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Characteristics of oil and gas generation, expelling and retention of coaly source rock

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Abstract: To understand the effectiveness of hydrocarbon generation, expelling, and retention capacities of coaly source rocks, we selected carbonaceous mudstones and mudstones in coal layers and interlayers of different sedimentary environments and ages to carry out the simulation experiments with a semi-open system operated at high temperature and high pressure, and a corresponding evolution model was established. With different depositional environments, the type II_2 coaly source rocks expelled oil in the oil generation window with gas generated. Therefore, they worked as source rocks for both oil and gas. However, for the coaly source rocks of type III kerogen, the generated oil was mainly retained during the oil generation window and the source rocks basically did not expel oil. As a result, this type of source rock was regarded as source rocks of gas only. The conversion rate of hydrocarbon generation was mainly controlled by the type of organic matter, while the ability to expel hydrocarbons was controlled by lithology and organic matter abundance. For each unit mass of rock, coal rocks had much higher conversion rates than carbonaceous mudstones and mudstones in their interlayers. In the full evolution stage of coal rock, both low-rank and high-rank coals had a strong ability for hydrocarbon gas generation and oil-and-gas retention, which showed a good potential for coal-bearing methane development. **DOI**: 10.11781/sysydz202103498-en

Keywords: hydrocarbon generation; hydrocarbon expelling; hydrocarbon retention; simulation experiment; source rock; coaly strata

Large-medium-sized gas reservoirs have been found in most petroliferous basins in China. The natural gas in these gas reservoirs is dominated by hydrocarbon gases with a large drying coefficient and less non-hydrocarbon content. Although natural gas has various origins, such as coal-type gas, oil-type gas, biological gas, and inorganic gas, the natural gas resources are mainly located in coal-bearing strata, especially the proven large-scale gas fields of 100 billion m^3, e.g., Sulige and Daniudi gas fields in Ordos Basin, Xinchang gas field in Sichuan Basin, and Chunxiao oil and gas field in the East China Sea. They are all oil and gas fields related to source rocks in coal-bearing strata [1–6].

The organic matter abundance (TOC) of source rocks in coal-bearing strata is relatively high, which generally refers to a set of organic-rich fine-grained sedimentary strata including coal [w(TOC) > 35%], carbonaceous shale [5% < w(TOC) < 35%], gray-black mudstone and silty mudstone, etc. [0.5% < w(TOC) < 5%] [7]. The kerogen of such source rocks is mainly composed of type II and type III, which are important source rocks of natural gas and light oil-condensate reservoirs. Although extensive studies have been conducted on evaluating the hydrocarbon generation potential and evolution characteristics of such source rocks, there are scarce reports on its ability to generate, expel, and retain hydrocarbon [8–10]. In fact, whether the source rocks of coal-bearing strata can be exploited as coalbed methane (CBM) or become effective source rocks for conventional hydrocarbon reservoirs is more closely related to the volume of hydrocarbon expelled and retained in different evolution stages, besides the conversion rate of hydrocarbon generation or production rate. In this paper, simulation experiments using a semi-open system operated at high temperature and high pressure under the diagenesis were conducted to comparatively study the evolution characteristics of hydrocarbon generation, expelling, and retention of source rocks in different types of coal-bearing strata, and corresponding evolution models were established. In addition, the following problems were discussed: the effectiveness of coal and coaly source rocks as oil source rocks, whether low-rank CBM can meet the requirements of commercial exploitation, and exploration of conventional–unconventional hydrocarbon in coal-bearing strata.

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Table 1 Basic geochemical parameters of samples

Sample No.	Lithology	Horizon	Profile	w(TOC)/%	Asphalt "A"/%	(S_1+S_2)/$(mg \cdot g^{-1})$	I_H/$(mg \cdot g^{-1})$	Kerogen type	R_o/%
H coal	Coal	C-P	Heidaigou Coal Mine	59.77	0.86	78.79	114	III	0.56
W coal	Coal	E	Wutu Coal Mine	50.76	0.67	131.75	259	II_2	0.47
Z carbonaceous mudstone	Carbonaceous mudstone	C-P	Heidaigou Coal Mine	23.29	0.12	18.39	79	III	0.63
Z silty mudstone	Black silty mudstone	T	Wutu Coal Mine	2.22	0.17	6.89	254	II_2	0.52

Table 2 Boundary conditions of simulation experiment for hydrocarbon generation and expelling of coaly source rocks

Simulated buried depth/m	Simulated temperature/°C	Overlaying lithostatic pressure/MPa				Fluid pressure/MPa				Differential hydrocarbon expelling pressure/MPa			
		H coal	W coal	Z carbonaceous mudstone	Z silty mudstone	H coal	W coal	Z carbonaceous mudstone	Z silty mudstone	H coal	W coal	Z carbonaceous mudstone	Z silty mudstone
1 100	200		26				13				2		
1 350	225		32				16				3		
1 650	250		40	40	40		20	20	20		3	3	3
1 800	265				43				22				4
1 900	275		46		46		23		23		4		4
2 150	300	52	52	52	52	26	26	26	26	4	4	4	4
2 350	315	56				28				5			
2 400	320		58		58		29		29		5		5
2 500	330	60				30				5			
2 600	340		62		62		31		31		5		5
2 700	350	65		65		32		32		5		5	
2 850	360		68				34				6		
2 950	370	71				35				6			
3 000	375			72				36				6	
3 050	380		73		73		37		37		6		6
3 150	390	76				38				6			
3 250	400		78	78	78		39	39	39		7	7	7
3 400	415	82				41				7			
3 450	420		83		83		41		41		7		7
3 600	430	86				43				7			
3 800	450		91	91			46	46			8	8	
3 900	460	94				47				8			
4 350	500		104	104	104		52	52	52		9	9	9

1 Experiment samples and methods

In order to understand the evolution characteristics of hydrocarbon generation, expelling, and retention of different types of source rocks in coal-bearing strata in different evolution stages, this paper selected four samples of typical immature–low mature coal and carbonaceous mudstones and mudstones in coal interlayers from Carboniferous–Permian (Upper Paleozoic) to Paleogene (Cenozoic). Among them, two samples were lignite obtained from Heidaigou Coal Mine in Inner Mongolia (sample No. HDG-15, hereinafter referred to as H coal) and its interbedded carbonaceous mudstone (sample No. Zhun-6-ni, hereinafter referred to as Z carbonaceous mudstone), both of which were type III kerogen; the other two samples were Paleogene lignite (sample No. WT-6, hereinafter referred to as W coal) and its interbedded black silty mudstone (sample No. ZJT-12, hereinafter referred to as Z silty mudstone) collected from Wutu Coal Mine, Shandong Province, both of which were type II_2 kerogen. All samples were in the immature–low mature evolution stage, which was suitable for the simulation experiment of hydrocarbon generation and expelling in the whole evolution stage. Table 1 shows detailed geochemical parameters.

The instruments and equipment described in Ref. [11] were used for the simulation experiment of hydrocarbon generation, expelling, and retention of total rocks in typical coal-bearing strata source rocks. The samples were of drilled small core columns, which could preserve the original mineral composition and bedding structure of the source rock samples as much as possible, and therefore the expelling and retention processes of underground hydrocarbon could be simulated reasonably. According to the C-P burial history of Well Futan-1 in the southern margin of Ordos Basin, the overlying lithostatic pressure and the formation fluid pressure were set. Moreover, the matching relationship between temperature, time, and vitrinite reflectance was simulated with the instruments, and a corresponding simulation experimental scheme [12] for hydrocarbon generation and expulsion of source rocks was prepared. See Table 2 for detailed boundary conditions in the experiment, and the flowsheet of hydrocarbon generation and expelling simulation experiment and the method for product collection can refer to Refs. [13–15].

2 Evolution characteristics of hydrocarbon products

2.1 Evolution characteristics of gas products

2.1.1 Total gas and CO_2

The gas products obtained from the simulation experiment of hydrocarbon generation and expelling from source rocks are mainly hydrocarbon gases and inorganic gases such as CO_2, H_2, CO, and N_2. Carbon in CO_2 and CO gas hereof is mainly formed through the thermal decomposition of oxygen-containing groups of organic matter [16]. In order to establish the evolution model of hydrocarbon generation and expelling in the diagenetic revolution process by using carbon mass balance and its conversion rate, it is necessary to understand the evolution characteristics of various products. According to the comparison of total gas and carbon dioxide production rate of different types of coaly source rocks in the whole evolution stage (Fig. 1), the total gas production rate of samples increases with maturity, and the total gas production rate of coal rocks is relatively higher than that of carbonaceous mudstone and mudstone, which is mainly related to the properties and element composition of sedimentary organic matter and lithologic association. The evolution of the CO_2 production rate has the following characteristics: ① The cumulative CO_2 production rate of all samples increases with the simulation temperature, and the oil generation window is the main hydrocarbon generation stage. The results indicate that its generation is primarily related to oil generation. The CO_2 production rate increases slowly and remains stable in the high mature–overmature stage; ② At the same evolution stage, the CO_2 production rate of coal rock is generally higher than that of type III carbonaceous mudstone or mudstone with sedimentary organic matter; ③ In the simulation experiment, CO_2 gas in the source rocks of coal-bearing strata mainly comes from organic carbon and organic oxygen in sedimentary organic matter, which is mainly restricted by the composition and maturity of original sediments. A large amount of CO_2 is produced in the diagenetic evolution process of coal, and is then mainly dissolved in the oil phase during oil generation, which thereby decreases its viscosity and density and increases its fluidity [17]. Therefore, it may have a great impact on the hydrocarbon expelling capacity of coal rocks, and more attention should be paid to this problem.

2.1.2 Hydrocarbon gas

From the hydrocarbon gas production rate curve (volume of hydrocarbon gas generated by unit organic carbon) and production curve (volume of hydrocarbon gas generated by each ton of source rock) (Fig. 2), the hydrocarbon gas generation process can be roughly divided into three stages during the diagenesis of source rocks in coal-bearing strata: ① In the evolution stage of oil generation ($R_o \le 1.20\%$), the hydrocarbon gas is generated slowly, and its production rate generally does not exceed 50 $m^3 \cdot t^{-1}$, which belongs to oil associated gas; ② In the stage of rapid hydrocarbon gas generation ($R_o = 1.20\%–2.50\%$), kerogen and retained oil are gradually transformed into hydrocarbon gas. In this stage, macromolecular liquid long-chain hydrocarbons are mainly condensed into short-chain hydrocarbons with smaller molecular weight, and hydrocarbon products are gradually transformed from light oil, condensate oil and gas, wet gas to dry gas, with obvious changes occurring to the hydrocarbon phase state; ③ After vitrinite reflectance reaches $R_o \ge 2.50\%$, although the source rocks of coal-bearing strata still have a certain ability to generate hydrocarbon gas, they tend to be stable and mainly produce dry gas dominated by methane.

Comparison of the hydrocarbon gas production rates of different types of source rocks in coal-bearing strata (Fig. 2(a)) suggests that the production rate is mainly controlled by kerogen type, and the greater the hydrogen index and the better the organic matter type, the greater the hydrocarbon gas production rate. Under the same evolution degree, the Paleogene lignite in the east (W coal) shows the highest hydrogen index (259 $mg \cdot g^{-1}$) and maximum hydrocarbon gas production rate (263 $m^3 \cdot t^{-1}$). The hydrogen index of C-P lignite (H coal) in Heidaigou Coal Mine in Ordos is lower (114 $mg \cdot g^{-1}$), and its maximum hydrocarbon gas production rate is 111.12 $m^3 \cdot t^{-1}$. The type III carbonaceous mudstone (Z carbonaceous mudstone) and type II_2 mudstone (Z silty mudstone) show similar evolution characteristics. The hydrocarbon production rate is mainly controlled by the type of primary sedimentary organic matter, which complies with the evolution law of hydrocarbon generation of all source rocks.

In addition to the hydrocarbon production rates of source rocks, the generation, expelling, and retention capacities of source rocks should also be taken as the standards to measure whether they are effective for the formation of conventional and unconventional oil- and gas-reservoirs [18]. Higher hydrocarbon generation potential only means that organic matter per unit mass has higher hydrocarbon generation capacity, and its expelling and retention are also related to

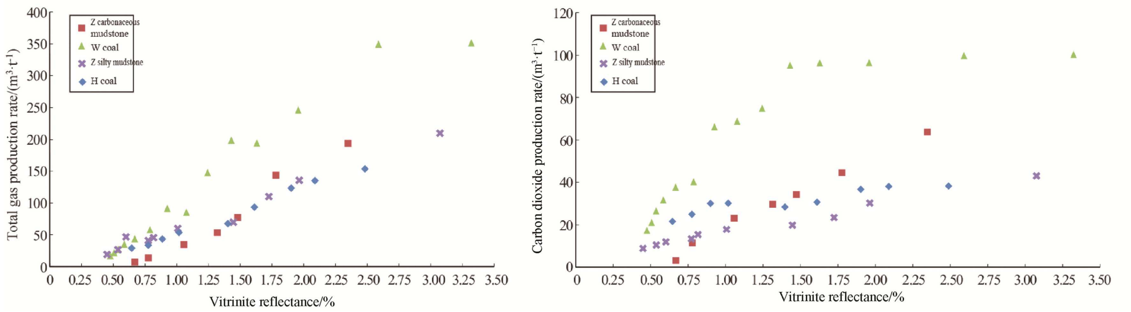

Fig. 1 Evolution characteristics of total gas and carbon dioxide production rates of source rocks in coal measures

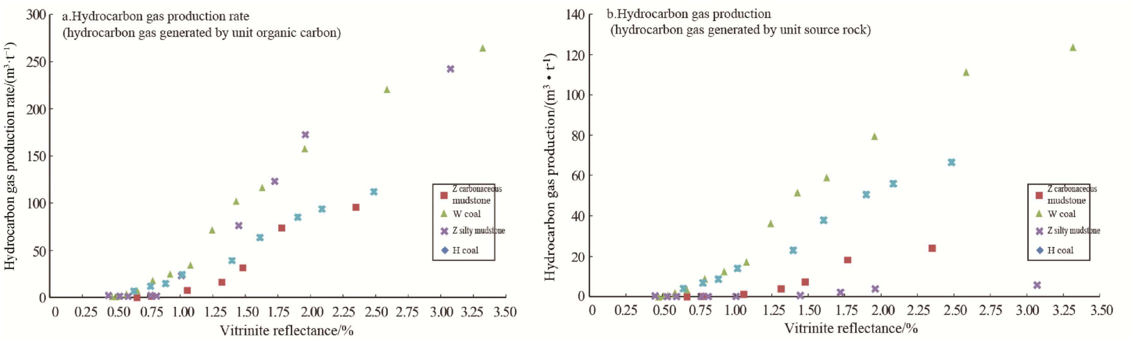

Fig. 2 Hydrocarbon gas production rate and production curves of source rocks in coaly formations

geological-physical-chemical factors, such as pore volume of source rocks, rock associations, and diagenesis. In order to more reasonably identify the effectiveness of different types of source rocks in coal-bearing strata for conventional and unconventional hydrocarbon accumulation, we adopted the amount of hydrocarbon generated by unit mass of source rocks as the hydrocarbon production parameter to characterize their effectiveness in the formation of hydrocarbon reservoirs. Figure 2(b) is the evolution characteristic curve of hydrocarbon gas production from those 4 samples. The following conclusions can be found: ① The hydrocarbon gas production of source rocks in coal-bearing strata is influenced and restricted by the type, abundance, lithology, diagenesis stage, and pore volume of sedimentary organic matter simultaneously. The hydrocarbon gas production of Paleogene type II_2 lignite is higher than that of Carboniferous–Permian type III lignite, and the hydrocarbon gas production of coal rock is far higher than that of carbonaceous mudstone and mudstone in coal-bearing strata. Although the hydrocarbon gas production rate of type III carbonaceous mudstone is lower than that of type II_2 mudstone (Fig. 2(a)), its hydrocarbon gas production is higher than that of silty mudstone because its organic carbon is much higher than that of mudstone (Table 1). ② Low-rank coal rocks also show the potential of CBM development. The low-rank CBM has been developed commercially abroad, and China is rich in low-rank CBM resources, but no breakthrough has been made yet due to complex reasons, such as insufficient theoretical understanding and lack of key technical support [19–25]. Low-rank coal rocks refer to lignite, long flame coal, and gas coal formed in the range of R_o = 0.50%–0.90%. As can be seen from Fig. 2(b), the hydrocarbon gas production of coal rocks in the low metamorphic stage is roughly 1.5–12 $m^3 \cdot t^{-1}$. According to the reserve calculation boundary stipulated in the national standard of the People's Republic of China "*Guidelines for the Utilization of Coalbed Methane (Coal Mine Gas): GB/T28754—2012*," the lower limit of CBM content is shown as follows: For lignite-long flame coal, the metamorphic degree is less than 0.7%, and the air content of air-dried basis is 1 $m^3 \cdot t^{-1}$; for gas coal-lean coal, the two values are 0.7%–1.9% and 4 $m^3 \cdot t^{-1}$; for meagre coal-anthracite, they are > 1.9% and 8 $m^3 \cdot t^{-1}$. Through comparison of the simulation results, the hydrocarbon gas production of coal rock far exceeds 1 $m^3 \cdot t^{-1}$ in the low metamorphic coal rank. Although the adsorption of solid organic matter in coal rocks and the dissolution of hydrocarbon gas by generated oil are considered, the production of free hydrocarbon gas in long flame coal and gas coal may also be higher than the lower limit of CBM content. For low-rank coal seams with appropriate thickness, CBM development can be considered.

2.2 Evolution characteristics of products from oil generation, expelling, and retention

As a kind of source rock highly enriched with organic matter, coal can be used as an effective source rock of conventional gas reservoirs, which has been generally recognized by academic circles. However, there have been great disputes over whether it has a certain oil expelling capacity in the oil generation window and can be used as an effective source rock. Some think that the oil expelling capacity of coal rock is very limited and obviously lower than that of lacustrine mudstones [26–27], while some believe that coal rock can expel hydrocarbon efficiently [28–29]. There are at least two reasons for such disputes: ① The conditions adopted by the hydrocarbon generation simulation experiment are quite different from the geological conditions. If a closed system simulation experiment is used, the generated oil cannot be effectively expelled, resulting in a serious underestimation of the hydrocarbon expelling efficiency. Nonetheless, if a fully open system simulation experiment is used, only the total hydrocarbon generation production rate can be obtained. Or it simply equates the experimental data of artificial evolution with the results of natural evolution. For example, the hydrocarbon expelling efficiency of the simulation experiment is inconsistent with the actual geological situation when the high-temperature thermal evaporation effect is not considered, and the hydrocarbon expelling path has undergone substantial changes by using crushed samples. ② Only oil production rate or oil expelling efficiency is used to evaluate whether it can be used as an effective oil source rock, while the dynamic transformation processes between hydrocarbon generation, expelling, and retention and the influence of the absolute quantity (including organic matter content) that can be generated, expelled, and retained per unit mass (or volume) of coaly source rocks on the effectiveness of oil sources are not fully considered. On the basis of this understanding, the original mineral composition structure and organic matter occurrence state (drilling small core columns) of the source rocks are kept as far as possible in this study, and the hydrocarbon-generating space close to the pore space completely is filled with high-pressure liquid water. Meanwhile, the overlying lithostatic pressure compaction similar to the geological conditions and the formation fluid pressure equivalent to the buried depth of the formation are considered. Then the hydrocarbon simulation experiment with controllable pressure difference is carried out [30].

2.2.1 Expelled oil products

As the maturity increases, the oil production rate and production increase as well, with the main oil expelling period of R_o = 0.80%–1.45% (Fig. 3). The oil production rate of Paleogene type II_2 coal rocks and mudstones is obviously higher than that of Carboniferous–Permian type III coal rocks and carbonaceous mudstones, among which the production of Paleogene type II_2 mudstones is the highest and that of type III carbonaceous mudstones is the lowest. Those findings indicate that the conversion rate of oil expelled from coal-bearing source rocks is mainly controlled by kerogen type. The maturity of effective oil expelling threshold is high and continues to the early stage of high maturity, suggesting that light oil-condensate is mainly expelled (Fig. 3(a)). However, because the production rate only characterizes the amount of organic carbon converted into oil and gas per unit mass, it cannot fully reflect its capacity to effectively expel hydrocarbon. As the organic carbon content of coal is much higher than that of mudstone, in terms of oil production, Paleogene type II_2 coal rock has the highest oil expelling capacity, which is much higher than that of type III coal rock, and the oil expelling capacity of type II_2 mudstone is higher than that of type III carbonaceous mudstone (Fig. 3(b)). Those results indicate that the oil expelling capacity of source rocks in coal-bearing strata is controlled by kerogen type and lithology at the same time [31].

The column-shaped samples with original mineral composition and bedding structure were adopted. However, considering that there must be a certain high-temperature thermal evaporation in the simulation experiment of source rocks in coal-bearing strata under the artificial evolution condition, the amount of oil expelled from the simulation experiment could not fully represent the amount of oil expelled under the actual geological conditions. In combination with the existing exploration practices [32–34], it is considered in this study that the source rocks of coal-bearing strata with effective oil expelling capacity may be the coal rocks with type II kerogen and the mudstone with high organic carbon abundance. However, type III kerogen coal-bearing source rocks do not have the oil supply capacity to form large-scale reservoirs.

2.2.2 Retained oil products

As the maturity increases, the production rate and production of retained oil in coaly source rocks have the characteristics of first increasing and then decreasing, with the trend of reaching the highest value near R_o = 1.0% and decreasing to a very low level in the overmature stage (Fig. 4). Through comparison of the production rate and production curves of retained oil (Figs. 4(a) and 4(b)), the source rocks of coal-bearing strata are quite different in lithology and kerogen types. Paleogene type II_2 mudstone has the highest production rate of retained oil, followed by coal rocks, and type III kerogen carbonaceous mudstone is the lowest. The evolution characteristics of retained oil production (Fig. 4(b)) show that it is mainly controlled by lithology, but has little correlation with kerogen type. The retained oil production of two coal rocks is much higher than that of mudstone or carbonaceous mudstone, because coal has strong adsorption to liquid oil and coal rocks have a higher porosity. By comparing the evolution characteristics of expelled oil products in Fig. 3, we can clearly see that the liquid oil generated in the oil generation window of coal-bearing source rocks is mainly retained in the source rocks, and the proportion of expelled oil is not large.

2.3 Evolution characteristics of total hydrocarbon products

The total hydrocarbon production rate is closely related to organic matter type and lithology (Fig. 5(a)). For the identical lithology, a higher hydrogen index of the original sample indicates better the kerogen types and greater total hydrocarbon production rates. When the kerogen type is the same,

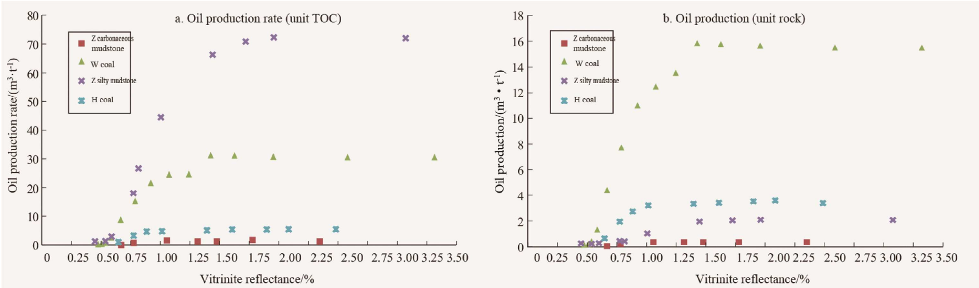

Fig. 3 Oil production rate and production curves of source rocks in coaly formation

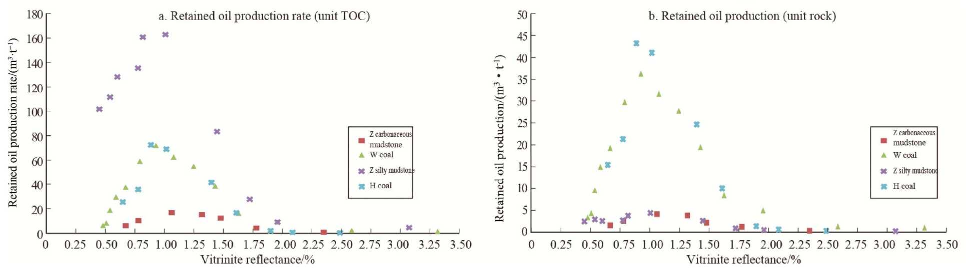

Fig. 4 Retained oil production rate and production curves of source rocks in coaly formations

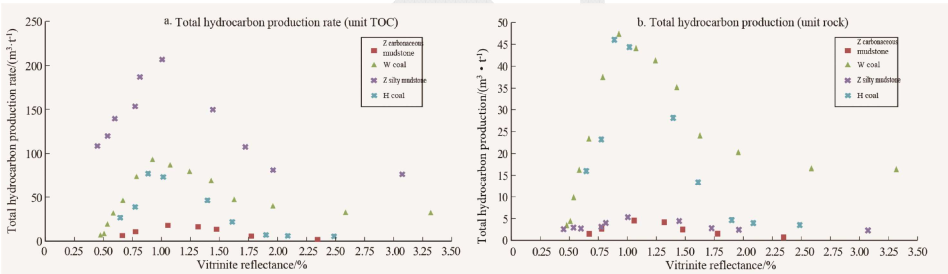

Fig. 5 Total hydrocarbon production rate and production curves of source rocks in coaly formations

the total hydrocarbon production rate of mudstone is higher than that of coal rock, and the influence degree of kerogen type is higher than that of lithology. For the above four samples, the sequence of total hydrocarbon production rate is Type II_2 mudstone > II_2 coal rock > type III coal rock > type III carbonaceous mudstone. However, the total hydrocarbon production is also related to organic matter abundance, besides kerogen type and lithology. The total hydrocarbon production of coal rock is much higher than that of mudstone and carbonaceous mudstone. For coal rock, kerogen type is the main controlling factor, while for mudstone, the influence of organic matter abundance is greater.

In general, whether the source rocks in coal-bearing strata are effective oil source rocks or can only be used as gas source rocks, whether they can be developed as unconventional hydrocarbon resources, or whether they are only effective for the formation of conventional hydrocarbon reservoirs, etc. should be comprehensively studied by the influence of kerogen type, lithologic associations, maturity, and organic matter abundance, and other factors on the hydrocarbon production rate in different evolution stages. In addition, more attention should be paid to the influence on their capacities to expel and retain hydrocarbon.

3 Evolution models for hydrocarbon generation, expelling, and retention of source rocks

3.1 Evolution models for hydrocarbon generation and expelling of coal rocks of different kerogen types

Organic carbon conversion rate refers to the percentage of organic carbon from generated, expelled, and retained hydrocarbon in the original organic matter. In different evolution stages, compared with the production rate, the organic carbon conversion rate of generated, expelled, and retained oil can better reflect its effectiveness in forming conventional and unconventional hydrocarbon reservoirs. Considering the results of hot-pressing simulation experiments with different types of coal rocks, and the evolution characteristics of production rate and production of generated, expelled, and retained oil with maturity, we establish the evolution models for hydrocarbon generation, expelling, and retention of type II_2 and type III coal rocks. The organic carbon converted into hydrocarbon in the total organic carbon of type III kerogen coal rock does not exceed 10%, and the conversion rate of total organic carbon in Type II_2 coal rocks is less than 20%.

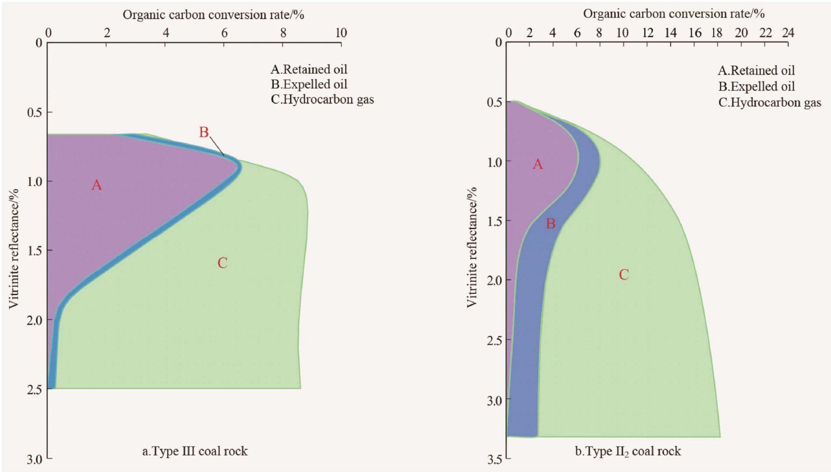

Fig. 6 Evolution models for hydrocarbon generation, expelling, and retention in coaly source rocks

In different coal metamorphic stages, the organic carbon conversion rates of generated, expelled, and retained hydrocarbon are different (Fig. 6). The evolution stage of diagenesis and hydrocarbon generation of coal rocks from lignite to anthracite can be divided into four metamorphic stages: ① Low metamorphic stage (R_o of 0.50%–0.90%), equivalent to the stage from lignite to gas coal, which is the main stage of kerogen in coal rocks transforming into hydrocarbon. The generated hydrocarbon is mainly retained oil, with the conversion rate of hydrocarbon gas less than 2% and almost no hydrocarbon expulsion; ② Medium metamorphism coalification stage (R_o of 0.90%–1.50%), equivalent to the metamorphism stage from rich coal to coking coal. In this stage, the retained oil begins to decrease [35], and type II_2 coal rock begins to expel oil and has a carbon conversion rate of expelled oil less than 3%, which is less than 30% of the conversion rate of total organic carbon. Namely, among the available carbon that can be converted into hydrocarbon, the effective organic carbon expelled in the form of oil is only less than 30%. In this evolution stage, low molecular liquid hydrocarbon and gaseous hydrocarbon begin to generate in large quantities. Type III coal rocks generally expel only hydrocarbon gas, and the CBM content is relatively low; ③ High metamorphic stage (R_o of 1.50%–2.50%) is equivalent to the metamorphic stage from lean coal to meagre coal. The conversion rate of total organic carbon reaches the maximum, and most of the retained oil has been converted into hydrocarbon gas; the residual oil amount is very low, and is no longer capable of expelling oil. With the further generation of hydrocarbon gas, there occurs a large amount of expelled and retained hydrocarbon gas (CBM); ④ Over-metamorphic stage ($R_o > 2.50\%$), equivalent to anthracite stage, with hydrocarbon gas mainly generated by residual kerogen. The generation rate is obviously slowed down, and the amount of hydrocarbon gas expelled in the stage is not high (Fig. 6).

After the oil generation peak is reached, in the late mature–high mature stages, hydrocarbon gas is mainly generated by retained oil. Therefore, it is more reasonable to measure hydrocarbon expulsion efficiency by dividing the organic carbon content in the expelled oil by the original organic carbon content than by dividing the expelled oil mass by the total oil mass.

3.2 Evolution model for hydrocarbon generation and expulsion of mudstone and carbonaceous mudstone in coal-bearing strata

The hydrocarbon generation evolution process of mudstone and carbonaceous mudstone in coal-bearing strata is similar to that of general lacustrine type III kerogen, and its hydrocarbon generation can be divided into five hydrocarbon evolution stages (Fig, 7): the immature stage, mature stage, late mature stage to early high mature stage, high mature stage, and overmature stage. ① Immature stage ($R_o \leq 0.5\%$). The source rocks already contain high soluble organic matter, and the carbon conversion rate of retained oil has accounted for about 20% of the conversion rate of total organic carbon, both in the form of retained oil; ② Mature stage ($0.5\% < R_o \leq 1.0\%$), a period of rapid transformation from kerogen to hydrocarbon. The peak of oil generation is reached when $R_o \approx 1.0\%$. At this time, the type II_2 kerogen mudstone with high abundance [w(TOC) > 2.0%] has a certain capacity to expel light oil, and the carbon conversion rate of the expelled oil has exceeded 3.0%. However, since the hydrocarbon generated by high abundance type III kerogen carbonaceous mudstone mainly retains in source rocks, they have no hydrocarbon expelling capacity and are not effective source rocks; ③ Late mature stage to early high mature stage ($1.0\% < R_o \leq 1.5\%$), a stage of hydrocarbon expelling. The oil expelled by type II_2 kerogen mudstone reaches its peak, and the retained oil begins to transform into hydrocarbon gas in large quantities. For type III kerogen carbonaceous mudstone, the conversion rate of organic carbon of retained oil decreases rapidly, but the conversion rate of total organic carbon begins to increase rapidly. This indicates that besides the conversion

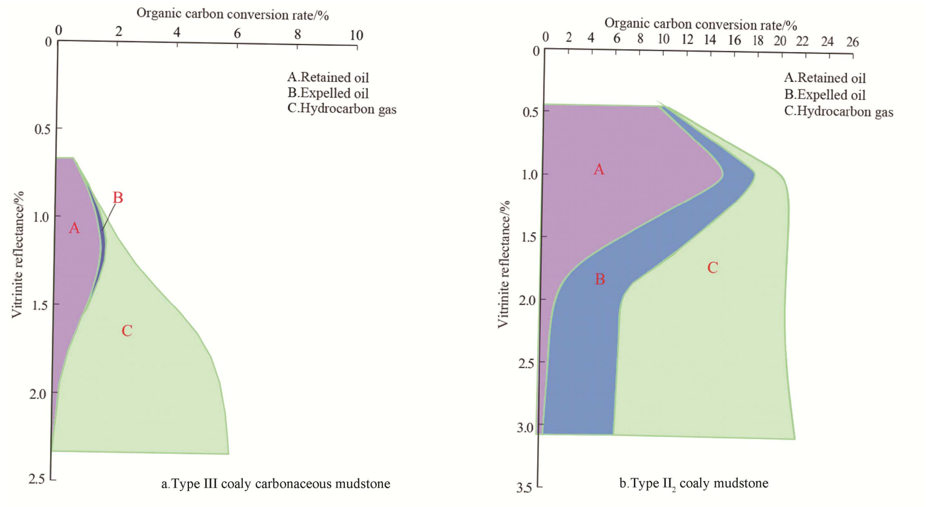

Fig. 7 Models for hydrocarbon generation, expelling, and retention in coaly mudstones and carbonaceous mudstones

of retained oil to hydrocarbon gas, residual kerogen directly generates hydrocarbon gas after oil generation. ④ High mature stage (1.5% < R_o ≤ 2.0%). The retained oil in type II_2 kerogen mudstone is further transformed into hydrocarbon gas, but the total conversion rate changes slightly. The conversion rate of total organic carbon of type III kerogen carbonaceous mudstone increases simultaneously and rapidly and reaches the maximum; ⑤ Overmature stage (R_o > 2.0%). The total organic carbon conversion increases slightly, dominated by wet gas transformed to dry gas, and the hydrocarbon generation capacities of residual kerogen and the retained oil are already very weak.

4 Conclusions

(1) With the increase of maturity, the production rate of hydrocarbon generated by source rocks in coal-bearing strata is mainly controlled by the type of sedimentary organic matter, while the production rate and production of retained hydrocarbon are controlled by kerogen type and lithology. Type II_2 kerogen coal rock and mudstone with higher organic matter abundance can expel a certain amount of light oil after the oil generation peak is reached. However, type III kerogen coal rock and carbonaceous mudstone basically have no oil expelling capacity.

(2) Coal rock and mudstone with the same kerogen type have similar hydrocarbon gas production rates, but the hydrocarbon gas production of coal rock in the low evolution stage can exceed 1.5 $m^3 \cdot t^{-1}$. For coal seams with appropriate thickness, CBM can be developed. The maximum hydrocarbon gas production of coal rock can exceed 50 $m^3 \cdot t^{-1}$, while the total hydrocarbon production of carbonaceous mudstone and mudstone is generally lower than 20 $m^3 \cdot t^{-1}$. For the same thickness and area, the effectiveness of coal rocks in coal-bearing strata for gas reservoir formation may be greater than that of mudstone.

(3) The evolution model for the organic carbon conversion rate of hydrocarbon generation, expelling, and retention in coal rock, mudstone, and carbonaceous mudstone is established. After the oil generation peak is reached, the generated hydrocarbon gases consist of both the product of retained oil transformation and the directly generated gas by residual kerogen. For different types of coal rocks and mudstones, there are huge differences in the proportions of hydrocarbon gases generated by retained oil and residual kerogen.

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