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Gas-bearing characteristics and controls of the Cambrian Shuijingtuo Formation in Yichang area, Middle Yangtze region

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Abstract: The Yichang area in the Middle Yangtze region is a new exploration target for shale gas outside the Sichuan Basin. The shale of the Cambrian Shuijingtuo Formation has an enormous gas resource potential in view of gas shows in most wells. The gas contents vary in different wells. We investigated the gas-bearing characteristics and controls of shale in the Cambrian Shuijingtuo Formation in the Yichang area integrating geological and geochemical data. The black rock series of the Shuijingtuo Formation in this area is mainly carbonaceous shale and gray shale, about 50–140 m thick. They have high total organic carbon (TOC) and are mainly of type I, generally thermally over-mature, showing a good hydrocarbon generation potential. The on-site measured gas content is 0.32–5.48 m^3/t, and the cumulative thickness of shale with gas content > 2 m^3/t is 44.05 m, which reflects a good overall gas content of shale in this area. The gas-bearing capacity of the Shuijingtuo Formation shale is affected by various factors such as sedimentary facies, organic carbon content, mineral composition, porosity, extent of fracture and formation pressure. The black carbonaceous shale deposited in the continental shelf facies has higher gas content than the gray calcareous shale of the slope facies, while the limited platform facies has the lowest gas content. The gas content has positive correlation with the organic carbon and quartz mineral contents, weak negative correlation with the carbonate mineral content, and poor correlation with the clay mineral content. Organic carbon content has a more significant control on gas content. Shale porosity and pore distribution variations are important factors leading to the differences in gas content. In addition, shale gas content is also closely related to reservoir fracture development and formation pressure.

Keywords: gas-bearing capacity; shale gas; Shuijingtuo Formation; Cambrian; Yichang area; Middle Yangtze region

The shale gas occurs in the natural fractures and pore space in the free state, or on the surface of mineral particles and organic matter particles in the adsorbed state [1]. The gas content of the shale gas refers to the sum of the free gas and adsorbed gas in the shale. Previous studies have shown that the organic carbon content, thermal maturity, mineral composition, physical structure, fracture development of shale and other factors, as well as the external factors such as stratum burial depth and formation pressure are the main controlling factors affecting shale gas content [2–7]. At present, the Lower Cambrian industrial shale gas wells that have been discovered are mainly concentrated in the interior and periphery of the Sichuan Basin [8–11]. The measurements show that shale gas is active in the Qiongzhusi Formation/Niutitang Formation of Weiyuan area in the central Sichuan, Jingyan-Qianwei area in the western Sichuan, and the Huangping area in the southern Guizhou. The total on-site desorption gas content is high, and industrial gas flow was obtained in multiple wells. The Lower Cambrian shale with large thickness and high organic matter content was widely developed in the Middle Yangtze region outside the Sichuan Basin, but there is no direct evidence of gas-bearing characteristics. Most shale gas wells have low gas-bearing capacity or contain more nitrogen [12–14]. A small number of shale gas wells contain gas but the regularity is not strong. The high value is limited to the mylonitizated fracturing system [15], the exploration effect is not prominent, and the main controlling factors affecting the gas-bearing capacity of shale are unclear. The Yichang area of Middle Yangtze region in the western Hubei is located in the periphery of oil and gas exploration, and has experienced multiple periods of complex tectonic movement [16]. The drilling is rare, and the exploration extent of Cambrian shale gas is low. In recent years, the Cambrian shale gas in the Yichang area has been discovered, and is expected to achieve breakthroughs in the exploration. This area is one of the favorable target areas for the exploration of marine shale gas in the Middle Yangtze. Based on the data analysis results of well Yiye-1 which has achieved industrial breakthrough, we

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analyzed the gas-bearing characteristics of the Lower Cambrian Shuijingtuo Formation shale in Yichang area in combination with the data of well Yidi-2, and discussed the influencing factors of gas bearing capacity to provide geological reference for the resource potential evaluation and the later exploration/deployment of shale gas in the region.

1 Geological settings

Yichang area is located in southwestern margin of Huangling uplift in Northeastern Sichuan-Daye counter thrust and interference belt in the Middle Yangtze fold belt (Fig. 1). It is connected with the Huangling uplift to the northwest, adjacent to the Tongchenghe fault and the Dangyang anticlinorium to the northeast, and it connects the Tianyangping fault and the Yidu-Hefeng anticlinorium to the west, with a total area of about 2 150 km^2. Controlled by the Huangling uplift and the Tianyangping fault on the west side, the study area shows a monoclinic structure, and the stratum is northeast-trending and south-eastward dipping, with a flattening occurrence; the dip angle of the stratum is 5°–15°, and the Nanhua–Permian and Cretaceous and Huangling granites are exposed on the surface (Fig. 1), exhibiting the characteristics of new developed ones in the southeastern direction and early developed ones in the northwestern direction. The Cretaceous stratum is exposed in the main body of the study area.

The Yichang area has undergone a relatively stable tectonic-sedimentary period since the Nanhua Period. It has experienced the extensional rifting in the early Caledonian period, the convergence and extrusion in the Late Caledonian period, the extensional rifting in the Hercynian–Early Indosinian period and the converging-squeezing-uplifting in the Late Indosinian–Himalayan period [17], forming the passive continental marginal basin of the Nanhua-Early Ordovicia, the foreland basin in the Middle Ordovician–Silurian period, the craton basin in the Devonian–Early Triassic and the foreland basin in the Middle Triassic–Early Jurassic, respectively. It experienced a strong deformation and transformation in the late Yanshanian period, and the stratum was unevenly uplifted and subjected to massive erosion, forming the current marine residual basin. In the early Cambrian period, the Yichang area was in the transitional zone between the platform and the deep-water shoal, and the thickness of the organic-rich shale varied greatly. The Dengying Formation was deposited in the early Cambrian period as the shoal facies of the platform margin in the Dengyingxia area, and the Yanjiahe lower member was developed westwards as the slope facies–shallow shelf facies in the Zigui Sixi–Yichang Yanjiahe area [18]. The extensive transgression in the Early Cambrian period resulted in wide coverage of deep-water shelf in the area, and the development of thick black rock systems in the shelf-slope belt.

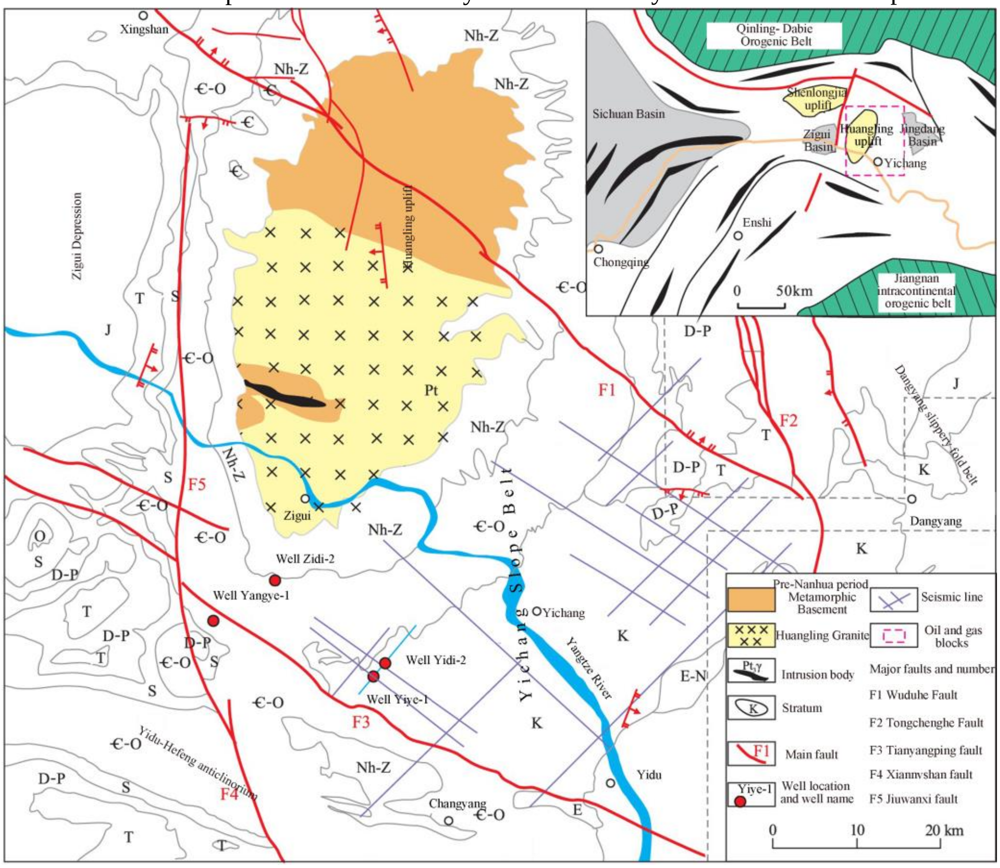

Fig. 1 Geological map and well location of the Yichang area, Middle Yangtze region

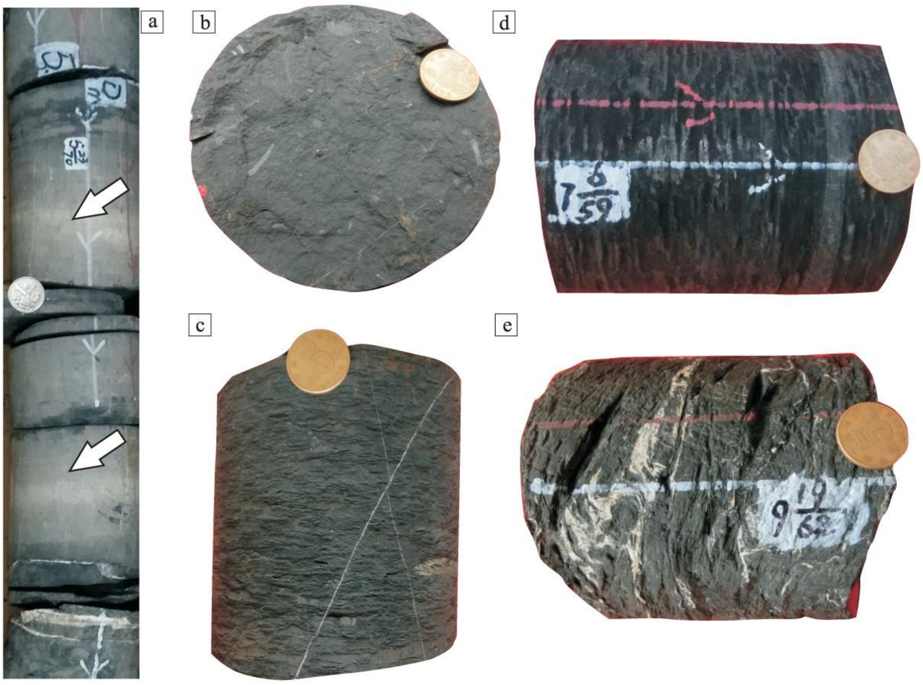

Fig. 2 Typical core photos of Shuijingtuo Formation in well Yiye-1, Yichang area, Middle Yangtze region.a. Gray argillaceous limestone and inter-layer cracks developed in the middle of the Shuijingtuo Formation, 1 799.4 m; b. Sponge ancient needle fossils and high-angle micro-cracks in black carbonaceous mudstone, 1 846.93 m; c. The calcite veins are filled with two intersecting high-angle cracks in the black carbonaceous mudstone, 1 868.74 m; d. Black gray mudstone interbedded with argillaceous limestone, 1 829.35 m; e. Wrinkle deformation between rock layers, 1 864.72 m

2 Gas-bearing capacity of shale

2.1 Characteristics of gas-bearing shale

The well Yiye-1 which is located on the Yichang slope encountered with 86 m shale of Cambrian Shuijingtuo Formation, with a burial depth from 1 786 to 1 872 m. The lithology is mainly dark shale and gray mudstone. The fine horizontal laminae were developed, and abundant floating algae biofossils were observed (Fig. 2). The shale of the Shuijingtuo Formation in the study area has a good hydrocarbon generation potential. The shale organic matter is dominated by type I, and the organic carbon content is 0.43%–10.45%, with an average value of 2.7%; the organic matter thermal maturity (R_o) is 2.35% on average, and at present it is in the period of over-maturity evolution. The quartz content of the gas-bearing shale is 12.5%–44.4%, the average content is 29.33%, and the average content of carbonate is 25.94%; the clay mineral content is 35.06% on average, and the illite–montmorillonite mixed layer is the dominant, accounting for 57.41%, and the content of illite is 32.59%. The organic-rich shale in the Shuijingtuo Formation forms a tight reservoir with the porosity of 0.96%–3.32%, about 2.08% on average, mainly distributed between 1.6% and 2.8%; and the permeability of shale is (0.01–3.05) $\times 10^{-3}$ μm^2.

2.2 Gas logging

Gas content is an important indicator for evaluating the potential of shale gas resources and measuring whether the shale gas target area has the economic exploitation value [19]. Gas logging, on-site desorption and fracturing gas testing all show that the study area presents good shale gas resource potential. As the most direct and continuous semi-quantitative indicator, gas logging can effectively reflect the macroscopic trend of gas showing [20], and it is one of the effective indicators for characterizing shale gas. Several shale gas wells in Yichang area have obtained good gas logging results when encounter the black shale in the Shuijingtuo Formation. With well Yiye-1 taken as an example, the gas logging value increased from top to bottom as a whole, and the total hydrocarbon content gradually increased from 0.11% to 2.71%. While the core was placed in water, the gas showing was strong, and the collected gas could be ignited with the light blue flame. The total hydrocarbon content in the upper limestone section was low, mostly 0.1%–0.2%. Gas logging anomaly was observed at the well depth from 1 744 to 1745 m, the total hydrocarbon content increased from 0.123% to 18.965%, and the methane content increased from 0.111% to 14.143%. Combined with cuttings analysis, it was induced by gas in the cracks. After the well depth of 1 790 m, the total hydrocarbon content increased to more than 0.5%. After the well depth of 1 837 m, the total hydrocarbon content increased to more than 1%. After the well depth of 1 855 m, the total hydrocarbon content increased to 1.5%, the highest value reached 2.71%, and the methane content was 1.98%, revealing that the Lower Cambrian exhibits good shale gas exploration potential.

Table 1 Shale gas desorption data of well Yiye-1, Yichang area, Middle Yangtze region

No.	Depth/ m	Gas-bearing capacity/ (m^3 t^{-1})			Lithology	No.	Depth/ m	Gas-bearing capacity/ (m^3 t^{-1})			Lithology
		Desorbed gas	Lost gas	Total gas content				Desorbed gas	Lost gas	Total gas content	
1	1 762.38	0.22	0.09	0.31	Dark gray limestone	31	1 841.24	1.30	1.05	2.35	Black carbona-ceous shale
2	1 763.78	0.40	0.27	0.68	Dark gray limestone	32	1 843.20	1.41	1.32	2.73	Black carbona-ceous shale
3	1 766.57	0.30	0.13	0.42	Dark gray limestone	33	1 843.75	1.17	0.84	2.01	Black carbona-ceous shale
4	1 772.54	0.29	0.17	0.46	Dark gray marl	34	1 846.47	1.40	0.83	2.23	Black carbona-ceous shale
5	1 775.74	0.33	0.26	0.59	Dark gray limestone	35	1 849.14	1.35	1.10	2.45	Black carbona-ceous shale
6	1 777.56	0.20	0.12	0.33	Marl	36	1 851.22	1.39	1.23	2.63	Black carbona-ceous shale
7	1 780.05	0.26	0.16	0.42	Dark gray limestone	37	1 853.31	1.44	1.13	2.57	Black carbona-ceous shale
8	1 782.74	0.23	0.10	0.33	Gray marl	38	1 854.35	1.69	1.67	3.36	Black carbona-ceous shale
9	1 790.17	0.55	0.21	0.76	Dark gray cal-careous shale	39	1 856.64	1.53	1.56	3.08	Black carbona-ceous shale
10	1 791.56	0.45	0.16	0.61	Dark gray cal-careous shale	40	1 858.72	1.50	1.82	3.31	Black carbona-ceous shale
11	1 792.02	0.41	0.21	0.62	Dark gray cal-careous shale	41	1 860.51	1.57	1.31	2.88	Black carbona-ceous shale
12	1 792.51	0.56	0.19	0.75	Dark gray cal-careous shale	42	1 862.43	2.38	2.39	4.77	Black carbona-ceous shale
13	1 793.97	0.43	0.14	0.58	Dark gray cal-careous shale	43	1 864.60	2.72	2.76	5.48	Black carbona-ceous shale
14	1 795.70	0.55	0.19	0.74	Dark gray cal-careous shale	44	1 866.06	1.93	1.84	3.77	Black carbona-ceous shale
15	1 804.91	0.54	0.18	0.72	Gray-black calcareous shale	45	1 868.43	1.71	1.57	3.28	Black carbona-ceous shale
16	1 809.14	0.75	0.27	1.02	Gray-black calcareous shale	46	1 870.84	2.62	2.21	4.83	Black carbona-ceous shale
17	1 809.73	0.92	0.38	1.30	Gray-black calcareous shale	47	1 874.40	0.93	0.36	1.28	Gray-black cal-careous shale
18	1 813.01	0.98	0.41	1.39	Gray-black calcareous shale	48	1 877.02	0.54	0.26	0.79	Dark gray lime-stone
19	1 814.32	0.61	0.15	0.76	Gray-black calcareous shale	49	1 880.82	0.64	0.24	0.88	Dark gray lime-stone

20	1 816.48	0.66	0.15	0.81	Gray-black calcareous shale	50	1 887.24	0.63	0.33	0.96	Dark gray marl
21	1 820.02	0.61	0.19	0.80	Gray-black calcareous shale	51	1 894.39	0.72	0.31	1.03	Dark gray marl
22	1 821.88	0.94	0.26	1.21	Gray-black calcareous shale	52	1 903.71	0.83	0.36	1.19	Dark gray marl
23	1 823.68	1.07	0.65	1.72	Gray-black calcareous shale	53	1 909.70	0.86	0.34	1.20	Dark gray marl
24	1 826.79	1.41	1.17	2.57	Gray-black calcareous shale	54	1 920.20	0.96	0.42	1.38	Dark gray marl
25	1 828.89	1.06	0.48	1.54	Gray-black calcareous shale	55	1 925.83	0.50	0.31	0.80	Black argillaceous siliceous rock
26	1 831.42	1.03	0.35	1.37	Black calcareous shale	56	1 927.59	0.34	0.13	0.47	Gray siliceous dolomite
27	1 833.05	0.93	0.26	1.19	Black calcareous shale	57	1 930.56	0.32	0.19	0.51	Gray-black siliceous mudstone
28	1 835.45	0.95	0.33	1.28	Black calcareous shale	58	1 934.08	0.30	0.18	0.47	Gray siliceous dolomite
29	1 837.69	1.12	1.07	2.19	Black calcareous shale	59	1 938.27	0.24	0.15	0.39	Gray siliceous dolomite
30	1 839.52	1.20	0.93	2.14	Black calcareous shale						

2.3 On-site desorption

The desorption experiment is the most direct method to measure the gas content of shale, referring to the oil and gas industry standard *Method for the Determination of shale Gas Content*: *SY/T6940–2013*. After the core was taken out of the cylinder at wellhead, about 30 cm of shale was selected to remove mud debris, weighed and placed into a closed metal desorption tank, and the time of encountering the stratum, the trip time, the bug time and the time of sealing the tank were recorded. The desorption temperature in the first three hours was the mud circulation temperature. After three hours, the core was desorbed under the formation temperature conditions. The ambient temperature and atmospheric pressure data were recorded, the data of gas content varying with time were acquired, and the natural desorption was continued until the desorption rate was less than 10 cm^3/day. According to the gas state equation, the volume was converted into the temperature of 0 ℃ and the pressure of 101.325 kPa to obtain the content of desorbed gas.

The lost gas volume was calculated by the USBM method, and the desorbed gas volume at the initial period was proportional to the square root of the time [21]. The time-desorbed gas volume curve was plotted and returned to the time zero point to calculate the lost gas volume. The residual gas was the volume of gas released by the pulverization after the termination of shale natural desorption. Due to the complexity of detection instrument and the difficulty in production process, the gas content in this study mainly included desorbed gas and lost gas.

The shale gas content of two wells drilled in this area was determined by on-site desorption method. 51 core samples from 1 642.8 to 1 731.5 m in well Yidi-2 were desorbed; 59 core samples from 1 762.38 to 1 938.27 m (lower Shuijingtuo Formation) in well Yiye-1 were desorbed, the desorption duration is usually 20–30 hours, and the gas content data are shown in Table 1. Fig. 3 illustrates the plot of on-site desorbed gas volume over time in well Yiye-1. The first-order desorption lasts for three hours at the mud circulation temperature to ensure that the gas escape rate in free state is the same as the escape rate in the mud, which simulates the gas loss of shale in the period of encountering, lifting, and to the surface, and shows the characteristics of high gas desorption rate; the amount of desorbed gas in this period accounts for 60%–85% of the total desorbed gas, which is consistent with the characteristic that free gas is dominant in conventional gas reservoirs and tight sandstone [22]. The second-order desorption adopts the formation temperature, but the desorption detection time is long, and the desorption rate is slow, so that the accumulated gas volume in the later period is almost a straight line extending with time, which is similar to the desorption characteristic that high-order coal is dominated by adsorption gas [23]. Since the free and adsorbed gas molecules in shale are relatively equilibrium, the influencing factors are numerous and complex. In this study, it is assumed that the lost gas and desorbed gas under the first-order temperature are approximately equal to the free gas, and the desorbed gas after second-order heating is absorbed gas.

2.3.1 Well Yiye-1

The desorbed gas content of well Yiye-1 is in the range of 0.31–5.48 m^3/t, with an average value of 1.57 m^3/t. The gas-bearing capacity of the upper argillaceous limestone section in Shuijingtuo Formation is poor, with a gas content of 0.31–0.67 m^3/t and an average value of 0.44 m^3/t. The gas bubble in core immersion test is weak. The thickness of continuous gas-bearing shale (1 786–1 872 m) in the lower Shuijingtuo Formation is 86 m, with a minimum gas content of 0.579 m^3/t and a maximum one of 5.48 m^3/t (about 2.05 m^3/t on average). Statistics show that (Table 1, Fig. 4), the cumulative thickness of shale with the continuous gas content of greater than 2 m^3/t is 44.05 m, that of shale with the gas content of greater than 3 m^3/t is 16.49 m, and it is 8.41 m for the gas content of greater than 4 m^3/t. The maximum gas content (5.48 m^3/t) occurs at the depth of 1 846.60 m.

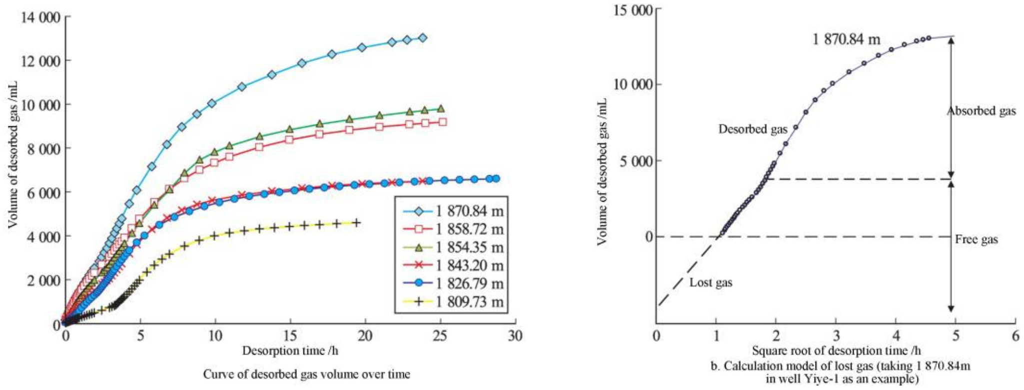

Fig. 3 Shale gas desorption of well Yiye-1, Yichang area, Middle Yangtze region

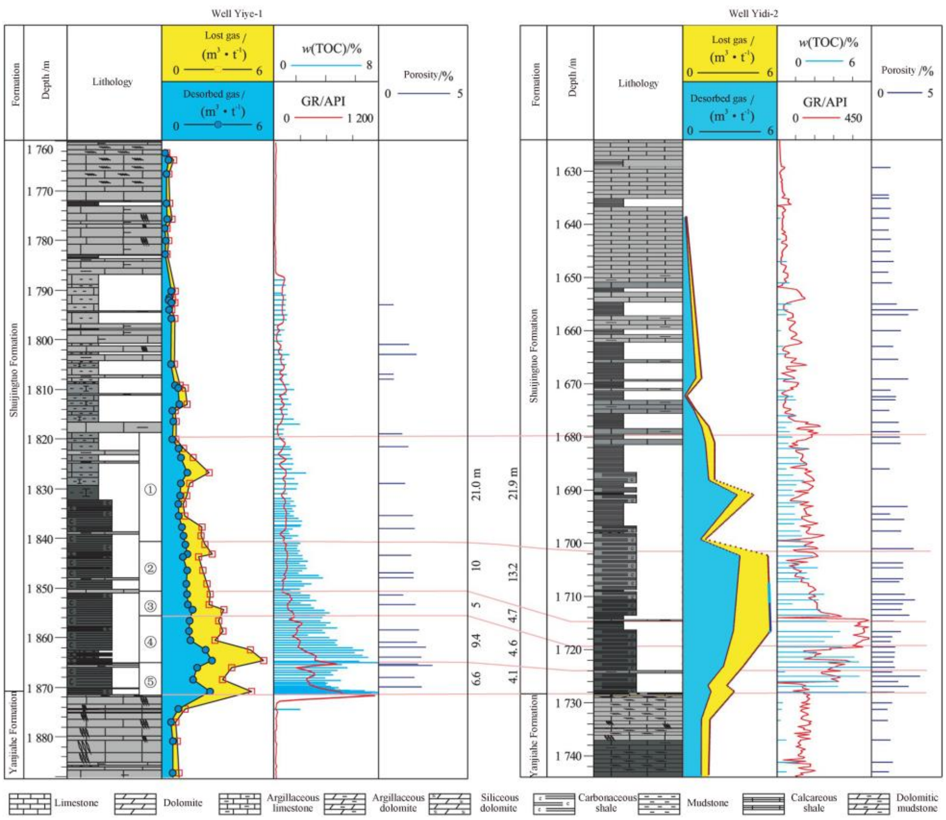

Fig. 4 Comparison of shale gas content and organic geochemical parameters between wells Yiye-1 and Yidi-2, Yichang area, Middle Yangtze region

2.3.2 Well Yidi-2

This well is located in Tucheng Township, Dianjun District, Yichang City, with a depth of 1 806 m. The drilling reveals that the thickness of continuous high-quality black shale is 72 m (1 656.09–1 728.09m) in the Shuijingtuo Formation, and the gas bubble in the core immersion test is strong. The total gas content of on-site desorption of the Shuijingtuo shale is 0.364–5.57 m^3/t, with an average value of 1.85 m^3/t, of which the desorbed gas volume is 0.194–3.65 m^3/t, and the best gas-bearing capacity occurs in the lower shale section. The average gas content at the depth of 1 702–1 728 m is up to 4.16 m^3/t (Fig. 4). The methane content in the gas sample component collected by on-site desorption is over 90%.

It is generally believed that the lower limit of commercial shale gas development is 2.0 m^3/t, and the gas contents in the large-scale developed Fayetteville shale in the Arkoma Basin, the Marcellus shale in the Appalachian Basin, and the Fuling Jiaoshiba shale are 1.70–6.23, 1.70–2.83, and 6.1 m^3/t respectively. Comparing with the commercially developed shale gas in North America, the gas content of Shuijingtuo shale in the Yichang area has reached the lower limit of shale gas development, showing the commercial development value.

3 Affecting factors of shale gas content

3.1 Lithology and gas content

Gas showing is widely observed in the wells targeting at organic-rich shale in the Shuijingtuo Formation, while the on-site desorption results show that the gas content varies greatly in different layers. In the longitudinal direction, the high-quality bottom shale has the highest gas content, and the total gas content of the Shuijingtuo shale gradually decreases from the bottom to top (Fig. 4). The lithology of Shuijingtuo Formation is dominated by carbonaceous shale, calcareous shale, marl and limestone, as well as siliceous dolomite. The lithology has a correlation with the gas content (Fig. 5). The carbonaceous shale has the highest gas content, generally 1.19–5.48 m^3/t, with an average value of 2.93 m^3/t; followed by calcareous shale, generally 0.58–2.57 m^3/t, with an average value of 1.08 m^3/t; the limestone and marl have the lower gas content, ranging from 0.31 to 1.37 m^3/t, about 0.73 m^3/t on average; the siliceous dolomite has the lowest gas content, with an average value of no more than 0.50 m^3/t.

The lithology has good correlation with the gas content in the study area, and the lithology can directly reflect the sedimentary environment. The lower Shuijingtuo Formation is composed of black carbonaceous shale and thin layer of calcareous shale from continental shelf facies, interbedded with dark gray mudstone lens. The continental shelf water body was deep, hydrocarbons were generated in the shale from organic matters like algae and reserved in-situ during the late burial period. The measured gas content is the highest, and the total gas content of the gray-black carbonaceous shale is 3.85 m^3/t. The calcareous shale was mainly deposited in the inner margin of the continental shelf in the Shuijingtuo Formation. The interbedded layers of mudstone and limestone diluted the organic matters, and the high limestone content is not conducive to the preservation of organic matters. The gas content is lower than that of the carbonaceous mudstone on the continental shelf, and the average measured gas content is 2.27 m^3/t. The upper Shuijingtuo Formation is mainly composed of deep gray argillaceous limestone within limited platform. The shale content is low, the gas content is the lowest, and the total gas content is less than 0.5 m^3/t.

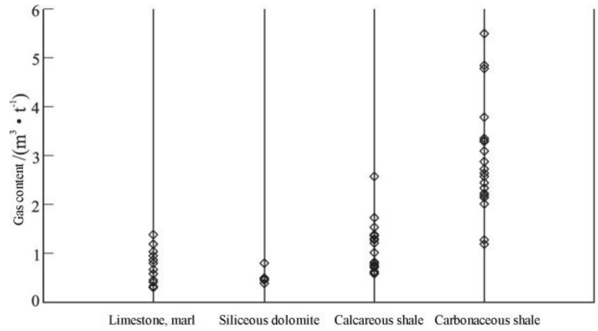

Fig. 5 Correlation between lithology and shale gas content in well Yiye-1, Yichang area, Middle Yangtze region

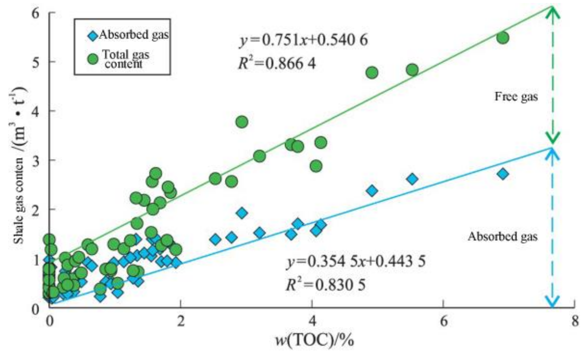

Fig. 6 Correlation between gas content and TOC content of Shuijingtuo shale in well Yiye-1, Yichang area, Middle Yangtze region

3.2 Organic carbon content and gas content

The analysis results show that (Fig. 4), the organic total carbon content (TOC) of Shuijingtuo shale is between 0.43% and 11.45%, with an average value of 2.97%, of which more than 58% of the samples have the TOC of over 2%. The TOC is relatively high, and it increases gradually from top to bottom. Overall, the shale presents a good original gas generation basis. Studies have shown that as the TOC of shale increases, the desorbed gas content and total gas content increase continuously (Fig. 6), and there is strong positive correlation between the desorbed gas content and TOC of shale. The fitting coefficient (R^2) is 0.866 4, which indicates that TOC is the main factor controlling the content of adsorbed gas. The gas occurrence in high TOC shale is mainly related to the organic matter particles, because the higher

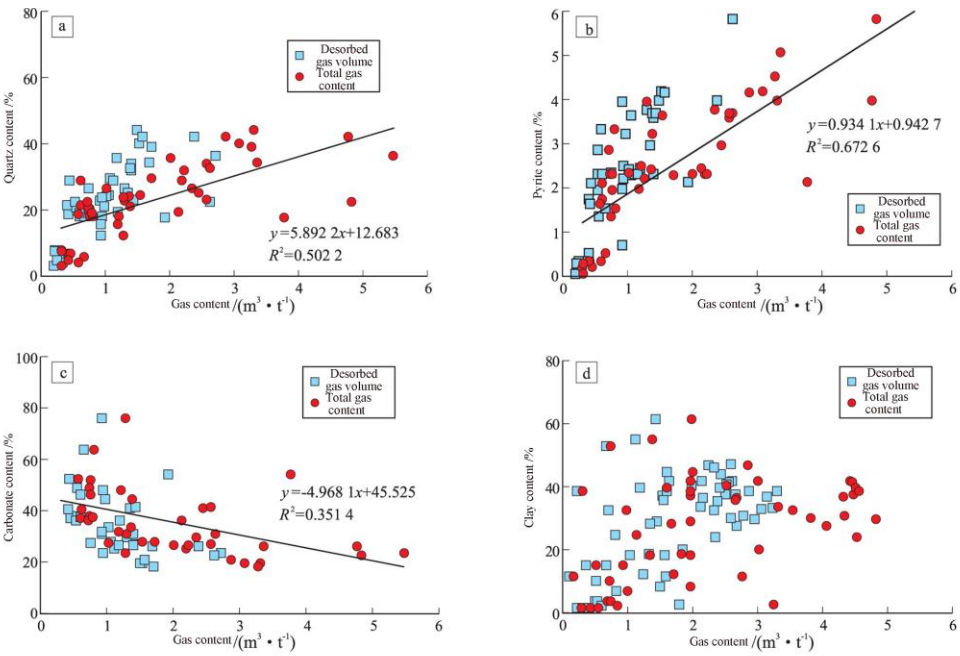

Fig. 7 Correlation between gas content and mineral content of Shuijingtuo shale in Yichang area, Middle Yangtze region

TOC indicates the larger generated shale gas volume, and the more developed organic pores; the higher TOC shale usually has higher porosity and gas saturation, which increases the storage space of free gas [24]. Furthermore, the specific surface areas of micropores and mesopores in shale increase with TOC [23]. The more developed micropores indicate the larger specific surface area of micropores. In addition to the lipophilic surface of organic matters, the adsorption capacity for gaseous hydrocarbons is strong, and the content of adsorbed gas increases as well.

3.3 Mineral composition and gas content

The inorganic minerals in the shale are mainly clay, quartz and calcite, and their compositional changes affect the pore structure of the shale, which in turn affects the gas adsorption capacity [25]. A large number of biological structured quartz is found in the black shale in the lower Shuijingtuo Formation in the study area, the shale gas content has significant positive correlation with the quartz content (Fig. 7a), and the correlation coefficient R^2 can be up to 0.5. Because quartz has strong anti-compacting ability, it can form a rigid grid, which is conducive to the preservation of pores. Therefore, the higher quartz content indicates that the porosity is larger and the gas content is higher. In addition, pyrite is common in the Shuijingtuo shale, and the core observation indicates that the pyrite is mostly scattered in shale in the millimeter-sized strawberry-like and microscopic star-like forms. Schlumberger logging interpretation suggests that the weight percentage of pyrite in gas-bearing shale formation is between 0.2% and 6.22%, with an average value of 2.55%. The pyrite has a synchronous positive change with the TOC and gas content (Fig. 7b), indicating that the reducing environment during the original sedimentation of shale is conducive to the preservation of organic matters. And the high marine biological productivity caused the organic carbon to be input in large quantities and resulted in the high-intensity sulfate reducing environment simultaneously. S^{2-} in water body or pore water existed in the form of iron sulfide, and was buried with organic matter simultaneously. The widely deposited primary pyrite is a manifestation of strong reducing environment.

There is a weak negative correlation between shale gas content and carbonate mineral content (Fig. 7c). According to the analysis of the mineral composition characteristics of the shale interval in the Shuijingtuo Formation, the carbonate mineral content in the shale is high, the calcite content is 3.6%–40.6%, the dolomite content is 1.2%–24.6%, and the carbonate content is about 26% on average. The increase in carbonate content will reduce the porosity of shale and lower the free gas reservoir space, especially the cementation of calcite in the burial process will further reduce the pore space.

Clay minerals are the important components of shale, and the gas content of well Yiye-1 has poor correlation with clay minerals (Fig. 7d). Previous studies have shown that [26–27], clay minerals have a relatively small particle volume and a relatively large micropore volume/specific surface area. Due to the difference on the crystal structure and morphology of minerals, the main mineral components of shale show different abilities in methane adsorption. The methane adsorption abilities are ranked as montmorillonite > illite–montmorillonite mixed layer > kaolinite > chlorite > illite > sandstone > quartz. The content of clay minerals in the Shuijingtuo shale in the study area is relatively high, and the reasons for the poor correlation between the amount of adsorbed gas and the content of clay minerals are complicated. On one hand, the increase in clay mineral content is conducive to the formation of intergranular pores, shrinkage joints and other reservoir spaces related to clay minerals [27], which is beneficial to the increase in free gas content. And high content of the illite–montmorillonite mixed layer has a strong adsorption capacity to shale gas, which is conducive to promoting the gas adsorption in shale; on the other hand, high clay content usually results in higher reservoir bound water content, and lowers the free gas saturation. The correlation coefficient between gas content and clay mineral content is low in this study, which may be related to the very high degree of irreducible water saturation in shale. The nuclear magnetic resonance (NMR) logging of well Yiye-1 shows that the NMR total porosity of 1 840–1 872 m high-quality shale reservoir is relatively high, about 3%–4% on average, but it is mostly occupied by clay bound water. The effective porosity of shale is relatively low, about 1.9%–2.9% on average, and the bound water porosity is between 1.0% and 2.0%. Previous studies have also shown that the water molecules adsorbed on the surface of clay minerals will occupy the adsorption space of methane molecules [28]. The reduction of effective porosity will reduce the free gas storage space, and ultimately lead to poor correlation between gas content and clay mineral content.

3.4 Porosity and gas content

The size of the reservoir space is an important factor affecting the content and occurrence state of shale gas [18]. The Shuijingtuo shale in the study area is compact, with an average porosity of 1.6%–2.8%, 77% of which have a porosity of 1.0%–3.0%, and 19.7% of which have a porosity of greater than 3%. The permeability is (1–3) $\times 10^{-3} \mu m^2$, belonging to the typical low porosity and low permeability shale reservoir. The statistics of measured porosity and desorbed gas content in wells Yidi-2 and Yiye-1 indicate that there is certain positive correlation between the two (Fig. 8a). The shale with high TOC content exhibits high porosity and gas saturation, showing high free gas content. The pore types of the Shuijingtuo shale can be divided into organic pores, clay mineral pores and brittle mineral pores. The pores of organic pores and clay minerals are dominant, and the organic pores are the most widely distributed, which provide the most important storage space for shale gas adsorption, exhibiting a positive correlation between the amount of adsorbed gas and shale porosity.

In addition to the pore volume, pore structure also affects the shale reservoir capacity, which in turn affects the shale gas content. The distribution of nanopores in shale was observed by mercury intrusion and liquid nitrogen adsorption. Mainly micropores and mesopores were developed in the shale of well Yidi-2, and a small number of macropores were developed. The pore sizes are mainly distributed between 0.5–1 nm and 13–15 nm. Among them, the pores of less than 2 nm account for 40.0%–70.0%, the pores of 2–50 nm account for 25.0%–40.0%, and a small number of macropores can have the pore size of hundreds to thousands of nanometers (Fig. 8b). The pores of Shuijingtuo shale are mainly composed of organic micropores and mesopores, and the macropores are less developed. The mesoporous pore volume is dominant in the total pore volume, indicating that the clay minerals and quartz mineral content control the storage space of free gas in shale. The specific surface areas of micropores and mesopores are roughly equivalent, and a large amount of specific surface area is mainly provided by the pores of less than 10 nm. Those pores are mainly represented by organic pores, and the adsorption capacity of shale is controlled by such pores. In addition, since the pore size of macropore exceeds the maximum organic pore size, it indicates that the inorganic pore is a major contributor to those macropores. In summary, the gas content of Shuijingtuo shale has positive correlation with the porosity, but the correlation coefficient between the two is low. The difference of micropore distribution in the shale is the main factor leading to the difference of gas content.

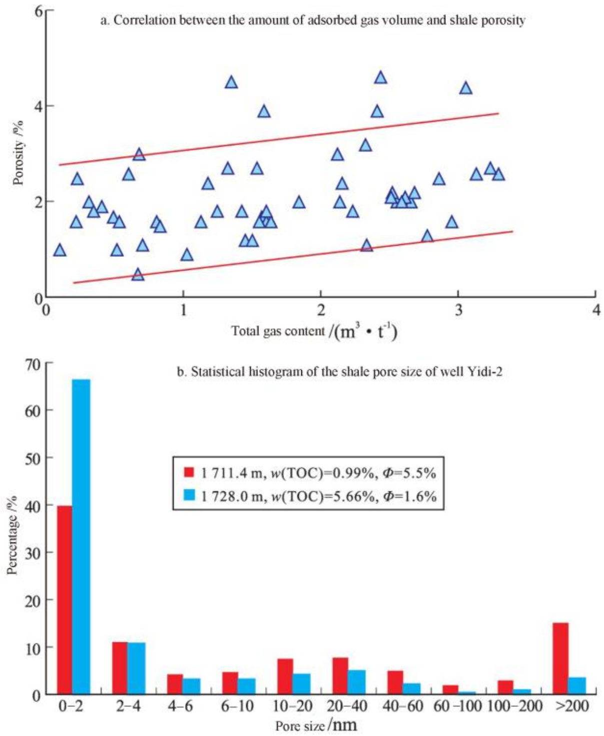

Fig. 8 Shale porosity characteristics of Shuijingtuo Formation in Yichang area, Middle Yangtze region

3.5 Fracture development and gas content

Although shale formations are generally gas-bearing, at present the shale gas reservoirs with industrial exploration value or sweet spots rely primarily on the fracture systems with a certain scale in shale formation. Among about 3 000 wells in the United States, the number of wells that have encountered fractured sweet spots with natural industrial capacity is only about 10%, indicating that the fracture system is an important factor in improving the industrial production capacity of shale gas wells [29–30]. Fractures are developed in most shale, and are characterized by fracture network with a variety of genesis (pressure difference, faulting, bedding, etc.). The fracture and dissolution of joint seam are the main reservoir spaces. The effect of fractures on reservoir physical properties is mainly reflected in the adjustment of reservoir space and the formation of seepage channels [31–32]. The fracture development zone can provide the storage and seepage space to free shale gas, and the natural micro-fractures can form the fracture network together with the hydraulic fractures of volumetric stimulation, which provide a transport channel for the migration and accumulation of shale gas.

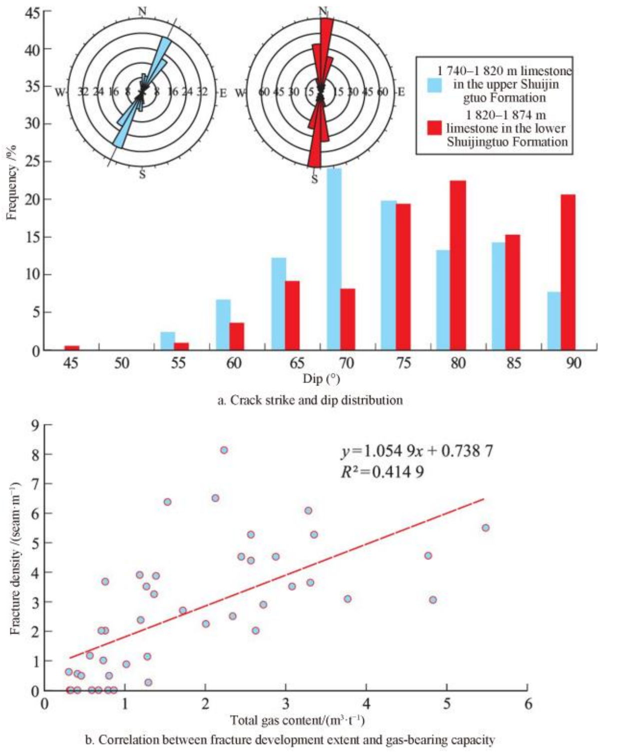

Fig. 9 Fracture distribution characteristics of shale in well Yiye-1, Yichang area, Middle Yangtze region

Natural fractures were developed in the Shuijingtuo shale of well Yiye-1 (Fig. 2a, Fig. 9). The core shows a large number of natural fractures caused by tectonic activity, including high-angle oblique fractures and horizontal bedding seams, and the fractures were fully or partially filled with high-resistance minerals like calcite. The high-angle oblique fracture was most developed, the fracture width is less than 1 mm, and it is mostly filled with calcite veins; the width of horizontal fracture is less than 1 mm, which is often filled with calcite and mud. The FMI imaging logging data were applied to conduct the fracture statistics of the Shuijingtuo Formation–Yanjiahe Formation. The target layer has developed 222 high-resistance fractures at the depth of 1 820–1 874 m, and the main frequency of fractures is 65°–75°; 91 high-resistance fractures were developed at the depth of 1 740–1 820 m, and the main frequency of fractures is 80°–90°; 115 high-resistance fractures were developed at the depth of 1 874–1 925 m, and the main frequency of fractures is 80°–85°. The fracture strike is close to that of the Tianyangping fault in the southwest (Fig. 9a), indicating that it is controlled by regional tectonic stress. The statistics on the distribution of high-resistance vertical fractures suggests that the density of high-resistance fractures in Shuijingtuo Formation shows its peak in the 5th and 2nd sub-layers, reaching 8–12 fractures/m.

The fracture density and gas strike dispersion are one of the important geological factors controlling shale gas production capacity [31–33]. The shale fracture development zone in the well Yiye-1 is far away from the peripheral Tianyangping fault, which has a positive influence on the enrichment and output of shale gas. The shale gas content in the lower Shuijingtuo Formation has a good correlation with the fracture development density (Fig. 9b), and the correlation coefficient of the two is $R^2 > 0.4$. The gas content at the depth of 1 854.35–1 870.84 m is high, and the core observation reveals that horizontal seam, vertical joint and high-angle oblique fracture were developed in this section, and most of the fractures were filled with calcite. The bedding slip occurs in the black carbonaceous mudstone at the depth of 1 863.9–1 871.51 m at the bottom interface of the Shuijingtuo Formation (Fig. 2e). The position and characteristics of the near-horizontal slip zone are controlled by subtle lithological changes. The carbonaceous mudstone is characterized by soft lithology, low strength, low density and easy deformation, especially the carbonaceous mudstone above the hard siliceous dolomite in the basement of Yanjiahe Formation, which is more prone to changes in structure, morphology and volume. And the specular scratches produced by the deformation are lumpily oblique to the bedding. The reservoirs at the bottom of the Shuijingtuo shale are tight, and the TOC content and maturity are not changed obviously. Along with the development of fractures in shale reservoir, the total gas content reaches its peak at the depth of 1 854.35–1 870.84 m, and the shale gas shows are good. Both of them are closely related to fracture development, and the natural fractures promote the shale gas-bearing capacity and yield of shale gas.

3.6 Formation pressure and gas content

The lower proportion of free gas in the Shuijingtuo Formation is also related to the normal pressure state of the formation. The statistics of free gas content in typical shale gas producing areas around the world (Fig. 10) show that the compositions of gas-bearing capacity under various formation pressures are very different. The Silurian Longmaxi Formation of the Jiaoshiba area is dominated by free gas, the free gas content obtained by on-site desorption is 56%–65%, and the formation pressure coefficient of the gas producing section is 1.4. The free gas content in North American shale is 40%–80%, of which the Antrim is biogas, the gas content is 1.13–2.83 m^3/t, and the formation pressure is normal; the Lewis is pyrolysis gas with low pressure, two sets of shale are dominated by adsorbed gas, and the gas content is low (less than 2 m^3/t); the shale gas layers such as Bamett, Marcellus and Haynesville are mostly overpressured, the gas content is high (2–9.9 m^3/t) and dominated by free gas, and the content of adsorbed gas does not exceed 50%.

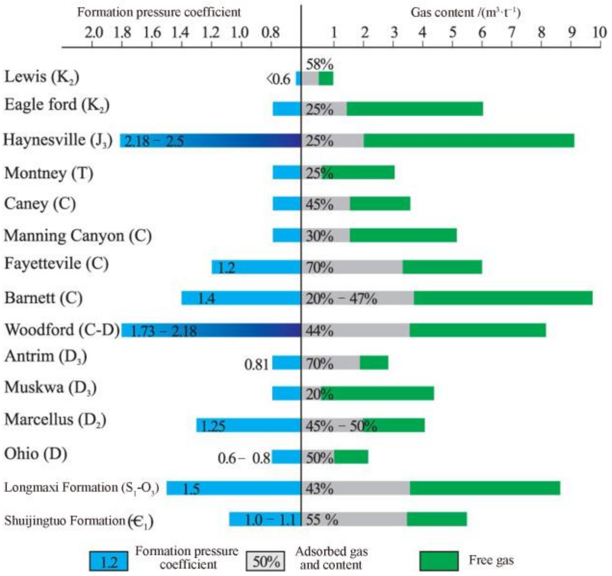

Fig. 10 Relationship among gas content, proportion of adsorbed gas and formation pressure of typical shale gas exploration areas in China and overseas

3.7 Other factors

In addition to the above geological factors, various geological factors such as organic matter maturity, shale thickness, and burial depth also affect the gas content of shale formations.

(1) When R_o is 1.0%–3.5%, the higher maturity of shale organic matters indicates that the accumulation will be better. For thermogenic gas reservoirs, the gas content increases with the organic matters maturity of shale. According to the exploration and production practices of marine shale gas in the North American and Southern China [35–36], the highest maturity of North American shale gas development zone occurs in the Marcellus shale, with the R_o of 1.0%–3.5%, but only less than 1/10 of shale distribution area has the R_o > 3.0%. The R_o of commercial shale gas reservoirs is generally 2.0%–3.5%. When the maturity is too high (R_o > 3.5%), the sum of mesopore and micropore spaces increases continually, whereas the specific surface area decreases after R_o > 3.5% [36], which is not conducive to the preservation of adsorbed gas. A significant feature of the Shuijingtuo shale in the Yichang area is that the thermal maturity is relatively low, and the measured R_o is less than 3.0%. As a rigid basement of the Proterozoic, the Huangling uplift is structurally stable, and the apatite fission track test data reveal that the sedimentary caprock of the Huangling uplift and its surrounding areas experienced a one-way cooling process, and it had been buried in the underground 210 ℃ geothermal isotherm after the Late Triassic-Middle Jurassic and the initial Early Cretaceous; after that, it had not experienced the high-temperature heating in the later period [37]. At present, the geothermal gradient in the surrounding area of the Huangling uplift is only 2.17 ℃/hm. Paleo-shales such as the Cambrian and other ancient shale in the periphery of the uplift underwent a lower paleo-geotemperature, and the shale thermal evolution was relatively low, which was favorable for the formation and enrichment of shale gas.

(2) The thickness of shale controls the scale and economic benefits of shale gas reservoir to some extent. Theoretical studies have shown that argillaceous rock can serve as the caprock when its thickness is greater than 1 m [14]. But in fact, the lateral stability of lithology must be considered, and hydrocarbon gases are always lost in the weakest areas. The increase in shale thickness will reduce or block the vertical communication of the connected pore throats, and prevent the gas from diffusing. The gas diffusion intensity in the geological history is proportional to the distance (thickness) of the caprock. Therefore, the lower limit of the thickness of gas-bearing shale with industrial value will be 15 m, and the thickness of high-quality shale gas reservoir with good economic benefits should be greater than 30 m. The shale gas wells in Yichang area have a shale thickness of greater than 70 m, exhibiting a remarkable scale of shale gas reservoir and the good storage/preservation of shale gas.

(3) Physical data research shows that in the absence of fissures and fault development, after the shale experienced a deepened burial depth, the older age, and the higher thermal evolution, due to the higher compaction of overlying strata, the mudstone pore throat radius and maximum connected pore throat radius decreased, the porosity and permeability were reduced, and the diffusion coefficient also decreased; the specific surface area, density and hardness were increased, the breakthrough pressure was increased as well, and the shale sealing ability was improved [38–39]. The burial depth in Yichang area has a direct impact on the shale gas content. For example, the maximum burial depth of shale in wells Yidi-2 and Yiye-1 is more than 1 700 m, and the shale gas-bearing capacity is good. The bottom burial depth of Shuijingtuo Formation in offset well Zidi-2 is no more than 360 m. The average nitrogen content of the desorbed gas components in this well is as high as 44.63%, which indicates that the preservation conditions of shale gas are poor under shallow burial depth and the gas-bearing capacity is weak.

4 Conclusions

(1) The Shuijingtuo shale in Yichang area has high gas-bearing capacity, and the gas logging anomaly in drilling is significant. The on-site desorption of 110 shale samples from two wells indicates that the thickness of gas-bearing shale section is 86 m, and it is mainly distributed in the lower Shuijingtuo Formation. The lithology is dominated by black carbonaceous shale and gray shale. The shale gas content is 0.32–5.48 m^3/t, with an average content of 1.57 m^3/t, and the gas content increases from top to bottom; the continuous gas

content is greater than 2 m^3/t and the formation thickness is 44.05 m. The gas content of Shuijingtuo shale is generally high and it shows the commercial development value.

(2) The correlation between lithology and gas content is good. The total gas content of black carbonaceous shale in the lower Shuijingtuo Formation is 3.85 m^3/t, the average gas content of the middle calcareous shale is 2.27 m^3/t, and the gas content of the upper marl is the lowest, generally less than 0.5 m^3/t. The gas-bearing capacity of shale is affected by many factors. The TOC content of shale, shale mineral composition, porosity and pore structure, as well as the development extent of shale fractures and formation pressure are the important factors affecting the gas-bearing capacity of shale.

(3) There is strong positive correlation between desorbed gas content and TOC of shale, indicating that TOC is the major factor controlling gas content. The shale gas content has a significant positive correlation with the quartz content, a weak negative correlation with the carbonate mineral content, and a poor correlation with the clay mineral content. The amount of adsorbed gas exhibits positive correlation with shale porosity and is also affected by the shale pore structure. In addition, the gas content is closely related to the fractures development of reservoir and the formation pressure.

References

[1] ZHANG J C, JIN Z J, YUAN Mingsheng. Reservoiring mechanism of shale gas and its distribution [J]. Natural Gas Industry, 2004, 24 (7): 15–18 (in Chinese with English abstract).

[2] ZHANG H R. Gas content of the Silurian shale in the SE Sichuan Basin and its controlling factors [J]. Natural Gas Industry, 2016, 36 (8): 36–42 (in Chinese with English abstract).

[3] ZOU C N, DONG D Z, WANG S J, et al. Geological characteristics, formation mechanism and resource potential of shale gas in China [J]. Petroleum Exploration and Development, 2010, 37 (6): 641–653 (in Chinese with English abstract).

[4] LI W G, ZHONG B, YANG H Z, et al. Evaluation of gas-bearing property for shale reservoir and its influence factors analysis: taking Changning–Weiyuan National Experimental Zone as an example [J]. Natural Gas Geoscience, 2014, 25 (10): 1653–1660 (in Chinese with English abstract).

[5] LIU L, BAO H Y, LI K, et al. Evaluation of gas content in shale reservoirs and analysis of influencing factors in Fuling shale gas field [J]. Petroleum Geology & Experiment, 2018, 40 (1): 58–63 (in Chinese with English abstract).

[6] WEI X F, LI Y P, WEI Z H, et al. Effects of preservation conditions on enrichment and high yield of shale gas in Sichuan Basin and its periphery[J]. Petroleum Geology & Experiment, 2017, 39 (2): 147–153 (in Chinese with English abstract).

[7] GAO F L, SONG Y, JIANG Z X, et al. Influence of clay minerals on shale storage space and adsorptive capacity [J]. Special Oil & Gas Reservoirs, 2017, 24 (3): 1–8 (in Chinese with English abstract).

[8] MENG X W, TIAN J C, ZHANG X, et al. Characteristics of shale gas of the Qiongzhusi Formation in Jingyan area of southwest Sichuan [J]. Journal of Mineralogy and Petrology, 2014, 34 (2): 96–105 (in Chinese with English abstract).

[9] DONG D Z, GAO S K, HUANG J L, et al. A discussion on the shale gas exploration & development prospect in the Sichuan Basin [J]. Natural Gas lndustry, 2014, 34 (12): 1–15 (in Chinese with English abstract).

[10] ZHOU W, XU H, YU Q, et al. Shale gas-bearing property differences and their genesis between Wufeng–Longmaxi Formation and Qiongzhusi Formation in Sichuan Basin and surrounding areas [J]. Lithologic Reservoirs, 2016, 28 (5): 18–25 (in Chinese with English abstract).

[11] ZHANG Y Y, HE ZL, GAO B, et al. Sedimentary environment of the Lower Cambrian organic-rich shale and its influence on organic content in the Upper Yangtze [J]. Petroleum geology & Experiment, 2017, 39 (2): 154–161 (in Chinese with English abstract).

[12] LIN T, ZHANG J C, LI B, et al. Shale gas accumulation conditions and gas-bearing properties of the Lower Cambrian Niutitang Formation in well Changye 1, northwestem Hunan [J]. Acta Petrolei Sinica, 2014, 35 (5): 839–846 (in Chinese with English abstract).

[13] ZHOU Q H, SONG N, WANG C Z, et al. Characteristics of shale and gas content of Niutitang Formation in Changde region of Hunan Province [J]. Natural Gas Geoscience, 2015, 26 (2): 301–311 (in Chinese with English abstract).

[14] WANG R Y, DING W L, GONG D J, et al. Gas preservation conditions of marine shale in northern Guizhou area: a case study of the Lower Cambrian Niutitang Formation in the Cen’gong block, Guizhou Province [J]. Oil & Gas Geology, 2016, 37 (1): 45–55 (in Chinese with English abstract).

[15] MA Y, ZHONG N N, HAN H, et al. Definition and structure characteristics of pores in mylonitized organic-rich shales [J]. Science China (Earth Sciences), 2014, 57 (12): 3027–3034 (in Chinese with English abstract).

[16] DENG M Z, HE D F, ZHANG Y Y. Tectonic evolution of Xiannüshan fault and its influence on hydrocarbon traps in Changyang anticline, Western Hubei fold belt [J]. Petroleum Geology & Experiment, 2018, 40 (2): 177–184 (in Chinese with English abstract).

[17] HE Z L, CHENG Z, XU X H, et al. Tectonic cycles and petroleum exploration potential in the East Qinling and Dabie Orogenic Belt [J]. Petroleum Geology & Experiment, 2009, 31 (2): 109–118 (in Chinese with English abstract).

[18] CHEN X H, LI H Q, CHEN L D, et al. Carbon and oxygen isotope features of the Sinian carbonate strata in the Three Gorges region [J]. Geological Review, 2003, 49 (1): 66–73 (in Chinese with English abstract).

[19] HUANG J L, ZOU C N, LI J Z, et al. Shale gas generation and potential of the Lower Cambrian Qiongzhusi Formation in southern Sichuan Basin, China [J]. Petroleum Exploration and Development, 2012, 39 (1): 69–75 (in Chinese with English abstract).

[20] LIU L, BAO H Y, LI K, et al. Evaluation of gas content in shale reservoirs and analysis of influencing factors in Fuling Shale Gas Field [J]. Petroleum Geology & Experiment, 2018, 40 (1): 58–63 (in Chinese with English abstract).

[21] BERTARD C, BRLYET B, GLNTHER J. Determination of desorbable gas concentration of coal (direct method) [J]. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 1970, 7 (1): 43–50.

[22] WANG F Y, HE Z Y, MENG X H, et al. Occurrence of shale gas and prediction of original gas in-place (OGIP) [J]. Natural Gas Geoscience, 2011, 22 (3): 501–510 (in Chinese with English abstract).

[23] ROSS D J K, BUSTIN R M. Impact of mass balance calculations on adsorption capacities in microporous shale gas reservoirs [J]. Fuel, 2007, 86 (17/18): 2696–2706.

[24] WANG F Y, GUAN J, FENG W P, et al. Evolution of overmature marine shale porosity and implication to the free gas volume [J]. Petroleum Exploration and Development, 2013, 40 (6): 819–824 (in Chinese with English abstract).

[25] FATHI E, AKKUTLU I Y. Matrix heterogeneity effects on gas transport and adsorption in coalbed and shale gas reservoirs [J]. Transport in Porous Media, 2009, 80 (2): 281–304.

[26] JI L M, QIU J L, XIA Y Q, et al. Micro-pore characteristics and methane adsorption properties of common clay minerals by electron microscope scanning [J]. Acta Petrolei Sinica, 2012, 33 (2): 249–256 (in Chinese with English abstract).

[27] WANG M Z, LIU S B, REN Y J, et al. Pore characteristics and methane adsorption of clay minerals in shale gas reservoir [J]. Geological Review, 2015, 61 (1): 207–216 (in Chinese with English abstract).

[28] TIAN H, ZHANG S C, LIU S B, et al. The dual influence of shale composition and pore size on adsorption gas storage mechanism of organic-rich shale [J]. Natural Gas Geoscience, 2016, 27 (3): 494–502 (in Chinese with English abstract).

[29] GUO Y H, ZHAO D F. Analysis of micro-scale heterogeneity characteristics in marine shale gas reservoir [J]. Journal of China University of Mining & Technology, 2015, 44 (2): 300–307 (in Chinese with English abstract).

[30] GUO X S. Enrichment mechanism and exploration technology of

Jiaoshiba area in Fuling Shale Gas Field [M]. Beijing: Science Press, 2014: 160–176 (in Chinese).
[31] DING W L, LI C, LI C Y, et al. Dominant factor of fracture development in shale and its relationship to gas accumulation [J]. Earth Science Frontiers, 2012, 19 (2): 212–220 (in Chinese with English abstract).
[32] PU B L, DONG D Z, NIU J Y, et al. Principal progresses in shale gas reservoir research [J]. Geological Science and Technology 1nformation, 2014, 33 (2): 98–104 (in Chinese with English abstract).
[33] GUO X S, HU D F, WEI X F, et al. Main controlling factors on shale fractures and their influences on production capacity in Jiaoshiba area, the Sichuan Basin [J]. Oil & Gas Geology, 2016, 37 (6): 799–808 (in Chinese with English abstract).
[34] HILL D G, NELSON C R. Gas productive fractured shales: an overview and update [J]. GasT1PS, 2000, 6 (2): 4–13.
[35] CHALMERS G R L, BUSTIN R M. Geological evaluation of Half-way-Doig-Montney hybrid gas shale-tight gas reservoir, north–eastern British Columbia [J]. Marine and Petroleum Geology, 2012, 38 (1): 53–72.
[36] CHENG P, XIAO X M. Gas content of organic-rich shales with very high maturities [J]. Journal of China Coal Society, 2013, 38 (5): 737–741 (in Chinese with English abstract).
[37] SHEN C B, MEI L F, LIU Z Q, et al. Apatite and zircon fission track data, evidences for the Mesozoic –Cenozoic uplift of Huangling Dome, Central China [J]. Journal of Mineralogy and Petrology, 2009, 29 (2): 54–60 (in Chinese with English abstract).
[38] HU D F, ZHANG L R, NI K, et al. Main controlling factors for gas preservation conditions of marine shales in southeastern margins of the Sichuan Basin [J]. Natural Gas Industry, 2014, 34 (6): 17–23 (in Chinese with English abstract).
[39] NIE H K, BAO S J, GAO B, et al. A study of shale gas preservation conditions for the Lower Paleozoic in Sichuan Basin and its periphery [J]. Earth Science Frontiers, 2012, 19 (3): 280–294 (in Chinese with English abstract).