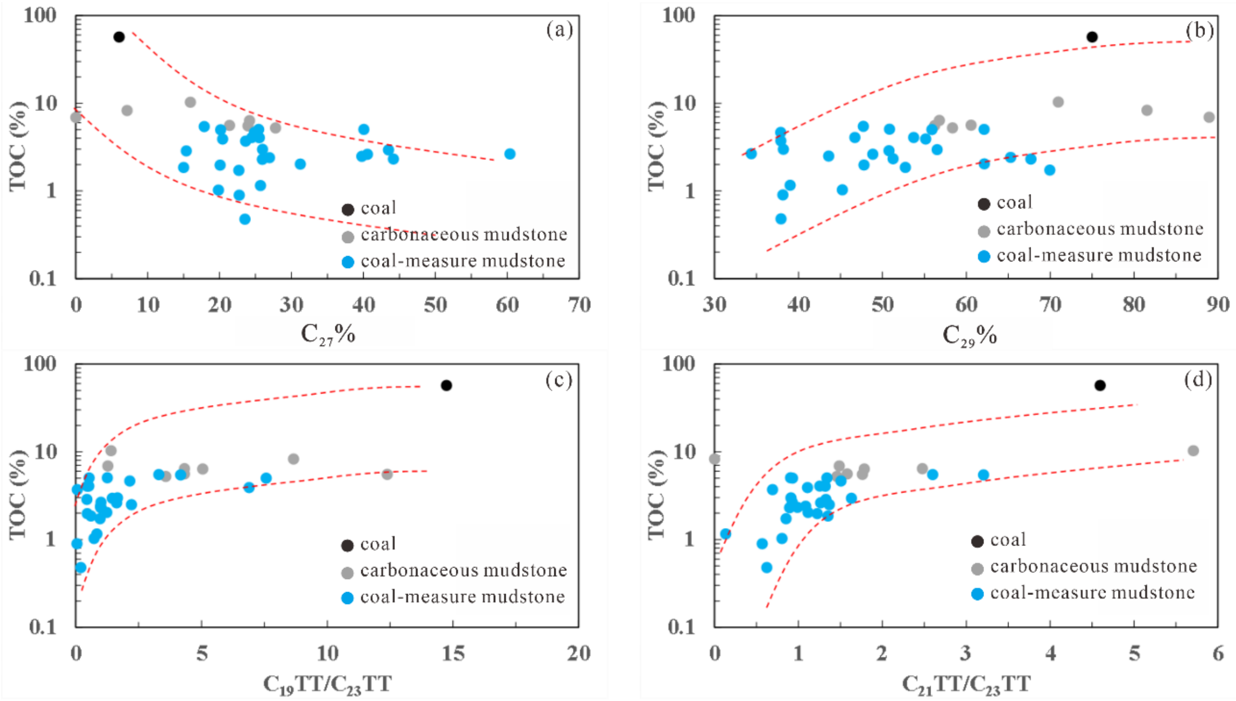

Figure 6. Cross plot of organic matter supply and TOC of the Jurassic coal-measure source rocks. (**a**) Cross plot of C_{27} regular sterane and TOC in coal-measure source rock; (**b**) cross plot of C_{29} regular sterane and TOC in coal-measure source rock; (**c**) cross plot between $C_{19}TT/C_{23}TT$ and TOC of coal-measure source rock; (**d**) cross plot of $C_{21}TT/C_{23}TT$ and TOC of coal-measure source rock.

To determine the redox degree of the depositional environment, it is frequently utilized to cross-plot the source rock's Ph/nC_{18} and Pr/nC_{17} data [45]. The distribution range of Ph/nC_{18} and Pr/nC_{17} of the coal-measure source rock in the Kuqa Depression is about 0.1~0.7 and 0.1~2, respectively. Partial oxidation characterizes the depositional environment, and the majority of the organic material comes from terrestrial sources rather than aquatic sources (Figure 7).

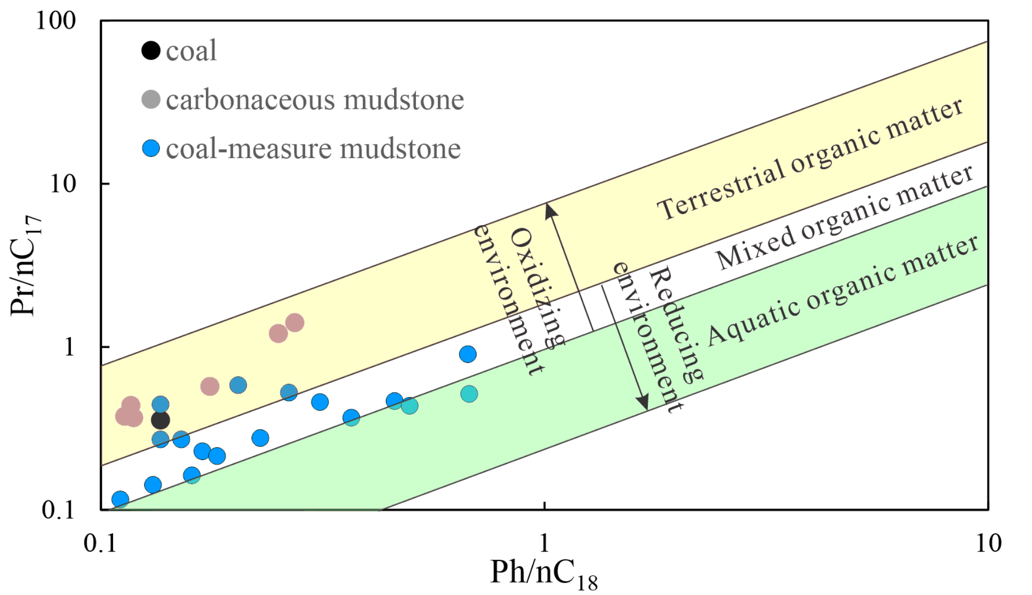

Figure 7. Cross plot of organic matter supply and TOC of the Jurassic coal-measure source rocks.

The primary metric that describes the level of redox reactions in depositional environments is the ratio of pristane to phytane (Pr/Ph). According to conventional wisdom, an environment is said to be reducing when the Pr/Ph ratio is less than 1, and oxidizing when the Pr/Ph ratio is greater [46]. The ratio of gammacerane to C30 hopane (Ga./C30H) is a commonly used parameter to evaluate water salinity [47]. Normally, Pr/Ph and Ga./C_{30}H show a negative correlation, and when the salinity of the water is high, the reducibility of the depositional environment is strong. The Pr/Ph of coal-measure source rocks in the Kuqa Depression is mostly greater than 1, with a distribution range of 0.8~4, indicating weak reducing and oxidizing environments. Ga./C_{30}H is usually less than 0.8, and the salinity of the water is relatively low. Pr/Ph and Ga./C_{30}H show a significant negative correlation, as shown in Figure 8a. While Ga./C_{30}H is positively correlated with TOC, the Pr/Ph of source rocks is typically adversely correlated with TOC. There is a weak positive association between Pr/Ph and TOC of coal-measure source rocks, which shows that the TOC of source rocks is high in an oxidizing environment (Figure 8b). There is no obvious positive correlation between Ga./C_{30}H and TOC, but a weak negative correlation exists, indicating that the TOC of source rocks in the freshwater environment is higher (Figure 8c). The clay mineral content and TOC in coal-measure source rocks have a modest negative connection rather than a positive association, indicating that the TOC in the source rocks is higher when the clay mineral content is lower (Figure 8d).

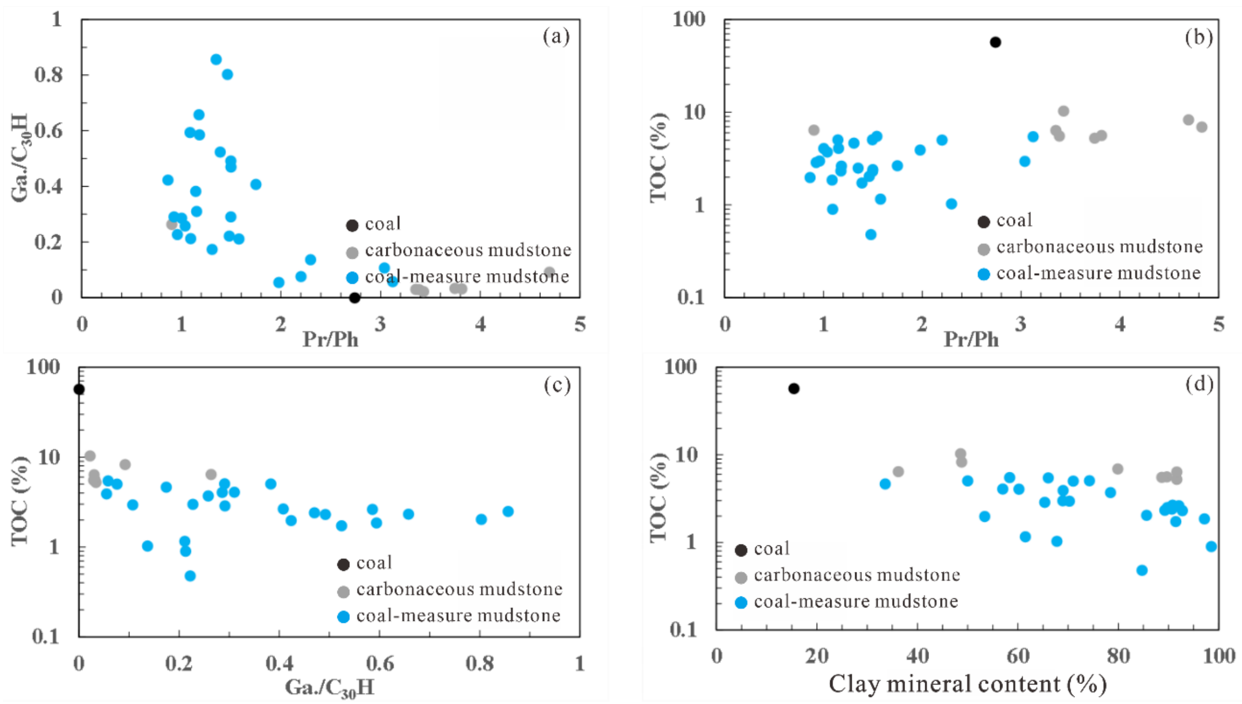

Figure 8. Organic matter preservation and TOC of the Jurassic coal-measure source rocks. (**a**) Cross plot of Pr/Ph and Ga./C_{30}H of coal-measure source rocks; (**b**) cross plot of Pr/Ph and TOC of coal-measure source rocks; (**c**) cross plot of Ga./C_{30}H and TOC in coal-measure source rocks; (**d**) cross plot of clay minerals content and TOC of coal-measure source rocks.

In conclusion, the coal-measure source rock's development is not strongly influenced by the organic matter preservation circumstances, as shown by the weak connections between the redox degree, water salinity, and clay mineral concentration of the depositional environment and TOC. This is in agreement with the sedimentary background of coal-measure source rocks with a significant input of terrigenous organic materials and partial oxidation of the depositional environment. At the two international seminars on "marine source rocks" (1983) and "lacustrine source rocks" (1985) organized by the Geological Society of London, there was debate about which is more important for the development of source rocks: organic matter supply or organic matter preservation. The conclusion is that the former is the more essential factor because, as long as the supply of organic matter is high enough, some organic matter will take too long to be degraded and enriched to form source rocks at the bottom of the oxygen-bearing water [48].

4.2.3. Organic Matter Dilution

The absolute amount of organic matter in the basin is influenced by the supply and preservation of organic matter, and whether the organic matter can be enriched to create source rocks depends on the amount of non-organic matter. The development of the source rock is hindered by the intake of a large amount of terrigenous detrital, which dilutes the organic matter and reduces its abundance. Due to the difficulty in quantitatively restoring the source quantity, the sedimentation rate is generally used to study the dilution effect of organic matter.

There are mainly two opposing views on the role of organic matter dilution in the development of source rocks. One theory holds that the dilution of organic matter is not obvious and that it is buried quickly at a high sedimentation rate, which reduces the time it takes for organic matter to degrade and is advantageous for its enrichment [49,50]. The enrichment of organic matter is at its best when the sedimentation rate is less than 1 cm/ka, according to another theory, which claims that the dilution of organic matter is obvious and only beneficial to the development of source rock when the dilution of organic matter is small [51,52]. In addition, some scholars believe that dilution only occurs when the sedimentation rate is high, which is not conducive to the development of source rocks. At the same time, it is also pointed out that the degradation of organic matter is serious when the sedimentation rate is too low, which is not conducive to the development of source rocks [53,54].

Due to the fact that compaction does not affect the relative relationship between sedimentation rate and organic carbon content, compaction correction is not required for the thickness of the formation in the study, and the sedimentation rate can be directly calculated based on the thickness and sedimentation time of the formation [50]. The average TOC value is calculated for a single well with more TOC data. The relationship between the average deposition rate of the source rock and the average TOC is shown in Figure 9. The sedimentation rates of coal and carbonaceous mudstone are generally low, with a corresponding sedimentation rate range of approximately 1~4 cm/ka. The range of mudstone sedimentation rates is wide, with sedimentation rates ranging from 0.5 cm/ka to 7.5 cm/ka. The trend of TOC changes in the coal, carbonaceous mudstone, and mudstone with the sedimentation rate is mostly consistent. Overall, TOC shows a trend of first increasing and then decreasing as the deposition rate increases. Because an increase in the deposition rate shortens the time it takes for organic matter to degrade, which is advantageous for the preservation of organic matter, TOC is positively linked with the deposition rate when it is less than 2 cm/ka. When the sedimentation rate is greater than 2 cm/ka, the excessive sedimentation rate leads to the obvious dilution of organic matter. The higher the sedimentation rate, the lower the organic matter abundance, and the TOC of the coal-measure source rock decreases with an increase in the sedimentation rate.

The sedimentary environment of the coal-measure source rock is often shallow water, and the association between the Jurassic coal-measure source rock's sedimentary rate and TOC in the Kuqa Depression is consistent with the characteristics of shallow water sedimentation. An increase in the sedimentation rate can greatly reduce the time it takes for organic matter to degrade in shallow water sedimentation, where the depositional environment is primarily one of weak oxidation, helping to preserve organic matter. A high rate of sedimentation results in a large dilution of organic matter and a decrease in the quantity of organic materials. As a result, it typically demonstrates a trend where TOC first rises and then falls as the deposition rate rises. The association between the source rock sedimentation rate and TOC in Erlian Basin's shallow lake basin is similar [55,56].

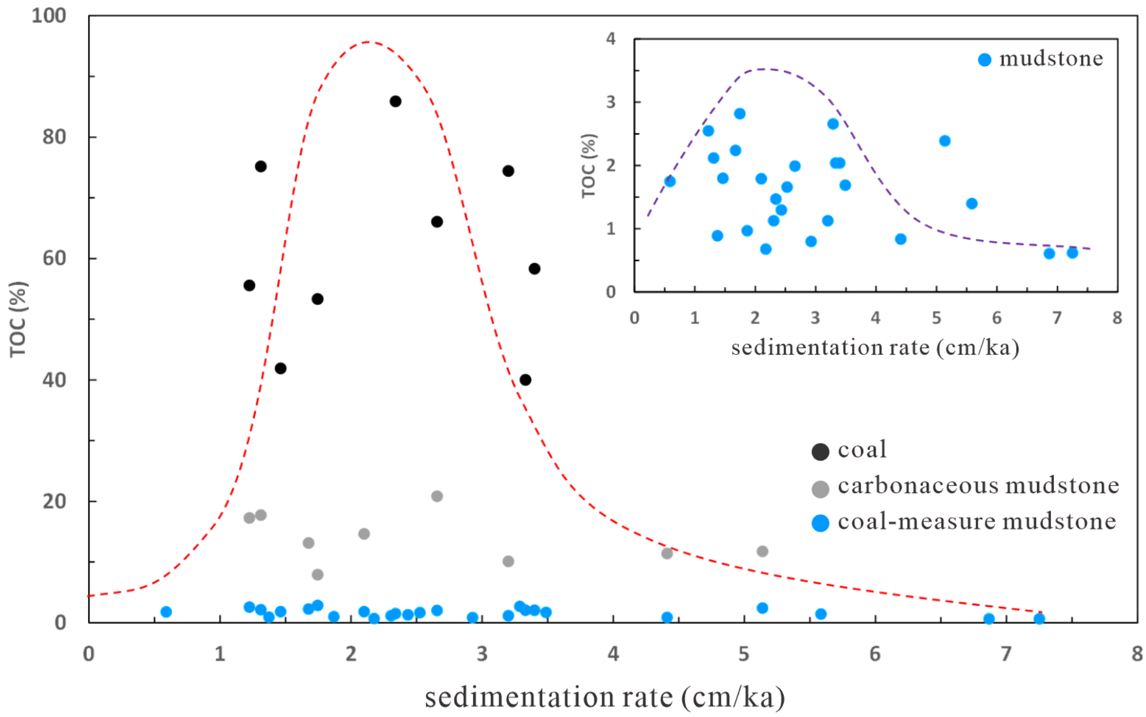

Figure 9. Relationship between the sedimentation rates and TOC of the Jurassic coal-measure source rocks.

4.3. Development Model of Coal-Measure Source Rock

The development model of the source rock has been the subject of extensive inquiry by forerunners [57], such as the marine model [58], marine upwelling current model and anticyclone current model [59], terrestrial marine source rock development model [60], green river shale model [61,62], deep lake hypoxia model [10,63,64], salt lake model [65], alkali lake model [66–68], and small faulted lake basin model [69,70]. There are many factors affecting the development of source rocks, including physical factors such as water depth, temperature, and humidity, chemical factors such as redox degree and salinity, and even disturbance of aquatic organisms. Although there are many factors influencing the development of source rocks, researchers have generally established a development model of the hydrocarbon source rock through the supply, preservation, and dilution of organic matter. It is believed that most development models belong to the "preservation model" or "high productivity model" [23,24,71]. As it has been discussed above, the development of coal-measure source rocks in the Kuqa Depression is mainly controlled by the input of terrestrial organic matter, and the sedimentation rate also has a certain effect but is less affected by the redox degree, salinity, and clay minerals.

The depositional environment of coal-measure source rocks in the Kuqa Depression is mainly delta and shallow lakes [21]. The input of terrestrial organic matter into the delta system is controlled by source and transport conditions. With an increase in transport distance, the input of terrestrial organic matter typically exhibits a characteristic of first increasing and then declining, and it typically reaches its highest value in the zone of a gentle slope [72]. Based on the analysis of major controlling factors, such as terrestrial organic matter input, sedimentation rate, and depositional environment, the development model of coal-measure source rocks in the Kuqa Depression is established, as shown in Figure 10.

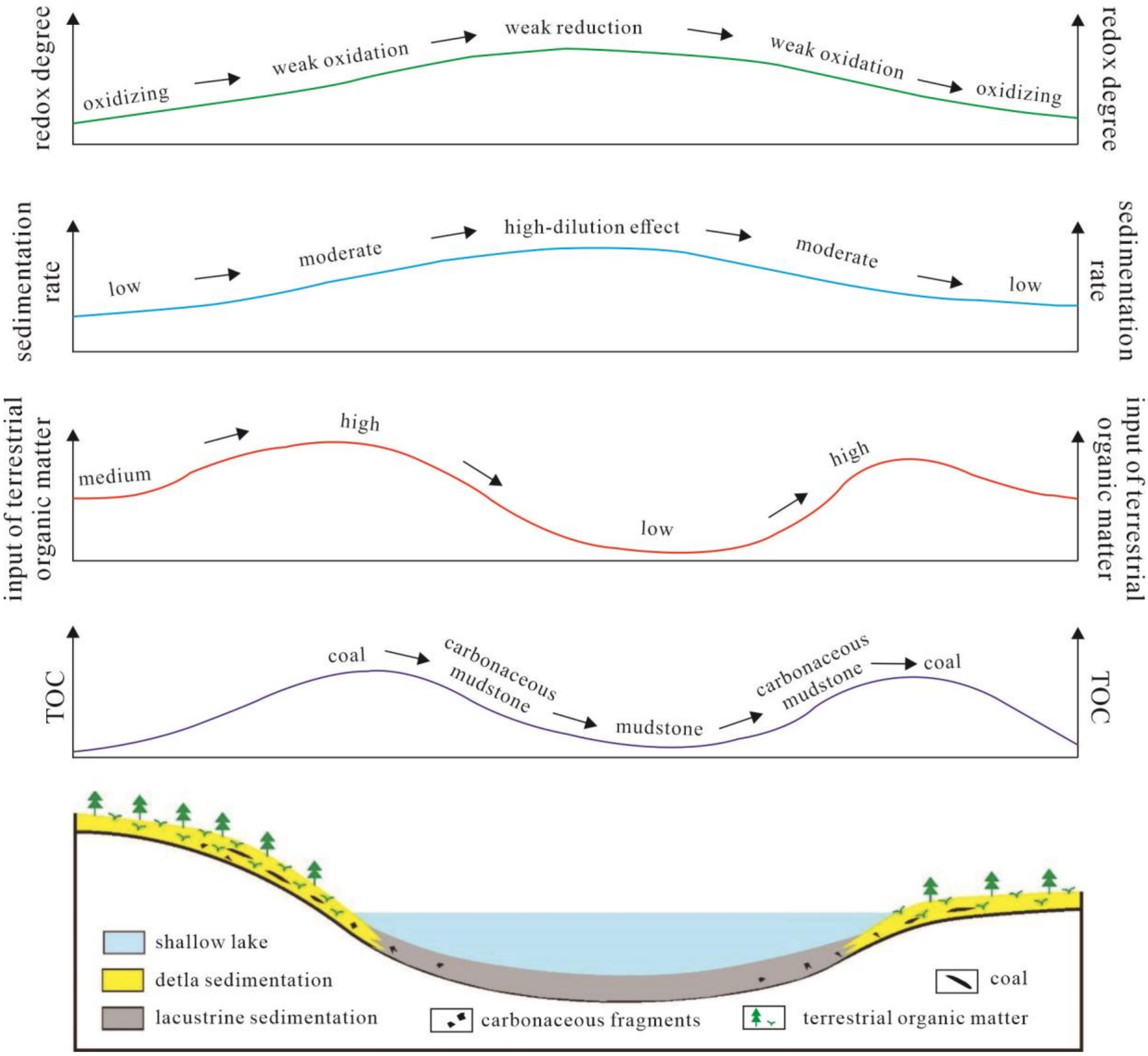

Figure 10. Development model of the Jurassic coal-measure source rocks in the Kuqa Depression.

The depositional environment of the delta is oxidizing, whereas that of the depositional environment of the shallow lake is weakly oxidizing. The central lake has the highest degree of reduction and is a weak reduction environment, with generally no strong reduction developing in the environment. The sedimentation rate of the coal-measure source rock gradually increases from the delta to the semi-deep to deep lake, and the dilution of organic matter gradually becomes obvious. The climate of the coal-measure source rock deposition period was mainly humid and hot, and the delta developed many higher plants, providing sufficient terrestrial organic matter. The intake of terrestrial organic matter first rises and then falls as sedimentation moves from the delta to the lacustrine zone, with the lake's center receiving the least amount of this material. Terrigenous organic matter input and sedimentation rate are the key determinants of how coal-measure source rock develops. The gentle slope zone has a large input of terrestrial organic matter, and a moderate sedimentation rate, and can develop coal, carbonaceous mudstone, and mudstone with the highest abundance of organic matter. The central lake basin has low terrestrial input, a high sedimentation rate, strong organic matter dilution, and mainly develops mudstone with a low organic matter abundance. The gentle slope has a higher richness of organic matter than the central lake basin, and the gentle slope is the primary development zone of coal-measure source rocks, as per the coal-measure source rock development model.

5. Conclusions

(1) The lithology of coal-measure source rocks in the Kuqa Depression is mainly mudstones, carbonaceous mudstones, and coal, which are medium- to good-quality source rocks, and the organic matter type is mainly II_2 and III.

(2) Combined with the depositional environment of isoprenoids and regular steranes, it shows that the depositional environment of coal-measure source rocks is mainly a shallow, freshwater continental environment with partial oxidation, and the source of organic matter is mainly terrestrial higher plants.

(3) The development of coal-measure source rocks is mainly controlled by the input of terrigenous organic matter and the sedimentation rate. Depositional environmental factors, such as redox degree, water salinity, and clay mineral content, have little influence on the development of coal-measure source rocks.

(4) Considering the main control factors of coal-measure source rocks, a development model of the coal-measure source rock is established. It is believed that the coal-measure source rock is more developed in the gentle slope zone than in the depression area. The development model and distribution characteristics of coal-measure source rocks are different from the traditional understanding of lacustrine source rocks.

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