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Organic Geochemical Characteristics of Source Rocks of Hongshuizhuang Formation in the Mengjiawopu Section of Lingyuan-Ningcheng Basin in North China

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Abstract

Through the regional geological survey, outcrop section measurement and other field geological work, a block of black shale is found at the outcrop of Mengjiawopu Section of Hongshuizhuang Formation in Jixian County, and organic geochemical source rock analysis and evaluation methods are used to study the source rocks in Hongshuizhuang Formation. The set of source rocks is mainly gray-black silty mudstone and gray-black shale, with a cumulative thickness of 78 m; the total organic matter (*TOC*) is generally high, with an average content of 1.35%, of which good and rich source rock samples account for 86%. A combined analysis of the stable carbon isotope of kerogen, the correlation between Pr/nC17 and Ph/nC18, and the ratio of saturated hydrocarbon to aromatic hydrocarbon identifies that the organic matter is mainly Type Ⅱ kerogen; the equivalent vitrinite reflectance R_o of organic matter is from 1.68% to 1.94%. R_c, the correlation of the methylphenanthrene index (*MPI*) against the vitrinite reflectance is from 1.63% to 1.81%, with an average of 1.71%, and the Odd/Even Predominance (*OEP*) value is between 0.87 and 1.11, both indicating that the source rocks of the Hongshuizhuang Formation are at the stage of high to over maturation. In summary, the set of source rocks in Hongshuizhuang Formation is characterized by high organic matter content, good kerogen types, and high to over maturation stage.

Keywords

Lingyuan-Ningcheng Basin, Geochemical Characteristics, Hongshuizhuang Formation, Source Rock, Outcrops

1. Geological Background

Lingyuan-Ningcheng Basin includes the western Lingyuan City, the majority of Ningcheng County, and the eastern Pingquan County. Located at the junction of Liaoning, Inner Mongolia and Hebei Provinces, it lies to the northeast of the North China Craton and borders the West Liaoning Depression and the North Hebei Depression, belonging to the transition zone of Songliao Plain. The basin is generally north-south distributed, and the northern part is mostly covered by the Quaternary strata and the volcanic strata of the Cretaceous Yixian Formation, and the Jurassic and Neoproterozoic strata are mainly exposed in the south (**Figure 1**).

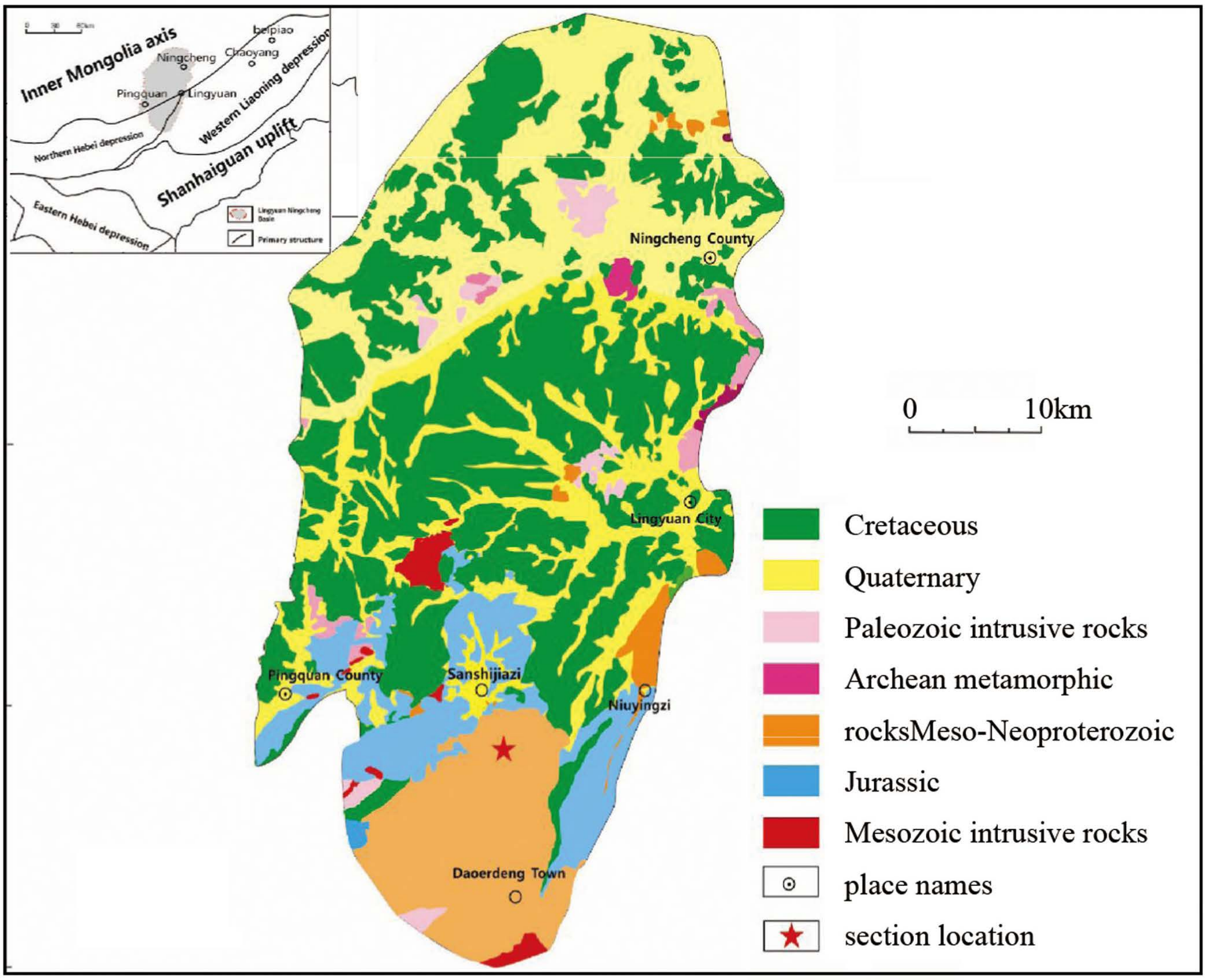

Figure 1. The geological map of Lingyuan-Ningcheng Basin. (1-Cretaceous; 2-Quaternary; 3-Paleozoic intrusive rocks; 4-Archean metamorphic rocks; 5-Meso-Neoproterozoic; 6-Jurassic; 7-Mesozoic intrusive rocks; 8-Place names; 9-Section location).

With a clear boundary, the well-developed Neoproterozoic strata include the Changcheng, Jixian and Qingbaikou Systems from bottom to up. Previous studies suggest that the potential source rocks of the Meso-Neoproterozoic strata in the northern North China include Gaoyuzhuang Formation at the top of the Changcheng System (the main lithology in the basin consists of gray-black shale interbedded with fine sandstone), Hongshuizhuang Formation in the middle and lower part of Jixian System, Tieling Formation (the main lithology includes gray-black shale, gray-black silt-stone, and gray-black shale interbedded with a thin layer of siltstone), and Xiamaling Formation at the bottom of the Qingbaikou System (the main lithology includes quartz sandstone, gray-black mudstone, ripple-bedded gray-yellow sand shale, and interbedded marlstone) [1] [2] [3] [4]. The Lingyuan-Ningcheng Basin is also a basin with good prospects for exploration in the south of the periphery of Songliao Basin. Oil-rich source is found in the Meso-Neoproterozoic strata of Well Niu D1 drilled in the basin [5] [6], which discloses to a certain extent the hydrocarbon generation and accumulation of the Meso-Neoproterozoic strata in the basin; therefore, it is significant to the exploration studies of the Meso-Neoproterozoic strata in the basin for discoveries of oil and gas. In this paper, the geochemical characteristics of the source rocks of the Hongshuizhuang Formation on the Mengjiawopu Section in Lingyuan-Ningcheng Basin are analyzed to assess its hydrocarbon generation potential further and to provide a basis for oil and gas exploration in the basin.

2. Section Survey, Sample Collection and Analysis

Mengjiawopu Section is located near the Mengjiawopu Village, Sanshijiazi Town in the southern part of the basin. The total length of the measured section is 570 m, and from bottom to top the section includes the Proterozoic Jixianan Tieling Formation, Hongshuizhuang Formation and Wumishan Formation. Wumishan Formation is in conformable contact with the Hongshuizhuang Formation, so is the Hongshuizhuang Formation with the Tieling Formation. The main lithology of Wumishan Formation is gray dolomite; Hongshuizhuang Formation is interbedded with siltstone and shale in alteration, and Tieling Formation is dominated with limestone. The section is divided into 15 layers, and dark mudstone/shale layers have six layers with a cumulative thickness of 78 m. Among them, Hongshuizhuang Formation has a set of dark marine shale, which forms the main potential layer of the source rock.

A total of seven dark mudstone/shale samples are collected from Hongshuizhuang Formation on the section and analyzed by the School of Resources and Environment, Yangtze University (Key Laboratory of Exploration Technologies for Oil and Gas Resources and, Ministry of Education) (**Figure 2**).

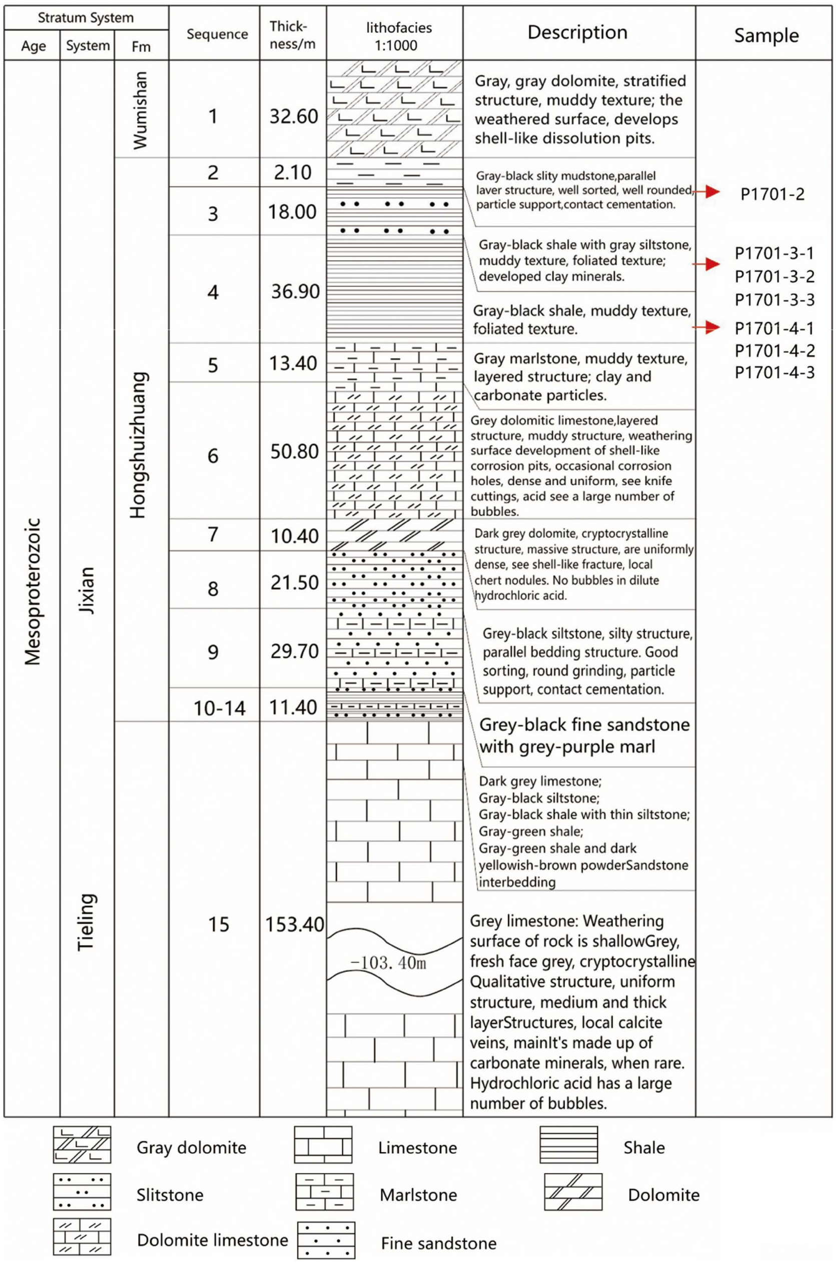

Figure 2. The composite columnar diagram of Mengjiawopu Section.

3. Organic Geochemical Characteristics

3.1. Organic Matter Abundance

The abundance of organic matter in source rocks reflects the quantitative characteristics of organic matter in rocks. It is the material basis for oil and gas formation and the primary indicator for evaluating source rocks. Parameters such as *TOC*, soluble organic matter chloroform bitumen A, total hydrocarbon (*HC*) and hydrocarbon generation potential ($S_1 + S_2$) are used for evaluation [7]. According to previous studies, the evolution stage of the source rocks of Hongshuizhuang Formation in northern North China is mostly at the mature stage and rich in organic matter [8]. In the process of hydrocarbon generation and expulsion, the original parent material hydrocarbon generation potential is exhausted, and the values of chloroform bitumen A and $S_1 + S_2$ are distorted, and the section samples are significantly affected by weathering. In this paper, only the organic carbon content analysis and test are used to evaluate the organic matter abundance. According to the analysis of seven samples from the section, the range of *TOC* variation is not extensive, ranging from 0.59% to 2.00%, and the average value is 1.35%. According to the evaluation criteria of the organic matter abundance of marine source rocks (Jarvie *et al.* 1991) [9], there are one normal source rock sample, five good source rock samples, and one rich source rock sample (**Figure 3**, **Table 1**). It can be seen that the source rocks of Hongshuizhuang Formation have a high abundance of organic matter with a good potential for hydrocarbon generation.

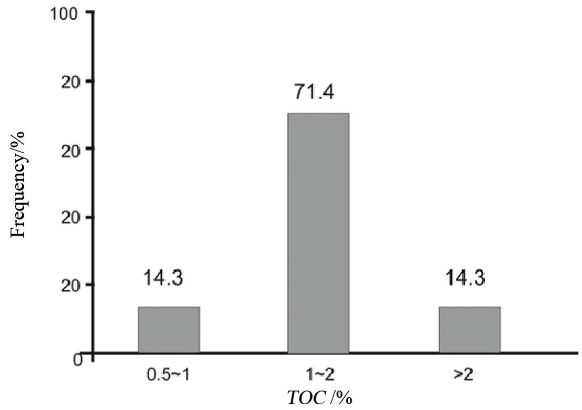

Figure 3. The frequency distribution of *TOC* of source rocks on Mengjiawopu Section.

Table 1. The statistics of organic geochemical data of the Jixianan source rock samples on the Mengjiawopu Section.

Sample	Lithology	*TOC*/%	Bitumen A/%	$(S_1 + S_2)/(mg \cdot g^{-1})$	R_o/%
P1701-2	Silty mudstone	0.59	0.04	0.04	1.93
P1701-3-1	Silty mudstone	1.50	0.08	0.08	1.94
P1701-3-2	Silty mudstone	1.15	0.04	0.04	1.68
P1701-3-3	Silty mudstone	1.17	0.06	0.06	1.71
P1701-4-1	shale	1.97	0.06	0.06	1.89
P1701-4-2	shale	1.06	0.02	0.02	1.77
P1701-4-3	shale	2.00	0.04	0.04	1.92

3.2. Organic Matter Type

3.2.1. Microscopic Identification of Kerogen Component

The microscopy identification of kerogen component uses a biological microscope with the function of projecting white light and epi-fluorescence to identify the microscopy kerogen components to determine the types of kerogen. The seven samples from the section are microscopically examined. The microscopy kerogen components are mainly amorphous sapropelinite with a little inertinite.

The seven samples are observed under the microscope, and a large amount of brown dispersed and flocculent saprolite, a minor amount of black inertinite, rare colorless transparent minerals are found, determining that the kerogen of all samples are Type II_1 (**Figure 4**).

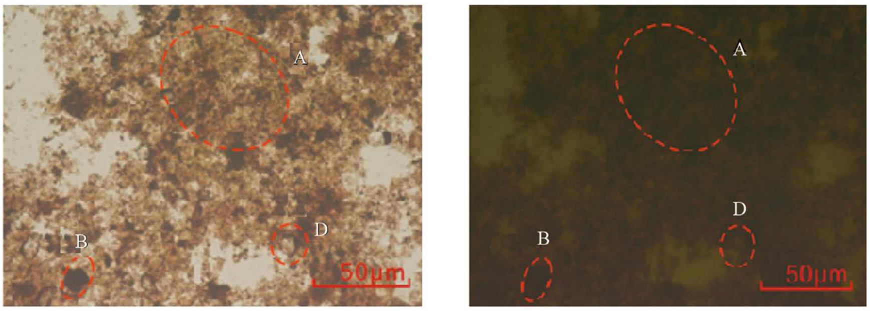

Figure 4. The photos of the microscopy kerogen components of source rocks on Mengjiawopu Section.

The microscopic observation (left) shows that the sample P1701-3-3 includes amorphous brown dispersed and flocculent sapropelinite (A), black inertinite (B) and colorless transparent mineral (D). The microscopic observation (right) shows that all organic components do not fluoresce under blue light excitation.

It is classified according to the classification method of organic matter type index (T_i) (Shuai Qin *et al.*, 2012) [10], T_i = (content of sapropelinite × 100 + content of exinite × 50 − content of vitrinite × 75 − content of inertinite × 100)/100. The type index of the seven samples varies between 56 and 78. The samples can be judged to be Type II_1 sapropelic kerogen, as shown in **Table 2**.

Table 2. The standard for evaluating the organic matter types by using microscopic kerogen component (Shuan Qin et al., 2012).

Type	T_i/1
I	>80
II_1	40 - 80
II_2	0 - 40
III	<0

3.2.2. Identification of Stable Carbon Isotope for Kerogen

For the hydrocarbon-forming parent material of kerogen, its stable carbon isotope composition has not changed much after a long and complicated evolutionary stage [11]. According to previous studies, the organic matter of the Mesoproterozoic source rocks in northern North China is mainly enriched in light carbon isotope [12]. Golyshev *et al.* [13] believe that the sapropelic kerogen is also enriched in light carbon isotopes and the range of $\delta^{13}C$ is between −27.5‰ and −32.2‰. According to the values of protein data bank (PDB) of the seven samples (**Table 3**), it can be concluded that the type is sapropelic kerogen, and the source of the parent material may be algae dominated lower aquatic organisms. According to the correlation diagram between kerogen types and $\delta^{13}C$ (Tissot *et al*., 1974) [14], most of the samples fall in the overlapped intervals of Type I and Type II kerogen, and one sample falling outside the interval may be due to over maturity (**Figure 5**). In summary, it can be identified that the samples may be Type I kerogen (Sapropelic) and Type II_2 kerogen (humic-sapropelic).

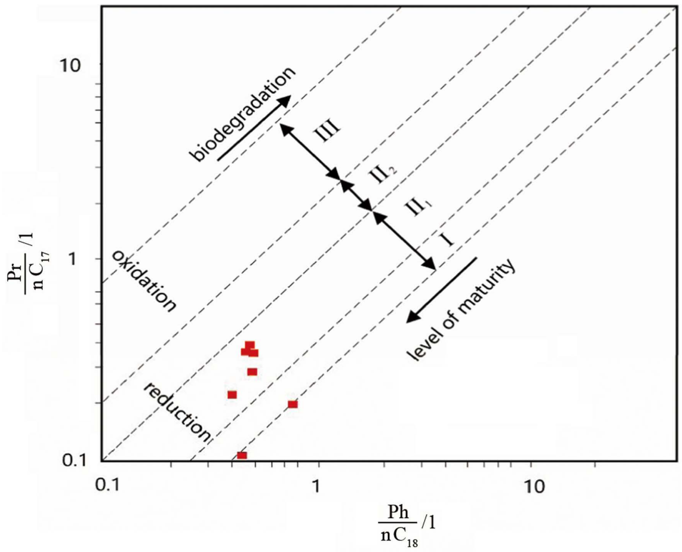

Figure 5. The relationship between kerogen types and $\delta^{13}C$.

Table 3. The values of kerogen $\delta^{13}C$.

Sample	Layer	Kerogen $\delta^{13}C$/‰
P1701-2	Jxh	−30.4
P1701-3-1	Jxh	−30.5
P1701-3-2	Jxh	−30.7
P1701-3-3	Jxh	−31
P1701-4-1	Jxh	−31.7
P1701-4-2	Jxh	−32.2
P1701-4-3	Jxh	−32.9

3.2.3. Characteristics of Saturated Hydrocarbon

Biomarker compounds contain many geochemical characteristics of source rocks, which have unique advantages in judging organic matter types. Shanmugam [15] uses the plot of Pr/n-C_{17} vs. Ph/n-C_{18} to determine the types of organic matter. Through the sampling point (**Figure 6**), all seven samples fall within the intervals of type I and type II_1. The ratio of Pr/nC_{17} is low, indicating that it is formed in a partial reduction depositional environment.

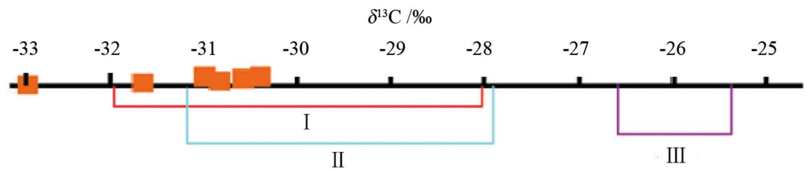

Figure 6. The correlativity of Pr/n-C_{17} vs. Ph/n-C_{18}.

3.2.4. Composition of Chloroform Bitumen A Group

The relative contents of saturated hydrocarbon, aromatic hydrocarbon, non-hydrocarbon, and asphaltene are obtained by extracting the section samples. These values can be used not only to study the parent material characteristics of the samples but also to judge the organic matter types by the relationship between the contents. Seven samples are analyzed for the composition of chloroform bitumen A group (**Table 4**). The saturated hydrocarbon content ranges from 13.16% to 41.07%, most of which are between 20% and 40%; the saturated/aromatic hydrocarbon ratio ranges from 0.83 to 3.7, mainly between 1 and 3. The non-hydrocarbon plus asphaltene content ranges from 21.62% to 61.91%, demonstrating that it's Type II (mixed type) kerogen, and Type II_1 is dominated.

Table 4. The analysis of the group composition of source rocks in Hongshuizhuang Formation on Mengjiawopu Section.

Sample	Group Composition/%				Total/%
	Saturated hydrocarbon	Aromatic hydrocarbon	non-hydrocarbon	Asphaltene	
P1701-2TYY	35.71	14.29	28.57	9.53	88.10
P1701-3-1TYY	33.33	8.89	40.00	13.33	95.55
P1701-3-2TYY	27.69	26.15	27.69	12.31	93.84
P1701-3-3TYY	13.16	15.79	31.58	15.79	76.32
P1701-4-1TYY	21.43	9.52	19.05	42.86	92.86
P1701-4-2TYY	25.00	20.45	15.91	31.82	93.18
P1701-4-3TYY	41.07	17.86	17.86	23.21	100.00

3.3. Maturity of Organic Matter

Level of organic maturity (LOM) is one of the important parameters for measuring the actual hydrocarbon generation capacity of organic matter, a key indicator for determining the degree of organic matter conversion to oil and gas, and an important basis for evaluating the hydrocarbon generation and resource prospects of a region or a source rock system [16]. There are also many other indicators for characterizing the level of organic maturity of source rocks, such as optical, chemical, biomarker parameters, and isomerization ratios.

3.3.1. Organic Matter Reflectance

For layers containing little vitrinite, the vitrinite reflectance of high-grade plant debris cannot be used as the criterion for maturity [17]. The sapropelic reflectance (R_D) and the reflectance after conversing the equivalent vitrinite reflectance were used for analysis (Zhong Ningning *et al.* 1995) [18]. The formula is: $R_o = 1.302 \times R_D + 0.185$. The organic matter reflectance R_o of the seven samples on the section ranges from 1.68% to 1.94%, with an average of 1.83%, which shows a high maturity stage with the potential to generate oil and gas.

3.3.2. OEP of N-Alkanes

The odd/even carbon number predominance (*OEP*) value is the predominant odd/even carbon value obtained by taking the two values near the main peak carbon. As the thermal evolution level of organic matter increases, the odd carbon number predominance will gradually decrease and tend to become 1. The *OEP* value of the seven samples varies from 0.87 to 1.11, with an average of 1.05, showing a higher thermal evolution level.

3.3.3. Phenanthrene Series Compounds

The phenanthrene series compounds are widely used in judging the maturity of crude oil and source rocks, especially at the high maturity stage [19] [20].

Regarding the organic matter reflectance value of the samples, the conversion formula $R_c = -0.50MPI + 2.27$ (Radke & Welte, 1981) [21] is used to obtain the parameters by calculation (**Table 5**). It can be seen that R_c ranges from 1.63% to 1.81%, and the average value is 1.71%, demonstrating high maturity and obvious potential of hydrocarbon generation.

Table 5. The conversion of methylphenanthrene index and reflectance.

Sample	*MPI*/1	R_c/%
P1701-2	1.05	1.75
P1701-3-1	1.17	1.69
P1701-3-2	1.28	1.63
P1701-3-3	0.98	1.78
P1701-4-1	0.93	1.81
P1701-4-2	1.20	1.67
P1701-4-3	1.21	1.67

4. Conclusions

1) There is a segment of argillaceous rocks in Hongshuizhuang Formation in the super thick marine carbonate rocks in the Mesoproterozoic Jixianan Strata. The sources are probably from lower aquatic algae with a functional material basis.

2) The evaluation of source rocks shows that the *TOC* of the source rocks is high in Jixianan Hongshuizhuang Formation on Mengjiawopu Section; the organic matter type is primarily Type II_1. According to the maturity of organic matter, the thermal evolution of the source rock in Hongshuizhuang Formation

is at the stage of high to over maturity; it is characterized by good organic matter types, and high maturity with obvious potential of hydrocarbon generation.

3) The Lingyuan-Ningcheng Basin in the basin group of the southern Songliao Basin has potential source rocks developed in the Mesoproterozoic, and it is worthy of further exploration.

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