Journal of Geo-Energy and Environment
http://dx.doi.org/10.62762/JGEE.2025.391517

RESEARCH ARTICLE

Quantitative Assessment of Shale Gas Preservation in the Longmaxi Formation: Insights from Shale Fluid Properties

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Abstract

The shale gas content of the Longmaxi Formation exhibits significant spatial variation in different structural parts of the Sangzhi area in Hubei Province, reflecting differences in preservation conditions. To quantitatively evaluate these conditions, this study integrates analyses of structural features, fault distribution, formation water chemistry, and shale gas composition from four wells. Results show that preservation is primarily controlled by the F1 and F3 faults. Wells distant from these faults (SY3 and SY5) display weak connectivity with surface water, feature $CaCl_2$-type formation water with high salinity and diagnostic ion coefficients, and contain hydrocarbon gases derived from organic pyrolysis. These characteristics lead to high gas content and favorable preservation conditions. In contrast, wells adjacent to faults (SY1 and SY6) exhibit strong connectivity with the surface, $NaHCO_3$-type water of low salinity, high N_2 and CO_2 contents of atmospheric origin, and low gas content, indicating poor preservation. These findings demonstrate that shale gas preservation in the Longmaxi Formation is jointly controlled by structural settings, water–rock interactions, and nonhydrocarbon gas sources, providing a quantitative framework for assessing preservation conditions in shale gas exploration.

Keywords: shale gas preservation, longmaxi formation, fluid properties, structural control, nonhydrocarbon gases.

1 Introduction

Lower Paleozoic marine shale in South China is currently the main focus of shale gas exploration and development in China. The shale gas development horizons include two sets of the Cambrian Niutitang Formation and Silurian Longmaxi Formation [1, 2]. The Silurian Longmaxi Formation and other shale strata are characterized by high TOC content, high-superheated evolution, large effective thickness, wide continuous distribution area and rich oil and gas resources [3]. The shale gas exploration and development of the Longmaxi Formation is mainly distributed in the Sichuan Basin and its surrounding areas. Many shale gas fields have been discovered

Submitted: 14 August 2025
Accepted: 22 August 2025
Published: 30 August 2025

Vol. 1, **No.** 1, 2025.
10.62762/JGEE.2025.391517

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Citation
Ren, G., Guo, W., & Yuan, L. (2025). Quantitative Assessment of Shale Gas Preservation in the Longmaxi Formation: Insights from Shale Fluid Properties. *Journal of Geo-Energy and Environment*, 1(1), 8–22.

in Weiyuan, Changning, Dingshan, Pengshui and Luzhou, showing great exploration potential [4].

With the gradual increase in shale gas production and the progress of exploration technology and means in the Sichuan Basin, shale gas exploration is gradually expanding to Hubei, Guizhou and other areas outside the basin, among which good shale gas is found in many areas of Hubei, and shale gas flow is found in Zigui, Huangling, Yichang and Sangzhi in Hubei, among which shale burial is shallow in the Sangzhi area. The shale of the Wufeng–Longmaxi Formation in the Sangzhi area is mainly formed in the sedimentary environment of the shelf in deep water [5–7]. The shale is in the stage of high organic matter content, the high to overmature stage, and has superior hydrocarbon generation conditions [5, 6]. Therefore, preservation conditions have become a key factor in determining whether shale gas accumulation can be achieved. At present, multiple shale gas drilling wells have been deployed in the Sangzhi area, including SY1, SY2, SY3, SY4, SY5 and SY6. Some wells display good shale gas, but there are obvious differences in the contents and gas components of different wells. This is mainly caused by differences in preservation conditions.

For the evaluation of shale gas preservation conditions, the early evaluation mainly considered the factors affecting the horizontal diffusion and vertical migration of shale gas [8]. Different scholars have proposed a variety of evaluation methods for different blocks. Previous studies believed that the spatiotemporal matching relationship between the hydrocarbon generation evolution of organic matter and tectonic movement, the failure of faults to roof and floor and the communication with permeable strata are two key factors affecting shale gas preservation [9, 10]. Therefore, research on shale gas preservation conditions mainly focuses on fracture development and sealing properties, time and amplitude of stratum uplift, top and floor integrity, etc [11, 12]. Different preservation evaluation systems have been developed in different regions, but they are all in the qualitative evaluation stage. Therefore, it has become an urgent problem to find a quantitative evaluation of preservation conditions.

From the perspective of rock mechanics, different scholars began to analyze the differences in the formation of faults in tectonic movement and the differences in the shale formed after the failure of the preservation conditions and carried out quantitative evaluation of the preservation conditions [13]. Generally, after the destruction of preservation conditions, communication between permeable strata and the surface will cause the exchange of shale fluid, and the shale gas composition and formation water properties will change greatly, which can indicate the damage degree of preservation conditions [14]. When the preservation conditions are poor, because of the strong connectivity between shale strata and the surface, surface water will permeate down along the passage and replace the original formation water, resulting in changes in the properties of formation water and gas components, indicating that it is feasible to quantitatively evaluate the preservation conditions based on formation water and gas components [15]. Combined with regional structural analysis, the preservation conditions of points and surfaces can be quantitatively evaluated [16]. Therefore, based on the analysis of the structural factors affecting the preservation of shale gas, this paper analyzes the connectivity between the Longmaxi Formation shale and the surface by means of the ion type, water type, gas composition and nonhydrocarbon gas sources of formation water to provide reference and guidance for shale gas exploration in similar areas.

2 Geological setting

The Sangzhi area is tectonically located in the middle north of the Yangtze Plate and is a second-order structural unit in the southern part of the western Hunan–Hubei block. The southeast side is the Jiangnan uplift fold belt [6], and the northwest side is the Yidu–Hefeng complex anticline belt. The type of fold is characterized by the closed type and ship type [17]. In the region, the east–southwest wing presents an alternating synclinal and anticlinal groove structure pattern. In general, the dip angles of the southwest and east wings are slightly smaller than that of the north wing, and local inversion occurs. The latest outlying strata are Triassic, and the oldest strata are Cambrian (see Figure 1). From the wing to the core, the Lower Cambrian Mingxinsi Formation is deposited successively to the Middle Silurian Luoyaping Formation, and the target Longmaxi Formation is outlying on both wings [18]. Three faults developed in the eastern synclinorium core, from west to east. The first fault is large and cuts through all strata, while the other two faults cut through strata above the Luojiaping Formation. The faults developed tight alternating anticlines, and the strata became steeper, reflecting the strong compression action in this area [19]. The geological structure is very complex, and the area is dominated by reverse

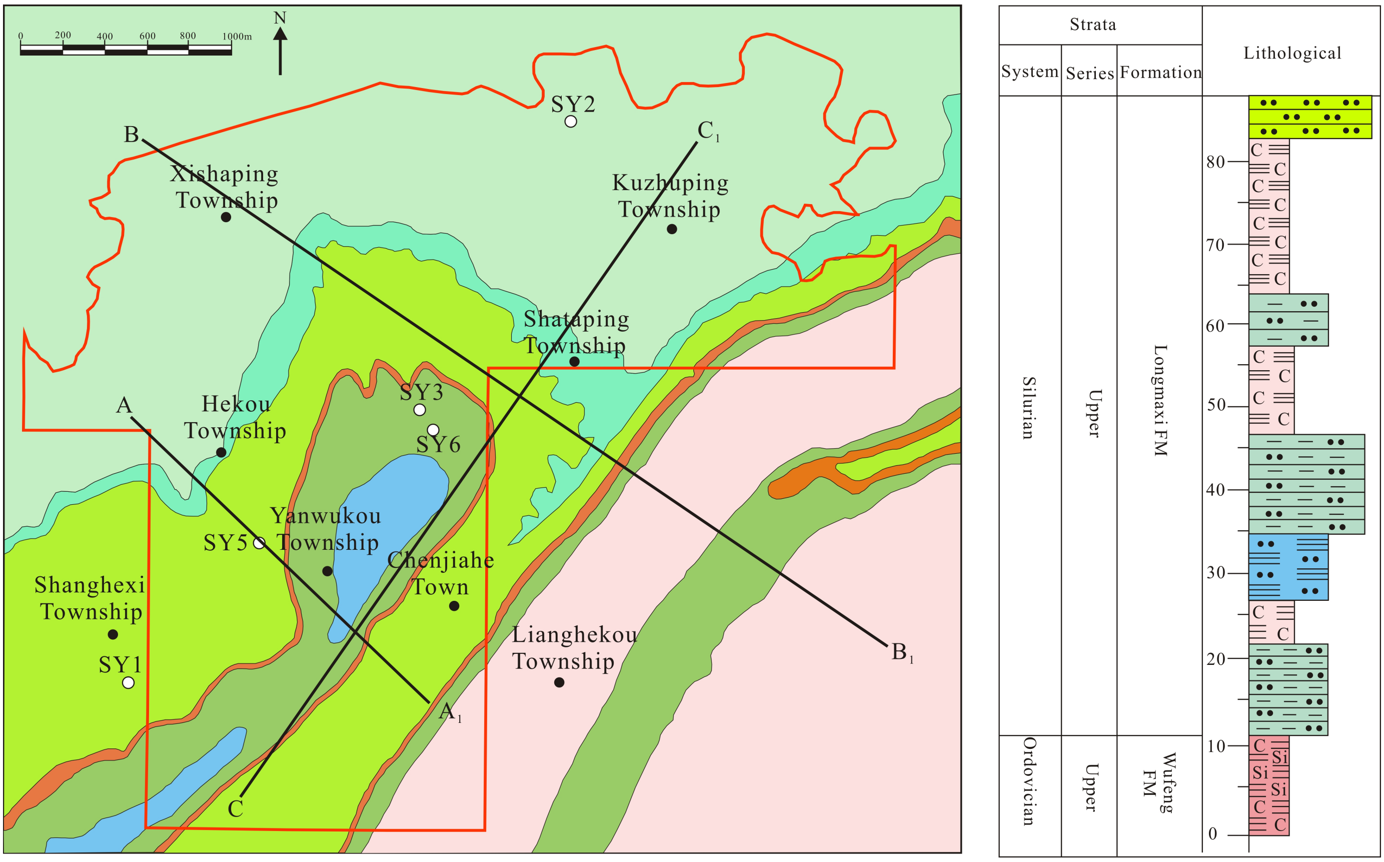

Figure 1. Regional geology(a) and lithology comprehensive histogram(b).

faults, mainly northeast trending and a small number of NW trending faults. The sedimentary facies of the Wufeng–Longmaxi Formation in the Sangzhi area are clastic shelf facies. In the early stage of the Wufeng Formation and the Longmaxi Formation, a deep-water shelf sedimentary environment was formed in the area, which mainly deposited the dark shale layer in the lower part of the Longmaxi Formation. Subsequently, the regressions made the sedimentary water shallower, and the sedimentary environment changed to a shallow shelf, depositing the middle and upper strata of the Longmaxi Formation [20].

The TOC content of the Wufeng Formation ranges from 0.36% to 4.05% and is generally greater than 1%, with an average of 1.85%, except for individuals less than 1%, which is a good to excellent source rock. The TOC content of the Longmaxi Formation ranges from 0.16% to 2.47%, with an average of 0.89%. The TOC content of the lower part is higher than that of the upper part of the Longmaxi Formation. According to the evaluation standard of organic matter abundance, the whole formation is poor to medium source rock, and the TOC content of the shale in the Longmaxi Formation increases obviously with increasing burial depth. Overall, the lower members of the Longmaxi Formation and Wufeng Formation are good source-rock types. The organic kerogen type is mainly I, while II_1 and II_2 are also distributed. The burial depth is generally more than 3500 m, indicating medium-shallow shale gas. The formation pressure coefficients of different structural parts in the study area are quite different. In exploration practice, shale gas content and single-well productivity are quite different, which reflects the differences in preservation conditions.

3 Samples and methods

Formation water and natural gas samples are all from different shale gas wells in the study area. To ensure the comparability of formation water type, salinity and various fluid coefficients, formation water with a long flowback time and relatively stable ion type and content is used for analysis. High-pressure steel containers are used for gas collection, and repeated exhaust flushing treatment is carried out on the cylinders before gas recovery to eliminate the effects of other gases.

3.1 Formation water ion test

Ion types and concentrations of different ions in formation water were tested by ion chromatography. The testing instrument was a CIC-D280 ion chromatograph produced by Qingdao Shenghan Chromatography Technology Co., Ltd. It was equipped with a built-in column constant temperature system and dual high-pressure gradient pump and used a resin-filled ion chromatography electrolytic self-regeneration inhibitor. During the test, the pump flow was set to 8 ml/min, and the pressure was set to 30 MPa.

3.2 Gas composition and content test

The gas chromatograms and mass spectrometry instrument produced by the Shimadzu Company of Japan was used to test the gas composition and content of shale gas. The instrument model was GCMS-QP2020. The EI power supply of the instrument ranged from 10 to 250 eV; the emission current ranged from 5 to 250 μA, and the heating temperature of the ion source ranged from 140 to 350 °C. During the experiment, ultrapure N_2 with a purity above 99.99% was used as the carrier gas after the passivation tube. The instrument was equipped with a differential vacuum system with an ion source and a four-bar mass analyzer. The whole test process was in accordance with the national standard of gas chromatography for the composition analysis of natural gas (GB/T 13610-2003).

3.3 Gas isotope analysis

A MAT253 nitrogen isotope ratio mass spectrometer produced by Finnigan of Germany was used for nitrogen isotope measurement. During the experiment, the temperature of the gas inlet was kept at 200 °C, and the injection split ratio was 20 : 1. The temperature was increased to 80 °C at a warming rate of 15 °C/min, and then the warming rate was reduced to 5 °C/min. The temperature continued to rise until the temperature reached 200 °C, and the temperature was maintained for 15 min. The nitrogen isotope value of nitrogen in the atmosphere was taken as the standard to calculate the nitrogen isotope value of nitrogen in shale gas and the carbon isotope of carbon dioxide gas.

A MAT271 mass spectrometer and Noblesse rare gas isotope mass spectrometer were used for He isotopes, with a high voltage of 7.0 kV and a current of 500 mA. ^{4}He was detected by a Faraday cup, and ^{3}He was detected by an ion counter. The whole detection process was carried out according to "GB/T6041-2002 General Rules for Mass Spectrometry Analysis" and "LDB 03-01-2016 Detection Method for Peak Height Ratio of Rare Gas Isotope Mass Spectrometry". A two-stage purification separation system was adopted. After the extracted gas was purified by a suction pump and separated and enriched by a cold trap, helium isotope analysis was performed. The experimental standard of He isotope Ra was $^3He/^4He = 1.4 \times 10^{-6}$, and the accuracy of the analysis was ±1.5‰.

4 Characteristics of structural deformation and fault development

The preservation of shale gas is influenced by many factors. The uplift of strata, the change in pressure conditions and the development of faults caused by tectonic movement in the later stage will lead to changes in the primary state of shale and thus, differences in preservation conditions [21]. The development of faults is particularly important for preservation conditions. Generally, the faults in the strong structural reconstruction zone are large in scale and high in density, and the damage to the shale roof and floor is strong, so the preservation conditions of shale gas are relatively poor. However, the development of faults in the structural stability zone is relatively small, and the fracture scale is small, which is a favorable target area for shale gas exploration [22].

The study area is located in the Sangzhi–Shimen syncline as a whole, with a tight anticline and wide syncline arranged in the northeast direction, including the Yanwukou syncline, Danguquan anticline and Lianghekou syncline. The shale burial depth of the Wufeng–Longmaxi Formation has a large span. The strata are exposed above the surface to the northwest of the study area, and the burial depth of the inner layer in the syncline area is 1000–3500 m. Under the influence of the Yanshan movement and Himalayan movement, a series of thrust faults with a large scale and some small faults with a NW trend developed in the study area. The ENE faults are distributed in the southeast wing of the Dangguquan anticline and the Yanwukou syncline. The dip angle of the faults is more than 60°, and the multistage faults are "Y" and "V" in the longitudinal direction (see Figure 2). The faults break through to the surface upward and disappear in the Sinian system downward. Previous research results show that the core of the Longmaxi Formation in the Sangzhi area has multiple types of fractures, with high-angle fractures and horizontal

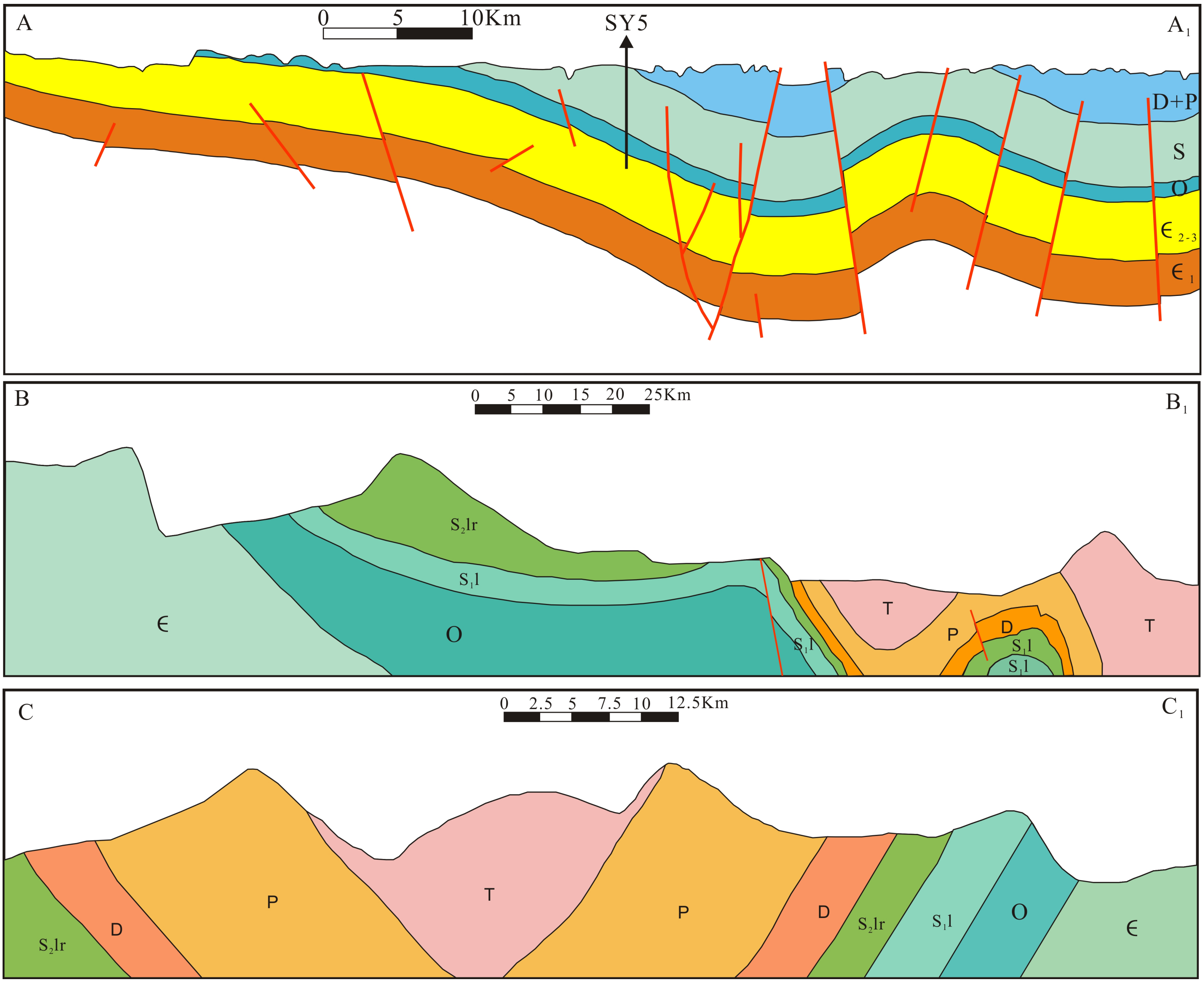

Figure 2. Cross-well section of typical structural style.

fractures formed along the bedding plane being the most developed. Meanwhile, there are a considerable number of unfilled fractures, and the core of the bottom of the Longmaxi Formation and Wufeng Formation in the longitudinal direction has a large scale of fractures.

5 Analysis of shale fluid conditions

As a complete reservoir system, shale fluid includes formation water and gas components [23]. Formation water ion concentration, formation water type and natural gas composition are all affected by multiple factors. The test results of Longmaxi Formation shale water from different wells in the Sangzhi area indicate that the ion types of formation water are consistent (see Table 1), but there are great differences in the concentration of anions, salinity and formation water type among different wells. The anions in formation water include Cl^-, HCO_3^- and SO_4^{2-}, and the content of HCO_3^- is similar to that of Cl^-. The average concentration of HCO_3^- is 662.918 mg/L; the average concentration of Cl^- is 661.845 mg/L, and the average concentration of SO_4^{2-} is 80.995 mg/L. The cations include K^+, Ca^{2+}, Na^+ and Mg^{2+}, among which the content of Na^+ is the highest, with an average concentration of 361.51 mg/L; Ca^{2+} is 177.1 mg/L; K^+ is 114.7155 mg/L and Mg^{2+} is 54.084 mg/L. The overall salinity of the formation water is high, but different wells have obvious differences. The salinity of the formation water in the SY1 well ranges from 1982.64 to 2088.2 mg/L, with an average of 1996.43 mg/L, and the salinity of the formation water in the SY3 well ranges from 2092.1 to 2206.8 mg/L. The average salinity of the formation water in well SY5 ranges from 1994.9 to 2145 mg/L, with an average of 2089.38 mg/L, and that in well SY6 ranges from 2125.8 to 2304.6 mg/L, with

Table 1. Ion types and concentrations of shale formation water in the Longmaxi Formation.

Samples	K^+ (mg/L)	Ca^{2+} (mg/L)	Na^+ (mg/L)	Mg^{2+} (mg/L)	Cl^- (mg/L)	HCO_3^- (mg/L)	SO_4^{2-} (mg/L)	Salinity (mg/L)
SY-1	165.4	49.8	355.6	46.2	308.3	923.6	86.2	1935.1
	183.2	52.3	361.4	42.6	298.5	967.4	90.86	1996.26
	205.3	60.7	329.7	44.2	298.4	966.7	77.64	1982.64
	196.8	54.7	348.2	43.1	323.2	933.46	80.49	1979.95
	230.4	53.5	364.1	40.5	338.6	972.4	88.7	2088.2
SY-3	70.5	245.7	384.7	50.4	845.2	514.2	89.5	2200.2
	68.7	218.6	366.5	56.7	802.5	493.7	85.4	2092.1
	74.5	246.3	377.4	57.8	878.6	494.8	77.4	2206.8
	63.8	235.1	366.9	61.2	827.8	509.3	88.4	2152.5
	65.7	237.9	361.4	55.8	839.8	479.8	72.9	2113.3
SY-6	62.8	240.5	371.6	54.8	847.2	489.9	72.4	2139.2
	71.4	239.4	346.8	65.4	833.4	504.7	80.5	2141.6
	66.8	258.4	350.9	52.2	829.9	508.2	78.6	2145
	201.4	52.2	325.7	58.9	318.7	959.8	78.2	1994.9
	219.5	49.8	332.2	49.7	288.9	1008.5	77.6	2026.2
SY-5	69.3	248.4	379.4	58.7	874.3	468.6	78.4	2177.1
	71.21	262.6	378.9	61.3	884.2	516.4	84.4	2259.01
	68.4	258.8	400.5	58.2	898.6	538.6	81.5	2304.6
	70.7	237.6	378.6	62.8	867.3	506.7	79.2	2202.9
	68.5	239.7	349.7	61.2	833.5	501.6	71.6	2125.8

Table 2. Composition and content of shale gas in Longmaxi Formation.

Samples	CH_4/%	C_2H_6/%	C_3H_8/%	N_2/%	CO_2/%	He/%	Ar/%
SY-1	3.5	1.3	93.9	0.74	0.02	0.38	0.16
	1.06	0.88	97.7	0.24	0	0.08	0.04
	2.8	1.5	94.5	1.1	0	0.06	0.04
	4.5	1.9	92.8	0.7	0.01	0.07	0.02
	3.6	0.9	93.9	1.3	0.2	0.08	0.02
SY-3	76.8	11.3	10.24	0.95	0.05	0.54	0.12
	88.4	6.8	4.2	0.06	0.02	0.37	0.15
	81.4	9.9	8.4	0	0	0.21	0.09
	79.9	10.2	8.8	0.04	0.01	0.68	0.37
	90.5	5.4	3.4	0	0	0.51	0.19
SY-6	5.7	2.8	89.9	1.1	0.2	0.21	0.09
	2.1	1.4	94.2	1.2	0.3	0.57	0.23
	3.9	2.5	90.8	2.1	0.1	0.44	0.16
	81.6	9.8	8.2	0.22	0.02	0.12	0.04
	75.5	11.7	11.4	0.88	0.04	0.36	0.12
SY-5	7.2	1.1	89.7	1.2	0.5	0.24	0.06
	3.9	2.4	90.4	1.9	0.7	0.46	0.24
	5.8	1.8	89.2	1.8	1	0.32	0.08
	8.4	1.5	88.6	0.8	0.5	0.11	0.09
	2.3	2.2	93.8	1.3	0	0.24	0.16

an average of 2133.882 mg/L.

The composition of shale gas is an important index to measure the development potential of shale gas reservoirs [24]. The analysis results of shale gas components show that the Longmaxi shale gas components in the study area include hydrocarbon gases, such as methane, ethane and propane, nitrogen and carbon dioxide, and a small amount of nonhydrocarbon gases, such as helium and argon. The methane content of hydrocarbon gas components is absolutely dominant, indicating that the shale has experienced a deep thermal evolution process [25]. The nonhydrocarbon gas is mainly nitrogen, and the contents of helium and argon are very small (see Table 2).

The content of CH_4 in well SY1 ranges from 3.40% to 10.74%, with an average of 7.11%; the contents of ethane and propane are relatively low and generally below 0.50%; the content of N_2 ranges from 76.8% to 90.5%, with an average of 83.40%; the content of CO_2 ranges from 5.4% to 11.3%, with an average of 8.72%. The total content of helium and argon is less than 1.5%. The content of CH_4 in well SY3 ranges from 92.8% to 97.7%, with an average of 94.56%; the content of ethane ranges from 0.24% to 1.30%, with an average of 0.816%; the content of propane is below 0.2%, and the content of N_2 ranges from 1.06% to 4.50%, with an average of 3.092%. The content of CO_2 ranged from 0.88% to 1.90%, with an average of 1.296%. The CH4 content in well SY5 ranges from 88.6% to 93.8%, with an average of 90.34%; the N2 content ranges from 2.3% to 8.4%, with an average of 5.52%, and the CO2 content ranges from 1.1% to 2.4%, with an average of 1.8%. The content of CH_4 in well SY6 ranges from 8.2% to 94.2%, with an average of 58.9%; the content of ethane ranges from 0.22% to 2.10%, with an average of 1.1%; the content of N_2 ranges from 2.1% to 81.6%, with an average of 33.76%, and the content of CO_2 ranges from 1.4% to 11.7%. The average is 5.64%.

The isotopic analysis of hydrocarbon gas and nonhydrocarbon gas shows that the $\delta^{13}C$ isotopic value of hydrocarbon gas in well SY1 is between −38.4‰and −35.2‰, with an average content of −36.907‰(see Table 3). The $\delta^{15}N$ isotopic value of nitrogen is 0‰, and the ^{13}C isotopic value of carbon dioxide is between 2.9‰and 7.3‰. The average value is 5.56‰, and the ratio of $^3He/^4He$ in helium is 0.332×10^{-6}~0.854×10^{-6}, with an average value of 0.62×10^{-6}. The $\delta^{13}C$ isotopic values of hydrocarbon gas components in well SY3 range from −38.4‰to −35.2‰, with an average content of −36.954‰; the $\delta^{15}N$ isotopic values in nitrogen range from −8.7‰to −3.6‰, with an average of −5.56‰, and the ^{13}C isotopic values in carbon dioxide gas range from 12.3‰to 16.2‰. The average value is 14.46‰, and the $^3He/^4He$ ratio in helium is 0.0287×10^{-6}~0.0547×10^{-6}, with an average value of 0.03948×10^{-6}. The $\delta^{13}C$ isotopic value of hydrocarbon gas components in well SY5 ranges from −39.3‰to −37.4‰, with an average content of −38.4‰; the $\delta^{15}N$ isotopic value of nitrogen gas ranges from −9.2‰to −4.1‰, with an average content of −6.96‰, and the ^{13}C isotopic value of carbon dioxide gas ranges from 13.7‰to 15.8‰. The average is 14.7 per thousand. The ratio of $^3He/^4He$ in helium gas ranges from 0.0672×10^{-6} to 0.0825×10^{-6}, with an average of 0.07728×10^{-6}. The $\delta^{13}C$ isotope value of hydrocarbon gas components in well SY6 ranges from −38.8‰to −36.2‰, with an average content of −37.7‰; the $\delta^{15}N$ isotope value of nitrogen gas ranges from −7.1‰to 0‰, with an average of −3.26‰, and the ^{13}C isotope value of carbon dioxide gas ranges from 5.8‰to 16.6‰, with an average of 11.74‰. The ratio of $^3He/^4He$ in helium gas ranges from 0.0542×10^{-6} to 0.241×10^{-6}, with an average of 0.12906×10^{-6}. The distribution range of $\delta^{13}C$ in hydrocarbon gas components is consistent in different wells in the study area, while the $\delta^{15}N$ and $\delta^{13}C$ in nonhydrocarbon gas components are significantly different in different wells, indicating that nonhydrocarbon gas components in different wells have different sources.

6 Comprehensive evaluation of preservation conditions

6.1 Indication of shale fluid properties for preservation

In the process of using the properties of formation fluid to indicate the sealing property of shale, formation water is an important index. The metamorphism and retention degree of formation water can be quantified according to the formation water ion concentration, type, formation water type derived from formation water, magnesium chloride coefficient, calcium magnesium coefficient, desulfurization coefficient, sodium chloride coefficient and other parameters to reflect the sealing property of shale. In practical applications, different parameters reflect different water environments.

In the process of long-term oilfield production testing, the formation water with a good production effect is generally the $CaCl_2$ type, and a small amount is the $MgCl_2$ type, indicating a good closed environment, while the formation water in some oilfield areas with a poor production effect is the $NaHCO_3$ type and Na_2SO_4 type, indicating strong communication between the formation and the surface, reflecting poor preservation conditions. Although shale formations

Table 3. Gas composition isotope analysis.

Samples	$^{13}C_{CH_4}/‰$	$^{13}C_{C_2H_6}/‰$	$^{13}C_{C_3H_8}/‰$	$^{15}N_{N_2}/‰$	$^{13}C_{CO_2}/‰$	$^{3}He/^{4}He$
SY-1	-38.4	-37.5	-38.1	0	2.9	0.854
	-34.7	-35.2	-35.6	0	7.3	0.779
	-37.4	-36.9	/	0	6.5	0.548
	-36.2	-37.7	-37.2	0	6.2	0.587
	-36.8	-38.1	/	0	4.9	0.332
SY-3	-35.2	-35.8	-36.2	-8.7	15.4	0.0547
	-36.6	-36.9	/	-6.2	16.2	0.0287
	-37.8	-37.2	/	-3.8	13.8	0.0361
	-38.4	-37.8	-38	-5.5	12.3	0.0358
	-36.7	-36.6	-37.2	-3.6	14.6	0.0421
SY-5	-38.8	-38.2	-37.7	-7.1	15.2	0.0542
	-37.6	-36.2	-37.9	-6.3	14.5	0.0857
	-36.9	-36.5	-37.1	-2.9	16.6	0.0774
	-37.7	-37.4	-38.2	0	6.6	0.187
	-38.2	-38.5	-38.6	0	5.8	0.241
SY-6	-39.1	-38.9	-39.3	-9.2	13.7	0.0825
	-37.6	-37.8	-38.5	-8.4	15.2	0.0753
	-38.9	-38.2	-39.3	-5.8	14.6	0.0794
	-38.3	-37.4	-38.8	-7.3	14.2	0.082
	-37.6	-37.9	/	-4.1	15.8	0.0672

are usually characterized by low porosity and low permeability, the developed shale strata will still have fluid exchange with surface water, resulting in changes in the properties of the formation fluids [26]. Therefore, the formation water type is still suitable for the evaluation of the sealing property of shale strata. The statistical results of the formation water type of shale gas wells with good production effects in the Sichuan Basin show that the formation water type of high-yield shale gas wells is mostly $CaCl_2$ formation water, but the formation water type of some wide and slow structure wells with shallow burial is the $NaHCO_3$ formation water type, which indicates that the analysis of shale sealing by only using formation water type has multiple solutions. To truly reflect the sealing property of shale strata, comprehensive evaluation can be carried out by combining multiple indices, such as the magnesium chloride coefficient, calcium/magnesium coefficient, desulfurization coefficient and sodium chloride coefficient, which reflect the degree of formation water retention and metamorphism. The sodium chloride coefficient can reflect the metamorphic degree of formation water. The average sodium chloride coefficient of normal seawater (0.85) is taken as the critical value. The smaller the coefficient is, the better the sealing property of formation water is. The calcium/magnesium coefficient reflects the metamorphic degree of underground brine, usually with 3 as the critical value. The higher the coefficient is, the higher the metamorphic degree of formation water, and the better the sealing property of the formation. The desulfurization coefficient is used to reflect the REDOX degree of formation water. The smaller the coefficient is, the better the sealing property of formation water will be. The larger the magnesium chloride coefficient is, the better the sealing property will be. The statistical results show that the oil and gas contents were good in the area with coefficients above 8.5.

According to the test results of the formation water ion

Table 4. Shale water characteristics of Longmaxi Formation in Sangzhi area.

Sample	Formation water type	Chlorine/agnesium coefficient	Calcium/magnesium coefficient	Desulfurization coefficient	sodium/chlorine coefficient
SY-1	NaHCO3	4.707606246	0.653665072	9.662648802	1.729279716
		4.943144631	0.744491943	10.43003795	1.815184743
		4.762611219	0.832787762	9.052576615	1.656521771
		5.290085158	0.769622877	8.698485767	1.615230231
		5.897942196	0.801062997	9.108655852	1.612169664
SY-3	CaCl2	11.83034836	2.956259356	3.893252131	0.682401099
		9.984597528	2.337948882	3.911811655	0.684708876
		10.72338606	2.584071261	3.26024216	0.644002742
		9.542069626	2.329534354	3.924936411	0.664506616
		10.61720622	2.585402448	3.214096186	0.645192481
SY-6	CaCl2/NaHCO3	10.90621286	2.661352705	3.165750694	0.657607531
		8.989681995	2.219802368	3.563517113	0.623882225
		11.21563437	3.00185644	3.496510994	0.633920248
		3.817115928	0.537431504	8.581331562	1.532190322
		4.100716393	0.607632321	9.318149129	1.723967626
SY-5	CaCl2	10.50729579	2.566146242	3.316670173	0.650599714
		10.17556698	2.597778749	3.522985794	0.642467428
		10.8921098	2.696554486	3.353306841	0.668210239
		9.742676537	2.294323773	3.375500631	0.654467799
		9.607773657	2.375114355	3.18170528	0.629023757

type and concentration (see Table 4), the classification basis of the SuLin water type is adopted [27]. Longmaxi shale formation water types in the Sangzhi area include the $NaHCO_3$ type and $CaCl_2$ type. There are obvious differences in formation water types among different wells, among which the formation water samples from the SY6 well have the $CaCl_2$ and $NaHCO_3$ types. This indicates that the primary formation water has experienced communication and the exchange of atmospheric water, but the exchange degree is low. The formation of wells SY3 and SY5 only develops $CaCl_2$-type water, indicating that the Longmaxi shale formation water where these two wells are located has been buried for a long time and is deep metamorphic water. The shale water type of the Longmaxi Formation in well SY1 is the $NaHCO_3$ type. This indicates that the formation water has been washed by surface water for a long time.

In the formation water of well SY1, the magnesium chloride coefficient ranges from 4.71 to 5.90, with an average of 5.12; the calcium/magnesium coefficient ranges from 0.65 to 0.83, with an average of 0.76; the desulfurization coefficient ranges from 8.698 to 10.43, with an average of 9.39; and the sodium chloride coefficient ranges from 1.61 to 1.81, with an average of 1.69. In the formation water of well SY3, the magnesium chloride coefficient ranges from 9.54 to 11.83, with an average of 10.54; the calcium/magnesium coefficient ranges from 2.33 to 2.96, with an average of 2.56; the desulfurization coefficient ranges from 3.21 to 3.92, with an average of 3.64, and the sodium chloride coefficient ranges from 0.64 to 0.68, with an average of 0.66. In the formation water of well SY6, the magnesium chloride coefficient ranges from 3.82 to 11.22, with an average of 7.81; the calcium/magnesium coefficient ranges from 0.54 to 3.0, with an average of 1.81; the desulfurization coefficient ranges from 3.17 to 9.32, with an average of 5.63; and the sodium chloride coefficient ranges from 0.62 to 1.72 with an average of 1.03. The magnesium chloride coefficient of well SY5 formation water is between 9.61 and 10.89 with an average of 10.19, the calcium/magnesium coefficient is between 2.29 and 2.70, with an average of 2.51; the desulfurization coefficient is between 3.18 and 3.52, with an average of 3.35; and the sodium chloride coefficient is between 0.63 and 0.69, with an average of 0.65. By analyzing the formation water type and metamorphic parameters of the above four wells, all of the indicators of SY3 and SY5 show the high retention of formation water and no communication exchange between formation fluid and the surface, indicating the strong sealing of the formation. The formation water of the SY1 well has typical characteristics of atmospheric fresh water, indicating strong communication between the formation and the surface under current conditions. The formation–surface-water exchange rate is high, and shale gas escapes along the exchange channel, resulting in a low shale gas content. For well SY6, the formation water type and the characteristics of each parameter have two characteristics: connected formation water and closed formation water.

At present, the gas components of shale gas reservoirs that have been successfully developed are mainly hydrocarbons and contain some nonhydrocarbon gas components. The content and source of nonhydrocarbon gas components are important indicators of the preservation quality of shale gas reservoirs. Nonhydrocarbon gas components in shale gas reservoirs include carbon dioxide, nitrogen and a small amount of inert gas. Nonhydrocarbon gas sources, such as nitrogen and carbon dioxide, can be divided into four types: large gas sources, pyrolysis ammoniation sources of organic matter, metamorphic sources of nitrogenous rock in the crust and deep mantle sources. When nitrogen is mainly derived from the atmosphere, it indicates that the preservation condition of shale gas is poor [28], and a certain amount of nitrogen will be formed by the ammoniation of organic matter. CO_2 also has organic and inorganic origins. Therefore, it is necessary to combine the gas sources in the evaluation of storage conditions using nonhydrocarbon gas components. The origin of carbon dioxide can be determined by the intersection identification chart of carbon dioxide content and ^{13}C in shale gas components.

According to the nonhydrocarbon gas content and gas carbon and nitrogen isotope test results, the natural gas components and nonhydrocarbon gas isotope contents of the four wells in this analysis are very different. The shale gas reservoirs of well SY3 and well SY5 are mainly hydrocarbon gas, containing a certain amount of nitrogen, carbon dioxide and inert gas, and shale gas is mainly oil-type cracking gas. The intersection diagram of carbon dioxide content and carbon isotopes of a single well shows that the sample points are evenly distributed within the range of organic origin. Meanwhile, the nitrogen content of the two wells is below 10%, with an average content of 4.306%, and the ^{15}N content of nitrogen is between $-9.2‰$and $-3.6‰$. According to the nitrogen source identification diagram, all of the sample sites were located in the ammoniation formation zone at the highly mature stage of organic matter. Combined with the crust-mantle-derived discriminant chart of inert gas, the inorganic gas in these two wells is formed in the process of hydrocarbon generation evolution of organic matter.

The nitrogen content of shale gas samples in well SY1 is above 75%; the carbon dioxide content is also above 5%, and the highest content is 11.3%. Meanwhile, according to the isotope analysis results of nitrogen, nitrogen and inert gas, the ^{15}N isotope value of nitrogen samples in nonhydrocarbon gas components in well SY1 is 0‰, and the R/R_a ratio is between 0.2395 and 0.6161. The ^{13}C isotope value of carbon dioxide gas is distributed between $2.9‰$and $6.5‰$. Combined with the analysis of the location of nitrogen origin and carbon dioxide origin identification chart of the well samples, nitrogen sources in SY1 can include large gas sources, volcanic or magmatic sources and organic ammoniation sources, while carbon dioxide gas is of inorganic origin. Combined with the regional geological analysis results, the study area is located in the northwest wing of the syncline as a whole, and there is no trace of basement volcanic activity in the study area. Therefore, the volcanic source and mantle magma source of nitrogen in the Longmaxi shale in the study area can be ruled out. If nitrogen is an organic hydrocarbon generation source in the gas components, the content of nitrogen should be equivalent to that of carbon dioxide. However, the nitrogen content in this well is much higher than the carbon dioxide content. Therefore, the nitrogen in well SY1 is mainly a large gas source, and there may be a certain amount of organic hydrocarbon source, while the carbon dioxide is an inorganic source. This indicates that the storage condition of the well is poor, and the shale rock is directly or indirectly connected to the atmosphere, resulting in gas exchange between shale gas and the atmosphere (see Figure 3).

The nonhydrocarbon gas components in well SY6 indicate a large range of nitrogen and carbon dioxide contents. Some samples are similar to those in well SY1. The ^{15}N isotope value in nitrogen is between $-7.1‰$and 0‰; R/R_a is between 0.0558 and 0.1739, and the ^{13}C isotope value in carbon dioxide is between $5.8‰$and $16.6‰$. This indicates that there are two types of gas sources and organic hydrocarbon sources in the gas component of well SY6, indicating that the shale gas reservoir in well SY6 experienced formation water scour exchange and gas component exchange,

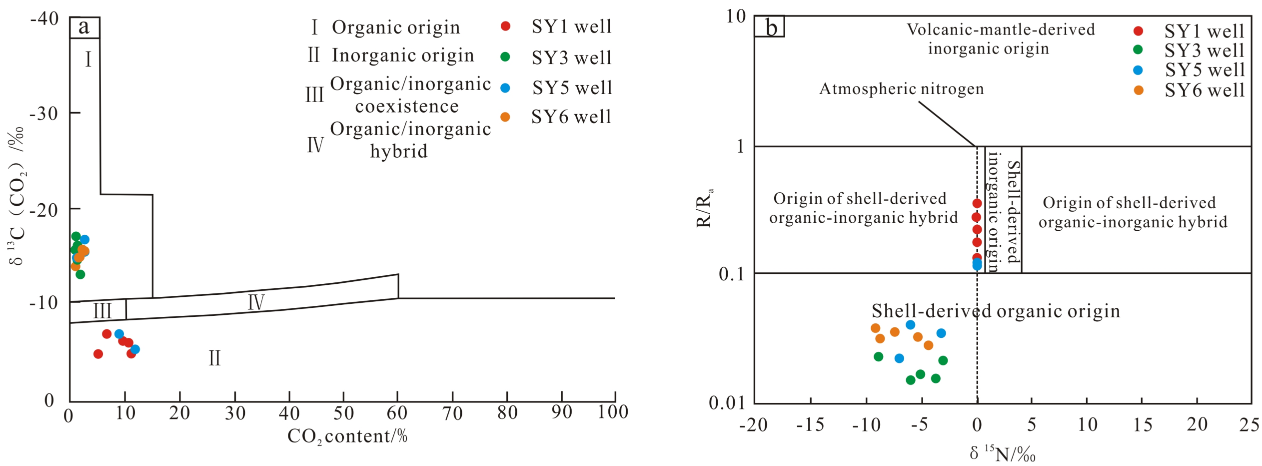

Figure 3. CO_2 and N_2 source identification plate of shale gas in Longmaxi Formation, Sangzhi Area (revised from [29]).

resulting in a low content of hydrocarbon gas in the gas component and a high content of nonhydrocarbon gas, indicating that shale gas preservation conditions are poor.

6.2 Comprehensive analysis of storage conditions

As mentioned above, there are obvious differences in the gas composition, source, formation water type and metamorphism of a single well in the study area, which reflects the differences in the communication between shale strata of different wells and other permeable strata and the surface. Since formation water and gas components alone have multiple solutions in the analysis process, the combination of formation water, gas composition and structural factors can determine the preservation conditions of shale more accurately.

Combined with the typical well-crossing profile, the gas-rich structure type in the study area is mainly a negative structure. Meanwhile, the burial depth of the Longmaxi shale in the study area is generally less than 2500 m, which belongs to the medium-shallow shale gas. The anticline structure is developed with a high-angle transnatural reverse fault, and the syncline side is exposed above the surface, which easily communicates with the surface water and atmosphere. This results in the exchange of shale fluid and gas components with the surface of the Longmaxi Formation. For the deeply buried section in the middle of the negative structure, a local strong retention environment may be developed, which is conducive to the preservation of shale gas.

Through the analysis of formation water and gas sources and structural differences in a single well in different well profiles, the advantages and disadvantages of preservation conditions are analyzed. The SY1 well is located in the south of the NW wing of the YanwukouI syncline and is only 0.5 km away from the F1 reverse fault. Influenced by the F1 fault, the fault has a NE strike (see Figure 4), breaks through the NW wing of the syncline and directly communicates with the surface upward. The fault dip angle is above 75°. The fault is poorly sealed, and the formation water analysis is of the heavy sodium carbonate type with low metamorphism. The nitrogen content in the gas components accounts for more than 75% of the total gas components, and the carbon dioxide content is also high. Meanwhile, the gas source detection and analysis results show that this portion of nitrogen and carbon dioxide is of atmospheric origin, and the gas content of shale is between 0.34 m^3/t and 0.96 m^3/t. The average content is 0.58 m^3/t, indicating poor preservation conditions of shale gas. Well SY5 is located in the middle of the northwest wing of the Yanwukou syncline; the burial depth of the Longmaxi shale is approximately 1200 m, and the two wings of the syncline are modified by the F1 fault and F3 fault. The single well spacing between the F1 and F3 faults is 3087 m and 828 m, respectively, and the fault dip angle is high. The formation water's salinity is above 2000 mg/L, and the formation water type is calcium chloride type, with high magnesium chloride and calcium magnesium coefficients, indicating that the formation water has experienced long-time retention and weak exchange with the outside world and surface water. The total content of alkanes in the gas components is above 90%, mainly methane gas, with a small amount of nitrogen and carbon dioxide. Hydrocarbon gas sources were detected as oil-type cracking gas, while nonhydrocarbon gas sources showed that the total nitrogen in the well was produced by the ammoniation of organic matter in the overmature stage, and carbon dioxide gas was also an organic hydrocarbon source. The gas content detection results indicated that the Silurian Longmaxi shale was 0.67 m^3/t ~2.58 m^3/t, and the Longmaxi shale was 0. The average content is 2.04 m^3/t. Compared with the shale gas drilling in the study area, the shale gas content in this well is the highest, and all of them are organic hydrocarbon generation sources, indicating good preservation conditions.

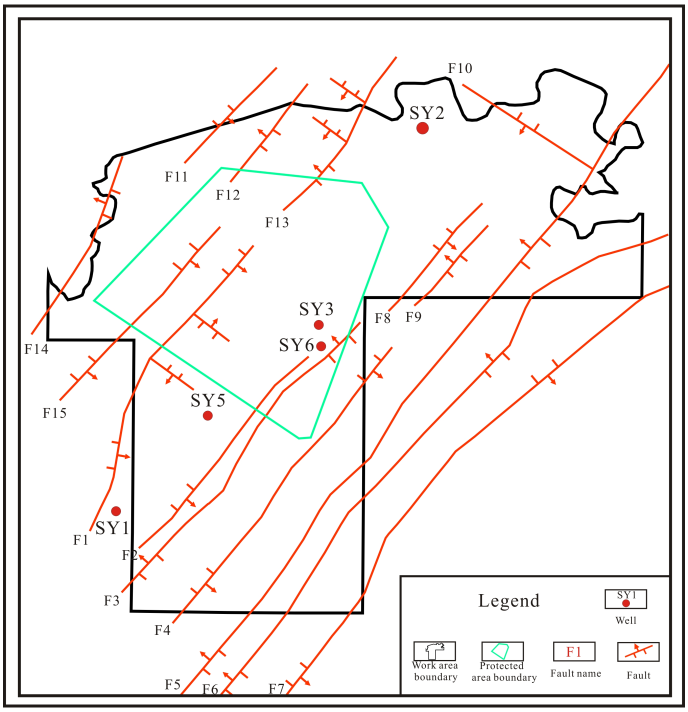

Figure 4. Distribution of faults on the top surface of Longmaxi Formation in Sangzhi area.

Well SY3 and well SY6 are located in similar structural positions. The depth of the Longmaxi Formation in well SY3 is approximately 2000 m, and the distance from fault F3 is 758 m and that from fault F1 is 347 m. The formation water is highly mineralized, and the formation water type is the calcium chloride type, featuring a high magnesium chloride coefficient and calcium magnesium coefficient and a low desulfurization coefficient and sodium chloride coefficient. The gas components are mainly alkanes, accounting for more than 93% of the total gas content, and the nonhydrocarbon gas content is low. The gas source test results show that nitrogen and carbon dioxide are the products of hydrocarbon generation by organic pyrolysis. The gas content test results of the Longmaxi Formation shale in a single well show that the gas content of shale is between 0.72~2.84 cm^3/g, with an average content of 1.88 cm^3/g, indicating excellent preservation conditions. However, the Longmaxi Formation shale of Well SY3 has a burial depth of approximately 2400 m and is located in the hedge structure controlled by the F1 and F3 faults, 315 m away from the F3 fault and 3798 m away from the F1 fault. The analysis results of the formation water of the Longmaxi Formation shale in this well show that there are two types of formation water: sodium bicarbonate and calcium chloride. Among the gas components, the content of methane gas is between 8.2% and 94.2%. The nonhydrocarbon gas components are mainly nitrogen, and the content of carbon dioxide is also high. The gas source detection results of nitrogen and carbon dioxide show that both nitrogen and carbon dioxide have gas sources and hydrocarbon sources generated by organic pyrolysis. The gas content of shale in well SY6 is 0.48 cm^3/g~2.58 cm^3/g, and the average value is 1.33 cm^3/g. Compared with the gas content difference and gas source detection results of well SY3 and well SY6, the two wells have similar structural positions, and the stratum burial depth of well SY3 is larger. However, due to the close distance to the F3 fault and the strong surface communication ability of the F3 fault, there is a certain degree of exchange between strata and surface water, resulting in the low gas content of shale in the SY3 well and the presence of nitrogen and carbon dioxide gas as gas source components, indicating that the preservation conditions are slightly poor.

7 Conclusion

(1) There are two types of water, sodium bicarbonate and calcium chloride, in the Wufeng–Longmaxi shale in the Sangzhi area of Hubei Province. The Longmaxi Formation water in wells SY3 and SY5 is characterized by high salinity, a high calcium magnesium coefficient, a high magnesium chloride coefficient, a high desulfurization coefficient and a low sodium chloride coefficient. It is mainly $CaCl_2$-type water, indicating a strong retention degree and high metamorphism degree of formation water. Longmaxi Formation shale water in well SY1 has the characteristics of low salinity, low desulfurization coefficient, low calcium magnesium coefficient and high sodium chloride coefficient. It is characterized by $NaHCO_3$-type water, indicating strong communication and exchange between strata and surface water, and the SY6 well has two types of water, including $NaHCO_3$-type water and $CaCl_2$-type water.

(2) The $\delta^{13}C$ of hydrocarbon components in the Longmaxi shale in the Sangzhi area is between −39.3‰and −34.7‰, which belongs to oil cracking gas. The $\delta^{15}N$ of nonhydrocarbon gas components in nitrogen is between −9.2‰and 0‰, and the $\delta^{13}C$

of carbon dioxide gas is between 2.9‰and 16.6‰, indicating that nonhydrocarbon gas components include large gas sources and organic ammoniation sources. indicating that nonhydrocarbon gas components include large gas sources and organic ammoniation sources. Wells SY3 and SY5 have low nitrogen and carbon dioxide contents, which are caused by the pyrolysis of organic matter. Well SY1 has high carbon dioxide and nitrogen contents, with $\delta^{13}C$ between 2.9‰and 6.5‰, and ^{15}N in nitrogen is 0‰, which is mainly from atmospheric sources. Nitrogen and carbon dioxide in well SY6 include two major gas sources and hydrocarbon sources generated by the pyrolysis of organic matter.

(3) The gas-bearing capacity of the Longmaxi shale in the syncline area of the study area is jointly controlled by the F1 and F3 faults, with large dips of faults, relatively shallow strata burial, low positive pressure of the cross section, strong communication between shale and surface in the area close to the fault, high exchange rate of formation water and gas components, development of sodium bicarbonate-type water, poor preservation conditions and low development degree of the central fault held by the two faults. The shilling–surface communication ability is weak; the formation water is in a state of strong retention, and the development of $CaCl_2$-type water and preservation conditions are good.

Data Availability Statement

Data will be made available on request.

Funding

This work was supported without any funding.

Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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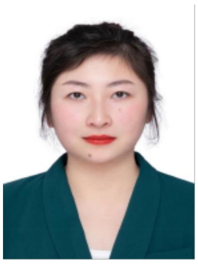

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