Research Article

Fengyu Sun, Gaoshe Cao*, Zhou Xing, Shuangjie Yu, and Bangbang Fang

Characteristics and evaluation of the Upper Paleozoic source rocks in the Southern North China Basin

https://doi.org/10.1515/geo-2020-0221
received August 1, 2020; accepted January 8, 2021

Abstract: The Upper Paleozoic coal measure strata in the Southern North China Basin have good potential for unconventional oil and gas exploration. However, there has been no systematic evaluation of potential source rock in this area; this affects the estimation of potential resources and the choice of exploratory target layers. In this study, full core holes ZK0901 and ZK0401, which perfectly reveal Upper Paleozoic strata in the study area, systematically collected and analyzed the samples for total organic carbon, rock pyrolysis, chloroform bitumen "A," organic maceral, vitrinite reflectance, and kerogen carbon isotopes. The results showed that in addition to coal rocks, mudstones and carbonate rocks are also potential source rocks in the Upper Paleozoic strata. Vertically, the source rocks are continuous in Taiyuan Formation, the lower part of Shanxi Formation, and Lower Shihezi Formation. The organic matter type in the Upper Paleozoic coal rocks and mudstone source rock belong to type III or II. This phenomenon is mainly attributed to the special transgressive–regressive sedimentary environment of the carbonate rocks. The higher degree of thermal evolution in the Upper Paleozoic source rocks may be related to the structure or a higher paleogeothermal gradient in this area. The coal layer and its upper and lower mudstone of the Shanxi Formation and Lower Shihezi Formation are the main target layers of unconventional oil and gas exploration. The results from this study can be used as a reference for the study on potential source rock for unconventional oil and gas exploration in the Southern North China Basin.

Keywords: hydrocarbon generation potential, Upper Paleozoic, source rocks, evaluation, Southern North China Basin

*** Corresponding author: Gaoshe Cao,** Institute of Resources & Environment, Henan Polytechnic University, Jiaozuo 454000, China; Collaborative Innovation Center of Coalbed Methane and Shale Gas for Central Plains Economic Region, Henan Province, Jiaozuo 454000, China, e-mail: caogs@hpu.edu.cn, tel: +86-137-8275-9519
Fengyu Sun: Institute of Resources & Environment, Henan Polytechnic University, Jiaozuo 454000, China; State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Beijing 102249, China; Collaborative Innovation Center of Coalbed Methane and Shale Gas for Central Plains Economic Region, Henan Province, Jiaozuo 454000, China
Zhou Xing: College of Geosciences, China University of Petroleum (Beijing), Beijing 102249, China
Shuangjie Yu, Bangbang Fang: Institute of Resources & Environment, Henan Polytechnic University, Jiaozuo 454000, China

1 Introduction

The Upper Paleozoic Permo-Carboniferous strata are coal-bearing strata in the eastern part of Southern North China Basin, which is part of the Late Paleozoic coal-accumulating basin in North China and one of the main coal-producing bases in Henan Province. It has abundant coal-bed methane resources and shale gas exploratory prospects. The occurrence rate and influencing factors of coal-bed methane [1] and geological conditions giving rise to shale gas reservoir formation have been studied [2–4], but there has been no systematic evaluation of the coal measure source rock in this area, which affects the estimation of resources and the choice of exploratory target layers.

The practice and research of unconventional oil and gas exploration at home and abroad show that coal measure strata form a good source rock foundation [5–10] and can form "sandwich" structures [11,12] with both superior sources and reservoirs. As good source rocks and coal-bed methane reservoirs, previous studies have paid ample attention to coal rock [13–16]. However, the different sedimentary environments of coal measure strata can produce different types of rock. Mudstones and carbonate rocks are potential source rock [17]. While most scholars believe that coal rocks are main source rocks of coal-bed methane in the Upper Paleozoic in this area [18], they have not paid significant attention to other types of source rock. Hence, there has been no systematic evaluation of potential source rock in this area. The systematic evaluation of different types of source rock and determination of distribution strata of favorable source rock are very important for oil and gas exploration in coal measure strata [2,8,9].

In this study, full core holes ZK0901 and ZK0401 (Figure 1), which perfectly reveal Upper Paleozoic coal measure strata in the Yongcheng mining area, systematically collected samples of coal rock, mudstone, and carbonate rock vertically, and conducted organic geochemical analysis of the samples. Comprehensive evaluation of the organic matter content, organic matter type, and evolution degree of source rock was conducted. We also determined the main development horizons of the Upper Paleozoic source rock in the Yongcheng mining area and analyzed the potential for oil and gas exploration of the coal measure source rock in this area according to the regional geological characteristics.

2 Geological background

The South China North Basin, where the study area is located, belongs to the southern part of the North China Plate in the Paleozoic. On its Archean–Paleoproterozoic metamorphic basement, stable sedimentary Mesoproterozoic and Paleozoic sedimentary caprocks are generally developed. Since the Mesozoic, the internal faults of the North China Basin (the Paleozoic North China plate extent) have been developed, and the sedimentary division was obviously controlled by it. The South China North Basin is a subtectonic unit surrounded by the faults of the interior of the

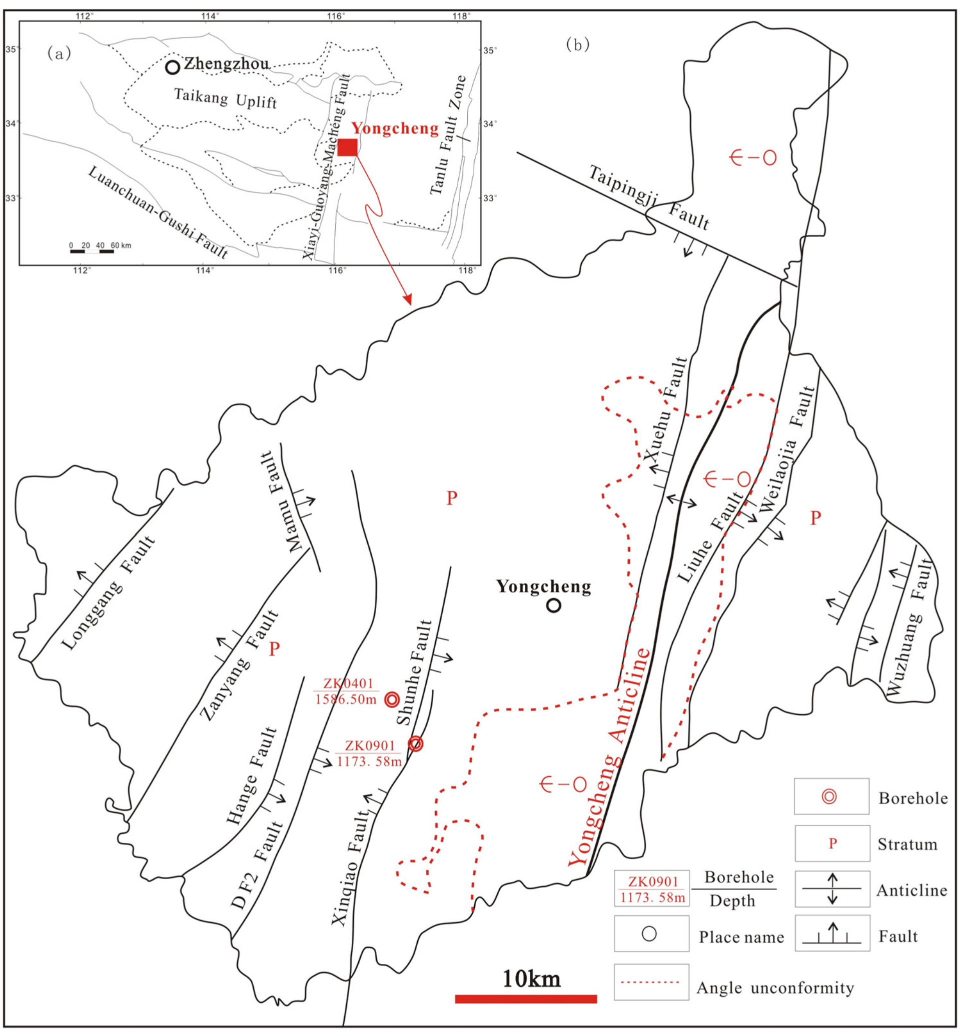

Figure 1: Geological sketch of the study area and locations of the samples. (a) Tectonic unit sketch of southern North China Basin (modified from ref. [19]); (b) geological sketch of study area (modified from ref. [20]).

North China Basin. The Yongcheng Area is located in the eastern part of the Taikang Uplift in the South China North Basin (Figure 1a) [19].

The Yongcheng Mining Area developed a series of high-angle normal faults trending in North-North-East and North-West directions, which form stepped fault blocks on both sides, and are arranged alternatively in wide and gentle anticline–syncline, thus forming the tectonic framework of this area, and controlling the occurrence and distribution of coal measure strata (Figure 1b) [19]. Due to the larger thickness and deep burial of the Upper Paleozoic in this area, the lower strata of the Upper Paleozoic (ZK0901) can be revealed only at the impact of normal faults and the uplift of the footwall, while other holes cannot reveal the lower strata. Therefore, in order to make an overall analysis of the changes in the Upper Paleozoic source rock in this area, borehole ZK0901 near borehole ZK0401 reveals the lower strata of the Upper Paleozoic as a complement, ZK0901 and ZK0401 revealed Upper Carboniferous Benxi Formation (C_2b), Taiyuan Formation (C_2t), Lower Permian Shanxi Formation (P_1s), Lower Shihezi Formation (P_1x), and Middle Permian Upper Shihezi Formation (P_2s) in the Upper Paleozoic (Figure 2).

The lithology of the Benxi Formation is mainly oolitic aluminous mudstone, including hematite aggregates, with a thickness of 13.03 m. Parallel unconformity contact occurs with the underlying limestone of Middle Ordovician Majiagou Formation (O_2m). The lithology of Taiyuan Formation is mainly composed of limestone, silty mudstone, and mudstone and thin coal bed with a thickness of 70.20 m. It can be divided into lower limestone member, middle clastic rock member, and upper limestone member. The lithology of Shanxi Formation is dominated by mudstone and silty mudstone, followed by sandstone, with a thickness of 51.32 m. The first coal bed (II_2), with a thickness of 4.48 m, is rich in plant fossil fragments. The lithology of Lower Shihezi Formation is mainly composed of aluminous mudstone, mudstone, sandy mudstone, and thin coal bed, with a smaller thickness of 51.07 m. The lithology of Upper Shihezi Formation is mainly composed of gray and light gray mudstone, sandy mudstone, and purple porphyry mudstone. The hole revealed a larger thickness of 656.74 m.

3 Standards for sample collection and evaluation

All mudstone and carbonate rocks with thicknesses >1.00 m had sample control. For mudstones and carbonate rocks with relatively larger thickness, the sample interval was generally <2.00 m; for coal rocks, there was also sample control. Considering previous works [8,9], the organic carbon content of coal rock can generally meet the standards of source rock. Furthermore, during the 2-year storage period of coal drill cores, the drilling unit collects more samples from coal rock, which results in less coal core preserved. Therefore, no samples were collected from all coal beds. Without the pollution of debris, drilling fluids, and other substances, the weight of the sample was generally around 1 kg, and the sample was wrapped in a sealed bag. Another 0.5 kg of the same sample was collected as a duplicate. A total of 85 samples were collected. The location and quantity of samples and sample distribution are respectively described in Figure 2 and Table 1. According to the requirements of rock pyrolysis analysis and total organic carbon (TOC) analysis on sample size, all samples were ground and passed through 80-mesh sieve to obtain samples with particle size less than 0.2 mm which can be used for organic carbon analysis. Then, the remaining samples were passed through 50-mesh sieve to obtain particles smaller than 0.5 mm for rock pyrolysis analysis. The samples were sliced and polished before the vitrinite reflectance experiment. A series of tests were carried out on all 85 samples, including rock pyrolysis analysis, TOC analysis, vitrinite reflectance measurement, maceral observation and identification, and argon ion polishing. The experimental instruments are YY-3000A rock pyrolysis instrument, DM LPWITH MSP200 vitrinite reflectance tester, Leica DM4500P research microscope, and PECSII Model685 argon ion polisher. Sample testing was mainly completed by Sinopec Zhongyuan Oilfield Petroleum Geology and Experiment Center and Henan Oilfield Geological Laboratory.

Due to the special sedimentary environment and parent material composition of the coal measure strata, the effective carbon content for oil and gas in the organic matter was relatively low. When evaluating coal measure source rock, we neither simply apply the general evaluation criteria for organic matter abundance of lacustrine mudstone nor improve the evaluation criteria for organic matter abundance, so as to determine other corresponding evaluation and classification criteria. Therefore, the evaluation criteria adopted in this study are coal measure mudstone and carbonaceous mudstone [21], which are different from carbonate rocks [22]. The kerogen-type index (KTI) is calculated based on the percentage of kerogen organic macerals, which is a key parameter to evaluate organic matter type. KTI = (sapropelinite% × 100 + exinite% × 50 − vitrinite% × 75 − inertinite% × 100)/100 [23]. According to KTI, organic matter types can be divided into four types, namely, type I with KTI larger than 80,

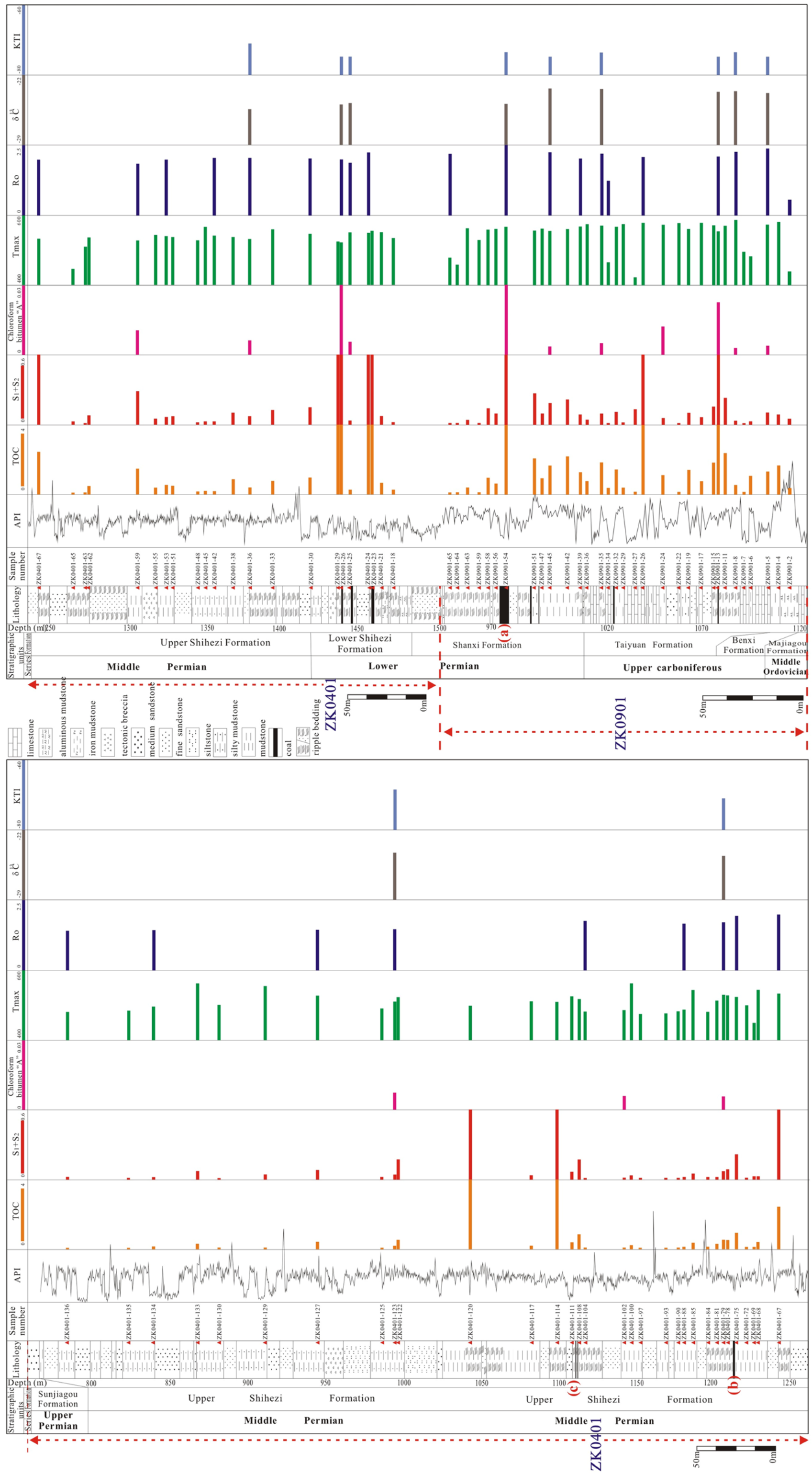

Figure 2: Synthetic histogram of locations and organic geochemical parameters of coal-bearing strata in the study area based on the samples.

type II_1 with KTI between 40 and 80, type II_2 with KTI between 0 and 40, and type III with KTI less than 0 [23].

The kerogen isotope, such as carbon isotope, has a strong inheritance and does not change much with maturity,

Table 1: Organic geochemical parameters of different coal-bearing layers in the study area based on the samples

Sample number	Depth (m)	Horizon	Lithology	TOC (%)	S_1 (mg/g)	S_2 (mg/g)	$S_1 + S_2$ (mg/g)	Chloroform bitumen "A" (mg/g)	T_{max} (°C)	Ro (%)	$\delta^{13}C$ (‰)
ZK0401-136	786.79	Upper Shihezi Formation	Mudstone	0.12	0.00	0.02	0.02		481	1.3966	
ZK0401-135	824.97	Upper Shihezi Formation	Mudstone	0.06	0.00	0.01	0.01		485		
ZK0401-134	841.11	Upper Shihezi Formation	Mudstone	0.16	0.00	0.02	0.02		497	1.4177	
ZK0401-133	869.62	Upper Shihezi Formation	Mudstone	0.37	0.00	0.09	0.09		566		
ZK0401-130	883.40	Upper Shihezi Formation	Mudstone	0.08	0.00	0.01	0.01		502		
ZK0401-129	913.34	Upper Shihezi Formation	Mudstone	0.17	0.01	0.04	0.05		559		
ZK0401-127	947.04	Upper Shihezi Formation	Mudstone	0.52	0.00	0.10	0.10		530	1.4370	
ZK0401-125	988.62	Upper Shihezi Formation	Mudstone	0.07	0.00	0.02	0.02		491		
ZK0401-123	997.22	Upper Shihezi Formation	Mudstone	0.21	0.01	0.04	0.05	0.0070	512	1.4581	−22.66
ZK0401-122	998.02	Upper Shihezi Formation	Mudstone	0.67	0.03	0.19	0.22		525		
ZK0401-120	1042.15	Upper Shihezi Formation	Carbonaceous mudstone	16.10	0.19	10.21	10.40		499		
ZK0401-117	1085.57	Upper Shihezi Formation	Mudstone	0.22	0.00	0.04	0.04		513		
ZK0401-114	1104.07	Upper Shihezi Formation	Carbonaceous mudstone	6.19	0.04	1.42	1.46		511		
ZK0401-111	1111.91	Upper Shihezi Formation	Mudstone	0.48	0.00	0.08	0.08		528		
ZK0401-108	1115.66	Upper Shihezi Formation	Carbonaceous mudstone	1.10	0.01	0.21	0.22		519		
ZK0401-104	1120.22	Upper Shihezi Formation	Mudstone	0.08	0.00	0.01	0.01		482	1.7452	
ZK0401-102	1145.31	Upper Shihezi Formation	Mudstone	0.07	0.00	0.01	0.01	0.0056	487		
ZK0401-100	1149.95	Upper Shihezi Formation	Mudstone	0.26	0.00	0.04	0.04		567		
ZK0401-97	1155.64	Upper Shihezi Formation	Mudstone	0.06	0.00	0.01	0.01		475		

Table 1: Continued

Sample number	Depth (m)	Horizon	Lithology	TOC (%)	S_1 (mg/g)	S_2 (mg/g)	$S_1 + S_2$ (mg/g)	Chloroform bitumen “A” (mg/g)	T_{max} (°C)	Ro (%)	$\delta^{13}C$ (‰)
ZK0401-93	1172.39	Upper Shihezi Formation	Mudstone	0.06	0.00	0.01	0.01		477		
ZK0401-90	1180.22	Upper Shihezi Formation	Mudstone	0.07	0.00	0.01	0.01		483		
ZK0401-88	1183.52	Upper Shihezi Formation	Mudstone	0.13	0.00	0.02	0.02		488	1.6369	
ZK0401-85	1189.74	Upper Shihezi Formation	Mudstone	0.45	0.00	0.06	0.06		547		
ZK0401-84	1199.32	Upper Shihezi Formation	Mudstone	0.14	0.00	0.02	0.02		481		
ZK0401-81	1205.13	Upper Shihezi Formation	Mudstone	0.36	0.00	0.02	0.02		515		
ZK0401-79	1209.93	Upper Shihezi Formation	Mudstone	0.67	0.00	0.09	0.09	0.0053	532	1.6946	−23.02
ZK0401-78	1211.53	Upper Shihezi Formation	Mudstone	0.66	0.00	0.11	0.11		531		
ZK0401-75	1217.87	Upper Shihezi Formation	Carbonaceous mudstone	1.20	0.01	0.27	0.28		526	1.9277	
ZK0401-72	1224.25	Upper Shihezi Formation	Mudstone	0.13	0.00	0.01	0.01		501		
ZK0401-69	1229.15	Upper Shihezi Formation	Mudstone	0.12	0.00	0.03	0.03		448		
ZK0401-68	1231.30	Upper Shihezi Formation	Mudstone	0.50	0.00	0.03	0.03		548		
ZK0401-67	1244.78	Upper Shihezi Formation	Carbonaceous mudstone	3.20	0.01	0.63	0.64		536	1.9738	
ZK0401-65	1267.24	Upper Shihezi Formation	Mudstone	0.08	0.00	0.03	0.03		445		
ZK0401-63	1275.09	Upper Shihezi Formation	Mudstone	0.09	0.00	0.01	0.01		512		
ZK0401-62	1278.38	Upper Shihezi Formation	Sandstone	0.59	0.00	0.10	0.10		540		
ZK0401-59	1308.82	Upper Shihezi Formation	Carbonaceous mudstone	1.91	0.01	0.36	0.37	0.0104	531	1.8305	
ZK0401-55	1320.49	Upper Shihezi Formation	Mudstone	0.47	0.00	0.06	0.06		547		
ZK0401-53	1327.60	Upper Shihezi Formation	Mudstone	0.67	0.00	0.08	0.08		544	1.9716	

Table 1: Continued

Sample number	Depth (m)	Horizon	Lithology	TOC (%)	S_1 (mg/g)	S_2 (mg/g)	$S_1 + S_2$ (mg/g)	Chloroform bitumen "A" (mg/g)	T_{max} (°C)	Ro (%)	$\delta^{13}C$ (‰)
ZK0401-51	1331.80	Upper Shihezi Formation	Mudstone	0.60	0.00	0.09	0.09		541		
ZK0401-48	1347.47	Upper Shihezi Formation	Mudstone	0.17	0.00	0.02	0.02		532		
ZK0401-45	1352.54	Upper Shihezi Formation	Mudstone	0.22	0.00	0.03	0.03		572		
ZK0401-42	1358.35	Upper Shihezi Formation	Mudstone	0.19	0.00	0.03	0.03		546	2.0348	
ZK0401-38	1370.62	Upper Shihezi Formation	Carbonaceous mudstone	1.10	0.00	0.13	0.13		541		
ZK0401-36	1379.47	Upper Shihezi Formation	Mudstone	0.48	0.01	0.08	0.09	0.0059	535	2.0406	−23.96
ZK0401-33	1395.96	Upper Shihezi Formation	Mudstone	0.98	0.01	0.15	0.16		564		
ZK0401-30	1420.28	Lower Shihezi Formation	Mudstone	1.24	0.01	0.18	0.19		551	2.0161	
ZK0401-29	1438.52	Lower Shihezi Formation	Carbonaceous mudstone	24.30	0.09	6.98	7.07		528		
ZK0401-26	1444.21	Lower Shihezi Formation	Coal	37.70	0.11	11.84	11.95	0.0393	525	1.9774	−23.42
ZK0401-25	1446.00	Lower Shihezi Formation	Mudstone	0.31	0.00	0.04	0.04	0.0053	555	1.8592	−27.33
ZK0401-24	1457.65	Lower Shihezi Formation	Carbonaceous mudstone	14.60	0.03	2.52	2.55		553	2.2281	
ZK0401-23	1462.70	Lower Shihezi Formation	Coal	46.90	0.19	1.51	1.70		560		
ZK0401-21	1466.48	Lower Shihezi Formation	Mudstone	0.84	0.00	0.09	0.09		556		
ZK0401-18	1473.79	Lower Shihezi Formation	Mudstone	0.31	0.00	0.02	0.02		538		
ZK0901-65	918.86	Shanxi Formation	Silty mudstone	0.09	0.00	0.01	0.01		478	2.1641	
ZK0901-64	923.11	Shanxi Formation	Silty mudstone	0.11	0.00	0.01	0.01		457		
ZK0901-63	933.44	Shanxi Formation	Mudstone	0.47	0.00	0.05	0.05		563		
ZK0901-59	945.15	Shanxi Formation	Aluminous mudstone	0.12	0.00	0.01	0.01		529		
ZK0901-58	956.12	Shanxi Formation	Silty mudstone	1.22	0.01	0.17	0.18		560		
ZK0901-56	963.97	Shanxi Formation	Mudstone	0.78	0.01	0.11	0.12		562		
ZK0901-54	975.80	Shanxi Formation	Coal	60.10	0.44	7.67	8.11	0.0957	568	2.4990	−24.95
ZK0901-51	986.15	Shanxi Formation	Mudstone	2.69	0.01	0.34	0.35		557		

Table 1: Continued

Sample number	Depth (m)	Horizon	Lithology	TOC (%)	S_1 (mg/g)	S_2 (mg/g)	$S_1 + S_2$ (mg/g)	Chloroform bitumen "A" (mg/g)	T_{max} (°C)	Ro (%)	$\delta^{13}C$ (‰)
ZK0901-47	992.56	Shanxi Formation	Mudstone	1.17	0.01	0.11	0.12		563		
ZK0901-45	994.56	Shanxi Formation	Mudstone	2.14	0.00	0.24	0.24	0.0033	556	2.2221	−23.41
ZK0901-42	1001.81	Shanxi Formation	Mudstone	2.83	0.01	0.27	0.28		562		
ZK0901-39	1007.97	Shanxi Formation	Mudstone	1.63	0.01	0.10	0.11		569	1.9924	
ZK0901-36	1012.97	Taiyuan Formation	Mudstone	0.97	0.00	0.05	0.05		576		
ZK0901-35	1019.97	Taiyuan Formation	Mudstone	2.39	0.00	0.12	0.12	0.0048	571	2.1705	−23.45
ZK0901-34	1022.27	Taiyuan Formation	Limestone	0.45	0.00	0.01	0.01		464	1.2111	
ZK0901-32	1027.60	Taiyuan Formation	Mudstone	1.83	0.01	0.13	0.14		568		
ZK0901-29	1031.40	Taiyuan Formation	Mudstone	0.47	0.00	0.02	0.02		576		
ZK0901-27	1035.92	Taiyuan Formation	Limestone	0.15	0.01	0.16	0.17		421		
ZK0901-26	1040.72	Taiyuan Formation	Limestone	7.53	0.03	0.90	0.93		580	2.0551	
ZK0901-24	1047.85	Taiyuan Formation	Mudstone	1.42	0.00	0.07	0.07	0.0119	574		
ZK0901-22	1052.01	Taiyuan Formation	Mudstone	0.15	0.00	0.01	0.01		579		
ZK0901-19	1064.17	Taiyuan Formation	Silty mudstone	1.82	0.00	0.13	0.13		562		
ZK0901-17	1070.25	Taiyuan Formation	Limestone	0.96	0.01	0.07	0.08		580		
ZK0901-15	1077.01	Taiyuan Formation	Mudstone	2.36	0.01	0.19	0.20		572		
ZK0901-13	1078.15	Taiyuan Formation	Coal	59.10	0.36	7.67	8.03	0.0224	554	2.0644	−23.73
ZK0901-11	1082.36	Taiyuan Formation	Mudstone	3.09	0.01	0.29	0.30		571		
ZK0901-8	1087.16	Taiyuan Formation	Mudstone	0.68	0.01	0.03	0.04	0.0026	588	2.2347	−23.67
ZK0901-7	1090.00	Taiyuan Formation	Limestone	0.15	0.00	0.01	0.01		495		
ZK0901-6	1093.65	Taiyuan Formation	Mudstone	1.37	0.01	0.02	0.03		482		
ZK0901-5	1105.20	Taiyuan Formation	Limestone	1.69	0.01	0.12	0.13	0.0036	574	2.3563	−28.64
ZK0901-4	1108.71	Benxi Formation	Mudstone	2.15	0.00	0.11	0.11		582		
ZK0901-2	1114.84	Benxi Formation	Mudstone	0.43	0.01	0.05	0.06		438		

which is a relatively stable indicator. The carbon isotopes of kerogen provide a basis for the evaluation of kerogen types for the source rocks with the high-mature to over-mature stage. According to the isotope values, kerogen types can be divided into three types, namely, type III with $\delta^{13}C$ larger than −25‰, type II with $\delta^{13}C$ between −26.5 and −25‰, and type I with $\delta^{13}C$ less than −26.5‰ [23].

4 Results

All samples were analyzed for TOC and rock pyrolysis, and representative samples were selected for analysis to obtain the parameters of chloroform bitumen "A," organic maceral, vitrinite reflectance, and kerogen carbon isotopes. The results are shown in Table 1.

4.1 Organic matter abundance

4.1.1 TOC content

In ZK0901, the TOC of the mudstone in Benxi Formation varies from 0.43 to 2.15%, with an average of 1.29% (2) (Note: The content in the parentheses after the average value represents the sample size), which is a poor source rock with a controlling thickness of 8.58 m (Table 2); the TOC of the mudstone in Taiyuan Formation varies from 0.15 to 3.09%. Among them, the mudstone of minimum TOC is aluminous mudstone with a controlling thickness of 3.05 m, not included in the average calculation. The average value of the other mudstone is 1.64% (10), which is medium source rock with a controlling thickness of 40.76 m. The TOC of the carbonate rock varies from 0.15 to 7.53%, with an average of 1.82% (6), which is medium-good source rock with a controlling thickness of 41.65 m. The TOC of the coal rock is 59.10%, which is good source rock, with a controlling thickness of 1.00 m; the TOC of the coal rock in Shanxi Formation is 60.10%, which is good source rock with a controlling thickness of 5.11 m. Bounded by the upper mudstones of II_2 coal bed (Figure 2a) (including these mudstones), the TOC of the lower mudstone varies from 0.78 to 2.69%, with an average of 1.78% (7), which is medium source rock with a controlling thickness of 51.54 m. The TOC of the upper mudstone varies from 0.09 to 0.47%, with an average of 0.20% (4), which does not meet the standards of source rock.

In ZK0401, the TOC of mudstones in Lower Shihezi Formation varies from 0.31 to 1.24%, with an average of 0.68% (4), which is nonsource rock and poor source rock with a controlling thickness of 12.66 m; the TOC of the carbonaceous mudstones varies from 14.60 to 24.30%, with an average of 19.45% (2), which is good source rock with a controlling thickness of 3.35 m. The TOC of the coal rock varies from 37.70 to 46.90%, with an average of 42.30% (2), which is good source rock with a controlling thickness of 4.04 m; the TOC of the carbonaceous mudstone of Upper Shihezi Formation varies from 6.19 to 16.10%, with an average of 11.15% (2), which is medium-good source rock with a controlling thickness of 44.01 m. The higher TOC of the mudstone varies from 1.10 to 3.20%, with an average of 1.42% (5), which is poor source rock with a controlling thickness of 39.27 m. The TOC of the other mudstone varies from 0.06 to 0.98%, with an average of 0.30% (38), which is nonsource rock.

Only in terms of TOC, source rock of ZK0901-ZK0401 is mainly developed in the lower part of the Upper Paleozoic (i.e., horizons below II_2). Coal rock, mudstone, and carbonate rock are all potential source rock in the Upper Paleozoic and are continuous with a controlling thickness of 148.64 m. Besides K_4 mudstone and sandstone in the lower part of Lower Shihezi Formation, the mudstone and carbonaceous mudstone of Lower Shihezi Formation generally meet the standards of source rock, with a controlling thickness of 20.05 m. In Upper Shihezi Formation, the carbonaceous mudstone meets the standards of source rock, and there are mudstone members with TOCs greater than 0.75% that are mainly developed in coal members 5 and 6 (Figure 2b and c), or nearby the coal bed, with a controlling thickness of 83.28 m.

4.1.2 Hydrocarbon potential ($S_1 + S_2$) and chloroform bitumen "A"

Hydrocarbon potential ($S_1 + S_2$) of mudstone in Benxi Formation at bore hole ZK0901 varies from 0.06 to 0.11 mg/g, with an average of 0.09 mg/g (2); $S_1 + S_2$ of mudstone in Taiyuan Formation varies from 0.01 to 0.30 mg/g, with an average of 0.11 mg/g (11); $S_1 + S_2$ of the carbonate rock varies from 0.01 to 0.93 mg/g, with an average of 0.22 mg/g (6). $S_1 + S_2$ of the coal rock is 8.03 mg/g; $S_1 + S_2$ of coal rock in Shanxi Formation is 8.11 mg/g, and $S_1 + S_2$ of the lower mudstone varies from 0.11 to 0.35 mg/g, with an average of 0.20 mg/g (7); $S_1 + S_2$ of the upper mudstone varies from 0.01 to 0.05 mg/g, with an average of 0.02 mg/g (4). $S_1 + S_2$ of the coal rock in Lower Shihezi Formation at ZK0401 varies from 1.70 to 11.95 mg/g, with an average of 6.83 mg/g (2). $S_1 + S_2$ of the carbonaceous mudstone varies from 2.55 to

Table 2: TOC content and its controlling thickness of different rocks in coal-bearing layers in the study area based on the samples

Borehole	Horizon	Lithology	TOC range (%)	TOC average (%)	Grade of source rock	Controlling thickness (m)
ZK0401	Upper Shihezi Formation	Other mudstones	0.06–0.98	0.30 (38)	Nonsource rock	371.80
		Mudstones with higher TOC	1.10–3.20	1.42 (5)	Poor	39.27
		Carbonaceous mudstones	6.19–16.10	11.15 (2)	Medium	44.01
	Lower Shihezi Formation	Mudstones	0.31–1.24	0.68 (4)	Nonsource rock/poor source rock	12.66
		Carbonaceous mudstones	14.60–24.30	19.45 (2)	Good	3.35
		Coals	37.7–46.90	42.30 (2)	Good	4.04
ZK0901	Shanxi Formation	Upper mudstones	0.09–0.47	0.20 (4)	Nonsource rock	7.24
		Coals	60.10	60.1 (1)	Good	5.11
		Lower mudstones	0.78–2.69	1.78 (7)	Medium	51.54
	Taiyuan Formation	Coals	59.10	59.1 (1)	Good	1.00
		Carbonate	0.15–7.53	1.82 (6)	Medium	41.65
		Mudstones	0.15–3.09	1.50 (11)	Medium	40.76

The contents in the parentheses after the average value represents the sample size, the same below.

7.07 mg/g, with an average of 4.81 mg/g, while that of the mudstone varies from 0.02 to 0.19 mg/g, with an average of 0.09 mg/g; $S_1 + S_2$ of the carbonaceous mudstone in Upper Shihezi Formation varies from 1.46 to 10.40 mg/g, with an average of 5.93 mg/g, and that of the mudstone with the higher TOC varies from 0.13 to 0.64 mg/g, with an average of 0.33 mg/g (5). $S_1 + S_2$ of all other mudstone varies from 0.01 to 0.28 mg/g, with an average of 0.05 mg/g (38).

The chloroform bitumen “A” of the carbonate rock in Taiyuan Formation at bore hole ZK0901 in the Yongcheng Area is 0.0036%; the chloroform bitumen “A” of the mudstone there varies from 0.0026 to 0.0119%, with an average of 0.0064% (3), while that of the coal rocks is 0.0024%; that of the lower mudstone in Shanxi Formation is 0.0033%; and that of the coal rock is 0.0957%. The chloroform bitumen “A” of the mudstone in Lower Shihezi Formation at bore hole ZK0401 is 0.0053%; that of the coal rocks there is 0.0393%; the chloroform bitumen “A” of the mudstone in Upper Shihezi Formation varies from 0.0053 to 0.0070%, with an average of 0.0060% (4) while that of the mudstone with the higher TOC is 0.0104%.

4.2 Organic matter type

4.2.1 Organic maceral

The vitrinite of the carbonate rock in Taiyuan Formation in bore hole ZK0901 is 75.54%, dominated by euvitrinite, with 24.5% exinite and a KTI value of −44; the vitrinite of the mudstone in Taiyuan Formation is 14 and 7%, with 86 and 93% exinite and a KTI value of 33 and 44; the vitrinite of the coal rock in Taiyuan Formation is 64%, with 36% exinite and a KTI value of −30; the vitrinite of the lower mudstone in Shanxi Formation is 6%, with 94% exinite and a KTI value of 43; the vitrinite of the coal rock in Shanxi Formation is 56%, with 44% exinite and a KTI value of −20. The vitrinite of the mudstone in Lower Shihezi Formation of bore hole ZK0401 is 3%, with 97% exinite and a KTI value of 46; the vitrinite of the coal rock in Lower Shihezi Formation is 49%, with 51% exinite and a KTI value of −11; the vitrinite of the mudstone in Upper Shihezi Formation varies from 1 to 4%, with an average of 2.67% (3), and the exinite varies from 96 to 99%, with an average of 97.33% (3), and a KTI value from 45 to 49, with an average of 46.67 (3). According to the criteria for determining the organic matter type by KTI and KTI-I_H (mg/g) correlation, both the mudstone and coal rock indicated the characteristics of type II or III kerogen macerals (Table 3, Figure 3).

4.2.2 Carbon isotopes

The kerogen carbon isotope of the carbonate rock of Taiyuan Formation at bore hole ZK0901 is −28.6‰ and that of the mudstone varies from −23.7 to −23.5‰, with an average of −23.56‰ (2); that of the coal rock is −23.7‰; that of the lower mudstone of Shanxi Formation is −23.4‰ and that of the coal rock is −25.0‰. The kerogen carbon isotope of the mudstone of Lower Shihezi Formation in

Table 3: Characteristics of Kerogen organic macerals of different rock types in the coal-bearing layers in the study area, based on the samples

Sample number	Depth (m)	Horizon	Lithology	Sapropelinite (%)	Exinite (%)	Vitrinite (%)	Inertinite (%)	KTI	Type
ZK0401-123	997.22	Upper Shihezi Formation	Mudstone	0	96	4	0	45	II$_1$
ZK0401-79	1209.93	Upper Shihezi Formation	Mudstone	0	97	3	0	46	II$_1$
ZK0401-36	1379.47	Upper Shihezi Formation	Mudstone	0	99	1	0	49	II$_1$
ZK0401-26	1442.21	Lower Shihezi Formation	Coal	0	51	49	0	−11	III
ZK0401-25	1446.00	Lower Shihezi Formation	Mudstone	0	97	3	0	46	II$_1$
ZK0901-54	975.80	Shanxi Formation	Coal	0	44	56	0	−20	III
ZK0901-45	994.56	Shanxi Formation	Mudstone	0	94	6	0	43	II$_1$
ZK0901-35	1019.97	Taiyuan Formation	Mudstone	0	86	14	0	33	II$_2$
ZK0901-28	1039.72	Taiyuan Formation	Limestone	0	24	76	0	−44	III
ZK0901-13	1078.15	Taiyuan Formation	Coal	0	36	64	0	−30	III
ZK0901-8	1087.16	Taiyuan Formation	Mudstone	0	93	7	0	41	II$_1$

bore hole ZK0401 is −27.3‰ while that of the coal rock is −23.4‰; that of the mudstone of Upper Shihezi Formation varies from −24.0 to −22.7‰, with an average of −23.08‰ (2). According to the criterion for distinguishing source rock type by kerogen carbon isotopes, mudstone and coal rock in all strata are type III or II kerogen.

4.3 Thermal evolution degree of organic matter

The kerogen vitrinite reflectance (Ro) of carbonate rocks of Taiyuan Formation in bore hole ZK0901 varies from 1.21 to 2.36%, with an average of 1.84% (3), while that of the mudstone varies from 2.17 to 2.24%, with an average of 2.20% (2), and that of the coal rock is 2.06%; Ro of the lower mudstone of Shanxi Formation varies from 1.99 to 2.22%, with an average of 2.11% (2), while that of the coal rock is 2.50% and that of the upper mudstone is 2.16%. Ro of carbonaceous mudstones of Lower Shihezi Formation in bore hole ZK0401, meanwhile, is 2.23%, that of the coal rock is 2.00%, and that of the mudstone varies from 1.86 to 2.02%, with an average of 1.94% (2); Ro of the mudstone of Upper Shihezi Formation varies from 1.40 to 2.04%, with an average of 1.70% (11), and that of the mudstone with the higher TOC varies from 1.93 to 1.97%, with an average of 1.95% (2). According to the criterion for the determination of organic matter evolution degree by Ro, the evolution degree of the source rock is generally in the high-mature to over-mature stage and shows a trend toward gradual increase with depth.

The peak temperature (T_{max}) of rock pyrolysis of the mudstone of Benxi Formation in bore hole ZK0901 in the Yongcheng Area varies from 438 to 580°C, with an average of 519°C (6); T_{max} of the carbonate rock of Taiyuan Formation varies from 421 to 588°C, with an average of 529°C (7); T_{max} of the coal rock is 554°C and that of the mudstone varies from 482 to 588°C, with an average of 565°C (11); T_{max} of the lower mudstone of Shanxi Formation varies from 556 to 569°C, with an average of 561°C (7); T_{max} of the coal rock is 568°C and that of the upper mudstone varies from 457 to 563°C, with an average of 507°C (4); T_{max} of the coal rock of Lower Shihezi Formation in bore hole ZK0401 varies from 525 to 560°C, with an average of 543°C (2), while T_{max} of the carbonaceous mudstone varies from 528 to 553°C, with an average of 541°C (2) and that of the mudstone varies from 538 to 556°C, with an average of 550°C (4); T_{max} of the mudstone of Upper Shihezi Formation varies from 445 to 572°C, with an average of 517°C (38), while T_{max} of carbonaceous mudstones varies from 499 to 511°C, with an average of

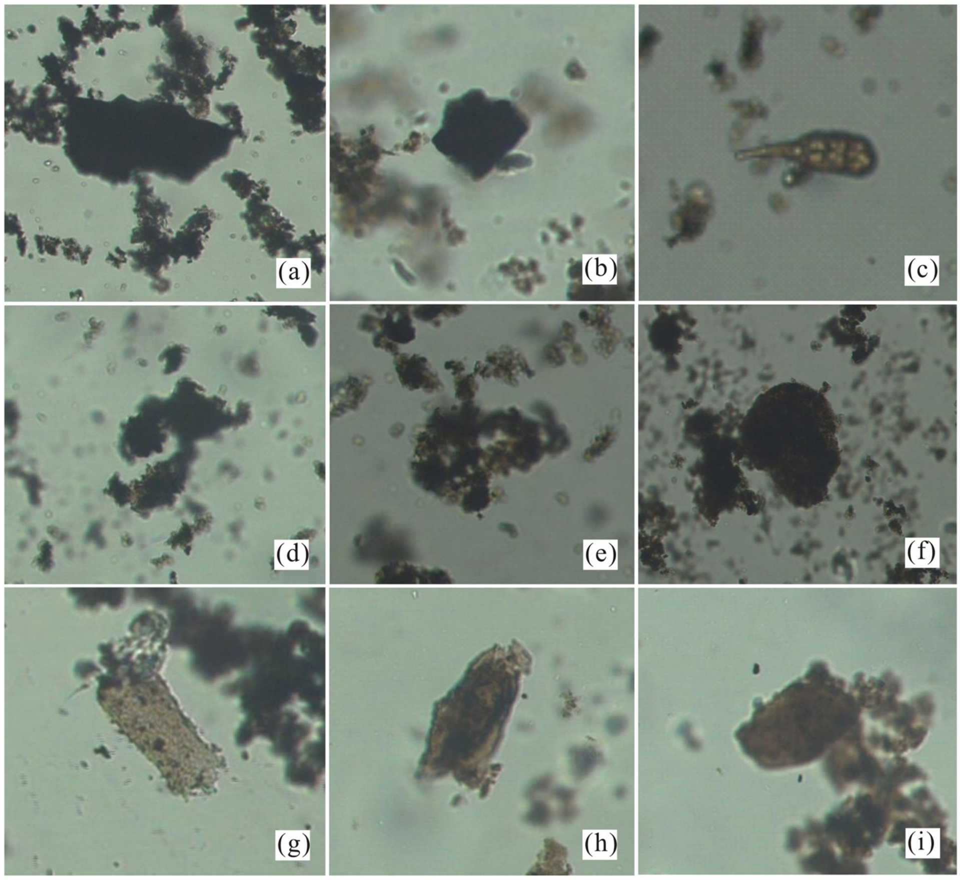

Figure 3: Kerogen organic macerals of different rocks in the coal-bearing layers in the study area based on bore holes ZK0901-ZK0401. (a) Euvitrinite in limestone of Taiyuan formation; (b) Euvitrinite in mudstone of lower Shihezi formation; (c) Fungus in mudstone of Upper Shihezi Formation; (d) Phyllovitrinite in limestone of Taiyuan formation; (e) Phyllovitrinite in mudstone of Upper Shihezi Formation; (f) Sporinite in mudstone of Upper Shihezi Formation; (g) Suberinite in mudstone of Shanxi formation; (h) Cutinite in mudstone of Upper Shihezi Formation; (i) Suberinite in mudstone of Upper Shihezi Formation.

505°C (2), and that of the mudstone with the higher TOC varies from 519 to 541°C, with an average of 531°C (4). According to the criteria for the determination of organic matter evolution degree by maximum pyrolysis temperature (T_{max}), the source rock basically indicates the characteristics of high-mature to over-mature, which is consistent with the characteristics reflected by kerogen vitrinite reflectance.

5 Discussion

5.1 Low hydrocarbon generation potential of the Upper Paleozoic source rocks

From the above analysis data, it can be seen that the hydrocarbon potential ($S_1 + S_2$) and chloroform bitumen "A" of the mudstone, carbonaceous mudstone, and coal rock at ZK0901-ZK0401 are low, and most of the samples cannot meet the standards of source rock. This major reason may be the high thermal maturity (Ro shown in Table 1), and a minor factor may be the long storage time of the core. According to the test data analysis (Table 1), which can support this finding, S_1 generally does not exceed 0.5 mg/g, remaining mostly 0 or 0.01 mg/g, and chloroform bitumen "A" is very low. In the case of deep-buried source rock with good caprock and fresh cores, higher hydrocarbon potential and chloroform bitumen "A" can be expected [8,9]. In the theory, $S_1 + S_2$ and chloroform bitumen "A" cannot be used to evaluate the organic matter content of source rock in this area; but according to the residual organic index and significant positive correlation between hydrocarbon potential ($S_1 + S_2$) and TOC (Figure 4), the hydrocarbon potential is also of significance for analyzing the quality of source rock under the same conditions.

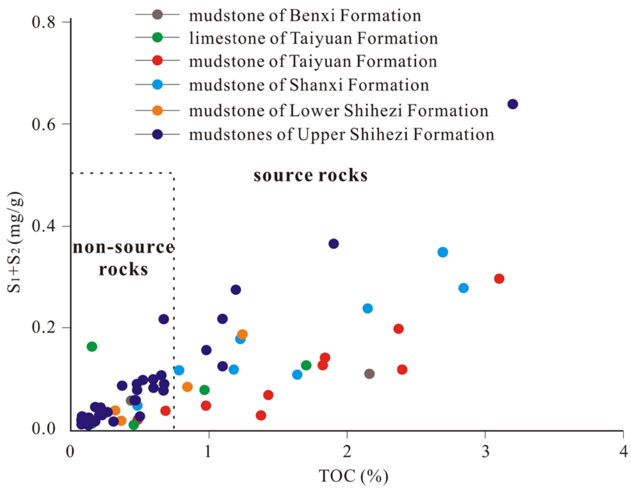

Figure 4: TOC-$S_1 + S_2$ correlation diagram of different coal-bearing layers in the study area based on the samples.

Test results of the Upper Paleozoic source rocks in the Southern North China Basin [8,9] show that coal rocks, mudstones, and carbonate rocks are all possibly potential source rocks in Upper Paleozoic. These source rocks are vertically continuous in Taiyuan Formation and in the lower part of Shanxi Formation, mainly distributed nearby coal bed with small thickness in the upper part of Shanxi Formation and XiaShihezi Formation, seldom in Shangshihezi Formation. The vertical variations and quality differences of the Upper Paleozoic source rocks may be mainly attributed to the sedimentary environment. Previous studies show that the Late Paleozoic coal-bearing stratum is a complete transgressive–regressive cycle [24], and that the thick coal rock of Shanxi Formation was formed in the transition point of a transgressive–regressive cycle. This set of strata has a stable sedimentary base for a long time and thereby have superior conditions for the formation of source rock [24]. Mudstone at the bottom of this set of strata (mainly including the lower mudstone of Benxi Formation, Taiyuan Formation, and Shanxi Formation) is developed in tidal flat environments and accompanied by sudden transgression [25,26]. Sea level frequently rises and falls, resulting in the alternating occurrences of carbonate rock and tidal flat facies mudstone so as to form the superimposition of a bioclastic limestone–mudstone–coal bed (seam), with good source rock development conditions. Subsequently, large-scale transgression developed, providing the sedimentary environment to develop source rock of Lower Shihezi Formation; Upper Shihezi Formation was mainly developed in a delta plain environment. Here, valuable coal beds were formed under discarded clastic tidal flat peat bogs, lower delta plain peat bogs, and water-covered bogs marked by coal rock (or carbonaceous mudstone). However, multiple secondary transgressions hindered the sustainable development of peat bogs. Therefore, only multilayered thin coal beds were formed [27], with smaller controlling thickness and poorer vertical continuity. Especially with the continuation of regression, the development conditions of the coal rock deteriorated gradually, generally resulting in poor source rock in Upper Shihezi Formation. According to the above analysis, the Upper Paleozoic source rock in the Southern North China Basin is dominated by coal rock and mudstone, and carbonate rock is mainly distributed in the upper and lower strata of the coal bed. Therefore, II_2 coal bed and its upper and lower mudstones in Shanxi Formation, and the thin coal rock and upper and lower mudstone of Lower Shihezi Formation are the most important source rock development horizons, followed by the coal bed (seam) of Taiyuan Formation and its nearby mudstone and carbonate rock.

The organic matter types of the Upper Paleozoic source rocks in the Yongcheng Area are mainly type III or II kerogen and kerogen macerals of mainly euvitrinite. It is found that Taiyuan Formation consists of several sedimentary sequences of limestone–fine clastic rocks. The upper limestones are mostly mudstones or siltstones with thin coal beds or carbonaceous mudstone above. The limestones of the next sedimentary sequence directly contact the coal bed or carbonaceous mudstones of the previous sedimentary sequence. The carbonate rock displays an obvious scouring structure, which is considered to be caused by frequent and sudden transgressions [28]. Therefore, the sedimentary environment of Taiyuan Formation changed rapidly during the sedimentary period and there was frequent seawater transgression–regression. For transgression, the water body deepened and the hydrodynamic force was strong, causing strong scouring to the underlying coal bed or carbonaceous mudstone. It not only interrupts coal accumulation, but also leads to the deposition of a large amount of eroded carbon debris in carbonate rocks, enriching the carbon debris in limestone and rapidly depositing it. This speculation has been confirmed by the large amount of carbon debris remaining after dilute hydrochloric acid dissolution of Taiyuan Formation limestone [17]. After rapid regression, the upper mudstones and coal beds were formed. As a result, Taiyuan Formation limestone has high organic carbon content.

5.2 High thermal evolution degree of the Upper Paleozoic source rocks

The Upper Paleozoic has basically reached the high-mature to over-mature stage, with the highest Ro of around 2.5%, increasing gradually with depth. Previous studies have shown that the thermal evolution degree of the Upper Paleozoic coal measure source rock in different regions of the Southern North China Basin is quite different [29,30]. Based on the restoration of the sedimentary and burial history in the area, through geothermal history simulation of the Upper Paleozoic and by comparing the relationship between the paleogeothermal field and the thermal evolution history in different areas of Southern North China Basin and the evolution degree of the source rock [31], it can be determined that this area had a high geothermal gradient during the Yanshanian and Himalayan periods, during which the regional magmatic thermal metamorphism played an important role in the study area [32]. In fact, it has become a common understanding that the evolution degree of the Upper Paleozoic in the Southern North China Basin varies greatly in different regions, which is also attributed to the differences in the Cenozoic geothermal gradients in different regions [31,33].

5.3 Geological process and tectonic evolution

Although this study only analyzed the basic characteristics of the Upper Paleozoic coal measure source rock in two boreholes in the study area, based on small changes of Late Paleozoic epicontinental deposits in the regional sedimentary environment, the boreholes can represent the basic characteristics and vertical distribution characteristics of the Upper Paleozoic source rocks in the Yongcheng. Tectonic and magmatic activities are frequent in the study area, especially in the Mesozoic Yanshanian period [32,34], which is characterized by folds and faults. The distribution of magmatic rocks is closely related to uplift and faults. The rock masses are basically distributed in near NNE trending anticline axes, and then invade along the weak part of the structure or soft stratum of two limbs of the anticline (mainly coal beds). However, due to the irregular intrusion of magmatic rocks, the distribution of various types of magmatic rocks cannot be accurately delineated. Aeromagnetic data show that there are a large number of magnetic anomaly areas around the study area, and it is speculated that there may be larger hidden rock masses in the deep part [32]. Vertically, Lower Shihezi Formation is more strongly intruded by magmatic rocks than Shanxi Formation. In plane, the western limb of the anticline mainly intrudes into the Shanxi Formation, while the eastern limb mainly intrudes into the Lower Shihezi Formation. Its spatial distribution is controlled by tectonics [32,35]. Strong tectonic movement and magmatic activity have had a great impact on the regional coal quality and coal body structure, which may lead to a large amount of coal-bed methane loss and affect the maturity of coal measure strata system [36,37]. However, in the study of the influence of igneous rocks on the secondary hydrocarbon generation of Carboniferous-Permian coal rocks in North China [38], it is found that magmatic rocks do participate in and affect the hydrocarbon generation of coal measure source rock. With igneous rock, the gas hydrocarbon yield of coal rocks increases by 11–28%, which has an obvious promoting effect on coal-to-gas. In addition, because of the high TOC of mudstone near the coal rock, large methane adsorption capacity and developed pores [5,39,40], the brittle mineral content in Shanxi Formation and Lower Shihezi Formation is higher, which provides good conditions for coal-formed gas accumulation and exploitation.

6 Conclusions

Coal rock, mudstone, and carbonate rock are all possible potential source rock in the Upper Paleozoic, in which the coal rock is the most important source rock. The organic matter type of coal rock and mudstone belongs to type III or II, which is related to the scouring of lower coal beds by sudden transgression.

The thermal evolution degree of the Upper Paleozoic source rock has reached high-mature to over-mature stage and increases gradually with depth. The phenomenon may be related to the high geothermal gradient in the Southern North China Basin.

The coal layer and its upper and lower mudstone are the main target layers of unconventional oil and gas exploration, which is highly useful in finding potential advantaged exploration area.

Acknowledgments: This research was funded by Investigation and Appraisal of Oil and Gas Strategic Areas throughout China (Grant No. 1211302108023-2) and State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Beijing (Grant No. PRP/open-1809).

References

[1] Lei CL, Liu CY. Reformed pattern of coal reservoirs in reformed coal basins and effect on favorable blocks of coalbed gas in the North China craton. Coal Geol Explor. 2004;2:20–3.

[2] Qu XR, Zhu YM, Li W, Tang X, Zhang H. Evaluation of hydrocarbons generated from the Permo-Carboniferous source rocks in Huanghua depression of the Bohai Bay Basin, China. Energ Explor Exploit. 2018;36(5):1229–44.

[3] Zhang JC, Yang C, Chen Q, Zhao QR, Wei PF, Jiang SL. Deposition and distribution of potential shales in China. Earth Sci Front. 2016;23(01):74–86.

[4] Sun J, Zheng QG, Wen ZH, Hou FH, Xiao R, Ren JZ. Shale gas reservoir-forming conditions and exploration prospect in permian Shanxi formation of the southern North China Basin. Mar Geol Front. 2014;30(4):20–7.

[5] Wu W, Wang Hj, Yu J, Pan JN. Geochemical characteristics of the Carboniferous-Permian source rocks in western Henan, China. Pet Sci Technol. 2019;37:519–27.

[6] Liu H, Ren JL, Lyu JF, Lyu XY, Feng YL. Hydrocarbon source rock evaluation of the lower cretaceous system in the Baibei depression, Erlian Basin. Energ Explor Exploit. 2018;36(3):355–72.

[7] Wang HJ, Wu W, Chen T, Dong XJ, Wang GX. An improved neural network for TOC, S1 and S2 estimation based on conventional well logs. J Pet Sci Eng. 2019;176:664–78.

[8] Xing Z, Cao GS, Bi JH, Zhou XG, Zhang JD. The evaluation of Upper Paleozoic hydrocarbon source rocks of ZK0606 in Yuzhou region at southern North China Basin. Nat Gas Geosci. 2018;29(4):518–28.

[9] Cao GS, Xing Z, Bi JH, Zhang JD. Evaluation of hydrocarbon source rocks of PJ5 in Pingdingshan, southern North China basin. J Henan Polytech Univ (Nat Sci). 2018;37(1):37–45 (in Chinese with English abstract).

[10] Qin JZ, Li ZM, Zhang ZR. Contribution of various coal measures source rocks to oil and gas reservoir formation. Pet Explor Dev. 2005;32(4):131–6.

[11] Li J, Luo X, Shan XQ, Ma CH, Hu GY, Yan QT, et al. Natural gas accumulation in the Upper Paleozoic of Ordos Basin, China. Pet Explor Dev. 2005;32(4):54–9.

[12] Yang H, Fu JH, Liu XS, Meng PL. Accumlation conditions and exploration and development of tight gas in the Upper Palezoic of the Ordos Basin. Pet Explor Dev. 2012;39(3):295–303.

[13] Wang Y, Qin Y, Yang L, Liu SM, Elsworth D, Zhang R. Organic geochemical and petrographic characteristics of the coal measure source rocks of Pinghu formation in the Xihu Sag of the East China Sea Shelf Basin: implications for coal measure gas potential. Acta Geol Sin-Engl Ed. 2020;94(2):364–75.

[14] Zhang GC, Wang DD, Zeng QB, Yang HZ, Li ZX, Zhao Z, et al. Characteristics of coal-measure source rock and gas accumulation belts in marine-continental transitional facies fault basins: a case study of the Oligocene deposits in the Qiongdongnan Basin located in the northern region of the South China Sea. Energ Explor Exploit. 2019;37(6):1752–78.

[15] Dai SX, Wang F, Gong YF, Hu P. Analysis of hydrocarbon generation thermal simulation experiment of coal measure source rock. Fresenius Environ Bull. 2019;28(7):5599–604.

[16] Gao JL, Ni YY, Li W, Yuan YL. Pyrolysis of coal measure source rocks at highly to over mature stage and its geological implications. Pet Explor Dev. 2020;47(4):773–80.

[17] Cao GS, Liu HH, Xing Z, Xu GM. Geochemical characteristics of carbonate rocks of Taiyuan formation in southern North China Basin. J Henan Polytech Univ Nat Sci. 2017;36(2):41–7.

[18] Qin F, Zhang JG, Wu HN, Yin LJ. Division of geological unit of coal derived (coalbed) methane accumulation in Carboniferous-Permian Huabei platform. Nat Gas Ind. 2009;29(3):117–20.

[19] Xu HL, Zhao ZJ, Yang YN, Tan ZW. Structural pattern and structural style of the southern North China Basin. Acta Geosci Sin. 2003;24(1):27–33.

[20] Henan Province Geological Mineral Resources Bureau. Regional geology of Henan Province. Beijing, China: Geological Publishing House; 1989. p. 180–214

[21] Chen JP, Zhao CY. Criteria for evaluating the hydrocarbon generating potential of organic matter in coal measures. Pet Explor Dev. 1997;24(1):1–5.

[22] Qin JZ, Liu BQ, Guo JY, Liu JW, Yu GY, Guo SZ. Discussion on the evaluation standards of carbonate source rocks. Pet Geol Exp. 2004;26(3):281–6.

[23] Gang WZ, Lin RZ. Applied oil and gas geochemistry. Beijing, China: Petroleum Industry Press; 2011. p. 92–210

[24] Feng ZQ, Zhang S, Fu XL. Depositional evolution and accumulation response of Yaojia-Nenjiang formation in Songliao Basin. Earth Sci Front. 2012;19(1):78–87.

[25] Lv DW, Zhang Y, Zong RF, Wang HY. Sedimentary characteristics and coal-forming model of transgressive events of paleozoic era in the North China plate. Energ Educ Sci Technol Part A Energ Sci Res. 2014;32(1):399–412.

[26] Lv DW, Li ZX, Chen JT, Liu HY, Guo JB, Shang LN. Characteristics of the Permian coal-formed gas sandstone reservoirs in Bohai Bay Basin and the adjacent areas, North China. J Pet Sci Eng. 2011;78(2):516–28.

[27] Lv DW, Chen JT. Depositional environments and sequence stratigraphy of the late Carboniferous_early Permian coal-bearing successions (Shandong province, China) sequence development in an epicontinental basin. J Asian Earth Sci. 2014;79:16–30.

[28] Li ZX, Yu JF, Guo JB. Study on coal accumulation under marine transgression events in the epicontinental basin of North China. Coal Geol Explor. 2002;30(5):1–5.

[29] Bai B, Zhou LF, Liu BH, Xie QF, Xie DN. Characteristics of hydrocarbon source rocks in Permian of southern area of North China Basin. Northwest Geol. 2006;39(3):48–53.

[30] Lin XY, Chen QL, Li J. Distributon and genchemical characteristics of Permian source rocks in the southern North China. Mar Geol Front. 2011;27(4):21–6.

[31] Zhang ZM, Li CS, Long SX, Xu HZ. Exploration prospect of Upper Palaeozoic natural gas in eastern area of North China. Nat Gas Geosci. 2006;17(3):330–4.

[32] Qin CF, Lu FY. Analysis of coal metamorphism in Yongcheng coalfield, Henan Province. Henan Geol. 1989;1:6–11.

[33] Zhao JF, Liu CY, Liu YT, He ZG, Mao W, Zhu B. Reconstruction of thermal evolutionary history of the Upper Paleozoic in the southern North China. Oil Gas Geol. 2011;32(1):64–74.
[34] Zhang JN, Zhou JS, Xiao DQ, Han GM, Zhao M, Fu LX, et al. Control of the Mesozoic tectonic movement on the hydrocarbon generation and evolution of Upper Paleozoic coal-measure source rocks in the Huanghua depression, Bohai Bay Basin. Nat Gas Ind. 2019;39(9):1–10.
[35] Shen ZG. Preliminarily explores on coal seam soccurrence and its influencing factors in Yongxia coal mine Henan province. China Min Mag. 2013;22(7):131–4.
[36] Liu JL, Liu C. Quantitative evaluation of gas generation from the Upper Paleozoic coal, mudstone and limestone source rocks in the Ordos Basin, China. J Asian Earth Sci. 2019;178:224–41.
[37] Cai LX, Xiao GL, Guo XW, Wang J, Wu ZQ, Li BG. Assessment of Mesozoic and Upper Paleozoic source rocks in the South Yellow Sea Basin based on the continuous borehole CSDP-2. Mar Pet Geol. 2018;101:30–42.
[38] Jin Q, Ma GZ, Wan CL, Wang L. Thermal stimulation of hydrocarbon generation from the Carboniferous-Permian coal with igneous rock existing conditions. Acta Petrol Sin. 2012;28(3):749–57.
[39] Pan JN, Peng C, Wan XQ, Zheng DS, Lv RS, Wang K. Pore structure characteristics of coal-bearing organic shale in Yuzhou coalfield, China using low pressure N2, adsorption and FESEM methods. J Pet Sci Eng. 2017;153(5):234–43.
[40] Liu L, Pan HP, Lin ZZ, Zhang SH, Qin Z, Li JW, et al. Reservoir characteristics and logging evaluation of gas – bearing mudstone in the south of North China plain. Sci Rep. 2020;10(1):8791.