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Difference analysis of shale gas-bearing property —a case study of the shale within lower Cambrian Niutitang Formation on the margin of palaeouplift

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Introduction: Shale gas has become an important field for increasing oil and gas reserves and production in China. The breakthrough of Cambrian shale gas in Sichuan Basin provides guidance for the exploration of shale gas in southern China. However, the Niutitang Formation shale on the periphery of Sichuan Basin exhibits multiple depositional subfacies and complex structural styles, and the factors of gas diversity are not clear.

Methods: By the methods of organic geochemistry experiment, reservoir physical property test and gas content test, combined with the hydrocarbon generation history and structural evolution history data, the gas content difference is analyzed of Hannan palaeouplift, Shennongjia palaeouplift, Huangling palaeouplift and Xuefengshan palaeouplift.

Results: The organic matter type of Niutitang Formation shale is mainly type I, the average organic carbon content is 1.50%–3.56%, the average R_o is 2.37%–3.90%, the brittle minerals are mainly quartz that the content is 28%–53%, and the average porosity is 0.51%–3.34%. The pores contain organic pores, inorganic pores and micro-fractures, and the fractures are mostly filled with calcite. Gas content $0.13m^3/t$–$4.19m^3/t$. Through comparative analysis of main controlling factors affecting gas content of shale, the causes of gas diversity of Niutitang Formation shale are identified.

Discussion: (1) the differences in preservation conditions caused by structural strength, fracture development degree and the coupling relationship with tectonic fractures are the key factors restricting the gas content of shale. (2) Early deep burial time, long deep burial time and fast deep burial are the key factors that cause the difference of thermal evolution degree of shale. (3) The difference of hydrocarbon generation potential caused by sedimentary subfacies in the same facies zone is an important factor restricting the gas generation capacity of shale. (4) The areas with the lower Plate of thrust nappe, the degree of thermal evolution is less than 3.0%, and the deepwater facies of trough are favorable directions for further exploration. This study will provides reference significance for shale gas exploration of Cambrian Niutitang Formation in the complex structural area periphery of Sichuan Basin in south China.

KEYWORDS

gas diversity, controlling factors, periphery of palaeouplift, shale gas, Niutitang Formation, lower Cambrian

1 Introduction

The shale gas revolution in the United States has made the United States the largest natural gas producer in the world (Hammes and Frbourg, 2012). Commercial production of major shale gas reservoirs from Barnett to Marcellus (Abouelresh and Slatt, 2012; Bruner et al., 2015), successfully reversed the situation of US natural gas imports to exports, while changing the world's energy market land-scape. China's shale gas has experienced nearly 20 years of exploration and has entered the substantial commercial development stage. The increase in production is mainly concentrated in the Wufeng-Longmaxi Formation, Sichuan Basin (He et al., 2016). In the background of carbon peak and carbon neutrality, it is urgent to increase the exploration and development of shale gas in new areas, new formations, new types and new fields (He et al., 2021a). Previous studies have shown that the periphery of palaeouplift has low thermal evolution and relatively stable structural characteristics, which is an important target area for the investigation of Cambrian shale gas in southern China (Bao et al., 2018). The predecessors established a new shale gas enrichment model in the slope belt of palaeouplift margin, which is "favorable facies zone is the foundation, organic matter content is the guarantee, basement uplift and evolution is the key," and guided the breakthrough of shale gas exploration. The Well EYY1HF in Huangling Uplift (Li et al., 2019; Zhang et al., 2020) and Well SNY1 in Hannan Uplift, achieving breakthrough in low-pressure shale gas reservoir. However, Well GDD1, HY1 and HD 1 in Xuefeng Uplift, Well EHD1 in Shenlongjia Palaeouplift and Well SNY1 in Hannan Palaeouplift only found oil and gas shows without shale industrial gas flow (Xie et al., 2014), demonstrating the gas diversity of Niutitang formation on the periphery of palaeouplift in the outer area of Sichuan Basin. Significant variations in hydrocarbon generation conditions, thermal evolution levels, and structural preservation conditions exist across different structural locations. These differences have resulted in considerable variability in gas content. The main controlling factors for the differential enrichment of shale gas in the Niutitang Formation on the periphery of the paleo-uplift remain unclear.

In this study, taking four typical wells around the palaeouplift as analysis objects, based on the analysis of shale gas geological conditions, the research focuses on discussing the influencing factors and main controlling factors that affect the gas content of shale gas, in order to find favorable areas for Niutitang shale gas exploration in the outer area of Sichuan Basin and serve new oil and gas prospecting breakthrough.

2 Geological setting and sampling sections

The Cambrian shales in south China generally have a high degree of thermal evolution, and the study area is located in the eastern and northern margins of Sichuan Basin, from north to south are respectively Hannan Palaeouplift, Shenlongjia Palaeouplift, Huangling Palaeouplift and Xuefengshan Palaeouplift. The paleouplift experienced tectonic uplift in the Paleozoic, and its rigid basement structure was stable, which was conducive to shale gas preservation. For the southern Cambrian, the paleouplift has early uplifting time and short deep burial time, and the thermal evolution of the Cambrian shale is lower than that of other regions.

Seven wells on the periphery of four ancient uplifts were selected as the research objects, including Well 1 and Well 2 on the southern margin of Hannan Ancient Uplift, Well 3 on the western margin of Shenlongjia Ancient Uplift, Well 4 on the southwest margin of Huangling Ancient Uplift and Well 5 on the southeast margin of Huangling Ancient Uplift, Well 6 and Well 7 on the southwest margin of Xuefengshan Ancient Uplift (Figure 1).

3 Samples and analytical methods

3.1 Samples

In this study, data were collected from 7 wells in the paleouplift, including 35 samples from Well 1, 25 samples from Well 2, 18 samples from Well 3, 120 samples from Well 4, 50 samples from Well 5, 49 samples from Well 6, and 12 samples from Well 7. Detail information of studied wells are listed in Table 1.

3.2 Experimental methods

In this study, seven wells were selected to carry out organic geochemical experiments, such as TOC, Asphalt reflectance, organic matter types, etc. Reservoir physical properties, such as rock and mineral composition, porosity, permeability, pore type, fracture development, etc. Gas content testing experiments, such as field Desorption gas content measurement, gas component analysis, isothermal adsorption, etc. In addition, the well logging data, hydrocarbon generation history and structural evolution history in the study area were studied.

The experiments of organic geochemistry and reservoir physical properties were determined by the Geochemical

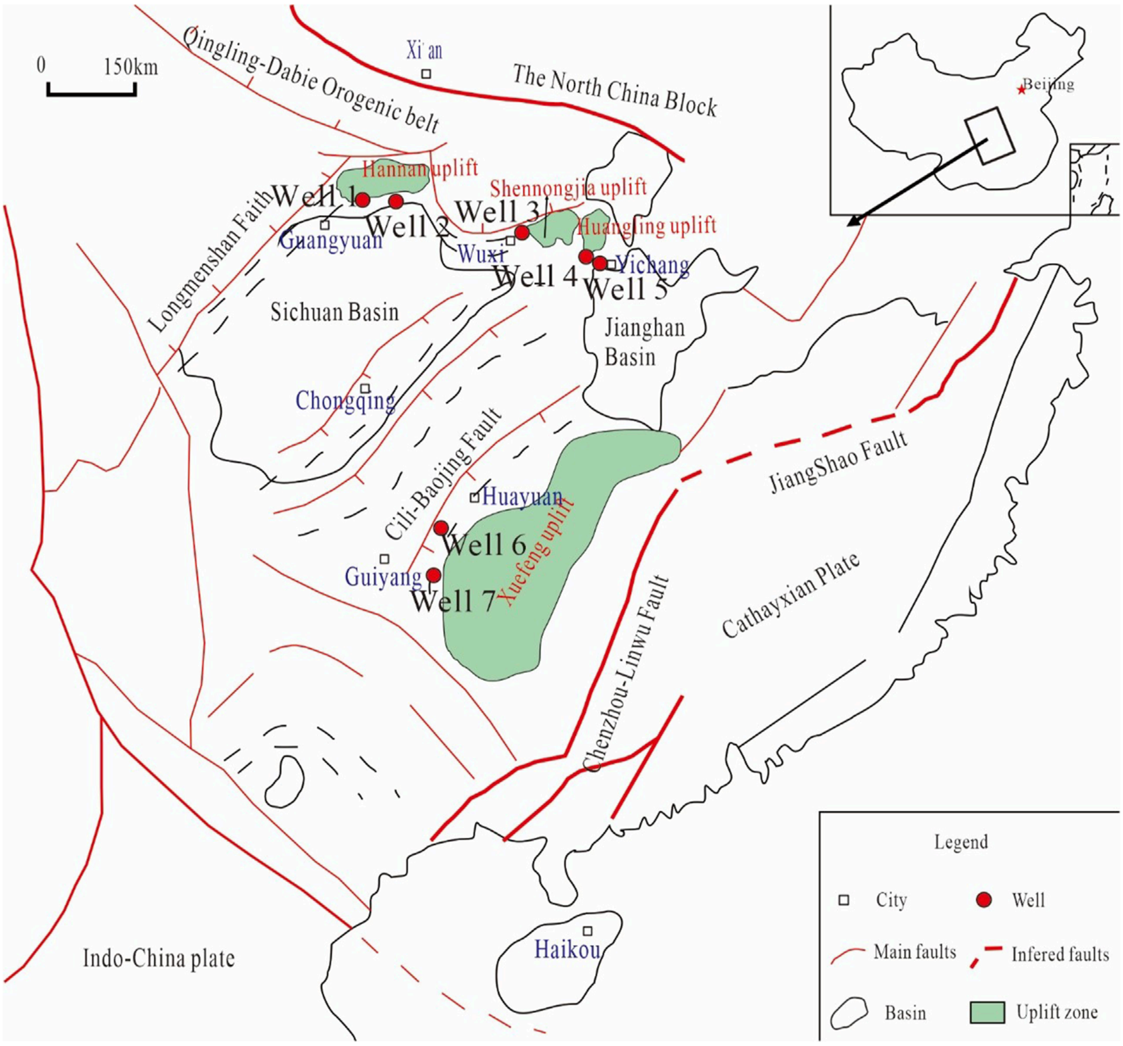

FIGURE 1
Study area and drilling structure location. Well 1 and 2 belong to the periphery of Hannan Palaeohigh, Well 3 belong to the periphery of Shennongjia Palaeohigh, Well 4 and 5 belong to the periphery of Huangling Palaeohigh, and Well 6 and 7 belong to the periphery of Xuefeng Palaeohigh.

Laboratory of Yangtze University. The porosity and permeability were tested by two methods: overburden porous test and mercury injection test. It should be noted that the sample comes from the ancient formation of Niutitang Formation, the sample does not contain vitrinite, and the Ro cannot be measured by conventional vitrinite reflectance. The asphalt reflectance of these samples is measured and converted to R_o. The gas content and gas composition were determined by YSQ-IV analytical analyzer, which was independently developed. During the measuring process, continuous drainage gas collection method was applied to collect gas samples and analyze gas composition. The desorption gas and residual gas were directly measured by this method, and the total gas content was finally calculated by combining with the simulation of lost gas.

4 Results

4.1 Organic geochemical characteristics

The research area consists of seven wells that are deposited in the continental shelf to slope facies. The dominant organic matter type is Type I, with high organic carbon content. These wells are located on the periphery of an ancient uplift. According to the theory “Reservoir control at the margin of paleo-uplift” (Zhai et al., 2017), Compared with southeast Chongqing area and West Hunan and Hubei area, the degree of thermal evolution in the study area is relatively low, which is the main consideration for drilling.

The kerogen type of shale in Well 1 is type I, and the organic carbon content is 0.52%–3.02%, with an average of 1.50%. TOC of

TABLE 1 Information of 7 wells.

Well number	Geographical position	Tectonic position	Well type	Formation	Depth m	Start drilling formation	Completed formation	Hydrocarbon indication
1	Nanzheng, Shaanxi	Between Hannan Uplift and Micang Mountain uplift	Parameter well	Niutitang Formation	2,150-2,380	Permian	Nanhuan (Nantuo Formation)	Gas showing
2	Zhenba, Shaanxi	Southeastern margin of Micang Mountain uplift	Survey well	Niutitang Formation	1,670-1750	Silurian	Sinian (Dengying Formation)	gas show strong
3	Shennongjia, Hubei	Northern wing of Shennongjia complex anticline	Survey well	Niutitang Formation	1,454-1852	Silurian	Sinian (Dengying Formation)	No gas show
4	Changyang, Hubei	South margin of Huangling uplift	Parameter well	Niutitang Formation	2,600-3,069	Cambrian	Nanhuan (Nantuo Formation)	Industrial gas flow
5	Dianjun, Hubei Province	South margin of Huangling uplift	Parameter well	Niutitang Formation	1787-1871	Cretaceous	Nanhuan (Nantuo Formation)	Industrial gas flow
6	Huangping, Guizhou	Southwest margin of Xuefeng uplift	Survey well	Niutitang Formation	1,286-1,406	Cambrian	Nanhuan (Nantuo Formation)	Gas showing
7	Danzhai, Guizhou	Southwest margin of Xuefeng uplift	Survey well	Niutitang Formation	960-1,070	Cambrian	Sinian (Doushantuo Formation)	Gas showing

shale with high gas content in middle and lower section can reach more than 2.0%. The value of R_o range from 2.48% to 4.36%, with an average of 3.0%, which is in the stage of over-mature evolution. The main organic matter types of shale in Well 2 are type I and type II_1 (Xu et al., 2019). TOC content of 31 core samples from Well 2 ranges from 0.88% to 8.61%, with an average value of 3.37%. The shale with TOC >2% has a thickness of 78m, and the maturity of 34 samples ranges from 2.04% to 3.14%, with an average value of 2.66%, and is in the over-mature evolution stage.

The TOC of shale in Well 3 is between 0.49% and 4.14%, with an average of 1.96%, The R_o is between 3.02% and 3.25%, which has entered the mature evolution stage, and the maceral of kerogen is dominated by sapropelic amorphous type. TOC of shale in Well 4 ranges from 0.04% to 3.88%, with an average of 2.01%, and the lower section of the second segment of Niutitang Formation with a better gas content ranges from 0.68% to 3.88%, with an average of 2.44%. The R_o is between 2.0% and 2.77%, which entered the mature to overmature stage. The TOC of shale in Well 5 ranges from 0.43% to 10.45%, with an average of 2.62%. The maceral of kerogen is mainly sapropelic amorphous type, The kerogen type of shale is type I, R_o ranges from 2.06% to 2.66%, with an average of 2.29%, which is in the stage of over-mature evolution.

The abundance of organic matter in Niutitang Formation in the South Guizhou Depression is generally high (Teng et al., 2008). The TOC of shale in Well 6 ranges from 0.60% to 8.89%, with an average of 3.55%. R_o ranges from 1.43% to 2.81%, with an average of 2.37%, which is in the early stage of maturation and overmaturity. The main kerogen is type I. In addition, 30 stable carbon isotope experiments of kerogen show that δ13C‰ ranges from −29.2‰ to −34.7‰ that the kerogen style is type I. The organic matter type of shale in Well 7 is mainly type I, the TOC is 0.25%–8.72%, with an average of 3.56%. The R_o value of upper and lower shale strata is high, the distribution range is 3.26%–4.4%, with an average of 3.90%, and it is in the late over-mature - metamorphic stage, especially after the bottom 997 m, R_o is greater than 4.00% which is in the metamorphic stage (Table 2).

4.2 Reservoir property

The brittle mineral content of core samples from Well 1 ranges from 52.7% to 74.1%, mainly quartz. The main clay minerals are chlorite, kaolinite, illite and montmorillonite. The measured porosity ranges from 0.02% to 5.17%, with an average value of 2.01% by Overburden pore permeability test. The porosity was 1.7%–2.78%, with an average value of 2.15% by mercury injection experiment. The permeability ranges from 0.00053 mD to 0.0041 mD, with an average value of 0.0008 mD, which belongs to the low porosity ultra-low permeability reservoir. The pores can be divided into three categories: mineral matrix pores, organic matter pores and micro-fractures, among which micro-fractures are mainly marginal cracks between organic matter and inorganic minerals, with a slit width of 0.5μm–8.6 μm (Wang et al., 2014). The brittle mineral content of shale in Well 2 ranges from 40.6% to 64.8%, with an average of 53.6%, among which quartz content is the highest, ranging from 47% to 25.6%, with an average content of 37.16%. The pore types are mainly mineral dissolution pores, intercrystalline pores of pyrite are occasionally found, and organic pores are few. Microfractures are abundant, and the seam width is 0.5 μm–8.6 μm (Wang et al., 2014).

The brittle mineral content of shale in Well 3 is the highest 74%, and the average is 50%. The porosity is 1.45%–8.04%, with an average of 3.33%, and the permeability is 0.0005 mD −0.004 mD, with an average of 0.0015 mD. The pore types include intergranular pores, intra granular pores, organic pores, solution pores, mold holes and micro-fractures. The fractures are mainly high Angle fractures with large dip Angle and low density. Some fractures have crossover phenomenon and are mostly filled with calcite.

There are differences in mineral composition among different formations of the shale of Niutitang Formation in Well 4. The lower section of the second segment of Niutitang Formation, which has the high gas content and organic matter abundance. It is dominated by quartz with an average content of 37%, followed by carbonate rock, clay (illite and chlorite), the average content of 19%, the pyrite content is relatively high, up to 3% on average. Other segment are dominated by calcite. The porosity ranges from 2.01% to 3.61%, with an average value of 2.88%. Permeability ranges from 0.00031 mD to 0.00078 mD, with an average of 0.00054mD. The pores are rich in organic matter, followed by the solution pores and micro-fractures, belonging to the low porosity and ultra-low permeability reservoir. A total of 34 filling cracks and 66 open cracks were picked up from the electrical imaging data. The dip Angle ranges from 20.3° to 89.7°, and the inclination is mainly south. The fracture trajectory is clear, indicating that the fracture has good connectivity and ductility (Liu et al., 2019) (Figure 2).

The brittle mineral content of Well 5 is high, ranging from 45% to 75%, shale gas-bearing interval from 1788 m to 1872 m, in which the content of carbonate and clay minerals is higher in the shale from 1788 m to 1832 m, and the content of quartz minerals is lower. The mineral content in the smaller depth section changes greatly, and the material composition is obviously heterogeneous. The content of quartz and clay minerals is high and the content of carbonate minerals is low in the shale of 1 832 m −1 872 m, and the mineral content changes relatively little in the shale of small depth, and the rock mineral composition is relatively stable. The reservoir space is divided into three types: inorganic pore, organic pore and microfracture. Microfractures are mainly layered fractures inside clay minerals, which have good extensibility and connectivity, and can optimize the transformation of pore system (Lee et al., 2003).

The brittle mineral content of Well 6 rangs from 37% to 68%, with an average of 51%. The quartz content is 28%–53%, with an average of 37.8%. The average porosity and permeability of shale are 0.51% and 0.001mD respectively. The microcosmic reservoir space is dominated by matrix pores, followed by organic pores. Pyrite is common and a few residual pores can be found. The fractures are mainly manifested as tensile cracks and slip cracks. Affected by the detachment structure, it is mainly filled with calcite veins. The above two groups of fractures have the characteristics of multi-phase, staggered with each other, and local grid shape.

The content of quartz minerals of shale in Well 7 is 35.1%–51.8%, with an average of 43.5%. The brittle mineral is conducive to the later fracturing. The upper section of Niutitang Formation has an average porosity of 2.00%, which corresponds to high gas content. The reservoir space is dominated by inorganic mineral matrix pores, with micro-fractures and organic pores are few. Micropores are connected with microfractures, forming a complex network of pores

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TABLE 2 Basic geological parameters of 7 wells.

Well number	Fault/ structure	Lithology	Thickness/m	TOC/%	R_0/%	Gas content m^3/t	Brittle mineral/%	Porosity/%	Permeability/mD	Fracture
1	Less/weak deformation	Black carbonaceous shale	103.5	0.52–3.02/1.5	2.48–4.36/3.0	0.2–4.4	52.7–74.1	0.02–5.17/2.01	0.00053–0.0041/0.0008	rich
2	Less/weak deformation	Dark grey siliceous carbonaceous shale interspersed with carbonaceous siltstone	90	0.88–8.61/3.37	2.04–3.14/2.66	0.77–3.39	40.6–64.8/53.6	—	—	rich
3	Many/strong structure	Gray-black calcareous silty mudstone interbedded with argillaceous limestone	397.86	0.49–4.14/1.96	3.02–3.25	0.0002–0.13/0.032	20-74/50	1.45–8.04/3.33	0.0005–0.004/0.0015	are mostly filled
4	Less/Structural stability	Shale, mixed with argillaceous limestone and argillaceous siltstone	468.5	0.04–3.88/2.01	2.0–2.77	0.26–4.48	55-75	2.01–3.61/2.88	0.00031–0.00078/0.00054	rich
5	Less/Structural stability and simple	Gray-black gray shale with dark gray argillaceous limestone	86	0.43–10.45/2.62	2.06–2.66/2.29	0.58–5.48	45-75	1.48–2.5	—	rich
6	Many/Strong structure	Black carbonaceous shale	119.95	0.60–8.89/3.55	1.43–2.81/2.37	0.09–1.31/0.42	37–68/51	0.2–1.8/0.51	0.0001–0.01/0.001	Slip fracture
7	Many/Strong structure	Black carbonaceous mudstone	105	0. 25-8.72/3.55	3.26–4.4	0.06–1.97	35.1–51.8/43.5	0.65–1.21	0.001–0.012	are mostly filled

Note: "/" represents the average value.

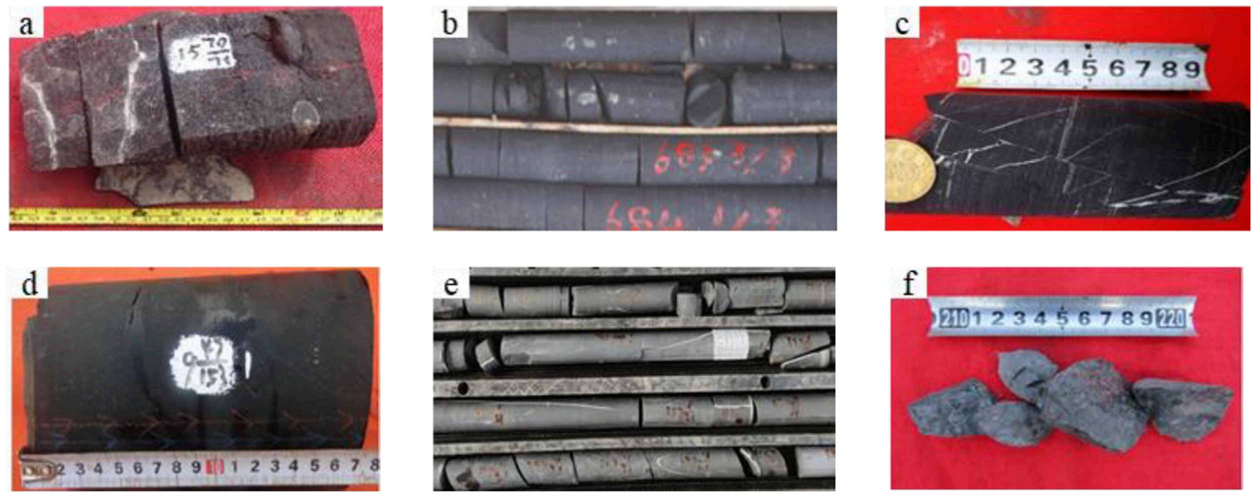

FIGURE 2
Core fractures of Niutitang Formation in different drilling wells. **(A)** Core fracture of Niutitang Formation in Well 1, along with bedding fracture, are partially filled; **(B)** The core fracture of Niutitang Formation in Well 2, along with the bedding joint, is not filled; **(C)** The cracks of Niutitang Formation in Well 3 are filled with calcite, and the filling degree is high; **(D)** The core crack of Niutitang Formation in Well 4 is open and not filled; **(E)** Niutitang Formation of Well 6 has high Angle shear fracture and high filling degree; **(F)** Core fracture of Niutitang Formation, Well 7, Slip cracks, core breakage.

and fractures with good connectivity (Diaz et al., 2013). More high-angle fractures are often filled with quartz, calcite, pyrite and other minerals, and the filling degree is relatively high.

4.3 Gas-bearing

The total hydrocarbon of Niuitang Formation in Well 1 is the highest at 2,201.00m–2271.00m and 2,353.00m–2387.00m, accounting for 4.28%. The Desorption gas content is 0.20 m^3/t –4.50 m^3/t, in which the gas content is greater than 2.00 m^3/t between 2,150 m and 2380m. The total gas content of Well 2 is 0.77 m^3/t –3.39 m^3/t, showing high gas content. The gas content increases gradually with the depth.

The overall gas content of Well 3 is low, and the maximum gas content is 0.13 m^3/t in the 1,156.62m–1852.76m. At the top of Niutitang Formation 1,454 m - 1591m, a gas anomaly occurred, with a maximum total hydrocarbon value of 3.65%.

The Desorption gas content of Well 4 is 0.13 m^3/t- 2.16 m^3/t, and the total gas content is 0.26 m^3/t- 4.48 m^3/t, among which 2,980 m - 3055m has a higher gas content with an average of 2.30 m^3/t. The core bubbles violently in water immersion test, and the gas ignition is flammable. The gas content of Well 5 is 0.58 m^3/t - 5.48 m^3/t. Among them, the gas content of the well depth of 1837 m - 1872m is greater than 2.00 m^3/t, and the average is 2.78 m^3/t; the gas content of the well depth of 1854 m - 1872m is greater than 3.00 m^3/t, and the average is as high as 3.80 m^3/t.

The Desorption gas content in Well 6 ranges from 0.09 m^3/t to 1.11 m^3/t, with an average value of 0.42 m^3/t. The gas content of Niutitang Formation in Well 7 ranges from 0.06 m^3/t - 1.97 m^3/t, with an average of 0.32 m^3/t. There are two high gas content segments in the middle and upper section. The first segment is 957 m - 975m with calcareous carbonaceous shale and the maximum gas content is 1.10 m^3/t. Second, in the 1005m–1013m segment, gas penetration occurred at the wellhead during drilling, and the maximum gas content was 1.97 m^3/t. The gas logging showed a high gas anomaly with a maximum value of 7.92% (Figure 3).

5 Discussion

5.1 Hydrocarbon control by sedimentation

Favorable sedimentary facies zones control the hydrocarbon generation capacity of source rocks, are the material basis of shale gas enrichment, and are closely related to gas-bearing properties. From the successful development examples and experiences of shale gas in Wufeng-Longmaxi Formation in China (Guo, 2014), it can be seen that deep-water facies deposits such as deep-water shelf are one of the most important theories in the "ternary enrichment model" theory of shale gas (Guo and Zhang, 2014). The favorable facies zone model of the Carboniferous platform basin-lower slope facies in the south of Guizhou and the middle of Guangxi has guided the shale gas investigation.

5.1.1 Sedimentary characteristics

The sedimentary environment determines the material basis of shale gas formation (Qiu et al., 2022), The division scheme of sedimentary environment of Niutitang Formation in the four palaeouplifts in the study area can be divided into two categories: The first type is classified as shelf facies, which can be subdivided into two subfacies: deep shelf and shallow shelf, which is adopted by most scholars. The second category is divided into rifting trough facies, which can be subdivided into aulacogen basin and slope subfacies (Zhai et al., 2017).

In general, southern Shaanxi belongs to passive continental margin deposits on the northern margin of the Upper Yangtze Block. According to the first classification scheme, the Niutitang Formation

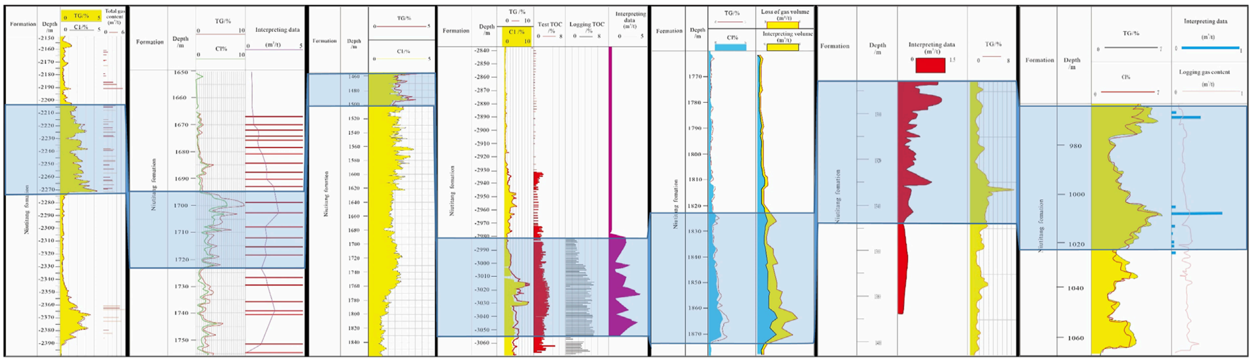

FIGURE 3
Gas content column of 7 wells (High gas content intervals are represented in the blue line). (High gas content intervals are represented in the blue line).

of Well 1 and Well 2 in southern Shaanxi is mainly shallow shelf sedimentary subfacies, and the high-quality shale segment is deep shelf subfacies. The better gas-bearing of the two wells is the middle and lower section of Niutitang Formation, and the lithology is dark gray carbonaceous shale, silty shale, silty carbonaceous shale with carbonaceous siltstone and marl.

The Niutitang Formation in Shennongjia area is mainly composed of sedimentary shelf facies and slope facies, among which shelf facies can be further divided into deep water shelf subfacies and shallow water shelf subfacies, and slope facies can be divided into slope foot subfacies (Xie et al., 2017). The Niutitang Formation can be divided into the first, second and third members from the bottom up, corresponding to deep shelf subfacies, shallow shelf subfacies and slope foot subfacies respectively. The first segment of Niutitang Formation with better gas-bearing is characterized by deep grayish-black calc-carbonaceous mudstone, black calc-carbonaceous mudstone, argillaceous siltstone lamination, rich pyrite nodules and pyrite bands.

Tectonic evolution controls the distribution of sedimentary facies zones in Yi-chang area of western Hubei. In the early Cambrian, influenced by the large-scale transgression of the Yangtze River, the sediments in this area were successively com-posed of tidal flat facies, shallow water facies and deep shelf facies from northeast to southwest (Zhang et al., 2023). Both Well 4 and 5 are deepwater shelf facies, and the former has deeper water. The second segment of Niutitang Formation, lithology of which is gray-black and black carbonaceous shale, is a deep water shelf deposit.

The paleogeothermal environment of Niuitang Formation in the Qiannan Depression has low water temperature and dark anoxic deposits, and the organic matter is well preserved. The sedimentary environment of Well 6 and 7 is deep shelf - subdeep sea basin deposition. The second member of Niutitang Formation with good gas-bearing capacity is gray-black mudstone, mixed with gray argillaceous limestone, containing pyrite nodules or bands. A complete trilobite fossil was found in Niutitang Formation in Well 6.

According to the second category, Well 1 is the slope subfacies, and Well 2 is the aulacogen basin facies of the rift trough, the Well 3 is rifted trough basin subfacies, Well 4 is aulacogen basin subfacies, Well 5 is slope subfacies, and Well 6 is aulacogen basin, and Well 7 is deep shelf deposition (Figure 4).

5.1.2 The relationship between sedimentary subphase and gas-bearing

The Niutitang Formation in the study area has the characteristics of multi-stage hydrocarbon generation of organic matter. The results show that the Niutitang Formation generally has the high organic matter abundance. However, the influence of organic matter abundance is usually ignored when analyzing the influencing factors of shale gas content in the Niutitang Formation. According to the analysis of sedimentary facies of 7 wells, all of them belong to rifting trough facies. However, in the case of similar thermal evolution degree and structural preservation conditions, although Hannan palaeouplift and Huangling palaeouplift belong to the same sedimentary zone - West Hubei Trough, due to different sedimentary subfacies, the hydrocarbon generation capacity of shale is affected, and thus the gas content of shale is affected (Figure 5). Although Well 1, 2 and 4 are all located in the same large rifting trough, and the R_o of the key factor for the Niutitang Formation is generally less than 3.00%, different sedimentary subfacies lead to differences in their gas-bearing properties. Well 2 and 4 are subfacies of rifting trough basin, while Well 1 is subfacies of rifting trough slope. The sedimentary environment is different, which leads to the lower hydrocarbon generation potential of shale in Well 1 than that in Well 2 and 4, resulting in the difference of gas content. In addition, the stable gas flow of 21 × 10^4 m^3/d in Well Shanzhenye 1 in Zhenba area, which is adjacent to Well 2, also confirms the controlling effect of sedimentary subfacies relative gas content.

5.2 Thermal evolution degree control zone

5.2.1 Differential tectonic subsidence affects the degree of thermal evolution

Although the seven wells are located in the periphery of the outer palaeouplift of Sichuan Basin, the differences of thermal evolution degree and hydrocarbon generation are caused by different tectonic subsidence in different regions. Compared with Huangling Palaeouplift and Xuefeng Palaeouplift, R_o in Wells 4 and 5 is generally lower than 3.00%, while the minimum of R_o in 7 wells are higher than 3.00%. The main reasons are as follows:

First, the deep burial time is late, the deep burial time is short, the thermal evolution degree is low, and it is in the best

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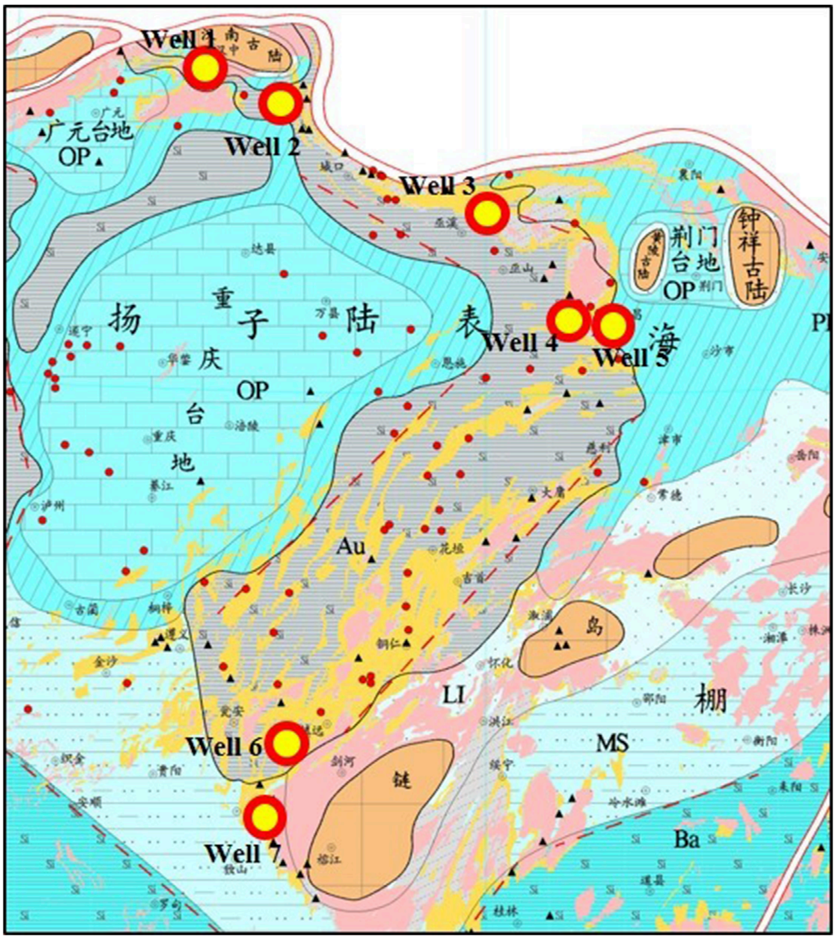

FIGURE 4
Sedimentary facies of Niutitang Formation in the study area (modified by Zhai Gangyi).

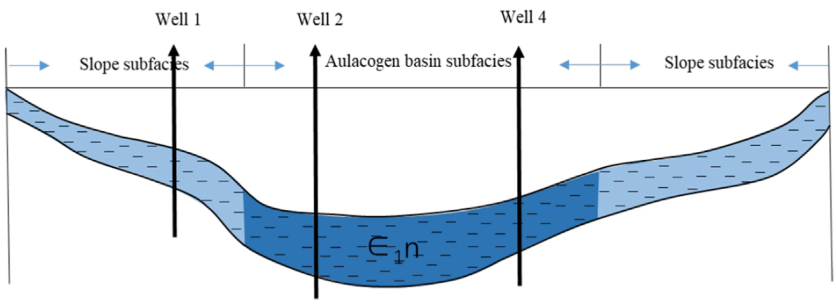

FIGURE 5
Schematic diagram in the Aulacogen basin sedimentary subfacies of Niutitang formation.

gas generation period, which is beneficial to gas enrichment. The Niutitang Formation shale of Huangling Uplift entered the oil-generating stage in the middle Silurian, entered the thermal cracking condensate oil-gas stage at the end of Permian, and remained relatively stable until the middle Triassic. At present, the shale R_o of Niutitang Formation in Well 4 and Well 5 is 2.26%–2.77%, and the latter is smaller with an average of 2.29%, which is in the best gas window range. From the end of Permian to the beginning of Triassic, it experienced rapid subsidence, and was in the deep burial period (>3500m) in the late Jurassic (before Yanshan uplift), with a deep burial time of about 85Ma (Figure 6). The hydrocarbon generation time of Niutitang Formation in Well 7 was early. The Niujutang Formation was buried rapidly after deposition, and entered the hydrocarbon generation threshold in the early Middle Cambrian

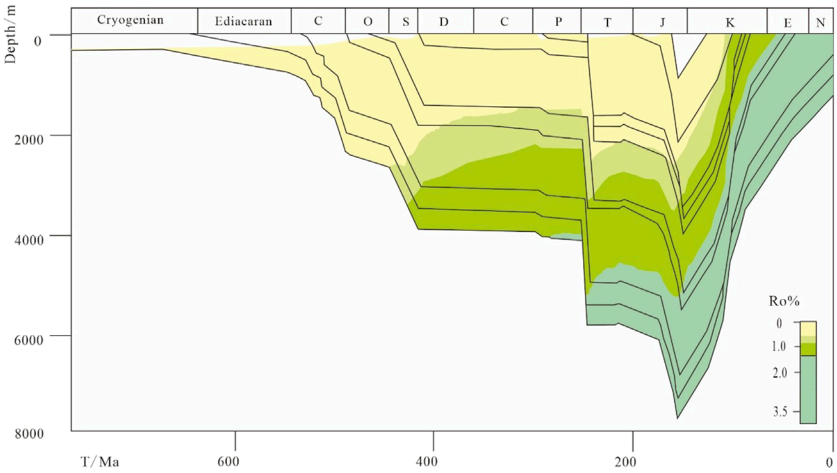

FIGURE 6
History of sedimentary burial in Huangling palaeouplift

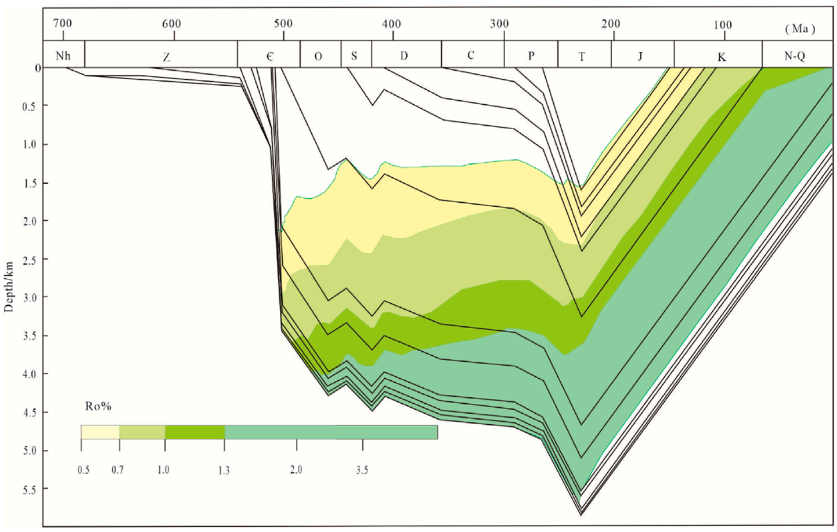

FIGURE 7
History of sedimentary burial in Xuefeng palaeouplift

(about 508 Ma), the burial depth exceeded 3,500 m in the Late Cambrian, reached the late oil-generation and early gas generation stage until the early Middle Triassic (before the Indo uplift), and was in the continuous deep gas burial stage with the maximum burial depth exceeding 5700m and the hydrocarbon generation time exceeding 270Ma. Deep burial time (>3500 m) exceeds 250Ma (Figure 7). The southern margin of Huangling Uplift is generally shorter than that of Niutitang Formation on the western margin of Xuefeng uplift (Nie et al., 2021) and the deep burial time is later, resulting in a lower degree of thermal evolution and still in the optimal gas generation stage, which is more conducive to shale gas enrichment.

Second, hydrothermal intrusion along the fault may lead to an increase in the degree of thermal evolution. The comparison of R_o between Doushantuo Formation and Niutitang Formation in Well 7 shows that the R_o of Doushantuo Formation is 3.32%–3.59%, but it is significantly lower than the lower part of Niutitang Formation. It is believed that the small fault drilled at the bottom of Niutitang may locally warm the shale in Niutitang, resulting in abnormal maturity, while the Doushantuo shale is normal geothermal warming, which is lower than the maturity of the lower part of Niutitang Formation. The main reasons are as follows: ① the first segment of Niutitang Formation consists of gray-black thin-layer siliceous rocks, phosphorus-bearing siliceous rocks and phosphorite nodules with thickness of 2 m–15 m. This phosphorus may be related to the volcano, and there may be volcanic hydrothermal intrusion, which increases the temperature of Niutitang Formation. (2) The fault was drilled at the bottom of Niuitang Formation, which penetrated the Dengying Formation, and hydrothermal minerals such as barite, fluorite and quartz were found in the cracks. From this point

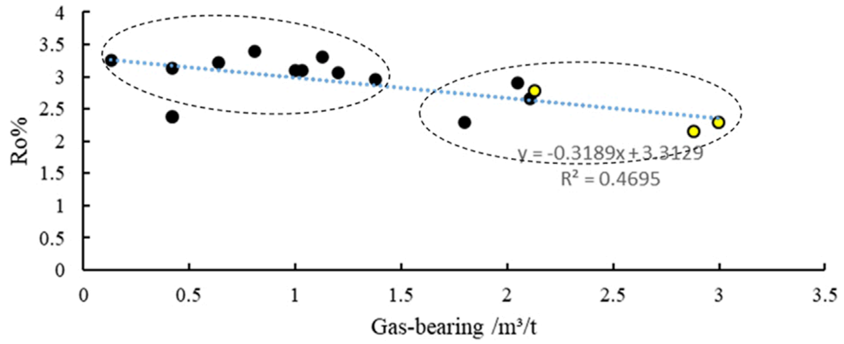

FIGURE 8
Relationship between Ro and gas content.

of view, the thermal migration of Dengying Formation along the fault probably affected the temperature of Niutitang Formation and accelerated the thermal evolution of organic matter.

5.2.2 Correlation between R_o and gas content

On the basis of the study of 7 wells, 9 wells in the adjacent area are investigated and analyzed comprehensively (Figure 8). Based on the relationship between R_o and gas content of 16 wells, it is found that: 1) the correlation between R_o and gas content is weak and linear, and the correlation coefficient is 0.47. 2). the value of R_o can qualitatively reflect the size of the gas content. ① As can be seen from the figure, there are 8 data with R_o higher than 3.00%, and the R_o value is 3.06%–3.40%, with an average of 3.20%. The gas content is 0.13 m^3/t - 1.20m^3/t, the average is 0.75 m^3/t, and the gas content of 50% data is less than 1.00 m^3/t. ② There were 7 datas whose R_o value was less than or equal to 3.00%, with a value of 2.15%–2.95% and an average of 2.57%. The gas content is 1.38 m^3/t - 3.00m^3/t, with an average of 2.19 m^3/t, and the gas content of 71% data is greater than 2.00 m^3/t. The average R_o of the three wells obtained shale gas flow is 2.40%, and the gas content is 2.13 m^3/t - 3.00m^3/t, with an average of 2.67 m^3/t. Therefore, the degree of thermal evolution is the key factor affecting gas content. The R_o of well 6 is 2.37% and the gas content is low. The reason is that the gas content of well 6 is not only affected by R_o, but also restricted by other factors.

5.3 Preservation controls the reservoir

5.3.1 Major faults characteristics

Fracture is closely related to shale gas-bearing and mainly controls the preservation conditions of shale gas. Faults can be used not only as a migration pathway of shale gas to cause gas loss and damage shale gas preservation (Gao et al., 2014), but also as a shale gas sealing formation to prevent gas loss and facilitate shale gas enrichment (Hu et al., 2014). It can even be used as a release pathway of tectonic energy to control the integrity of the formation. Therefore, by analyzing the fractures and their properties of different research objects, the influence of fractures on shale gas preservation can be comprehensively judged.

The fault structure of Qinling region in southern Shaanxi is complex, and in addition to some regional plate edge faults and intraplate faults, there are also buried faults (Zhang et al., 2004). Under the influence of late Indosinian and Yanshanian strong uplift, the Micangshan tectonic belt is a forward-spreading structure from north to south caused by the superposition of two thrust nappe structures in different directions. From the initial underwater uplift, it rose to land after the Indochina movement. Among them, Well 1 is mainly affected by the Yangpingguan-Yangxian fault in the near east-west direction, while Well 2 is surrounded by the Dachimba-Zhenba fault in the near east-west direction and the Sishang-Xiaoyangba fault in the north-west-southeast direction (Chen et al., 2018).

There is a regional fault-Yangriwan Fault on the western margin of Shennongjia (He et al., 2021b). And Well 3 is located about 1 km to the south of the fault. Several fracture zones and a buried fault were found during drilling. The core of the dark shale section has different degrees of fractures and is partially or completely filled with calcite.

There are fault structures of different periods, different scales and different directions in western Hubei, which form regular network. Some important faults constitute the division boundary of the secondary tectonic units, and have obvious control over the regional structural styles, and are also of great significance to the preservation of shale gas. Well 4 and 5 are located on the Yichang slope, with the Wuduhe fault in the southeast, which breaks into the core of the uplift and serves as the boundary of the stable region of the southern Yichang slope belt together with the Tianyangping fault (Figure 9).

The eastern part of the Qiannan Depression is bounded by the Tonren-Sandu fault and the Xuedeng Uplift (Bai et al., 2010). The southeast part is bounded by the Libo Fault and the Guizhong Depression. The southwest part is bounded by the Ziyun-Luodian-Nandan -Du ‘an fault and the Luodian Fault depression; the northwest part is bounded by the Guiyang-Zhenyuan fault and the Qianzhong Uplift, and the plane is a triangle that is wide in north and narrow in south. It mainly presents three groups of fault systems with different scales in the NNE - near SN, NW, NEE - near EW direction (Peng et al., 2019).

5.3.2 The relationship between structural preservation and gas-bearing

Well 4 and 5 are located in the bottom of thrust nappe, with relatively stable, simple structure and few faults, which is conducive to the preservation of shale gas. The Niuitang Formation of Well 1 is deformed by long-term compression, with deep gully, broken

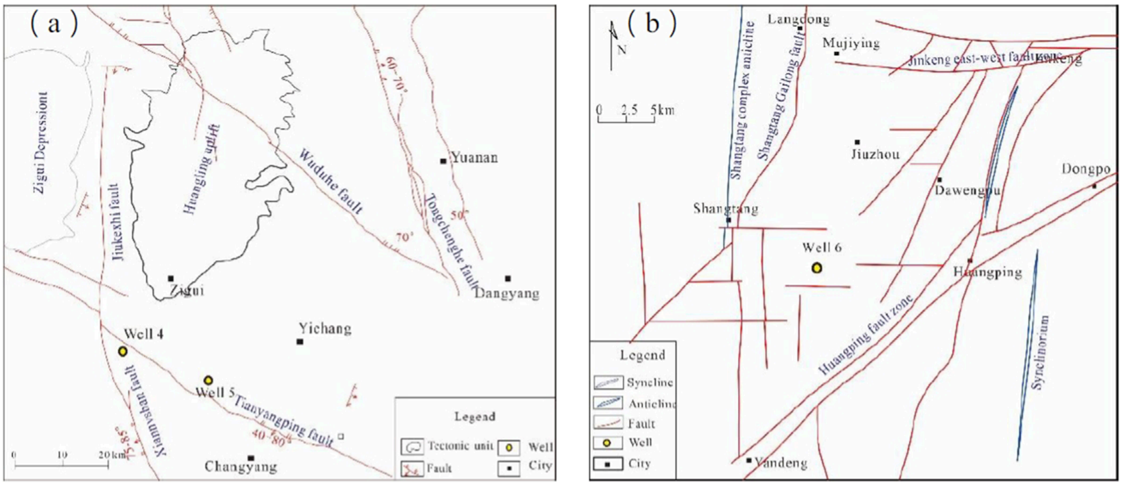

FIGURE 9
Distribution of major faults. **(A)** periphery of Huangling Uplift. **(B)** periphery of Xuefeng Uplift.

terrain and strong dynamic geological action, which is not conducive to shale gas preservation. Well 4 is located about 1 km south of the major fault, encountered several fracture zones and a buried fault during drilling. The core of the dark shale section has varying degrees of fractures, and is partially or completely filled with calcite. The mirror scratches can be seen in the core of the two wells 1824.06m–1824.12m, which indicates that the tectonic movement in this area is relatively intense, which is not conducive to the preservation of shale gas.

Although Well 6 and Well 7 are located in the Qiannan Depression, Well 7 is located in the Danzhai area, which is far from the fault position, the formation of Niuitang Formation is stable, and the degree of structural deformation is relatively weak (Dan et al., 2023). However, there are three regional large faults around Well 6, and a number of secondary small faults develop near the well. Due to the relatively staggered formation, the low-grade tension-torsion fault develops in the direction of 65° NW, making the Huangping fault zone more complicated and damaging the preservation conditions (Ge et al., 2018; 2020), resulting in slightly lower gas content in Well 6 than Well 7. In addition, there are many faults in the south Guizhou Depression with multi-stage and complex structure, and the gas components can reflect the destructive effect of faults on the gas content of shale. The nitrogen content of Well 7 is 30%, while the nitrogen content of Well 6 is 50%–79%, indicating that the gas may contains atmospheric components. Considering that the gas-bearing formation is connected with the atmosphere through fracture, the enrichment of shale gas is destroyed. The higher atmospheric content in Well 6 also confirms that the gas reservoir is more destructive and has relatively lower gas content.

In addition, the fracture is favorable to the gas content of shale gas. The Niutitang Formation, where Well 4 and 5 are located, is located in the footwall of thrust nappe and has a stable structure. It plays an effective role in releasing stress during multi-stage structural transformation, thus protecting the upper overlying Sinian, Cambrian, Upper Ordovician and Lower Silurian shales from being strongly damaged on the rigid base. From the perspective of integrity and stability of source rock development, fracture has a favorable influence on shale enrichment.

5.4 Differential enrichment of shale gas in the periphery of palaeouplift

Through these studies, the differential enrichment mechanism of shale gas on the periphery of palaeouplift is summarized:

(1) Variations in hydrocarbon generation potential within the same facies zone are significantly influenced by depositional subfacies. The main reason that the gas content of Well 1 is lower than that of Well 2 is that the former is slope facies of rifting trough and the latter is deep water facies of rifting trough basin. The difference of hydrocarbon generation potential caused by sedimentary subfacies in the same facies zone is an important factor restricting the gas content of shale.
(2) The difference in the degree of thermal evolution caused by the beginning time, time span and rate of deep burial is the key factor restricting the gas bearing of shale. The rigid basement on the periphery of the ancient uplift has the effect of "heat insulation and preservation", which makes the thermal evolution degree of the periphery generally low, and most of them have not entered the graphitization stage. Due to the impact of tectonic evolution and hydrothermal intrusion, significant variations in the thermal maturity of organic matter exist across different structural units. The degree of thermal evolution is moderate, and it is in the best gas generation period, which is conducive to the enrichment of shale gas.
(3) The structural preservation conditions are the key factors affecting the enrichment of shale gas. The paleouplift peripheral areas are characterized by high structural stability, weak deformation, and undeveloped faults and fractures, which provide favorable conditions for the enrichment and preservation of shale gas. This stable structural environment can effectively prevent gas from escaping through faults or

fractures, enhance the sealing of the cap layer, and reduce the risk of compression and failure of the reservoir, thereby maintaining the pore structure and adsorption capacity of the reservoir. In addition, structural stability helps to maintain a moderate geothermal gradient and avoid the adverse effects of too high or too low thermal evolution on shale gas generation and preservation. In summary, the structural features of the periphery of the palaeouplift promote the enrichment and long-term preservation of shale gas by reducing gas escape, protecting reservoir physical properties and optimizing thermal evolution conditions.

6 Conclusion

(1) Hydrocarbon control by sedimentation. Sedimentary facies zones determine the paleoproductivity of shale deposits and the redox conditions of water bodies, which in turn control the enrichment of organic matter and lead to differences in hydrocarbon generation potential. In the Cambrian system surrounding the paleouplift, various sedimentary types are observed. Among these, the rifting trough subfacies exhibit superior organic matter enrichment conditions compared to the rifting trough slope subfacies, providing a favorable material basis for shale gas accumulation.

(2) Thermal evolution degree control zone. The rigid basement on the periphery of the ancient uplift has the effect of "heat insulation and preservation," which makes the thermal evolution degree of the periphery generally low, and most of them have not entered the graphitization stage. However, the differences in the thermal evolution degree of the Niutitang shale on the periphery of different ancient uplift due to the deep burial starting time, deep burial time span and deep burial rate are the key factors restricting the gas content of the shale.

(3) Preservation control the reservoir. The tectonic deformation around the paleouplift was weak, the rigid basement of granite formed in the early stage weakened the tectonic failure. The tructural stability is beneficial to maintain a moderate geothermal gradient and avoid the adverse effects of too high or too low thermal evolution on shale gas generation and preservation. The difference in preservation conditions caused by the structural strength, fracture development degree and the coupling relationship with tectonic fractures is the key factor restricting the gas-bearing of shale.

(4) The geological conditions of shale gas enrichment at the periphery of palaeouplift, favorable preservation conditions such as lower plate of thrust nappe, the moderate thermal evolution degree and deep water facies area of trough are favorable directions for further exploration.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MG: Conceptualization, Investigation, Methodology, Writing–original draft, Writing–review and editing, Data curation, Formal Analysis. SB: Writing–review and editing. YW: Writing–review and editing. HaL: Writing–review and editing. TW: Writing–review and editing. HoL: Writing–review and editing.

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Conflict of interest

Author HL was employed by PetroChina Research Institute of Petroleum Exploration and Development.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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