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Comparison of geological conditions and prospects of exploration potential of shale gas in upper permian Wujiaping formation and Longtan Formation, Sichuan Basin

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Shale gas is a vital transitional energy source during the energy transformation period. With the ongoing development of the Longmaxi Formation shale gas field in the Sichuan Basin, identifying new alternative stratigraphic sequences has become a key focus of current shale gas exploration. The Upper Permian Longtan and Wujiaping Formations in the Sichuan Basin, characterized by contemporaneous heterotopic facies, have demonstrated favorable hydrocarbon shows during previous drilling operations. To evaluate the resource potential and exploration prospects of these two formations, this study utilized various experimental methods, including shale gas content measurement, field emission scanning electron microscopy (FE-SEM), total organic carbon (TOC) analysis, vitrinite reflectance (Ro), and X-ray diffraction (XRD). These techniques were utilized to systematically investigate gasbearing characteristics, organic geochemical properties, reservoir spaces, and mineral compositions of both formations, thereby establishing comprehensive evaluation criteria for favorable exploration zones and geological resource calculation. Results indicate that the Longtan Formation, of sea-land transitional facies, consists of multiple thin shale layers, with a single-layer thickness of 0.5-20.0 m. Its average TOC content is 2.7%, its kerogen types are II₂ and III, and its Ro ranges from 1.4% to 2.8%. The reservoir space is mainly composed of interlayer pores of clay minerals, with an average porosity of 4.5%, an average brittle mineral content of 41.7%, and an average gas content of 5.0 m³/t. The favorable area is in the Guangan-Zigang-Shibao region, with a resource abundance of about $1.60 \times 10^8 \text{ m}^3/\text{km}^2$. The Wujiaping Formation belongs to the deep-water shelf facies, with a single layer thickness of 6-12.0 m. Its average TOC content is 3.5%, its kerogen types are I and II1, its Ro ranges from 2.0% to 2.8%. The reservoir space is mainly composed of organic matter pores, with an average porosity of 5.5% and an average brittle mineral content of 76.6%. The average gas content of the shale section at the top of Wujiaping Formation can reach 8 m^3/t , and the favorable area is in the Dazhou Liangping block, with a resource abundance

of $3.30 \times 10^8 \text{ m}^3/\text{km}^2$. Both of these formations have broad exploration prospects and can provide crucial support for shale gas succession in the Sichuan Basin.

KEYWORDS

shale gas, upper permian, longtan formation, Wujiaping formation, Sichuan Basin

1 Introduction

Given the depletion of conventional energy resources and the current inadequacy of renewable energy feasibility and efficiency to independently meet global energy demands, shale gas has emerged as a crucial transitional alternative during the energy transformation, owing to its superior combustion characteristics and potential applications in hydrogen production and synthetic fuel development (Bellani et al., 2021). However, over the past 2 decades, shale gas production has not been able to meet demand, despite advances in shale gas development and increasing energy needs (Bellani et al., 2021). In 2024, shale gas production in the United States declined compared to 2000, while China is still experiencing rapid growth due to delayed development. Nevertheless, shale gas production accounts for only 15% of total natural gas production. Therefore, exploring new shale gas production layers is vital to ensure the continued success of shale gas exploration. Previous research has identified differences in the geological characteristics, hydrocarbon generation conditions, and occurrence mechanisms of shale formed by different sedimentary facies zones (Wu et al., 2022; Gürbüz and Kose, 2021). These factors will directly impact the reform of horizontal well drilling and hydraulic fracturing technology, the control of single well investment costs, and the management of mining pollution (Wei et al., 2021; Selçuk and Ikbal, 2016). Consequently, conducting research on geological conditions and evaluating the exploration potential of new shale formations is crucial for supporting subsequent production and ensuring energy security.

The Sichuan Basin hosts eight shale formations rich in organic matter, identified as having considerable potential for shale oil and gas resources. Among these, the Wujiaping Formation and Longtan Formation shales have emerged as significant sources of hydrocarbons in the Luojiazhai, Doukouhe, and other gas fields across Northeast China. This is due to their extensive geographical reach, substantial thickness, favorable hydrocarbon generation conditions, and moderate burial depth, indicating great hydrocarbon generation potential (Bai et al., 2024; Zhang et al., 2020; Wang and Sun, 2023). In the context of shale gas exploration, PetroChina has achieved notable success in drilling the DY1 shale gas well in the Wujiaping Formation in the eastern Sichuan Basin, with a daily production of approximately 320,000 cubic meters. A similar outcome was achieved by Sinopec's operations in the same region, yielding a production of 55,000 cubic meters per day from the Wujiaping Formation (Zhang et al., 2020; Liu et al., 2018). Furthermore, the Longtan Formation's shale gas well CLC1, managed by the Sichuan Provincial Bureau of Geology and Mineral Resources in southern Sichuan, attained a production rate of 1,600 cubic meters per day following vertical well perforation and fracturing tests, amassing nearly 10,000 cubic meters over 3 months (Zhang et al., 2020; Liu et al., 2018). These exploration breakthroughs strongly substantiate the considerable prospects of these two formations in future shale gas exploration endeavors.

Considering the latest advancements in exploration and the urgent energy demand, researchers have conducted an in-depth study of the Longtan and Wujiaping formations. The research primarily focuses on analyzing the geological structure of these shale formations, the physical characteristics of the reservoirs, and the gas-bearing laws. Lin et al. (2018) systematically studied the paleogeographic setting, detailing the paleogeographic evolution process, rock types, shale thickness variations, and organic material characteristics in the area. The sedimentary environment within the basin transitions from southwest to northeast, encompassing fluvial, estuarine, tidal flat, and shallow marine environments, with the shallow marine shelf and sea-land transition facies exhibiting the greatest shale thickness. Conducted a comprehensive study on the Longtan Formation shale in the sea-land transitional zone, identifying clay mineral pores as the main pore type and noting a significant positive correlation between increased TOC content and enhanced methane adsorption capacity. Yang et al. (2021) investigated the organic properties, formation causes, and depositional conditions of the Longtan Formation, revealing an average TOC content of 3.04%, indicative of high maturity. They suggested that the organic matter in the Longtan Formation is primarily derived from the marine and terrestrial ecosystems of the Paleozoic era. Du et al. (2022) analyzed the trends of organic matter accumulation in the Wujiaping Formation, identifying two distinct units in the black shale. The upper water body exhibits higher primary productivity due to greater light availability, leading to more substantial organic matter accumulation compared to the lower water body. These research findings provide robust theoretical support for exploring the formation mechanism and enrichment mode of shale gas and lay a solid theoretical foundation for subsequent exploration and development. However, the exploration potential, favorable areas, and geological resources of these two shale formations in the Sichuan Basin remain unclear, limiting the preparation of future exploration and development plans.

This article summarizes the geological characteristics of shale gas in the Wujiaping and Longtan Formations based on core sample experiments and logging data. It compares key factors such as geological characteristics, reservoir conditions, resource scale, and mining technology with those of commercially produced Longmaxi Formation shale gas in the Sichuan Basin, thereby establishing criteria for favorable area division in this study. Subsequently, the geographical locations of potential shale gas areas in the Wujiaping and Longtan Formations within the basin were delineated, and the geological resources of each favorable area were calculated. The potential for shale gas exploration and development in these areas was also assessed.

2 Regional sedimentary background

Located in the Upper Yangtze Craton, the Sichuan Basin is a geologically complex superimposed basin that has undergone multiple tectonic evolution (Cao et al., 2015; Liang et al., 2014; Wang et al., 2014). At the end of the Middle Permian, the Upper Yangtze Craton and its adjacent areas were jointly shaped by the Dongwu Movement and the large-scale eruption of the Emei Basalt, forming a transitional area with tensile stress characteristics. This transition area is the key area to study the geological and historical changes of this area, which brings together the geological structural changes caused by the Dongwu Movement and the evidence of magmatic activity left by the Emezi Mountain basalt eruption. The geological transformations that ensued during this period exerted profound and enduring influences on the regional tectonic framework, subsequent sedimentary processes, magmatic events, and the spatial distribution of mineral resources (Bai et al., 2024; Liang et al., 2013). During an important geological period, the basement in the southwest of the basin rose significantly while the Mianyang Ocean expanded, and the northern margin of the basin was further affected by stretching and faulting. These geological factors interact to form the palaeogeographic features of the highlands in the southwest and the lowlands in the northeast of the basin, which provide an important basis for exploring the historical changes of the region and its wider geological background (Wang et al., 2014). Limited by the scale of transgression and combined with the continuous changes of the Kaijiang-Liangping trough in the Wujiaping stage of the late Maokou period, the Sichuan Basin showed diverse sedimentary characteristics in corresponding geological periods, gradually changing from the continental Xuanwei Formation in the southwest to the marine Wujiaping Formation in the northeast, accompanied by the appearance of the marine and sea-land transitional Longtan Formation. These sedimentary characteristics are of great significance for the in-depth study of the geological history of the Sichuan Basin (Deng et al., 2013; Deng et al., 2012) (Figure 1).

Emeishan basalt and continental Xuanwei Formation, which are mainly continental shale sandwiched with coal seams, exist from the edge of Kang-Dian ancient land to Chongzhou-Meishan-Yibin, and coarse sandstone and fine sandstone at the bottom are in scouring contact with Emeishan basalt (Deng et al., 2012). Longtan Formation extends from Chongzhou-Meishan-Yibin to Mianyang-Nanchong-Changshou, with sandstone, shale, and marl mixed with limestone and is rich in coal seams. To the north of the area encompassing Mianyang, Nanchong, and Changshou lies the Wujiaping Formation, characterized primarily by marine carbonate deposits. In the Wanfang-Liangping area, the deepwater siliceous shale deposits of the Wujiaping Formation evidently manifest the characteristics of sedimentary facies of the deepwater shelf. This phenomenon is indicative of the area's distinctive geological background, thereby providing valuable data resources for oil and gas exploration activities and sedimentology-related research (Liu et al., 2021; Luo et al., 2014).

3 Materials and methods

To investigate the fundamental geological characteristics of the new shale formations and optimize favorable exploration zones, this study collected core samples from six wells, which marked in red in the Figure 1, rock samples from one outcrop section, and logging data from 62 wells. A series of analyses were conducted on the rock samples, including shale gas content tests, FE-SEM, digital core scanning, porosity, TOC, kerogen carbon isotope, R₀, XRD. These analyses provided critical insights into the gas-bearing properties, organic geochemistry, reservoir pore structure, mineral composition, and fracturing potential of the target formation. By integrating data from all wells, the vertical and lateral distribution of coeval heterogeneous mud shales and the thickness of organicrich shale intervals within the study area were mapped. Finally, the geological characteristics of the new shale formation were systematically compared with those of existing productive shale gas systems and their favorable zone evaluation criteria. Based on this comparative analysis, a tailored evaluation framework was developed to delineate shale gas enrichment sweet spots. The geological resource potential within these favorable zones was quantified using the Total Gas Content Volumetric Method and the Resource Abundance Analogy Method (Figure 2).

The special experimental methods are introduced as follows, FE-SEM testing was conducted at the Sichuan Keyuan Evaluation Center. Samples were first polished using a GATAN PECS II 685 precision ion etching and coating system, followed by microscopic observation with a Zeiss Gemini SEM 300 field emission scanning electron microscope, achieving a minimum resolution of 2 nm.

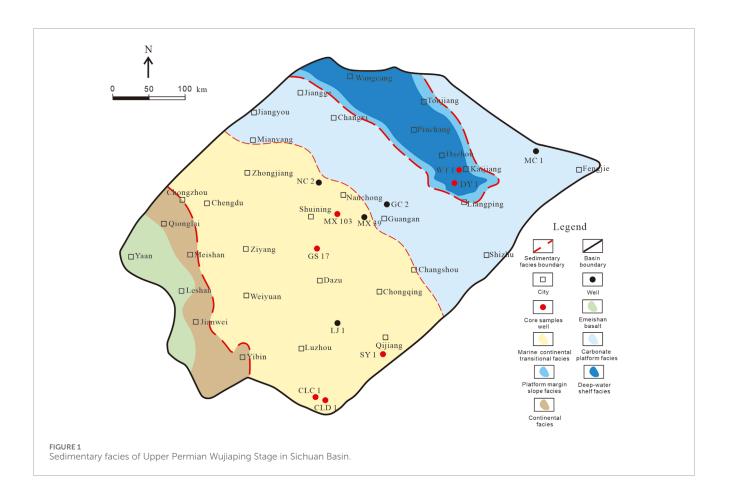
Shale gas content measurements were performed by PetroChina Southwest Oilfield Company. The desorbed gas content was initially recorded using a YYHQ-IV apparatus under drilling fluid temperature conditions, with data points collected every 5 min for 1 h. Subsequently, the temperature was adjusted to formation temperature to continue desorption until the gas release rate fell below $3 \text{ cm}^3/30$ min, with the cumulative volume recorded as the desorbed gas content. Post-desorption, samples were sealed, crushed, and connected to a gas metering system. Residual gas content was measured by collecting gas volumes at 2-h intervals over 4 h. Lost gas content was calculated using the USBM direct method based on the square root of desorption time versus gas volume. The total gas content was derived as the sum of desorbed, residual, and lost gas components.

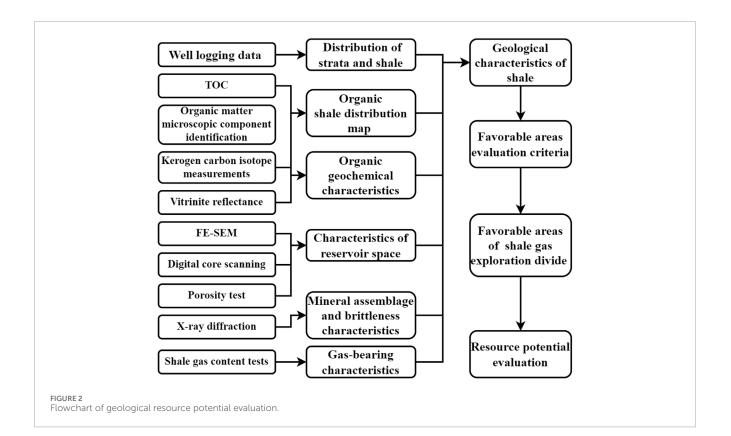
Digital core scanning was carried out at PetroChina Southwest Oilfield Company using a GE Measurement and Control VTome XM300^{$-\Delta\Delta CT$} scanner. Cylindrical core samples with a diameter of 25 mm were scanned, achieving a minimum resolution of 10 µm.

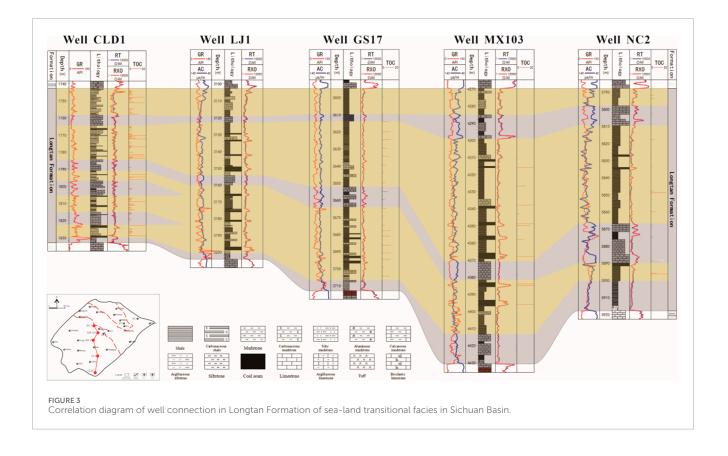
4 Geological characteristics of shale in Wujiaping Formation and Longtan Formation

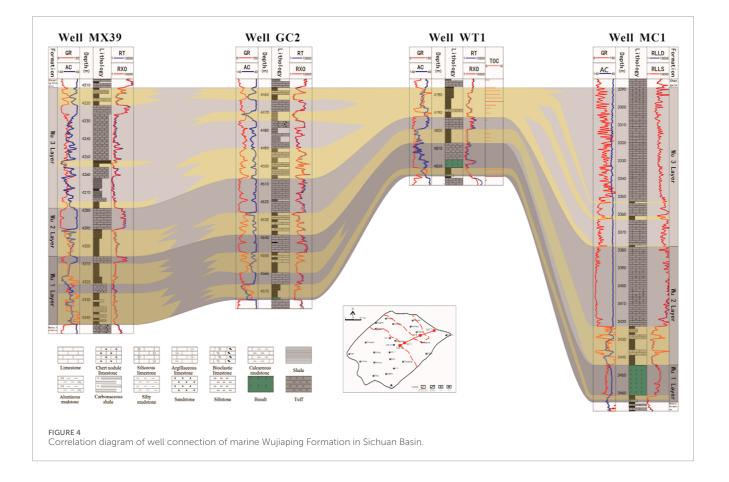
4.1 Vertical and horizontal distribution of strata

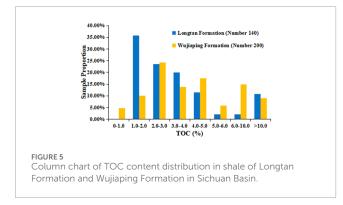
The drilling core analysis indicated that the lithology of the Longtan Formation during the sea-land transitional phase mainly











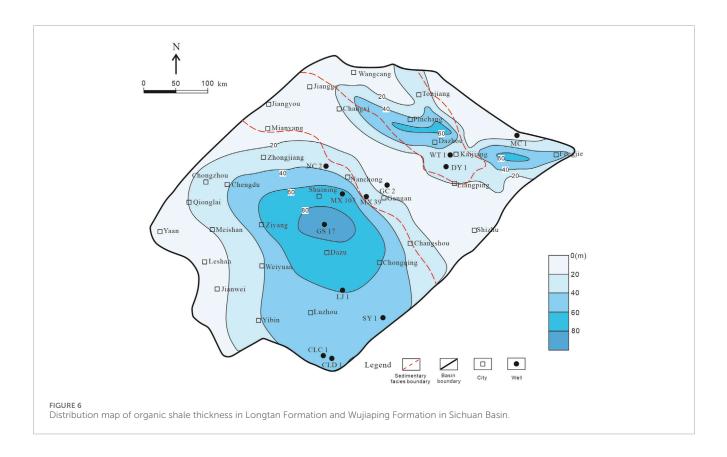
consists of thin interbedded layers of coal and rock, alongside mud shale mixed with argillaceous siltstone (Zhang et al., 2020). A crosssectional analysis of wells in the sea -land transitional facies shows the overall stratigraphic layout of the Longtan Formation in centralsoutheastern Sichuan, the layers are comparatively thick, measuring between 120 m and 160 m, gradually thinning towards the south, where the depth in the Gulin region varies between 60 m and 80 m; a slight decrease in thickness is observed to the northwest, with an increase in the proportion of limestone (Figure 3). The shale section, distinguished by vertically stacked thin layers and well-developed interlayers, is predominantly situated within the central and lower layers of the Longtan Formation. The thickness of individual shale layers ranges from 0.5 m to 20.0 m, with a cumulative thickness reaching 45 m-120 m. This area is rich in coal reserves, and some drilling exploration results show that there are up to ten layers of coal seams and their stratification limits, and the thickness of coal seams ranges from 0.11 m to 1.32 m, demonstrating the extensive coverage and diverse forms of coal resources. The characteristics of these coal seams not only indicate the good potential of coal mining, but also contain important clues about the geological structure, sedimentary history and palaeoclimatic conditions, which are of great significance in promoting the sustainable development and utilisation of coal resources and deepening geological scientific research (Zhang et al., 2020; Deng et al., 2012).

The lithology of the marine Wujiaping Formation is primarily limestone and shale, with tuff and basalt developed locally (Luo et al., 2014). The continuous shales outside the trough are comparatively underdeveloped, the continuous shale outside the trough is relatively undeveloped, but the single-layer thickness inside the trough is about 6–12 m, with a cumulative thickness of 10–40 m (Figure 4). However, it is noteworthy that the Wujiaping Formation shale exhibits characteristics such as a substantial thickness in a single layer and a considerable interlayer interval, thereby ensuring its excellent continuity along the longitudinal axis.

4.2 Organic geochemical characteristics

The TOC of the Longtan Formation shale primarily ranges from 0.5% to 5.0% (Figure 5), in the Gulin-Suyong, Gamo, and Dazhou regions, this content exceeds 5%, indicating localized areas of high enrichment. The TOC of the Wujiaping Formation predominantly lies between 3.0% and 10.0% (Figure 5), with the central section of the trough exhibiting values above 3.0%, while the outer section

Total ras	Ū		16.0 1.58~1.83	7.5 1.55
Brittle mineral Total	ŭ	8.0~65.7 1.78~9.77	65.2~92.6 2.5~16.0	24-44 2.0-7.5
		e 0.63~8.57	2.81~17.40	2.0-8.0
and Longmaxi Formation		Inorganic matter pore	Organic matter pore	Organic matter pore
, Wujiaping Formation, a	0	II 1.4–2.4	2.0-2.8	I 1.6–3.6
ristics of Longtan Formation, Wujiapii		0.5–5.0 III ₂ -III	3.0–10.0 I-II ₁	1.0-6.0 І-П
TABLE 1 Geological characteristics of Longtan Formation, Wujiaping Formation, and Longmaxi Formation shale in the Sichuan Basin. Coological TOC (%) Coological TOC (%)	U	Longtan Formation 0.	Wujiaping Formation 3.0	Longmaxi Formation 1.(



generally shows lower values (Figure 6). Compared with the TOC of the Longmaxi Formation shale gas production layer (Table 1), the Longtan Formation is slightly lower and the Wujiaping Formation is superior.

Organic-rich shales are defined as those containing over 2% organic carbon. The Longtan Formation's organic-rich shales comprise several relatively thin layers, each displaying a high concentration of organic carbon throughout its length. In contrast, the shales located in the Gaoshimo Creek area of central Sichuan are thicker, with individual layers measuring between 1.2 and 3.7 m, resulting in a total cumulative thickness ranging from 12 to 75 m, characterized by notable sedimentary enrichment. Furthermore, in the deep-water land-shelf region of the trough, the organic matter-rich shell layer of the Wujiaping Formation is deposited in a continuous and intensive manner, reaching a cumulative thickness of approximately 20–50 m, thus creating favorable conditions for the exploration and development of shale gas resources (Zhang et al., 2020).

Based on the kerogen carbon isotope test results, the type of organic matter can be determined. In Longtan Formation shale, the kerogen carbon isotope values range from -26% to -20%, with coal seam and carbonaceous shale samples falling between -22% and -20%. The predominant kerogen types are Type II₂ and Type III. For the Wujiaping Formation shale, the kerogen carbon isotope values span from 30% to 25‰, indicating a predominance of Type I and Type II₁, similar to the Longmaxi Formation (Table 1).

The vitrinite reflectance transitions from a high maturity stage to an over-maturity stage from the southeast to the northwest of the basin. In most areas of southern Ya'an-Leshan-Ziyang-Guang'an, the R_O ranges from 1.4% to 2.0%, while in the northern areas, it ranges from 2.0% to 2.8%. The R_O of Longtan Formation varies between 1.4% and 2.4%, and the R_O of Wujiaping Formation within the trough ranges from 2.0% to 2.8%. Both exhibit significant prospects for oil and gas exploration (Bai et al., 2024). Compared to the Longmaxi Formation (Table 1), both are slightly lower, but both have reached the gas generation stage.

4.3 Characteristics of reservoir space

In this study, scanning electron microscopy and digital core analysis methods are used to conduct a thorough investigation of core in the shale reservoir of the Longtan Formation. The pore structure is primarily composed of interlayer fractures in clay minerals, along with minor dissolved pores, micro-fractures, and organic matter pores. Figures 7, 8 provide visual representations of these pores. Organic matter pores mainly consist of irregular hydrocarbon-generating pores formed by organic matter particles inside and at the edges during the hydrocarbon generation process (Zhang et al., 2016), as well as circular pyrolysis pores formed by organic matter during the pyrolysis process, with a relatively small overall number (Figures 7a-d). The reservoir space of Wujiaping Formation shale is primarily composed of organic matter pores and clay mineral interlayer fractures. These organic matter pores predominantly exhibit a honeycomb-like structure, akin to those found in the Longmaxi Formation (Figure 9; Table 1). Honeycomb-like organic matter pores are irregular voids formed due to stress during the thermal evolution of the sapropel group. Additionally, some organic matter pores are developed around organic matter particles, similar to those observed in the Longtan

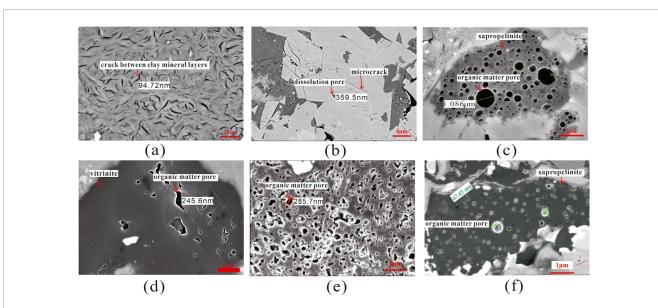
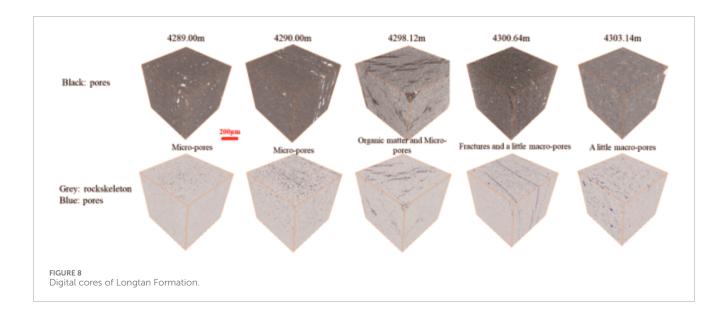


FIGURE 7

Sem of longtan formation and wujiaping formation. (a) CLC1 Well -Longtan Formation -crystalline pores and fractures in I/ S mixed-layer mineral. (b) CLC1 Well -Longtan Formation - corrosion holes and micro cracks in Siderite. (c) zk2003 Well -Longtan Formation- organic matter pyrolysis pores, with a maximum pore size, 1.086 μm. (d) CLC1 Well -Longtan Formation- a few irregular organic pores in fragmented organic matter, 245.6nm. (e) Yuanjiacao Profile - Wujiaping Formation- Irregular organic pores (f) HY1 well - Wujiaping Formation- organic matter pyrolysis pores.



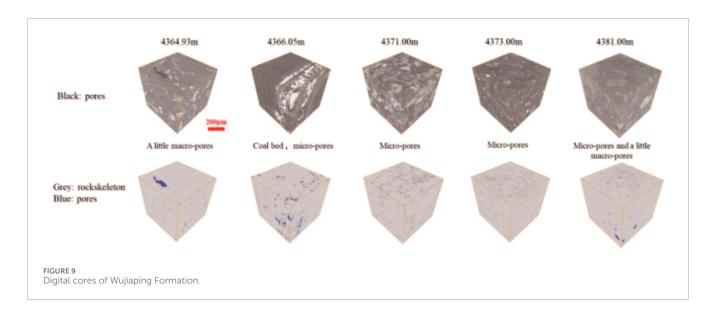
Formation (Figures 7e, f). The development of organic matter pores is significantly influenced by macerals, with sapropel playing a crucial role in pore development, whereas vitrinite tends to resist pore formation (Zhang et al., 2020). Compared to the Longmaxi Formation shale, the marine sedimentary rocks of the Wujiaping Formation exhibit higher sapropel components in their organic matter (Tang et al., 2014).

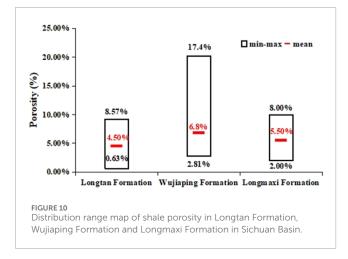
The porosity of Longtan Formation shale ranges from 0.63% to 8.57%, with an average of 2.7%, while the internal coal interlayers in the shale exceed 10%. The porosity of Wujiaping Formation shale in the trough area is between 2.81% and 17.4%, with an average of 6.8% (Figure 10). The porosity of shale in the Longtan Formation and Wujiaping

Formation is comparable to the Longmaxi Formation (Table 1), indicating that both formations possess favorable reservoir properties.

4.4 Mineral assemblage and brittleness characteristics

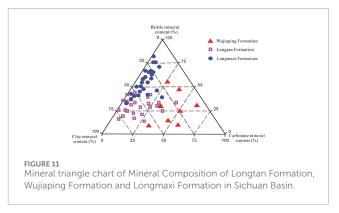
The abundant presence of brittle minerals enhances the likelihood of fracturing and fracture development (Ross and Marc, 2009; Ross and Bustin, 2007). In the organic shale of the Longtan Formation, clay minerals are significant, with their content varying between 5.0% and 92.3%, reflecting considerable variability, and an





average clay mineral content reaching 59.2%. The brittle minerals in this formation range from 8.0% to 65.7%, averaging 41.7%, predominantly consisting of quartz. Conversely, the organic shale of the Wujiaping Formation is characterized by high carbonate and silica content, with brittle minerals comprising between 65.2% and 92.6%, averaging 76.6%, and mainly consisting of quartz and carbonate minerals. The clay mineral content in this formation varies from 8.1% to 30.9%, with an average of 16.1%. Compared to the Longmaxi Formation (Figure 11; Table 1), the Longtan Formation shale exhibits lower brittleness, making it less suitable for fracturing development, whereas the Wujiaping Formation shale possesses higher brittleness, making it more suitable for fracturing.

Based on logging interpretation results, the brittle mineral content in the Longtan Formation shale in the Gulin area of southern Sichuan and the Zigong-Anyue-Suining region of central Sichuan exceeds 50%. The brittle mineral content in the Wujiaping Formation shale within the trough is also over 50%, with the brittle mineral content reaching up to 70% in the Kaijiang-Liangping region.



4.5 Gas-bearing characteristics

Shale gas content tests were conducted on Well CLD1 of the Longtan Formation in the Guxu area of southern Sichuan and Well DY1 of the Wujiaping Formation within the trough. Well CLD1 analyzed 25 mud shale samples from the Longtan Formation section, revealing a total gas content ranging from 0.23 m³/t to 19.17 m³/t. Specifically, the content of carbonaceous shale and mud shale was between 1.78 m³/t and 9.77 m³/t, while the content of coal-bearing interbedded shale was between 11.80 m3/tand 21.44 m3/t, and the content of silty mudstone ranged from 0.23 m³/t to 1.13 m³/t. This indicates that the Longtan Formation's organic-rich shale and coalbearing interbedded shale exhibit good gas-bearing properties. In the southeastern Sichuan region, the total gas content in field tests of the coal seam and carbonaceous mudstone in Well SY1 reached an average of 18.5 m³/t and 4.08 m³/t. Well DY1 revealed the presence of Wujiaping shale gas, with a gas content ranging from 2.5 to 16.0 m³/t. Notably, the average gas content of the top shale in Wujiaping reached as high as 8 m³/t. Compared to the Longmaxi Formation shale, the organic-rich shale, coal-bearing interbedded shale, and top shale of the Wujiaping Formation in the Longtan Formation have similar gas contents, with slightly higher values in some well sections. This suggests that both formations of shale have good gas content and significant potential for shale gas exploration.

Through comprehensive analysis of the logging data, it was found that the shale gas content of the Longtan Formation shale located between the Junlian and Gulin districts in southern Sichuan and the Qijiang area in eastern Sichuan is above 3.0 m^3 /t. Meanwhile, it was observed that the gas content of the Wujiaping Formation in the area between Kaijiang and Liangping was particularly high, reaching a level of more than 5.0 m^3 /t.

4.6 Preservation conditions

An analysis of the exploration and development impacts of commercially extracted shale gas within the Wufeng Formation-Longmaxi Formation reveals that the degree of enrichment in shale gas reservoirs is influenced by both depositional environments and preservation conditions. Key factors that affect the preservation conditions of shale gas include the characteristics of the upper and lower boundaries, burial depth, and structural attributes. The upper boundary of the Longtan Formation consists of a dense muddy limestone from the Changxing Formation, exceeding 50 m in thickness, while the lower boundary is comprised of clay rocks, with its lower section featuring a dense, thick (over 50 m) bioclastic micrite limestone from the Maokou Formation, both of which provide favorable sealing conditions. Additionally, the burial depth of the Longtan Formation in the central and southern Sichuan region typically ranges from 500 to 4,000 m, which is considered moderate. The Longtan Formation at the SY1 well in southeastern Sichuan exhibits a maximum total hydrocarbon content of 23.99%, with drilling fluid densities ranging from 1.85 g/cm³ to 1.90 g/cm³. Moreover, the Longtan Formation at the CLD1 well in southern Sichuan has recorded 19 layers of abnormal gas readings. The Gaoshiti-Moxi well area in central Sichuan shows active oil and gas indications within the Longtan Formation, suggesting that the overall preservation conditions in the basin for the Longtan Formation are favorable.

The stratigraphy at both the top and bottom of the Wujiaping Formation aligns with that of the Longtan Formation, although the conditions at the top and bottom of the Wujiaping Formation are generally superior, with the exception of localized high-energyphase reservoirs found at the platform edge of the Changxing Formation in the Upper Permian System, particularly in the Puguang area and beyond. In eastern Sichuan, the Wujiaping Formation is slightly deeper than the Longtan Formation, typically ranging from 3000 m to 4500m, indicating a moderate depth. Additionally, the stratigraphic pressure coefficients measured in older wells in the Kaijiang region of eastern Sichuan can reach values between 1.58 and 1.83, indicating abnormally high pressures that suggest favorable preservation conditions.

5 Evaluation criteria and optimization of favorable areas

Based on the China shale gas geological evaluation standard (2015), considering the factors of reserves, reservoirs and gas content, and analysing sedimentation, organic matter, porosity,

permeability and preservation conditions. Based on the latest exploration data, experimental data and numerical simulation, the formation, migration and enrichment mechanism of shale gas is discussed, providing scientific support for effective exploration and development. A multidimensional evaluation of shale gas in the Wujiaping and Longtan formations of the Sichuan Basin was conducted, and corresponding favorable area evaluation standards were established (Table 2).

The initial occurrence of stratum erosion and fractures in specific areas of the Longtan formation in southern Sichuan has resulted in the consolidation of assessment criteria such as "distance from the denudation line" and "distance from a grade I fault" within the preservation conditions. If the shale gas reservoir is buried more than 3.0 km from the denudation line and more than 0.7 km from the main fault, its conservation efficiency is significantly improved. Such geological conditions are conducive to the longterm preservation of natural gas resources. On the other hand, the exploration history of the Longmaxi Formation is an important scientific guide and data source for assessing the development potential of shale gas in the study area. Current technical capabilities indicate that the optimal depth for exploration and development is primarily within 4,500 m. This depth limit has been determined through a comprehensive evaluation of geological characteristics, mining technical capabilities, cost-effectiveness considerations, and environmental protection requirements. Thirdly, considering that the Longtan Formation is a coal-bearing series characterized by high organic carbon levels in carbonaceous mudstone, the organic carbon content index for shale has been revised to 2.0% to facilitate a more thorough investigation and assessment of shale gas resources. Fourthly, due to the elevated clay content within Longtan Formation shale, the lower threshold for brittle mineral content has been lowered to 35%, while the upper threshold for clay mineral content has been increased to 65%. Lastly, the lithology and lithofacies of the Longtan Formation exhibit rapid vertical variations, and there are limited sections of organic-rich shale with a consistent thickness exceeding 15 m. The effective cumulative thickness ranges between 12 m and 75 m, and the shale with toc2.0% has some hydrocarbon generation capacity, as does the coal measures interlayer. As a result, the continuous effective shale thickness is replaced by the cumulative effective shale thickness, which exceeds 10 m, and the interlayer thickness is increased to 5 m. The Wujiaping Formation comprises two to three layers of shale strata rich in organic matter, which are formed in a deep water shelf environment and possess distinctive sedimentary facies characteristics. The single-layer continuous thickness of these shale layers varies between 5 and 25 m, indicating a relatively stable deposition process. When considered as a whole, the effective cumulative thickness of these organic-rich shale layers is between 20 and 50 m, revealing significant vertical organic accumulation areas.

According to the evaluation criteria, this paper systematically defines the favourable shale gas areas of Longtan Formations and Wujiaping Formations in Sichuan Basin. By comprehensively considering the geological structure, sedimentary environment, reservoir characteristics and other factors, the rich area is accurately locked. The identified favorable blocks for the Longtan Formation include the Guang'an-Zigong-Shi Bao block, while for the Wujiaping Formation, it is the Dazhou-Liangping block (Figure 12).

Parameter type	Evaluation parameter	Longtan formation	Wujiaping fm	National standard
Geochemical characteristics	Organic carbon content (%)	>2.0	>2.0	Marine facies> 2.0; Transition phase> 1.0
	Maturity of organic matter (%)	>0.9%	>1.3%	$\begin{split} \text{III}, \ \ \text{II}_2 > 0.9\%, \text{I}, \ \ \text{II}_1 \\ \text{type>1.3\%} \end{split}$
Compressibility characteristics	Brittle mineral content (%)	>35.0	>35.0	>40.0
	Clay mineral content (%)	<65.0	<65.0	<60.0
Physical characteristics	Porosity (%)	>2.0	_	>2.0
	Water saturation (%)	<45	_	<45
Gas bearing property	Gas content (m ³ /t)	>1.0	>1.0	>1.0
Preservation condition	Formation pressure	Atmospheric pressure-overpressure		Atmospheric pressure-overpressure
	Tectonic conditions	The structure is relatively stable and the degree of transformation is low		The structure is relatively stable and the degree of transformation is low
	Distance from Class I fracture	>0.7 km	_	_
	Distance from denudation line	>3.0 km	_	_
Shale distribution	Effective shale cumulative thickness (m)	>10	>20	Continuous effectiveness: marine facies 30–50; Transition phase> 15
	Interlayer thickness (m)	<5	<1	Marine facies <1; Transition phase <3
	Mud-to-soil ratio (%)	>70		>70
	depth of burial	500-4,500	1,000-4,500	_

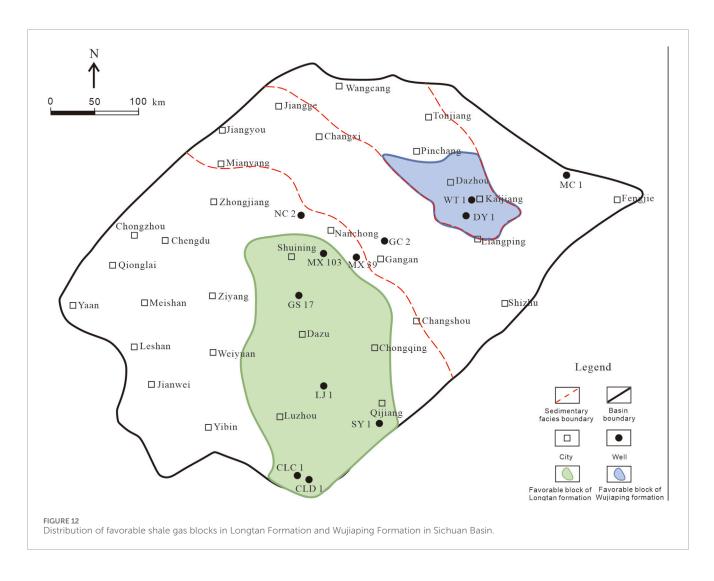
TABLE 2 Determination conditions and lower limit standards of shale gas favorable areas of Longtan Formation and Wujiaping Formation in Sichuan Basin.

6 Exploration potential and prospects

6.1 Resource potential evaluation

In order to accurately quantify shale gas resources in favourable blocks, this paper adopts appropriate resource assessment methods according to the current exploration status. In the research process of shale gas resources in Sichuan Province in 2020, based on the drilling practice of CLD1 and CLC1 wells, the gas content information of Longtan formation in the ancient forest zone was directly measured with high accuracy. This information is very important to deepen the understanding and accuracy of shale gas resource potential assessment, and provides reliable data support for the construction of a resource evaluation system. However, there are few measured gas-bearing data of this interval in other areas, and trial production data is limited, so the overall exploration and research degree is low. To evaluate shale gas resources, the total gas volume method and resource abundance analogy method are chosen as the main methods, and the analogy method and volume method are supplemented. The shallow geological resources in the Guang an-Zigong-Shibao block with a buried depth of 4,500 m are estimated to be nearly 4 trillion cubic meters, with a resource abundance of about $1.60 \times 10^8 \text{ m}^3/\text{km}^2$. Compared with (Guo et al., 2019) and others, according to Dongyeshen one well, the shale gas geological resources in the Qijiang-Chishui favorable area in southeast Sichuan of Longtan Formation are 1,259.3 × 10⁸ m³, and the resource abundance is $2.45 \times 10^8 \text{ m}^3/\text{km}^2$, which is close to the resource abundance obtained this time and has good resource potential.

The shales from the Wufeng Formation to the Longmaxi Formation exposed in the Changning and Weiyuan areas show remarkable similarities and consistent trends in key geological elements such as sedimentary setting, rock type classification and organic matter content. Given the obvious similarity between the Wujiaping Formation shale and known prolific shale formations in terms of key characteristics, this study decided to systematically evaluate the shale gas resources of the Wujiaping Formation using a scientifically accepted and technically complete analogy method. Specifically, we use the analogy method commonly used in resource evaluation, i.e., the reservoir geological characteristics and production potential of the Wujiaping Formation shales are compared in detail



with the well-studied Wufeng-Longmaxi Formation shales (Bai et al., 2024). Based on the resource assessment carried out during the 13th Five-Year Plan, the projected resource availability in Changning and Weiyuan areas is roughly $5.40 \times 10^8 \text{ m}^3/\text{km}^2$ and $5.00 \times 10^8 \text{ m}^3/\text{km}^2$, respectively. The Wujiaping Formation in the Dazhou-Liangping block has lower effective reservoir thickness and gas content compared to the Longmaxi Formation, with similarity coefficients of 0.59 and 0.69. The Dazhou-Liangping Block encompasses a promising area of 1,400 square kilometers, characterized by a relatively shallow depth of 4,500 m, a geological resource of about 450 billion cubic meters, and a resource abundance of $3.18 \times 10^8 \text{ m}^3/\text{km}^2$ - $3.45 \times$ $10^8 \text{ m}^3/\text{km}^2$. The geological resources of Wu two member in Hongxing area are 260.98 billion cubic meters, and the resource abundance is 2.88 \times 10 8 m $^3/\rm{km}^2$ (Liang and Li, 2021), which is close to the resource abundance obtained by analogy method in this paper and has significant resource potential.

6.2 Evaluation of exploration potential

The Moxi to Gaoshiti area in the central Sichuan Basin and the Chishui to Qijiang area in the south-eastern Sichuan Basin, the research team detected significant hydrocarbon activity in the Longtan Formation during drilling activities, and some of the well sites showed industrial airflow characteristics with commercial production value. This indicates that the shale gas resources of the Longtan Formation in the above areas have good development potential and economic benefits. In the paleosequence block, during the implementation of the CLC1 small hole parameter drilling project by the Sichuan Provincial Geology and Mineral Bureau, a 17 m long high-quality shale formation in the lower part of the Longtan Formation was identified as a target through extensive geological survey and evaluation, and a small area perforation fracture test was carried out, the trial production reached 1600m³/day, and the cumulative production in the following 3 months was nearly 100,000 cubic meters. The average gas content from Sinopec's Dongyeshen 1 well located in the Chishui-Qijiang area stands at 2.02 m³/t. In the Moxi to Gaoshiti Block in the central part of the Sichuan Basin, the scientific research team successfully detected obvious signs of oil and gas in the Longtan Formation during the geological survey activities. With itsgeological characteristics in the sea-land transition facies, we propose to focus the exploration and development work on the block with good thickness continuity and stable lateral distribution of the Longtan Formation.

The organic rich shale of Wujiaping Formation is mainly concentrated in the deep-water shelf facies, contains three layers of organic-rich shales. The Wu-2 member's shale was tested by Hongye 1 from China Petrochemical Company, yielding an output of $55,000 \text{ m}^3/\text{d}$. Meanwhile, the DY1 well, a high-stakes exploratory project initiated by PetroChina in the Kaijiang-Liangping region of eastern Sichuan encompassed an evaluation of the oil output derived from the shale situated within the Wu-3 Formation, achieving an impressive industrial gas flow of nearly $320,000 \text{ m}^3/\text{day}$ (Yang et al., 2023).

7 Conclusion

- (1) The Longtan Formation shale, a sea-land transitional facies shale, consists of multiple thin layers ranging from 0.5 to 20.0 m in thickness. The TOC content primarily varies from 0.5% to 5.0%, with an average of 2.7%. The kerogen types present are II₂ and III, and the Ro varies between 1.4% and 2.8%. The reservoir space is predominantly composed of interlayer pores in clay minerals, exhibiting a porosity range from 0.63% to 8.57%, with an average of 4.5%. The brittle mineral content ranges from 8.0% to 65.7%, averaging 41.7%. The carbonaceous mud shale possesses excellent gasbearing properties, with gas content ranging from 1.78 m³/t to 9.77 m³/t and an average of 5.0 m³/t. Notably, the coal-bearing shale demonstrates a range from 11.80 m³/t to 21.44 m³/t, averaging 15.5 m³/t.
- (2) The Wujiaping Formation shale is characterized by deep-water shelf facies. Within the Kaijiang-Liangping trough, individual shale layers exhibit substantial thickness, ranging from 6 to 12 m. The TOC content primarily falls between 3.0% and 10.0%, with values exceeding 3% in the trough. The kerogen predominantly consists of type I and type II, with the Ro ranging from 2.0% to 2.8%. The organic matter pores are well-developed, and the porosity of the shale in the trough varies from 2.81% to 17.4%, averaging 6.8%. The content of brittle minerals is high, ranging from 65.2% to 92.6%, with an average of 76.6%. The gas content varies between 2.5 m³/t and 16.0 m³/t, with the shale section at the top of the Wujiaping Formation exhibiting the highest gas content, averaging 8 m³/t.
- (3) Based on the geological characteristics of the two shale formations, the evaluation criteria for favorable areas are adjusted to relax the requirements for compressibility. Specifically, the criteria stipulate that the brittle mineral content must exceed 35%, while the clay mineral content should be below 65%. Additionally, preservation conditions are subject to more stringent requirements, including a minimum distance of 0.7 km from Class I fractures and a minimum distance of 3.0 km from denudation lines. Furthermore, the distribution characteristics of shale are expanded, with the interlayer thickness in the Longtan Formation being less than 5 m, the cumulative effective shale thickness in the Wujiaping Formation exceeding 15 m.
- (4) The favorable regions for the Longtan Formation within the Sichuan Basin are primarily located in the

Guang'an-Zigong-Shibao block, characterized by a resource abundance of approximately 1.60 \times $10^8\,m^3/km^2$ and a geological resource volume nearing 4 trillion cubic meters. Meanwhile, the favorable regions for the Wujiaaping Formation are situated in the Dazhou-Liangping block, with a resource abundance of about $3.30 \times 10^8 \text{ m}^3/\text{km}^2$ and a geological resource volume of nearly 125.9 billion cubic meters. Successful industrial gas flows have been achieved through vertical fracture stimulation in Well CLC1 targeting the Longtan Formation and horizontal fracture stimulation in Well DY1 targeting the Wujiaaping Formation, thereby validating their significant exploration potential. Exploration activities targeting Longtan Formation shale gas in the central Sichuan region hold promise for realizing a breakthrough in sea-land transitional facies shale gas. Additionally, the Wujiaaping Formation represents a crucial follow-up domain for shale gas exploration, succeeding the marine shale gas reservoirs of the Longmaxi Formation.

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

MC: Conceptualization, Data curation, Formal Analysis, Investigation, Software, Supervision, Writing-original draft. JY: Conceptualization, Funding acquisition, Methodology, Project administration, Validation, Writing-original draft. ZL: Investigation, Validation, Writing-review and editing. YM: Data curation, Resources, Writing-original draft. HW: Data curation, Resources, Writing-original draft. SC: Writing-review and editing. WZ: Writing-review and editing.

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Conflict of interest

Authors MC, JY, YM, HW, and WZ were employed by Exploration and Development Research Institute of PetroChina Southwest Oil and Gasfield Company.

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.

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