

Article

Geochemical Characteristics and Depositional Environment of Coal-Measure Hydrocarbon Source Rocks in the Northern Tectonic Belt, Kuqa Depression

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Abstract: A total of 21 samples were selected from a total of Jurassic coal-measure source rocks in the northern structural belt of the Kuqa Depression, in the Tarim Basin. By using a carbon-sulfur content analyzer, Rock Eval 7 rock pyrolysis instrument and gas chromatography–mass spectrometry (GC-MS), the abundance, type, depositional environment, and source of organic matter are confirmed. The factors that control the development of coal-measure hydrocarbon source rocks are analyzed. The pyrolysis parameters of rocks, such as total organic carbon (TOC), hydrocarbon generating potential ($S_1 + S_2$), hydrogen index (HI) and the highest pyrolysis peak temperature (T_{max}), show that good to excellent coal-measure source rocks constitute the majority, and the types of organic matter are predominantly type III and occasionally type II. Low S/C ratio, high Pr/Ph value, and high C_{29} regular sterane levels suggest that the environment in which the coal-measure source rocks were deposited was oxidative, and the majority of the organic matter comes from higher terrestrial plants. In addition, the cross plot of isoprenoids with n -alkanes and the triangle diagrams of regular sterane also show that the primary source of organic matters in coal-measure source rocks is terrestrial higher plants. Because the shallow and turbulent water body is not easily stratified, the gammacerane content is low, which reflects the characteristics of low salinity. Combined with the cross plots of isoprenoids, it might be demonstrated that the freshwater environment is where the coal-measure source rocks were deposited. Comprehensive analysis shows that the oxidational and freshwater depositional environment is favorable to coal-measure source rock development.

Keywords: coal-measure source rock; biomarkers; depositional environment; source of organic matter



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1. Introduction

One of China's most significant oil and gas basins, the Tarim Basin, provides the gas for the West-to-East Gas Transmission Project [1,2]. The Kuqa Depression is the main source of natural gas in the Tarim Basin [2]. The oil and gas potential of petroliferous basins depends on the existence of high-quality source rocks. The Kuqa Depression's source rocks were primarily formed in Jurassic and Triassic ages [3,4]. From old to new, there are mainly six sets of Triassic-Jurassic source rocks, including the middle Upper Triassic Karamay Formation (T_{2-3k}), Upper Triassic Huangshanjie Formation (T_{3h}) and Taliqike Formation (T_{3t}), Lower Jurassic Yangxia Formation (J_{1y}), Middle Jurassic Kezilenur Formation (J_{2kz}), and the Qiakemake Formation (J_{2q}) [3,4]. Lacustrine mudstone, coal-measure mudstone, carbonaceous mudstone, and coal make up the majority of source rock types. Lacustrine mudstone is the mudstone of a formation without coal, coal-measure mudstone is the mudstone of a coal bearing formation with TOC less than 6 wt.%, carbonaceous mudstone

is the mudstone of a coal bearing formation with TOC between 6 wt.% and 40 wt.% and coal is the rock with TOC > 40 wt.% [5].

The upper sections of the Karamay Formation (T_{2-3k}) and Huangshanjie Formation (T_{3h}) comprise mainly dark mudstone of deep and semi-deep lacustrine facies source rocks, and they are widely developed in the Kuqa Depression. The T_{2-3k} and T_{3h} source rocks are thick, and the thickest part reaches 434 m and 444 m, respectively [6]. The Taliqike Formation (T_{3t}) of the Upper Triassic is formed mainly by lacustrine and swamp alternating facies coal-measure mudstone, carbonaceous mudstone, and coal rock, with a limited distribution area and a thickness of less than 100 m [6]. The Yangxia Formation (J_{1y}) of the Lower Jurassic and the Kezilenur Formation (J_{2kz}) of the Middle Jurassic develop gray-black mudstone, carbonaceous mudstone, and coal rock, with a large thickness and wide development of lacustrine-swamp facies, and the thickness of source rock is 400–550 m [6]. The Middle Jurassic Qiakemake Formation (J_{2q}) is composed mainly of shallow and semi-deep lacustrine facies mudstone, shale, and oil shale, and the thickest part is 155 m [6].

The Cretaceous layers of the middle and southern Kuqa Depression were the principal areas of early exploration and study. There was no drilling involved and very little core sampling because of the deep burial of Jurassic layers. Most of the Jurassic source rock samples were field outcrop samples. Numerous exploration wells have revealed the Jurassic strata and retrieved core samples of the Jurassic coal-measure source rocks as a result of the exploration and development of the northern structural belt. The importance of Jurassic coal-measure source rocks has been confirmed [7]. However, the depositional environment, source of organic matter and factors that control the development of coal-measure source rocks are different from deep and semi-deep lacustrine source rocks [8], which need to be further clarified. As a result, the research of coal-measure source rocks in the northern structural belt of the Kuqa Depression contributes positively to the enrichment of the theoretical framework for source rock development and oil-gas exploration.

Utilizing total organic carbon and total sulfur analyses, rock pyrolysis data, geochemical properties and biomarker characteristics may reflect the depositional environment of the source rocks. In this study, the following issues are fully addressed using Rock Eval pyrolysis and molecular proxies: (1) geochemical features of coal-measure source rocks; (2) redox degree, organic matter source and depositional environment of coal-measure source rocks; (3) factors that control the development of coal-measure source rocks.

2. Geological Setting

The study area is located in the northernmost region of the northern tectonic belt, the Kuqa Depression in the Tarim Basin. The northern tectonic belt is connected with the South Tianshan orogenic belt in the north, Tabei Uplift in the south, and Wushi Depression and Yangxia Depression in the east and west, respectively (Figure 1). The northern tectonic belt started its development during the Late Permian, and experienced the superposition of multiple tectonic movements. The northern tectonic belt is a Mesozoic-Cenozoic superimposed foreland basin, including the Northern Monoclinical Belt, the Kelasu Structural Belt, the Yiqikelike Structural Belt, Baicheng Sag, Yangxia Sag, Wushi Sag, Qiulitage Structural Belt and Southern Slope Belt [9,10] (Figure 1).

A total of 6800 m² is occupied by the northern tectonic belt. The oil and gas are considered to be sourced from T_{3h} and J_{2q} lacustrine mudstones, as well as from T_{3t}, J_{1y}, and J_{2kz} coal-measure strata [11,12] (Figure 2). The coal-measure source rocks in the northern tectonic belt are characterized by great thickness and an abundance of organic matter, and are generally considered fair to good source rocks [6,13,14]. Organic matter is predominantly type III and occasionally type II [6,13,14]. Multiple source rocks and middle-lower Jurassic reservoirs are superimposed in a “sandwich” manner, forming two sets of high-quality source-reservoir-cap assemblages, which are as follows: the first one comprises the Triassic Huangshanjie Formation (T_{3h}) and Taliqike Formation (T_{3t}) as source rocks, Jurassic Ahe Formation (J_{1a}) glutenite as the reservoir, and Yangxia Formation (J_{1y}) coal-measure strata as caprock; the second set comprises the coal-measure strata of the Yangxia

Formation and Kezilenur Formation (J_2kz) as the source rock, Yangxia Formation and Kezilenur Formation as the reservoir, and the mudstone of Jurassic Qiakemake Formation (J_2q) and Qigu Formation (J_3q) as the caprock (Figure 2) (Ju et al., 2014). Due to its abundance of oil and gas deposits and excellent development potential, one of the most significant exploration sites in the Kuqa Depression in the past few years has been the northern structural belt [12,15].

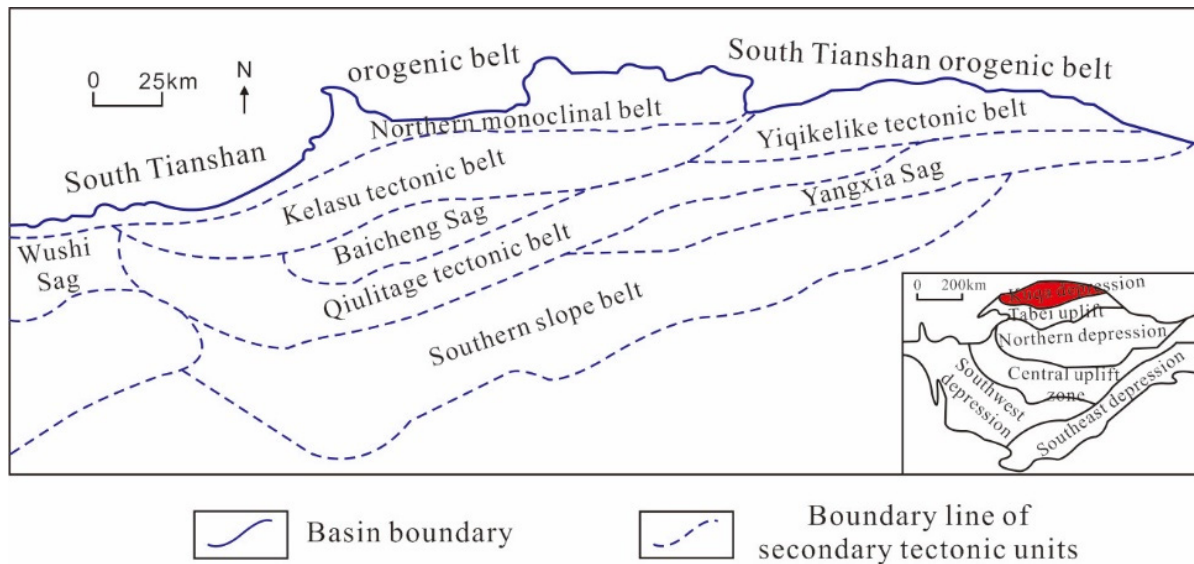


Figure 1. Geographical location of the northern tectonic belt of Kuqa Depression (after Wang et al., 2021 [12]).

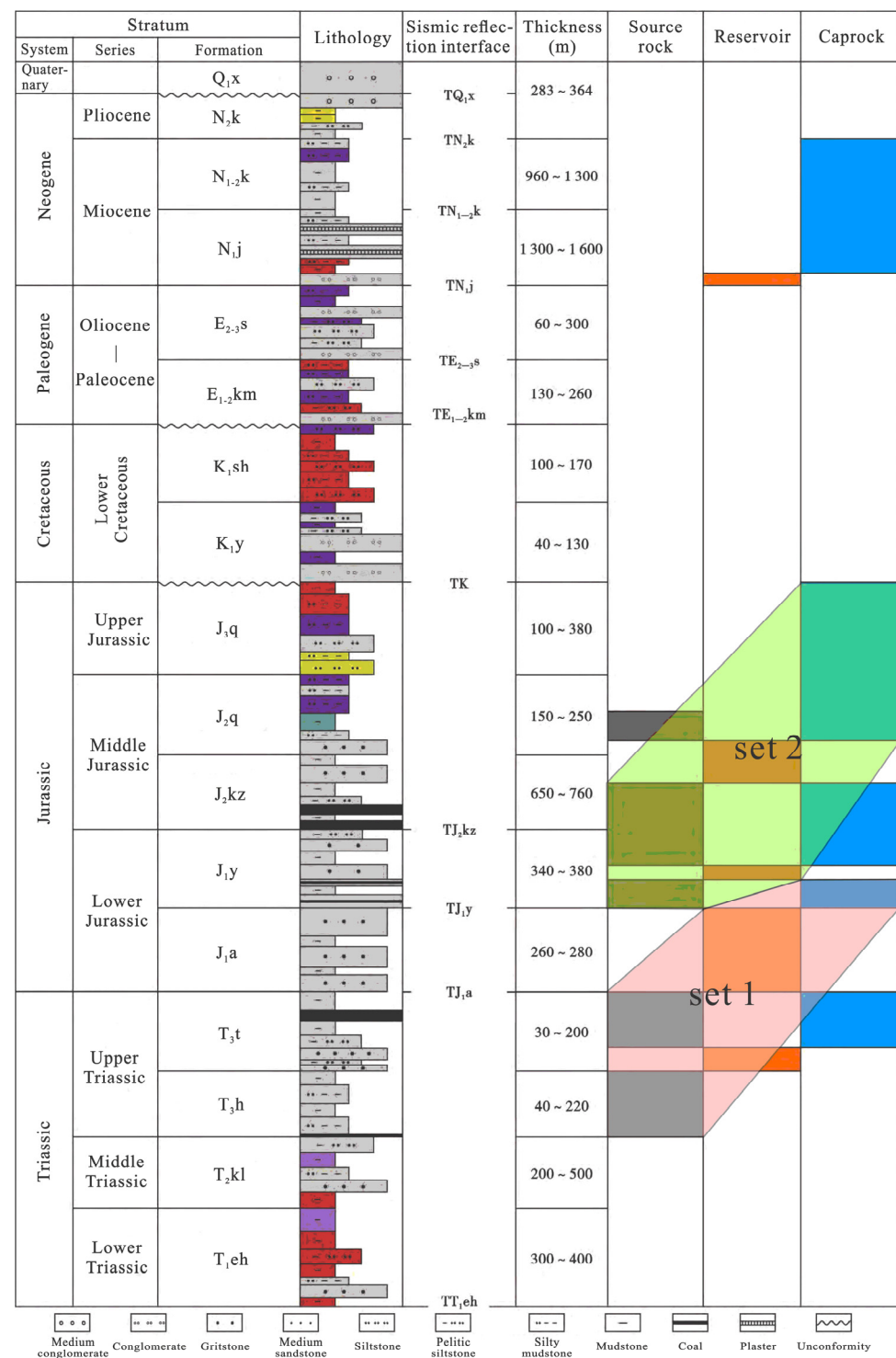


Figure 2. Mesozoic Cenozoic stratigraphic system in the northern tectonic belt of Kuqa Depression (after Wang et al., 2021 [12]).

3. Samples and Analytical Methods

3.1. Samples

The 21 Jurassic source rock samples were collected from J₂kz, J₁y and J₁a strata in the northern tectonic belt, including 17 mudstone (TOC < 6 wt.%) samples, 3 carbonaceous mudstone (6 wt.% < TOC < 40 wt.%) samples and 1 coal (TOC > 40 wt.%) sample (Table 1).

Table 1. Total organic carbon and sulfur contents (wt.%), *n*-alkane, regular isoprenoid ratios and biomarker parameters of the northern tectonic belt.

Lithology	Stratum	TOC	S ₁ + S ₂	HI	T _{max}	TS	S/C	Pr/Ph	Pr/nC ₁₇	Ph/nC ₁₈	C ₂₇ %	C ₂₈ %	C ₂₉ %	Ga/C ₃₀ H	C ₂₄ Te/C ₂₆ TT	DBT/P
M	J ₂ kz	0.56	-	-	-	0.15	0.27	0.86	1.10	0.47	25.49	29.22	45.30	-	-	0.04
M	J ₂ kz	0.54	-	-	-	0.15	0.28	0.72	1.36	0.51	35.89	28.59	35.53	-	-	0.05
CM	J ₂ kz	17.10	43.82	250	443	0.43	0.02	4.01	0.71	0.13	29.14	20.16	50.70	-	-	0.04
M	J ₂ kz	2.96	2.87	79	442	0.15	0.05	1.24	1.37	0.47	12.42	19.24	68.35	-	-	0.04
C	J ₂ kz	43.90	-	-	-	0.87	0.02	2.12	0.28	0.08	22.55	21.38	56.07	-	-	0.05
CM	J ₂ kz	33.10	76.38	198	449	0.57	0.02	1.08	0.31	0.17	11.37	25.04	63.59	-	-	0.05
M	J ₂ kz	1.44	0.97	44	432	0.16	0.11	0.79	1.97	1.14	26.35	23.98	49.67	0.15	0.58	0.02
M	J ₂ kz	0.73	0.60	62	432	0.10	0.14	0.87	1.03	0.48	21.07	25.92	53.01	0.26	0.98	0.03
M	J ₁ y	1.55	5.51	117	468	0.13	0.08	0.91	0.55	0.52	37.24	28.09	34.67	0.24	0.42	0.05
M	J ₁ y	3.29	21.51	187	466	0.18	0.05	1.02	0.51	0.41	32.16	29.30	38.53	0.23	0.52	0.05
M	J ₁ y	3.51	14.44	228	437	0.23	0.07	1.54	0.39	0.17	22.68	25.98	51.33	0.09	1.18	0.03
M	J ₁ y	2.18	2.74	74	430	0.18	0.08	1.44	0.39	0.17	33.03	23.81	43.16	0.10	4.77	0.04
M	J ₁ y	1.96	4.93	150	442	0.15	0.08	0.81	1.35	1.14	16.44	20.55	63.01	0.07	5.77	0.06
M	J ₁ y	1.72	2.52	119	439	0.13	0.08	0.60	0.98	0.97	27.17	23.99	48.84	0.13	1.23	0.05
M	J ₁ a	1.39	2.23	124	448	0.12	0.08	1.85	0.95	0.39	36.95	22.60	40.44	-	-	0.05
M	J ₁ a	1.14	1.71	82	455	0.10	0.09	0.78	1.01	0.80	26.60	39.85	33.55	-	-	0.04
CM	J ₁ a	13.90	7.77	55	502	0.36	0.03	0.70	1.06	0.69	34.84	28.18	36.98	0.17	0.37	0.09
M	J ₁ a	4.20	3.13	36	508	0.18	0.04	0.84	0.85	0.73	33.70	30.06	36.24	0.21	0.42	0.09
M	J ₁ a	0.75	0.53	27	319	0.13	0.17	0.53	1.04	0.88	32.69	31.94	35.36	0.24	0.34	0.08
M	J ₁ a	0.63	-	-	-	0.13	0.21	0.72	1.32	0.86	36.81	26.28	36.92	0.28	0.42	-
M	J ₁ a	0.53	-	-	-	0.09	0.18	0.62	0.99	0.79	32.48	29.15	38.37	0.24	0.44	0.05

Note: M, mudstone; CM, carbonaceous mudstone; C, coal; TOC, total organic carbon (wt.%); TS, total sulfur content (wt.%); S₁, soluble hydrocarbon content; S₂, pyrolysis hydrocarbon content; T_{max}, pyrolysis temperature corresponding to the highest point of P₂ peak (°C); Pr/nC₁₇ = pristane/C₁₇ n-alkane; Ph/nC₁₈ = phytane/C₁₈ n-alkane; Pr/Ph = pristane/phytane; C₂₇₋₂₈₋₂₉%, C₂₇₋₂₈₋₂₉ sterane/(C₂₇ + C₂₈ + C₂₉) sterane; Ga/C₃₀H = gammacerane/C₃₀ hopane; C₂₄Te/C₂₆TT = C₂₄ tetracyclic terpane/C₂₆ tricyclic terpane; DBT/P = dibenzothiophene/phenanthrene.

3.2. Analytical Methods

Rock pyrolysis analysis, GC-MS analysis, and carbon-sulfur content analysis are some of the analytical techniques used in this work.

3.2.1. Carbon-Sulfur Content Analysis

Rock sample powders were pre-treated. First, we soaked the sample in excess HCl: H₂O = 1:7 dilute hydrochloric acid for the full reaction time to remove inorganic carbon. Then, we washed the sample with ultrapure water and dried it. After pretreatment, we put the samples into the CS-230 analyzer of LECO Company to analyze the total sulfur and total carbon content of the rock sample powder. The analysis standard of carbon and sulfur content was GB/T 19145-2003.

3.2.2. Rock Eval Analysis

The fundamental purpose of a Rock Eval analysis is to offer several pyrolysis parameters for assessing the abundance, type, and maturity of organic matter in source rocks. Multiple parameters are combined into the following three fundamental pyrolysis parameters: soluble hydrocarbon content S₁ (mg (hydrocarbon)/g (rock)), pyrolysis hydrocarbon content S₂ (mg (hydrocarbon)/g (rock)) and pyrolysis hydrocarbon peak temperature T_{max} (°C). The Rock Eval 7 rock pyrolysis instrument is used for rock pyrolysis analysis, and the analysis standard is GB/T 18602-2012.

3.2.3. GC-MS Analysis

The samples of source rocks were first washed and pulverized. Using the Soxhlet extraction method, we extracted the samples with a mixed solution of dichloromethane and methanol (volume ratio 93:7) for 72 h, and then the asphaltene in chloroform asphalt was separated with petroleum ether. The maltenes were then divided into saturated and aromatic hydrocarbons using a chromatographic column made of silica gel and alumina. The separation standard of the group components was SY/T 5119-2008, and finally tested by GC-MS. GC-MS adopts the gas chromatography-mass spectrometer manufactured by Agilent, and the GC model is Agilent 9000. The determination standard of chloroform asphalt in rock is SY/T 5118-2005. Mass spectrometry, relative retention time, and literature comparisons are used to identify compounds.

4. Results and Discussion

4.1. Abundance and Types of Organic Matter in Source Rocks

TOC is an important indicator and, when combined with $S_1 + S_2$, can evaluate the abundance of organic matter in source rocks. The TOC of the coal sample is 43.9 wt.%; the TOC distribution of the carbonaceous mudstone samples is 13.9~33.1 wt.%, with an average of 21.4 wt.%, and the $S_1 + S_2$ value is 7.77~76.38 mgHC/g rock, with an average of 42.66 mgHC/g rock. The TOC distribution of dark mudstone samples is 0.53~4.2 wt.%, with an average of 1.71 wt.%, and the $S_1 + S_2$ value is 0.53~21.51 mgHC/g rock, with an average of 4.90 mgHC/g rock. Generally speaking, the rock display is predominantly good to excellent (Figure 3).

Pyrolysis is a typical technique used in Rock Eval to determine the type and maturity of organic matter [16,17]. The HI of carbonaceous mudstone samples is distributed between 55 mgHC/gTOC and 250 mgHC/gTOC, with an average of 167.7 mgHC/gTOC; the HI of dark mudstone samples ranges from 27 mgHC/gTOC to 228 mgHC/gTOC, with an average of 102.2 mgHC/gTOC. The type of organic matter is predominantly type III, occasionally type II, as shown in Figure 4.

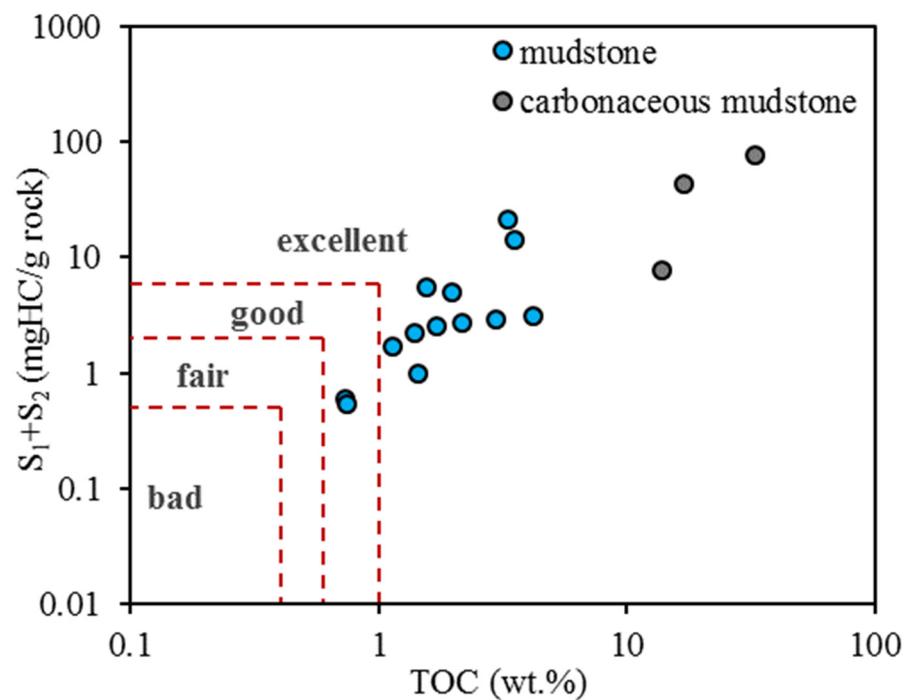


Figure 3. Organic matter abundance of coal-measure source rocks.

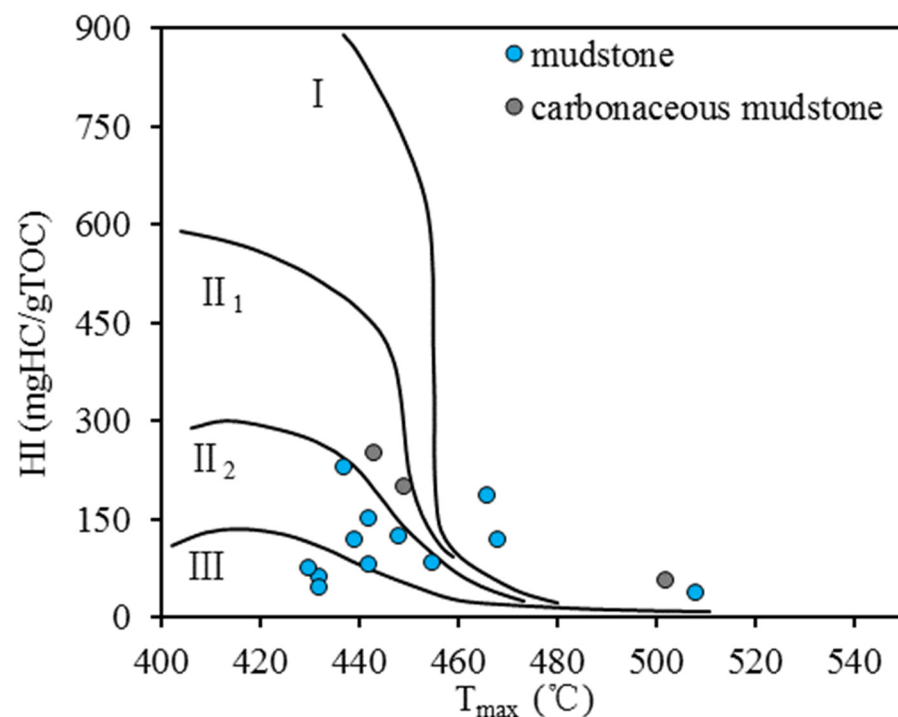


Figure 4. Organic matter types of coal-measure source rocks.

4.2. Geochemistry Features as Indication for Organic Matter Input and Depositional Conditions

In assessing the type and maturity of organic matter, depositional environment, degree of biodegradation, and lithology, biomarker characteristics are crucial [18]. We investigated the depositional environment and source of organic matters in coal-measure source rocks using biomarkers such *n*-alkanes, hopanes, and steranes.

4.2.1. Depositional Environment

The depositional environment can be described by the total organic carbon and total reduced sulfur content in sediments [19,20]. The sulfur content of the coal sample is 0.87 wt.%; the sulfur content of carbonaceous mudstone samples is 0.36–0.57 wt.%, with an average of 0.45 wt.%; the sulfur content of mudstone samples is 0.09–0.23 wt.%, with an average of 0.14 wt.%. Modern freshwater sediments rich in organic matter have a substantially greater C/S ratio than marine sediments with a similar organic matter concentration [21]. The S/C ratio also represents how much microbial sulfate reduction occurs during the decomposition of organic matter, and this information can be utilized to describe the redox conditions of the depositional environment [22,23]. The S/C ratio of oxic marine sediments is generally lower than 0.36 [24], while the S/C ratio in anoxic environment is generally greater than 0.36 [25]. The S/C ratio of coal sample in this study is 0.02; the S/C ratio of carbonaceous mudstone samples is between 0.02 and 0.03, with an average of 0.02; the S/C ratio of dark mudstone samples is between 0.04 and 0.28, with an average of 0.12. It indicates that these source rock samples were deposited in the oxidation and freshwater environments.

Sampei et al. (1997) proposed that the slope of TS-TOC scatter regression line is a more effective tool for judging depositional environment [26]. Wu et al. (2012) found in the study of samples from the Yangtze River Delta that the slope of TS-TOC scatter regression line is higher in marine and lacustrine environments with high water salinity, while the slope of TS-TOC is significantly lower in estuarine areas affected by strong freshwater [27]. Lyons and Berner (1992) calculated that the regression slope of TS-TOC in the normal marine environment was 0.36 [28], while the regression slope of TS-TOC in the sample is only 0.02 (Figure 5), indicating the freshwater depositional environment.

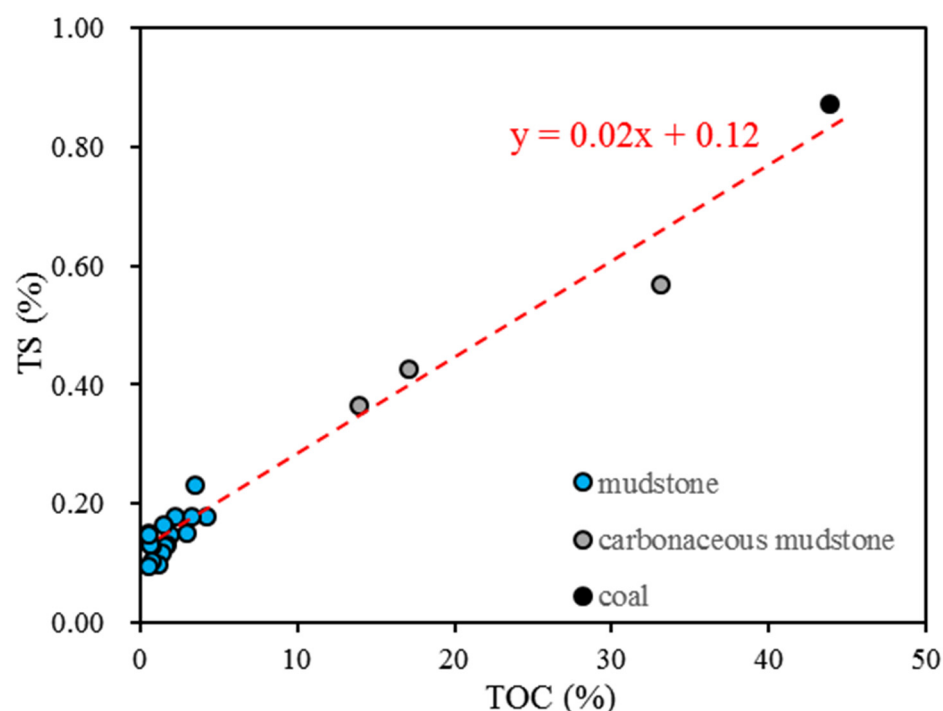


Figure 5. Relationship between TS and TOC for coal-measure source rock.

Phytane and pristane are often the two most significant acyclic isoprene alkanes [29,30]. Their combination with nC_{17} and nC_{18} can characterize the depositional environment. It is widely accepted that a low Pr/Ph ratio (<0.8) indicates reduction environment, medium Pr/Ph ratio ($1.0\sim3.0$) indicates weak oxidation environment, and high Pr/Ph ratio (>3.0) reflects terrestrial organic matter input under oxidation conditions [29–32]. The Pr/Ph ratio of the coal rock sample is 2.12; the Pr/Ph value of carbonaceous mudstone samples is between 0.70 and 4.01, with an average of 1.93; the Pr/Ph value of dark mudstone samples is between 0.53 and 1.85, with an average of 0.95. Generally speaking, the depositional environment of source rocks in the study area is oxic to slightly dysoxic.

Furthermore, many researchers used the crossplot of Pr/ nC_{17} and Ph/ nC_{18} to represent oil maturity, as well as the source rock depositional environment [33–36]. Compared with coal, the ratio of isoprenoid to normal alkane in dark mudstone is relatively high. The Pr/ nC_{17} and Ph/ nC_{18} values of coal are 0.28 and 0.08, respectively, the average Pr/ nC_{17} and Ph/ nC_{18} values of carbonaceous mudstone are 0.69 and 0.33, respectively, and the average Pr/ nC_{17} and Ph/ nC_{18} values of dark mudstone are 1.01 and 0.64, respectively (Table 1). From this plot (Figure 6), it is evident that the source rock samples were deposited in a freshwater swamp lacustrine facies environment.

The abundance ratio of sterane can also indicate the depositional environment [37,38]. Huang et al. (1979) counted the sterane content of organic matter in different depositional environments and devised a plot of the C_{27} , C_{28} and C_{29} sterol contents [37]. They discovered that the higher plant samples are located close to the C_{29} corner, whereas the plankton samples are situated closed to the C_{27} corner. The equivalent regions in the triangle's center are home to the gulf, bay, and terrigenous sediments, which receive organic inputs from plankton and/or higher plants (Figure 7).

C_{29} regular sterane accounted for a relatively large proportion of the samples selected in this study. The $C_{29}\%$ value of the coal sample is 56.1%. The $C_{29}\%$ value of carbonaceous mudstone samples is 37.0%–63.6%, with an average of 50.4%. $C_{29}\%$ in dark mudstone samples ranges from 33.5% to 68.3%, with an average of 44.3%. The depositional environment of samples is mainly a terrestrial and shallow water environment, as shown in Figure 7.

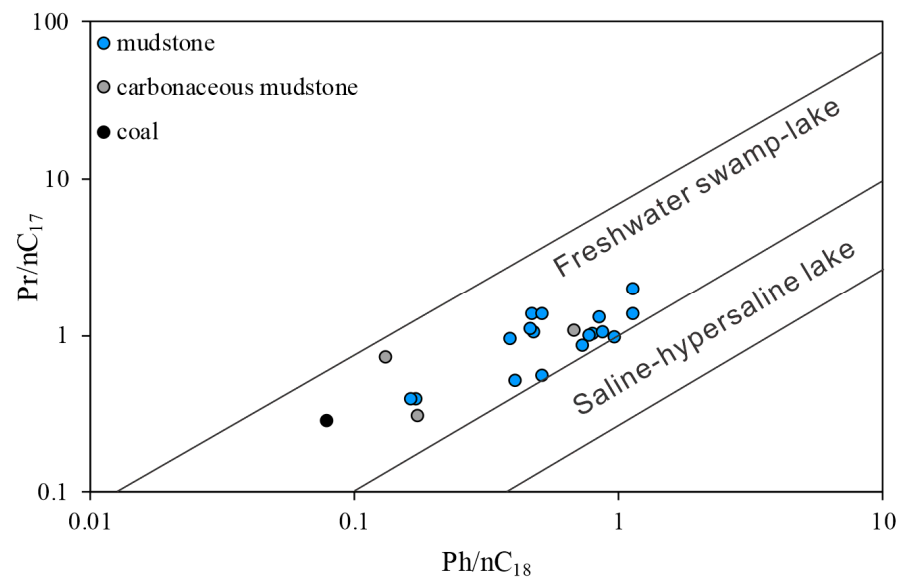


Figure 6. Cross-plot of Pr/nC_{17} vs. Ph/nC_{18} for coal-measure source rocks (after Duan et al., 2006 [36]).

Terpane parameters are also commonly used as biomarker parameters to characterize the depositional environment. For example, gammacerane is a sign of stratification of a depositional water body [39], and its ratio to C_{30} hopane can usually characterize the salinity of a water body [40,41]. The gammacerane index ($\text{GI} = \text{Ga}/\text{C}_{30}\text{H}$) of coal-measure source rock samples is generally low, and because the environmental water body formed by coal-measure source rocks is shallow and turbulent, and the possibility of water stratification is small, only some dark mudstone samples can identify gammacerane. The gammacerane index is between 0.07 and 0.28, with an average of 0.19 (Table 1). The lower gammacerane index indicates the low salinity freshwater depositional environment, which is the same as the above conclusion.

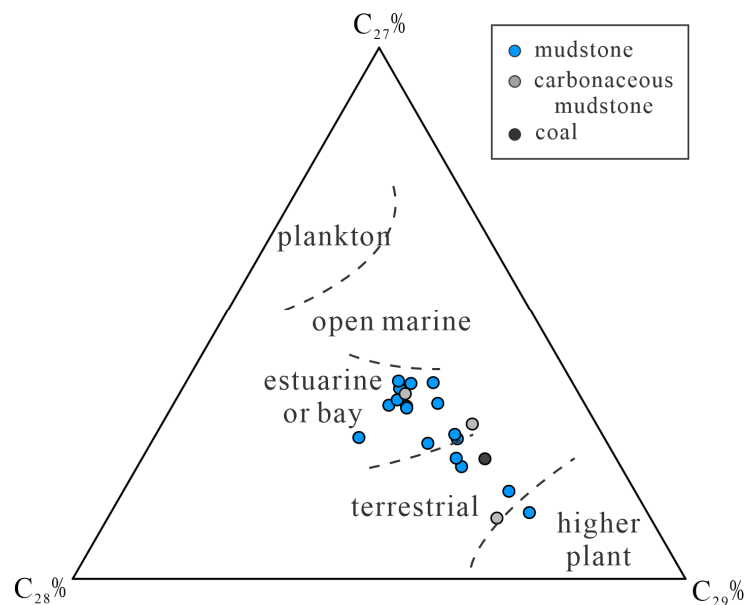


Figure 7. Ternary plot of regular steranes, showing the normalized abundance of C_{27} , C_{28} and C_{29} sterane isomers and their depositional facies (after Huang and Meinschein, 1979 [37]).

Dibenzothiophene (DBT) and phenanthrene (P) in aromatic hydrocarbon parameters can indicate the depositional environment. The DBT/P ratio combined with the Pr/Ph ratio can divide the depositional environment and lithology of source rock samples, which is an effective parameter to distinguish marine and continental source rocks. Hughes et al.

(1995) [42] developed a practical approach for determining the depositional environment of crude oil and source rocks by combining the ratios of dibenzothiophene (DBT) to phenanthrene (P) and pristane to phytane. It is widely accepted that marine source rocks have high DBT values and low phenanthrene content, while continental source rocks have low DBT values and high phenanthrene content. The DBT/P ratio of coal-measure source rock samples is very low, all lower than 0.1, with an average of 0.05 (Table 1). Figure 8 shows that all of the source rock samples were deposited in a continental environment, mostly a lacustrine environment with little sulfur.

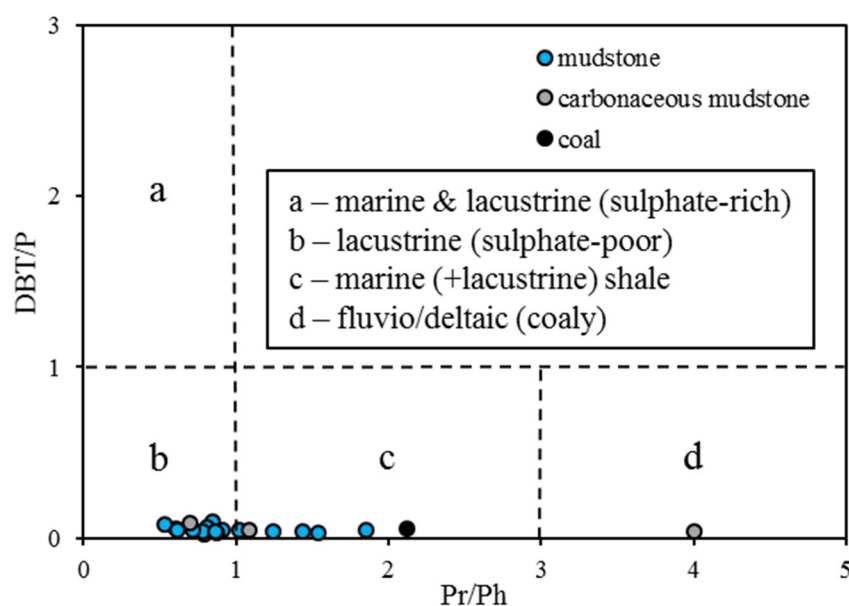


Figure 8. Cross plot of DBT/P ratios vs. Pr/Ph (after Hughes et al., 1995 [42]).

4.2.2. Source of Organic Matter

The characteristics of *n*-alkanes, pristanes and phytane in the extracts of source rocks can reflect the source of organic matter. In the lacustrine samples with low maturity, the higher content of *n*-alkanes with small carbon numbers may indicate that organic matter comes from lower hydrobiotics, while the higher content of *n*-alkanes with large carbon numbers or odd-even predominance may indicate that the organic matter may come from terrestrial higher plants [43].

It is common practice to identify the origin of organic materials in source rocks using isoprenoids and *n*-alkanes. Al-Areeq et al. (2015) [44] used the Ph/*n*C₁₈ versus Pr/*n*C₁₇ cross plot to characterize the source of organic matter in source rocks and oil, achieving good result. The relationship between Ph/*n*C₁₈ and Pr/*n*C₁₇ reflects the fact that higher terrestrial plants and a mixture of terrestrial and algae are the sources of organic matter (Figure 9).

An important metric used to identify the source of organic matter in source rocks is the abundance ratio of sterane [37,45]. Previous scholars believe that C₂₇ steranes mainly come from algae, low C₂₈ steranes characterize the lacustrine depositional environment, and C₂₉ steranes mainly come from terrestrial higher plants or cyanobacteria [37,46]. The relative content of C₂₉ sterane in the sample is high, which indicates that the source of organic matter is mainly terrestrial higher plants. As shown in the Figure 10, the source of organic matter is higher plants and the mixed source of higher plants and plankton.

The ratio of C₂₄ tetracyclic terpane to C₂₆ tricyclic terpane (C₂₄Te/C₂₆TT) is correlated with the input of terrestrial organic matter. High terrestrial organic matter contribution is indicated by high C₂₄Te/C₂₆TT ratios [30]. The C₂₄Te/C₂₆TT ratio of dark mudstone samples is between 0.34 and 5.77, with an average of 1.40, which is positively correlated with the Pr/Ph value (Figure 11).

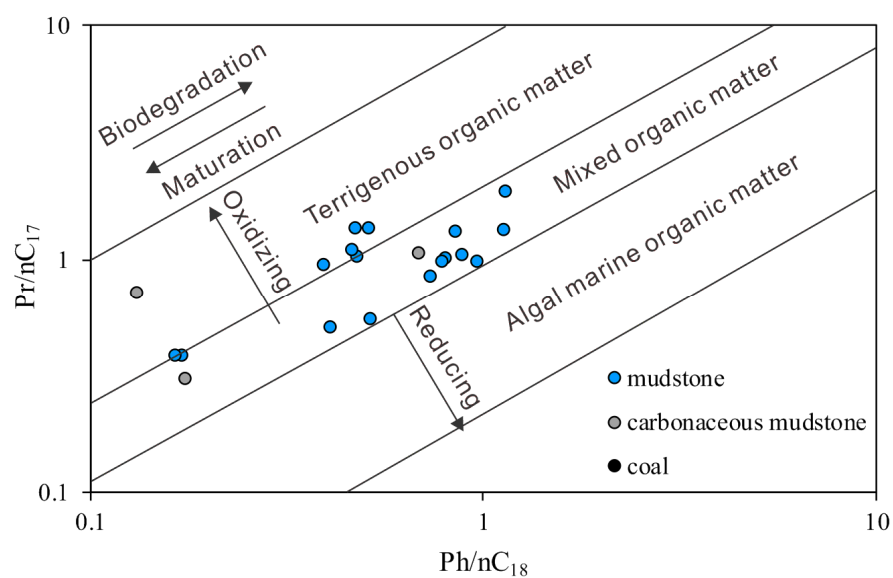


Figure 9. Cross plot of Pr/nC_{17} vs. Ph/nC_{18} for coal-measure source rocks (after Al-Areeq et al., 2015 [44]).

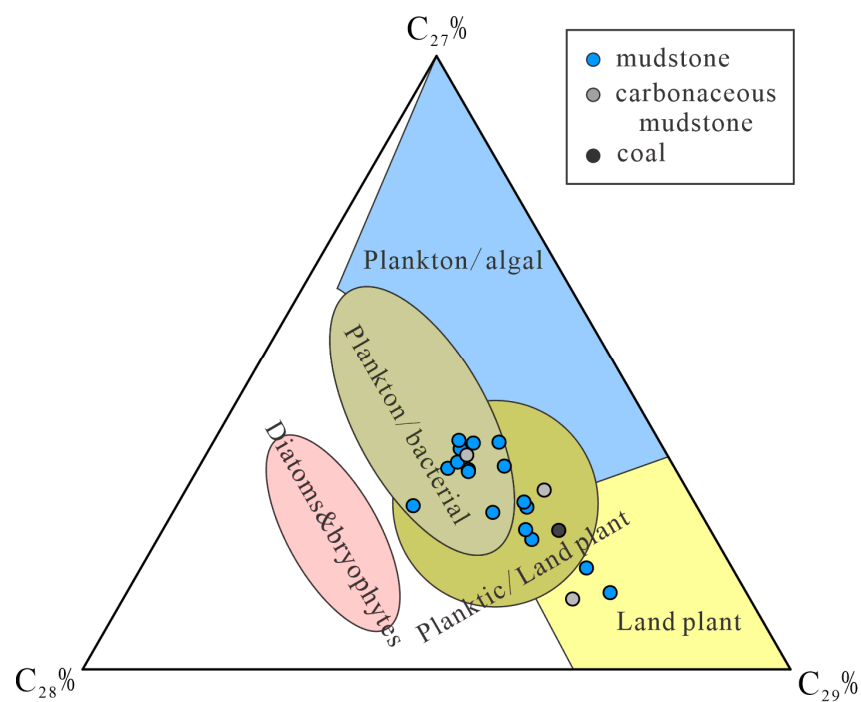


Figure 10. Ternary diagram of regular steranes (C_{27} , C_{28} and C_{29}) showing the relationship between sterane compositions and organic matter input (modified after Huang and Meinschein, 1979 [37]).

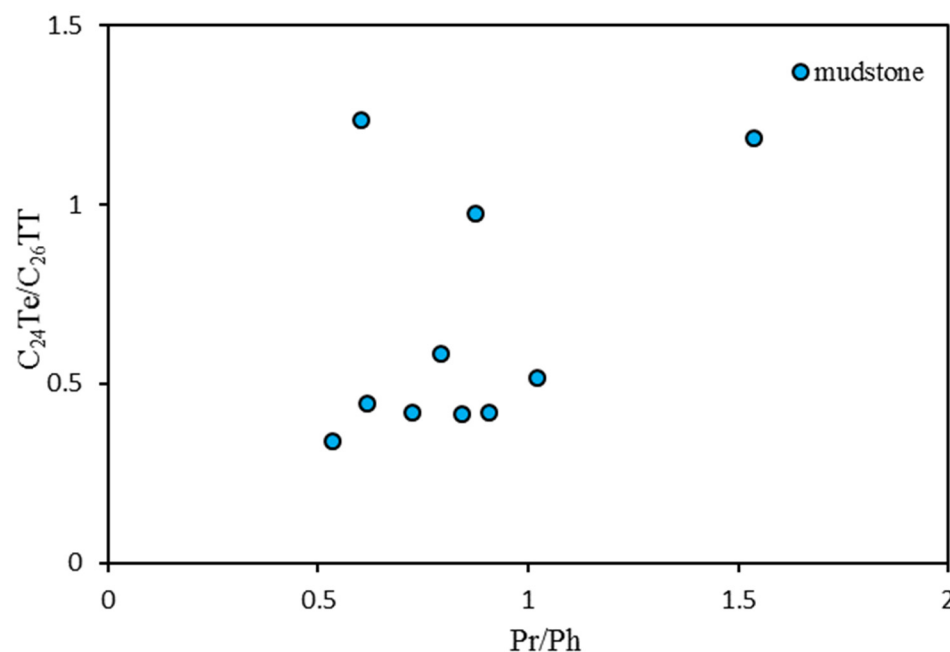


Figure 11. Relationship between $C_{24}Te/C_{26}TT$ and Pr/Ph for coal-measure source rock.

4.3. Controlling Factors of Source Rock Development

The development environment of coal-measure source rocks is different from that of deep–semideep lacustrine facies source rocks. Deep–semideep lacustrine facies source rocks are mainly developed in an anoxic reducing environment with good preservation conditions, and the organic matter mainly comes from phytoplankton and algae. However, coal-measure source rocks are mainly developed in an oxidational shallow water environment, and the organic matter is mainly from terrestrial higher plants (Figure 12). Therefore, the factors that control the development of coal-measure source rocks cannot simply be equal to lacustrine source rocks.

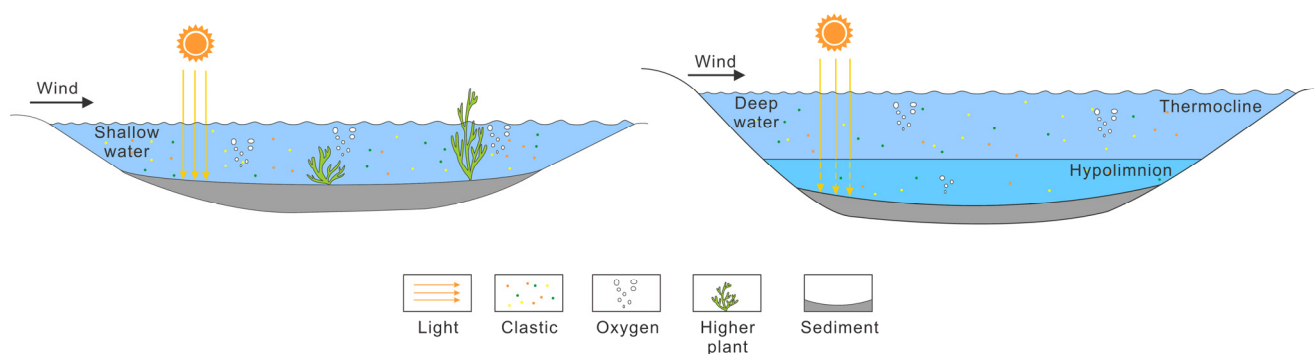


Figure 12. Schematic diagram of shallow and deep water environment.

Since the organic matter of coal-measure source rocks mainly comes from terrestrial higher plants, there should be a certain correlation between the biomarker parameters that characterize higher plants and TOC. C_{29} sterane and $C_{24}Te/C_{26}TT$ can both characterize terrestrial higher plants, and make their own cross plots with TOC. It is found that in the coal, carbonaceous mudstone and low TOC ($TOC < 3\%$) dark mudstone samples, C_{29} sterane content demonstrates good correlation with TOC (Figures 13 and 14). However, in dark mudstone samples with high TOC ($3\text{ wt.}\% < TOC < 6\text{ wt.}\%$), C_{29} sterane content has poor correlation with TOC (Figure 13). The specific reasons need to be studied. The cross plot of the $C_{24}Te/C_{26}TT$ ratios to TOC for dark mudstone also have a similar law (Figure 15). In general, the abundance of organic matter in coal-measure source rocks is positively correlated with the input of terrestrial higher plant organic matter.

Because the TOC of carbonaceous mudstone and coal is large and that of dark mudstone is small, the distance between them when they appear on the linear coordinate axis at the same time is very different. In addition, the number of samples of carbonaceous mudstone and coal is very small, so it is difficult to find systematic rules in the figure. Therefore, we only discuss the factors that affect the development of dark mudstone source rocks in the following paragraphs.

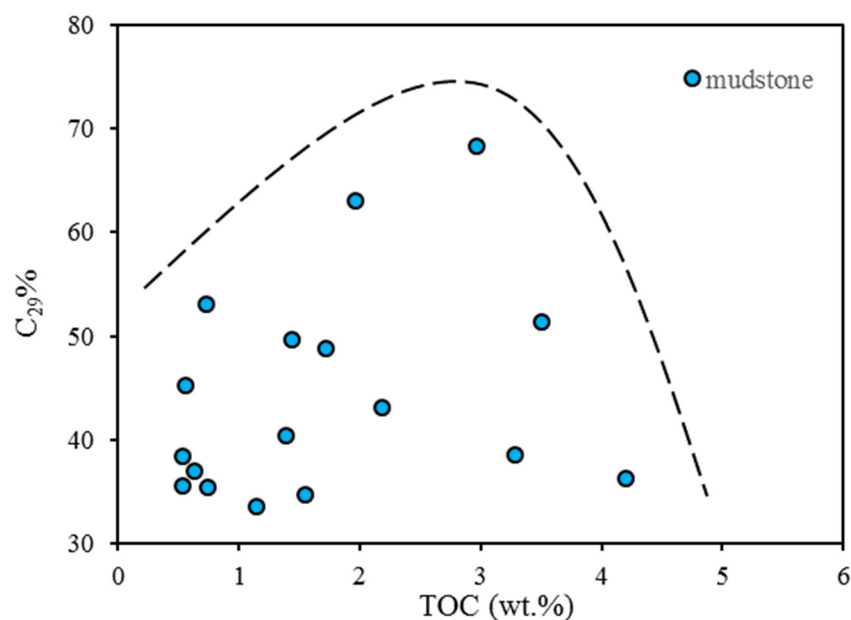


Figure 13. Relationship between C₂₉ sterane content and TOC for dark mudstone.

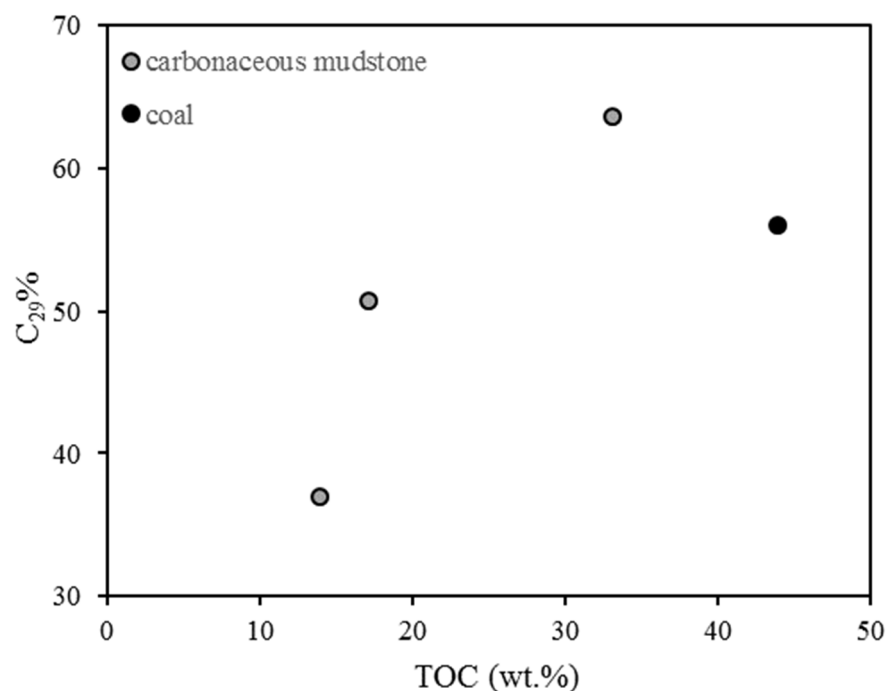


Figure 14. Relationship between C₂₉ sterane content and TOC for carbonaceous mudstone and coal.

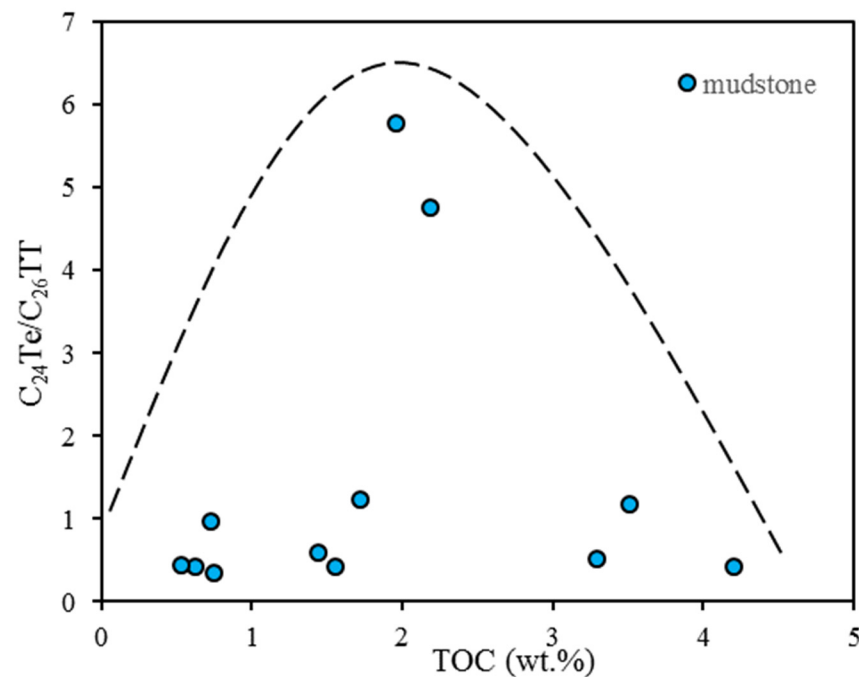


Figure 15. Relationship between $C_{24}Te/C_{26}TT$ and TOC for dark mudstone.

Since the organic matter of coal-measure source rocks mainly comes from terrestrial higher plants, we have reason to believe that the environment suitable for the development of higher plants is also suitable for coal-measure source rocks. The environment suitable for the development of higher plants is the shallow water environment with low salinity. The gammacerane index of dark mudstone is cross plotted with TOC, and it is found that there is a good negative correlation between them when TOC is low ($TOC < 3$ wt.%) (Figure 16), indicating that the low salinity environment controls the development of coal-measures source rocks.

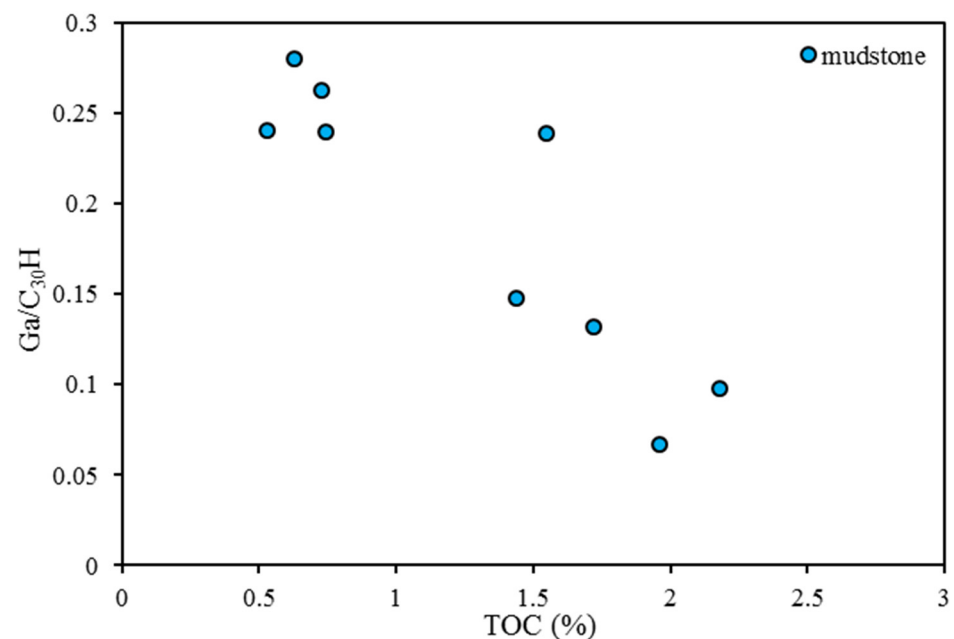


Figure 16. Relationship between $Ga/C_{30}H$ and TOC for coal-measure source rocks.

The shallow water environment is turbulent, with high oxygen content and strong oxidation (Figure 12), which seems to be detrimental to the preservation and enrichment

of organic matter. However, after drawing the cross plot of Pr/Ph to TOC, we found that the TOC of most dark mudstone increases with the increase in Pr/Ph value (Figure 17), indicating that the partial oxidation environment is more advantageous to the enrichment of organic matter in coal-measure source rocks. This demonstrates that the factors that influence the development of deep–semideep lacustrine facies source rocks and coal-measure source rocks are distinct.

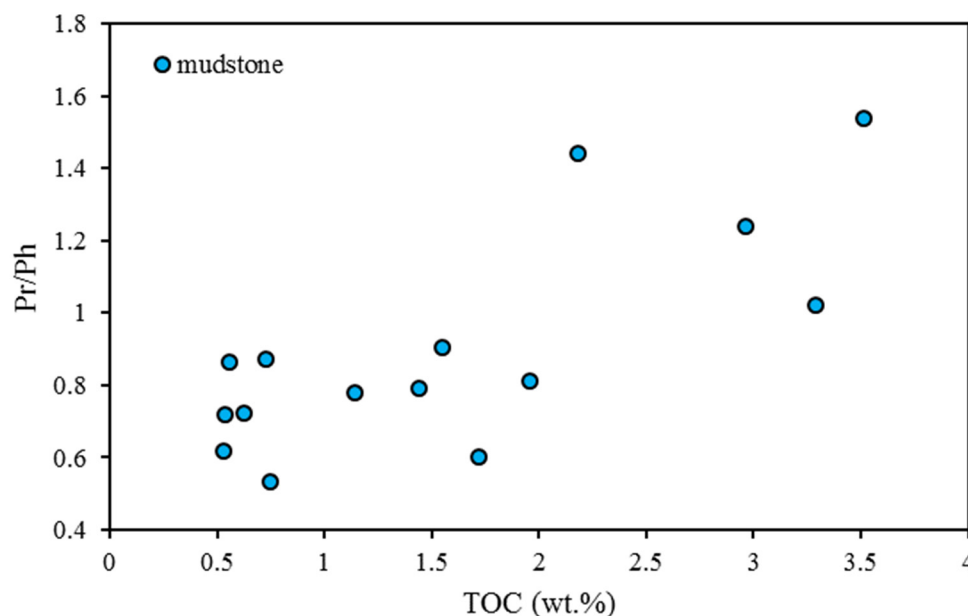


Figure 17. Relationship between Pr/Ph and TOC for coal-measure source rocks.

5. Conclusions

The geochemical characteristics and depositional environment of coal-measure source rocks in the northern tectonic belt are inferred based on the analysis of geochemistry and biomarkers, and the following findings are made.

- (1) The abundance of coal-measure source rocks is high, which means that the samples are good to excellent source rocks as a whole. Organic matter is predominantly classified as type III and occasionally type II.
- (2) Low S/C ratio, low gammacerane index, high C₂₉ sterane content, and very low DBT/P ratio are characteristics of the coal-measure source rocks. Combined with the depositional environment of isoprenoids and regular steranes and the division chart of organic matter sources, 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) Under certain conditions, the higher the degree of oxidation, the lower the salinity and the more terrestrial organic matter input are more advantageous to the enrichment of organic matter in coal-measure source rocks.

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