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Natural Gas Geochemistry of Jurassic Shaximiao Formation in the Western Sichuan Basin, China: Fault-Controlled Differentiation in Accumulation Process

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The Jurassic Shaximiao Formation in western Sichuan has made significant contributions to the natural gas reserves and production of China, with many gas fields successively discovered. The accumulation evolution progress and discrepant gathering law are continuously improved with the constantly deepened exploration and development. In order to find evidence for the difference in gas accumulation and the method to reshape the migration and accumulation of natural gas and their dynamic processes based on time and space, this study analyzes the dynamic accumulation process of the Middle Jurassic Shaximiao reservoir in the Zhongjiang gas field using the geochemical parameters, including the conventional composition of natural gas, light hydrocarbon components, carbon isotope, and formation water, of more than 160 natural gas samples from 155 wells. The results show that the natural gas-filling period, migration patterns, and phase state, etc., of the Shaximiao Formation are closely related to the distance between the hydrocarbon source faults. The geochemistry tracer parameters of natural gas and formation water reveal abundant information about the accumulation process. The Sha-3 gas reservoir, featuring a two-period hydrocarbon supply, has two migration patterns, i.e., seepage and diffusion, dominated by the water-soluble phase. Similarly, the Sha-2 gas reservoir, featuring a late single hydrocarbon supply, has the same migration patterns, dominated by the miscible phase of the water-soluble phase and free phase. The main migration pattern of the Sha-1 reservoir, which features a late single hydrocarbon supply, is seepage, dominated by the free phase. From the lower part of the Sand-3 gas reservoir to the upper part of the Sha-1 gas reservoir, the natural gas exhibits a trend where the early–late continuous filling turns into the late single filling, the lateral migration distance of oil and gas becomes shorter gradually, and the gas-rich range of the gas reservoir decreases gradually. The results of this study can provide a valuable reference for gas reservoirs controlled by faults and river sand bodies.

Keywords: geochemical tracing, dynamic process of hydrocarbon accumulation, Shaximiao formation, Zhongjiang gas field, Sichuan basin

1 INTRODUCTION

The Sichuan Basin is one of the major gas-bearing basins in China and has wide influence over the exploration and development of the Jurassic tight sandstone natural gas. In recent years, great achievements have been made in the exploration and development of narrow channel tight sandstone gas reservoirs in the Shaximiao Formation of the Zhongjiang gas field. Industrial capacity has been realized in eleven sand groups of JS_1^{1}~JS_3^{3-3}, and large-scale gas fields have been built, leading to beneficial development (Li et al., 2016). The gas reservoir of the Shaximu Formation in the study area is dominated by fault-controlled accumulation, with the good distribution of favorable hydrocarbon faults and channel sand bodies as sufficient and necessary conditions. Previous research has summarized the geological characteristics of the Shaximiao Formation accumulation in the Zhongjiang gas field, such as "retiform hydrocarbon supply, broken sand dredging, and efficient migration." However, the existing producing tests have revealed that the gas accumulation range of the Shaximiao reservoir is significantly different from the individual well deliverability, indicating that the gas accumulation range decreases vertically from bottom to top, and that the average individual well deliverability of the lower Shaximiao Formation is higher than that of the upper Shaximiao Formation.

Extensive research has been conducted on the origin, source, and geochemical characteristics of the Jurassic natural gas in the western Sichuan depression. However, the geochemical characteristics of natural gas and formation water in the study area are relatively complex (Shen et al., 2008; Wang et al., 2011; Zhu et al., 2011; Zhou et al., 2016; Wang LH. et al., 2017). The study on the maturity of the Jurassic natural gas in the middle section of the western Sichuan depression shows that the maturity of natural gas gradually increases from bottom to top, and that the natural gas of the Shaximiao Formation has the characteristics of pyrolysis gas (Zhu et al., 2011). The natural gas of the Shaximiao Formation in the Zhongjiang area is dominated by hydrocarbon gas, containing a small amount of non-hydrocarbon gas, which is coal-type gas from the pyrolysis of humic kerogen, with the hydrocarbon source rocks of the fifth member of the Xujiahe Formation as its main source (Wang et al., 2017). Wang et al. (2015) analyzed the mechanism of tracing the gas migration by geochemistry indexes of the Jurassic natural gas in the western Sichuan depression and its effectiveness. Meanwhile, they considered that the CH_4 content would rise with the increase of the migration distance in different migration phases and was the most effective tracer indicator of gas migration directions (Wang P. et al., 2017). Ye et al. (2017a) carried out a study on the organic–inorganic geochemistry tracer of natural gas migration in the Jurassic gas reservoirs in the western Sichuan Basin. They considered that the migration phase of the Middle-Jurassic natural gas in the western Sichuan depression was dominated by a water-soluble phase and featured low-salinity formation water associated with the gas reservoir, light isotopic composition of carbon and oxygen of authigenous calcite in gas-bearing sandstones, and high homogenization temperature and low salinity of brine inclusion containing hydrocarbon. After that, they presented the organic–inorganic geochemical tracer indexes, with which the migration directions and paths of the Jurassic natural gas in the western Sichuan depression were effectively determined (Ye et al., 2017b). Previous studies seldom focused on the reshaping of the dynamic accumulation progress and migration patterns of the natural gas in the Shaximiao reservoir of the Zhongjiang gas field based on time and space because the main difficulty is the unknown accumulation process and rule of differential accumulation (Chen et al., 2014; Li et al., 2017; Liu et al., 2017).

On the basis of previous studies, this study used the geochemistry tracers, including conventional natural gas components (C_1/C_2), light hydrocarbon components (iC_4/nC_4 values), methane carbon isotopes ($\delta^{13}C_1$ values), formation water salinity (TDS), and Na/K ratio, to emphatically analyze the relationship among the aforementioned characteristic parameters, the distance from the hydrocarbon source fault to the accumulation regularity through the analysis of the geochemical characteristics of the Shaximiao Formation, and the geological characteristics of its accumulation. This study discussed the natural gas-filling periods, migration patterns and phases, and the dynamic evolution characteristics of the accumulation in the Sha-3, Sha-2, and Sha-1 reservoirs, respectively, and explored the dynamic accumulation progress of the Shaximiao Formation in the Zhongjiang gas field and its control on the difference in accumulation. The geological evolution progress of the dynamic accumulation of the Shaximiao gas reservoir regarding time and space was reshaped into different migration patterns, multi-period hydrocarbon supplies, and differential accumulation in various accumulation periods, providing a reference for the exploration and development of blocks with the same geological background.

2 GEOLOGICAL BACKGROUND

The Zhongjiang gas field (**Figure 1**), situated on the eastern slope in the middle part of the western Sichuan depression, Sichuan Basin, is bounded by the Zitong sag to the north, the Xiaoquan-Xinchang tectonic belt and Chengdu sag to the west, the Zhongxingchang syncline to the south, and the Jinhuachang tectonics in the middle of the Sichuan ancient uplift to the east. Generally, it features a structure of three uplifts and two sags, including the Gaomiao-Fenggu tectonic belt, the Hexingchang-Zhixinchang-Shiquanchang tectonic belt, the Zhongjiang-Huilong-Fuxing tectonic belt, the Yongtai syncline, and the Zhongxingchang syncline. Meanwhile, the faults of F2, F3, F6, and F14 in the west of the gas field developed downward to the Xujiahe Formation, which played an important role in the accumulation of the Shamiaoxi Formation. Based on the matching relationship between the active period of the faults and the accumulation time of the gas, the faults can be classified as early faults, late faults, and persistently active faults. The strata in the area are Quaternary, Tertiary, Cretaceous, the thick Jurassic, and upper Triassic, respectively, from the upper part to the lower part. The Penglaizhen and Shaximiao Formations in the Jurassic are the main oil–gas exploration strata with thick

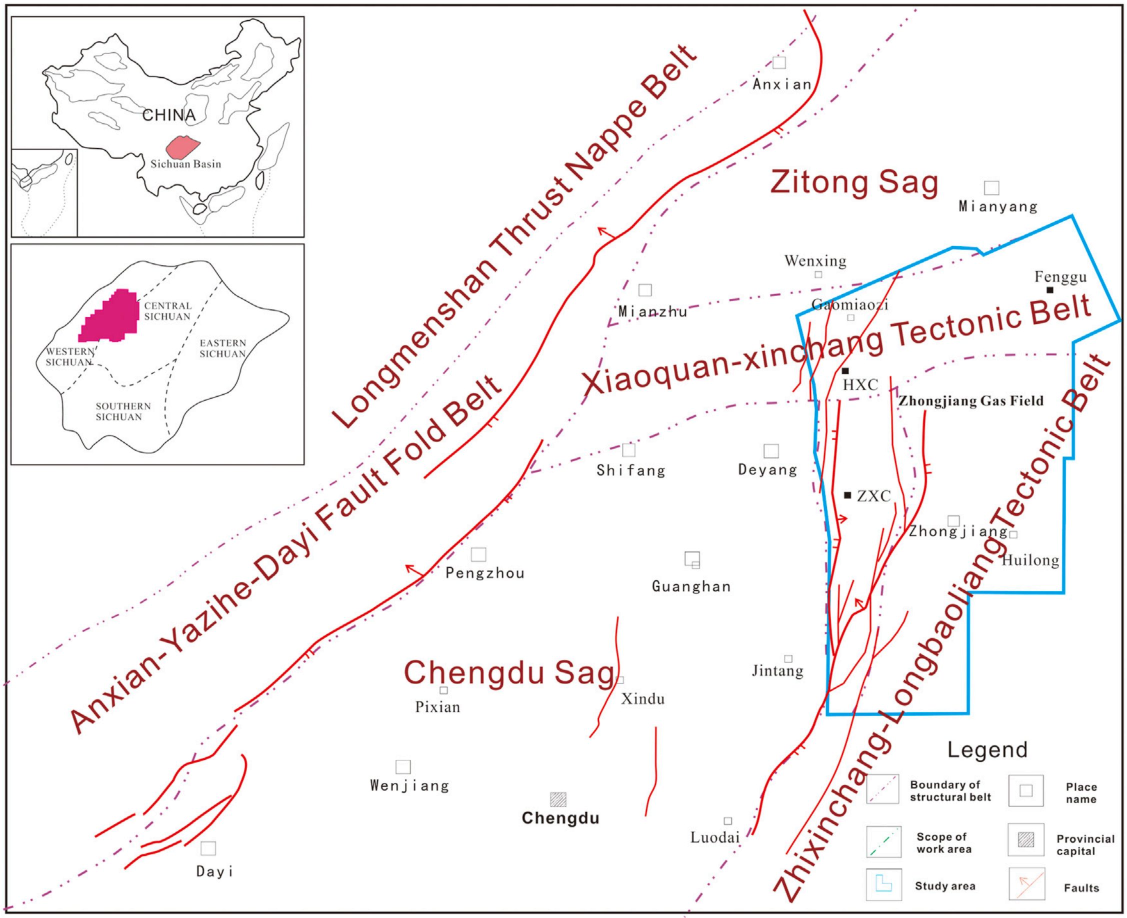

FIGURE 1 | Location of the Sichuan Basin and research area in the western Sichuan depression.

sand bodies and good gas reservations. According to the principle of high-resolution sequence stratigraphy (Fredrik Bockejtr, 1991; Johannessen et al., 1996), the Shaximiao Formation can be divided into the Upper Shaximiao Formation and the Lower Shaximiao Formation, of which the latter can be further divided into three sections, i.e., Sha-3, Sha-2, and Sha-1, from the lower part to the upper part (**Figure 2**).

The gas reservoir of the Shaximiao Formation in the area, far from the sources, typically features generation in the lower part and storage in the upper part, with gas mainly from the dark mudstone in the fifth member of the Xujiahe Formation of the underlying upper Triassic (Shen et al., 2008; Wang et al., 2011; Zhu et al., 2011; Zhou et al., 2016; Wang LH. Et al., 2017; Yuan et al., 2018). The Shaximiao Formation developed a shallow-water delta sedimentary system and a favorable sedimentary microfacies of delta underwater distributary channel, with multi-stage-channel superimposed sand bodies developed, which is generally NNE spread. The reservoir of the Shaximiao Formation is a tight reservoir with low porosity and permeability and has an average porosity of 8.3% and an average permeability of 0.1 mD. The reservoir is porous and has its porosity and permeability well correlated with each other. The Sha-3, Sha-2, and Sha-1 gas reservoirs were developed from the lower part to the upper part. Among them, the Sha-1 reservoir has the highest porosity, with an average value of 9.8% and a median value of 10.15%, while the Sha-3 reservoir has the highest permeability, with an average value of 0.234 mD. The storage space mainly consists of residual intergranular pores and intergranular dissolved pores, followed by intragranular dissolved pores.

The overlying Suining Formation is a regional cap rock with good quality in the western area of the Sichuan Basin and is dominated by mudstone sediment. In addition, the interchannel mudstone developed in the Shaximiao Formation plays a role of a direct cap rock in the underlying sand bodies. These regional direct cap rocks have effectively preserved the natural gas. The formation water has high salinity and is $CaCl_2$ type, which indicates that the condition of the study area has been well preserved.

3 SAMPLING AND METHODOLOGY

3.1 Sampling

For this study, 155 natural gas samples of the Shahejie Formation were, respectively, collected from 155 wells located in the study area (**Figure 3**). Multiple approaches, including composition

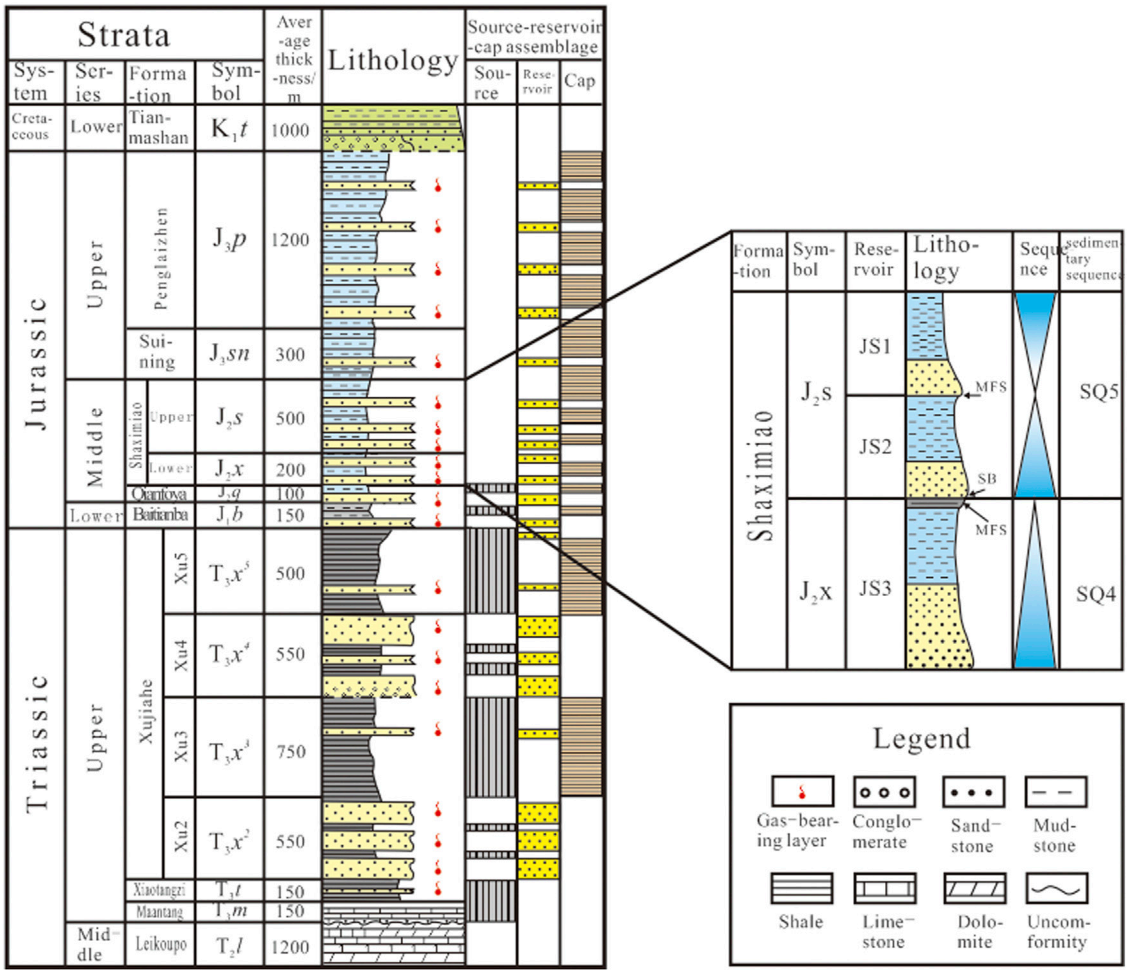

FIGURE 2 | Upper Triassic–Cretaceous stratigraphy and source–reservoir–cap rock combination in the Zhongjiang gas field.

analysis and stable carbon isotope measurements, were applied to the geochemical characterization of the natural gas samples. Seventy-four copies of data of formation water salinity were collected from the database of the Exploration & Development Institute of SINOPEC Southwest Oil & Gas Company, Chengdu, Sichuan.

3.2 Analytical Methods

The natural gas compositions were measured using an Agilent 6890N gas chromatograph (GC) equipped with a flame ionization detector. The gas components were separated from each other using a capillary column (Plot Al_2O_3 50 m × 0.53 mm). The GC oven temperature was initially set to 40°C and maintained for 7 min and then heated to 180°C by 10°C/min. The analysis complied with SY/T 0542-2008 Components of natural gasoline analysis—Gas chromatography method under the Chinese Oil and Gas Industry Standard.

The stable carbon isotope values in the natural gas were measured using a Thermo Delta V mass spectrometer (MS) equipped with an Agilent 6890NGC. The natural gas components were separated from each other using a fused silica capillary column (Plot Q 30 m × 0.32 mm) on a GC, converted into CO_2 in a combustion interface, and then introduced to the MS. The GC oven temperature was ramped from 35 to 80°C by 8°C/min, then increased to 260 °C by 5°C/min, and maintained for 10 min. The natural gas samples were analyzed in triplicate. The stable carbon isotopic values were reported in δ notation per mil (‰) relative to the VPDB standard. The analytical precision is within ±0.3‰ of the VPDB standard (Li et al., 2003).

4 RESULTS

4.1 Geochemical Characteristics of Natural Gas

According to the analysis data of the samples, the natural gas in the Shaximiao Formation is dominated by methane, which accounts for more than 90%, featuring high content of methane, low content of heavy hydrocarbon, nitrogen, and carbon dioxide and no hydrogen sulfide (**Table 1**).

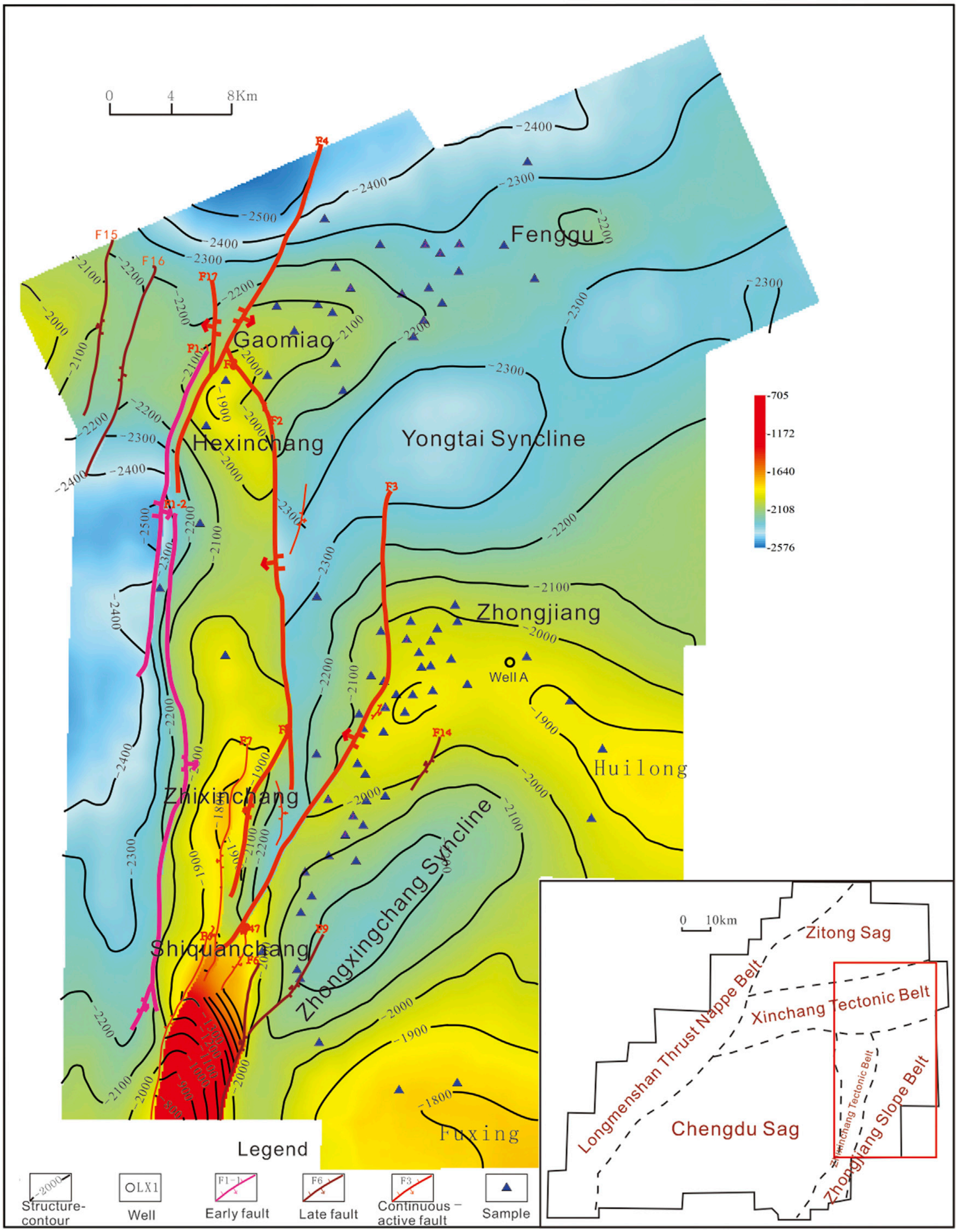

FIGURE 3 | Top structure map of the Shaximiao Formation in the Zhongjiang gas field.

4.1.1 Characteristics of the Conventional Component

The C_1/C_2 values of the samples are between 10.75 and 39.07. Among them, the C_1/C_2 values of the Sha-3 gas reservoirs are lower than those of the Sha-2 and Sha-1 gas reservoirs, and thus it demonstrates an ascending trend of C_1/C_2 values and maturity from the lower part to the upper part. The cross plot of the C_1/C_2

TABLE 1 | Natural gas composition and the carbon isotopic composition of methane in the Middle Jurassic Shaximiao Formation in the Zhongjiang gas field.

Stra	Reservoir	CH_4 (%)	C_2H_6 (%)	C_1/C_2	iC_4/nC_4	CO_2 (%)	N_2 (%)	δ^{13} C_1 (‰)
J_2s	JS1	85.99–94.31 92.08 (34)	2.23–5.85 4.23 (34)	14.89–38.63 22.66 (34)	0.88–1.50 1.05 (34)	0–3.19 0.30 (34)	0.41–5.13 1.33 (34)	−37.68~−30.4 −35.46 (7)
	JS2	81.48–95.72 90.91 (45)	1.9–8.68 4.09 (45)	11.57–39.07 24.06 (45)	0.50–1.50 1.06 (45)	0–1.72 0.35 (42)	0.38~3.71 1.5 (34)	−38.6~−34.5 −36.29 (4)
J_2x	JS3	82.31–94.76 91.67 (82)	2.3–8.19 4.74 (82)	10.75–38.65 20.36 (82)	0.75–1.57 1.01 (82)	0–0.9 0.14 (82)	0–4.09 1.06 (78)	−40.54~−34.7 −36.98 (15)

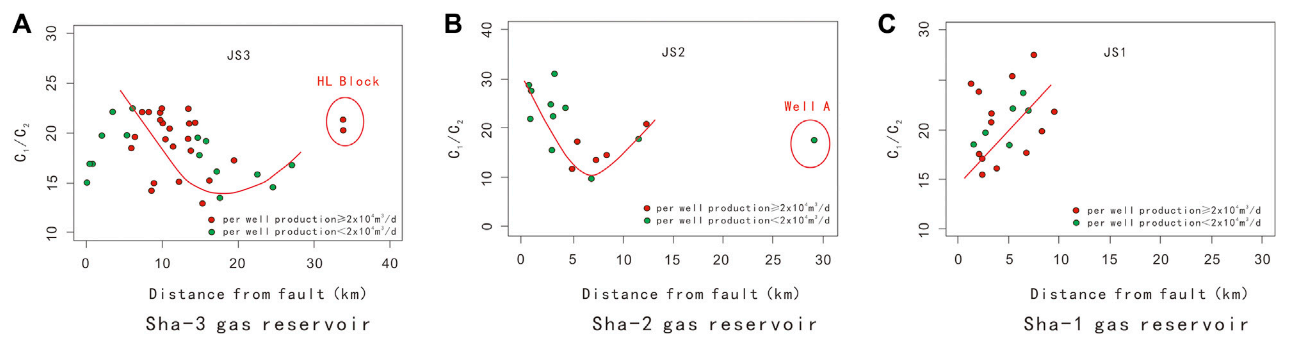

FIGURE 4 | Intersection of natural gas maturity (C_1/C_2) values and distance from the fault in the Shaximiao Formation reservoir, Zhongjiang gas field.

values and the distance from the fault reveal that the C_1/C_2 values of the Sha-3 and Sha-2 gas reservoirs first descend with the increase of the distance from the fault and then showing an opposite trend (**Figures 4A,B**), while the C_1/C_2 values of the Sha-1 gas reservoir ascend with the increase of the distance from the fault (**Figure 4C**).

4.1.2 Characteristics of the Light Hydrocarbon Component

It can be seen that the iC_4/nC_4 values of the samples are distributed between 0.5 and 1.57, and the iC_4/nC_4 values from the Sha-3 gas reservoir to the Sha-1 gas reservoir show an increasing trend (**Table 1**).

4.1.3 Methane Carbon Isotope Composition

The analysis of the isotope composition (δ^{13} C_1 value) of methane carbon in the samples indicates that the δ^{13} C_1 values range from −40.54‰ to −30.4‰, with an average value of −36.5‰. Generally, the δ^{13} C_1 values present a trend of being heavier from the lower part to the upper part (**Table 1**).

4.2 Formation Water Chemistry Characteristics

According to the analysis data of the samples, the salinity of formation water varies from 0.6 to 90 g/L, mainly including three types:① Type 1: the formation water of high salinity (>30 g/L) and high Na/K value (>200), which is mainly distributed near the faults and has characteristics similar to those of the formation water of the Xujiahe Formation. ② Type 2: the formation water of medium salinity (0–30 g/L) and medium Na/K value (100–200), which presents the characteristics of the original formation water of the mid-Jurassic Shaximiao Formation. ③ Type 3: the formation water of low salinity (<10 g/L) and low Na/K value (>2,100), which has the characteristics of condensate water (**Figure 5**).

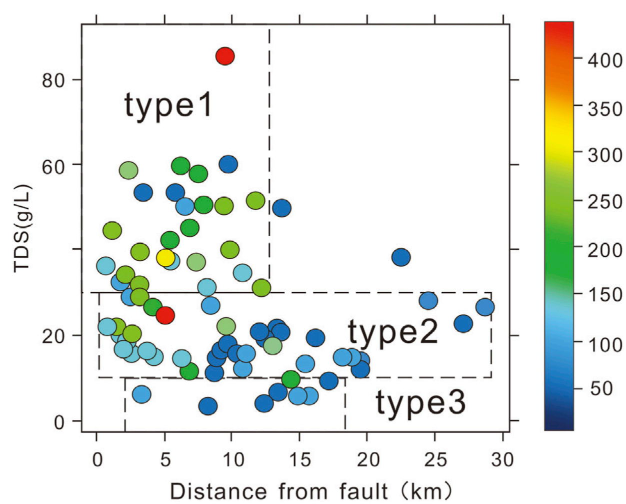

FIGURE 5 | Intersection of formation water salinity value, Na/K value, and distance from the fault in the Middle Jurassic Shaximiao Formation in the Zhongjiang gas field.

5 DISCUSSION

For the analysis of the dynamic accumulation process of natural gas, previous researchers have carried out a lot of studies based on the geochemical characteristics of natural gas and established a geochemical tracer system of the natural gas accumulation process (Liu et al., 2005; Liu et al., 2007; Chen et al., 2008; Luo et al., 2009; Cao et al., 2018; Yang et al., 2019), where the geochemical indexes, including CH_4 content, N_2 content, C_1/C_2 value, iC_4/nC_4 value, and $\delta^{13}C_1$ value, are widely used, demonstrating relatively good performance. Meanwhile, previous studies have found that the chemical characteristics of formation water can provide solid guidance for the determination of the path and direction of oil and gas migration and accumulation (Liu et al., 2007; Lou et al., 2009; Luders et al., 2012; Ye et al., 2014; Wang P. et al., 2017; Lin et al., 2017; Liu et al., 2018). This study adopted the geochemistry tracer parameters of natural gas, including conventional components (C_1/C_2 value), light hydrocarbon components (iC_4/nC_4 value), methane carbon isotopes ($\delta^{13}C_1$ value), formation water salinity (TDS), and Na/K value, to emphatically analyze the relationship between the aforementioned characteristic parameters, and the distance from the hydrocarbon resource faults, in order to reveal the natural gas-filling periods, migration patterns and phases, and dynamic evolution characteristics of accumulation in the Sha-3, Sha-2, and Sha-1 gas reservoirs. The aforementioned geochemical analysis data used in this study can represent the overall situation of the Jurassic Shaximiao Formation gas reservoirs in the study area.

5.1 Natural Gas-Filling Periods

Among the natural gas geochemistry parameters (Qin et al., 2006; Xu et al., 2017; Qin et al., 2018), the C_1/C_2 values go up with the increase of maturity or migration distance (Ye et al., 2017a), while the iC_4/nC_4 values go down with the increase of maturity but rise with the increase of migration distance in the case of loose reservoirs. However, they descend with the increase of migration distance in the case of tight reservoirs (Li et al., 2002; Zhang et al., 2022a). In addition, $\delta^{13}C_1$ values rise with the increase of maturity (Liu et al., 2007; Liu et al., 2007; Liu, 2021). These three parameters can reflect the maturity and migration patterns of natural gas and further reflect the natural gas-filling periods (Li et al., 2011).

It can be seen that the relationship between the C_1/C_2 values of the Sha-3 reservoir and the distance from the fault features two stages (**Figure 4A**). When the distance from the fault is less than 15 km, the C_1/C_2 values of natural gas are mainly affected by maturity and little by migration fractionation. As the migration distance increases, the C_1/C_2 values of natural gas descend, indicating that the early low-maturity natural gas and late high-maturity natural gas continuously supply hydrocarbon. The early low-maturity natural gas was first filled and always in the front of the migration direction, while the late high-maturity natural gas was subsequently filled and located on the side of the adjacent fault. When the distance from the fault is more than 15 km, the effect of migration fractionation gradually increases. Meanwhile, the C_1/C_2 values of natural gas increase and the iC_4/nC_4 values decrease as the migration distance increases. There are two possible reasons why the C_1/C_2 and iC_4/nC_4 values of natural gas are higher in the Huilong region. One is that the reservoir is loose, which leads to the increase of the C_1/C_2 and iC_4/nC_4 values along with the increase of migration distance, while the other is that the late fault hydrocarbon supply might exist in the Huilong region, and the natural gas migrated upward fast along the fault, resulting in high values of C_1/C_2 and iC_4/nC_4.

The cross plot between the C_1/C_2 values of the Sha-2 gas reservoir and the distance from the fault also features two stages (**Figure 4B**). When the distance from the fault is less than 5 km, the C_1/C_2 values of natural gas are mainly affected by maturity and little by migration fractionation. As the migration distance increases, the C_1/C_2 values of natural gas decrease, indicating that the early low-maturity natural gas and late high-maturity natural gas continuously supply hydrocarbon. The early low-maturity natural gas was first filled and always in the front of the migration direction, while the high-maturity natural gas was subsequently filled and located on the side of the adjacent fault. When the distance from the fault is more than 5 km, the effect of migration fractionation gradually increases. Meanwhile, the C_1/C_2 values of natural gas increase and the iC_4/nC_4 values decrease as the migration distance increases. The natural gas of Zhongjiang Gas Field Well A has medium C_1/C_2 values and high iC_4/nC_4 values, indicating that it may come from the hydrocarbon supplied by the F14 fault in the late stage.

It can be seen that the Sha-1 reservoir overall presents contemporaneous accumulation and is dominated by late natural gas of higher maturity (**Figure 4C**). Natural gas is greatly affected by migration, and the C_1/C_2 values of natural gas increase and the iC4/nC4 values decrease as the migration distance increases. Meanwhile, a small amount of late high-maturity natural gas could be found near the late active fault.

Generally, the Sha-3 and Sha-2 gas reservoirs both feature two-stage hydrocarbon supplies and accumulation, while the Sha-1 reservoirs feature late contemporaneous accumulation. In addition, the geochemical evidence, high salinity, and Na/K value of the formation water near the fault also indicate that the Shaximiao Formation gas reservoir features late hydrocarbon supplies. The original formation water of the Xujiahe Formation has high salinity and Na/K values, while the associated water of early hydrocarbon-generating gas reservoirs in the Xujiahe Formation usually has low salinity. According to the cross plot of formation water salinity, Na/K value, and the distance from the fault, the salinity and Na/K value of the formation water in the Shaximiao Formation gas reservoir are negatively correlated with the distance from the fault, which is mainly surrounded by late formation water of the Xujiahe Formation, featuring late high salinity and Na/K values (**Figure 5**).

5.2 Migration Pattern of Natural Gas

It can be seen that the iC_4/nC_4 values of the Sha-3 and Sha-2 gas reservoirs are mainly distributed around 1 (**Figures 6A,B**) and the iC4/nC_4 values of the Sha-1 reservoir are mainly distributed above 1 (**Figure 6C**), indicating that the Sha-3 and Sha-2 gas reservoirs have two migration patterns, i.e., vertical seepage and

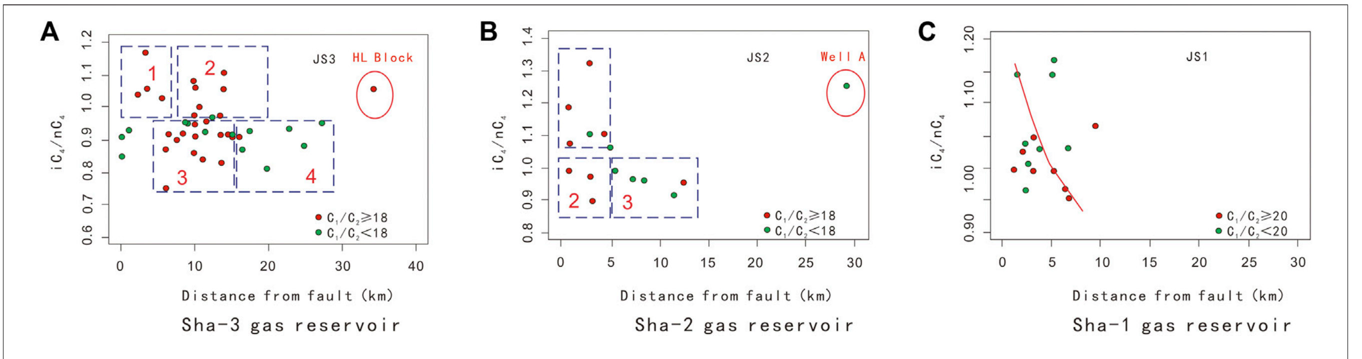

FIGURE 6 | Intersection of natural gas iC_4/nC_4 values and distance from fault in the Shaximiao Formation reservoir, Zhongjiang gas field.

lateral diffusion, while the main migration pattern of the Sha-1 reservoir is vertical seepage (Sima et al., 2017).

The Sha-3 reservoir has two migration patterns, seepage and diffusion, and two types of natural gas, low-maturity and high-maturity. Therefore, it can be divided into four types of combinations based on different migration patterns and maturity: the first one is late relatively high-maturity natural gas, which has higher values of C_1/C_2 and iC_4/nC_4, with the lateral migration distance less than 5 km; the second one is the mixture of late high-maturity natural gas and early low-maturity natural gas, which has medium-high C_1/C_2 values and high iC_4/nC_4 values, with the lateral migration distance less than 15 km and loose reservoirs; the third one is the mixture of late high-maturity natural gas and early low-maturity natural gas, which has higher C_1/C_2 values and lower iC_4/nC_4 values, with the lateral migration distance less than 15 km and tight reservoirs; the fourth one is early low-maturity natural gas, which has lower values of C_1/C_2 and iC_4/nC_4, with the lateral migration distance more than 15 km and tight reservoirs (**Figure 6A**).

The Sha-2 gas reservoir has two migration patterns, seepage and diffusion, and two types of natural gas, low-maturity and high-maturity. Therefore, it can be divided into three types of combinations based on different migration patterns and maturity: the first one is late relatively high-maturity natural gas, which has higher values of C_1/C_2 and iC_4/nC_4, with the lateral migration distance less than 5 km; the second one is the late high-maturity natural gas, which has higher C_1/C_2 values and lower iC_4/nC_4 values, with the lateral migration distance less than 5 km; the third one is early low-maturity natural gas, which has lower values of C_1/C_2 and iC_4/nC_4, with the lateral migration distance less than 5 km and tight reservoirs (**Figure 6B**).

The Sha-1 reservoir is dominated by the migration pattern of seepage and high-maturity natural gas. Therefore, it can be divided into two types of combinations based on migration patterns and maturity: the first one is late relatively high-maturity natural gas, which has medium-higher C_1/C_2 values and higher iC_4/nC_4 values, with the lateral migration distance between 0 and 10 km; the second one is the late high-maturity natural gas, which has higher C_1/C_2 values and lower iC4/nC4 values, with the lateral migration distance between 0 and 8 km (**Figure 6C**).

5.3 Dynamic Evolution Process of Accumulation

In the first stage, i.e., the early accumulation stage of the Shaximiao reservoir (141-128Ma, J_3-K_1), the source rocks in the fifth and third members of the Xujiahe Formation entered the hydrocarbon expulsion threshold with limited hydrocarbon expulsion and the gas gathering near the source, while the low-maturity natural gas and the associated low-salinity water entered the Sha-3 reservoir first and the Sha-2 gas reservoir partly (**Figure 7A**). In the second stage, i.e., the middle accumulation stage (105-88Ma, J_1-K_2), the source rocks in the Xujiahe Formation entered the period of hydrocarbon expulsion peak with enough hydrocarbon expulsion, and the high-maturity natural gas entered the Sha-3, Sha-2, and Sha-1 reservoirs from the lower part to the upper part along the faults (**Figure 7B**). In the third stage, i.e., the late accumulation stage (83–68Ma, late K_2), the high-maturity natural gas and the high-salinity formation water of the Xujiahe Formation entered the Sha-3, Sha-2, and Sha-1 reservoirs in a hybrid phase state from the lower part to the upper part along the faults (**Figure 7C**).

Therefore, the Shaximiao reservoir in the Zhongjiang gas field shows the characteristics of local enrichment and different accumulation in time and space. The Sha-3 and Sha-2 gas reservoirs have two stages of hydrocarbon supplies with enough hydrocarbon and an extensive range of gas accumulation, in which hydrocarbon is mainly supplied by persistent active faults. The Sha-1 reservoirs only have one stage of late hydrocarbon supplies with relatively sufficient hydrocarbon and a small range of gas accumulation, in which hydrocarbon is mainly supplied by persistent active faults.

From the aforementioned discussion, it can be concluded as follows: the effective hydrocarbon source faults have obvious control over the accumulation of the Jurassic tight sandstone gas reservoirs; the filling and accumulation types of natural gas are obviously different from each other due to accumulation stages, and the fault properties and the distance from the channel sand bodies to the hydrocarbon source faults are closely related to filling efficiency. These conclusions are instructive to similar gas fields in the Sichuan Basin and other basins.

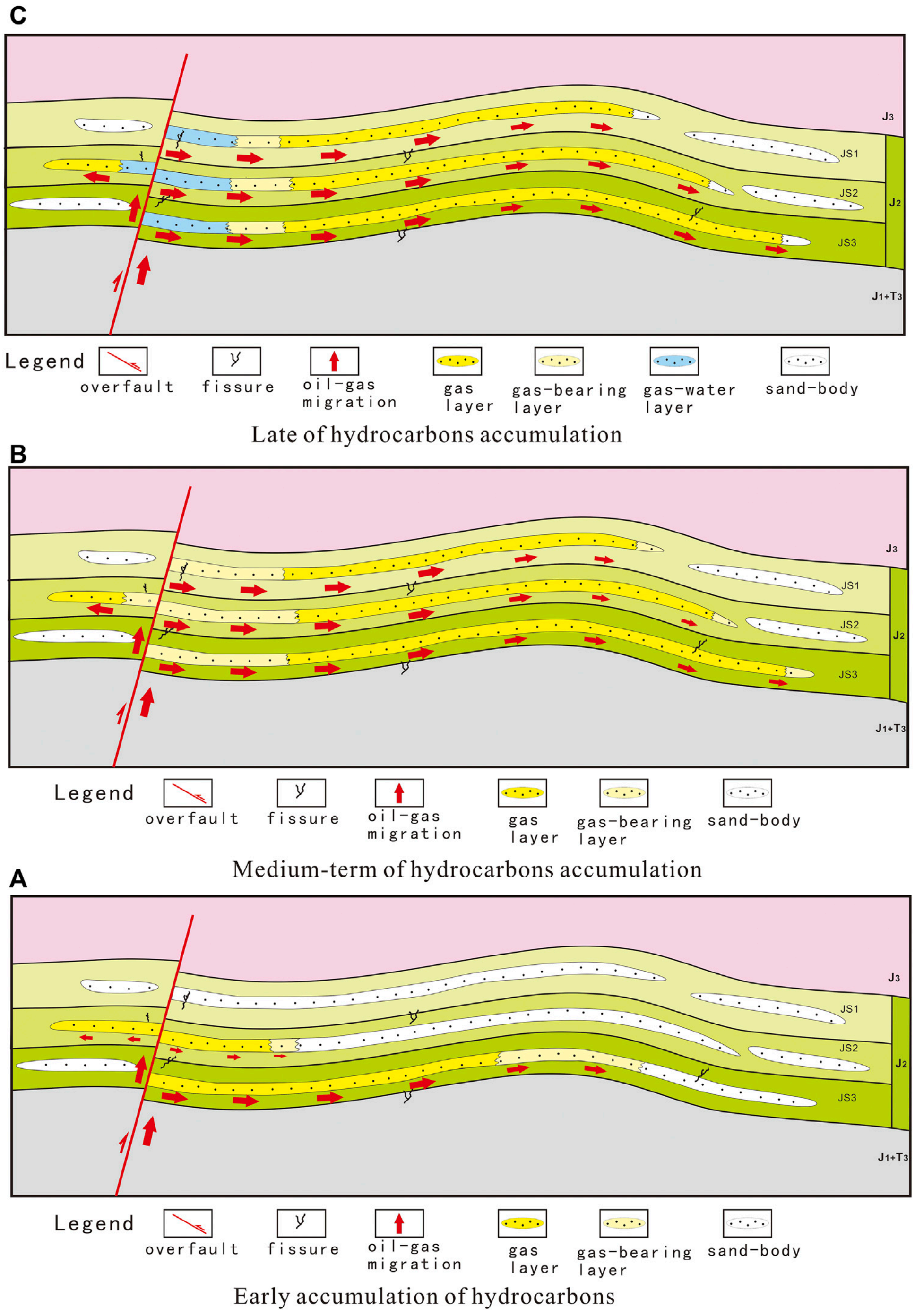

FIGURE 7 | Dynamic model evolution of the Middle Jurassic Shaximiao Formation in the Zhongjiang gas field **(A,B,C)**.

6 CONCLUSION

1) The Sha-3 and Sha-2 gas reservoirs in the Shaximiao Formation of the Zhongjiang gas field feature two stages of hydrocarbon supplies and accumulation, while the Sha-1 reservoir features late single hydrocarbon supplies and contemporaneous accumulation. The salinity and Na/K values of formation water are negatively correlated with the distance from the fault, which is surrounded by formation water of the Xujiahe Formation, featuring late high salinity and Na/K values.
2) The Sha-3 reservoir can be divided into four types of combinations based on its two migration patterns, i.e., seepage and diffusion, and is dominated by the water-

soluble phase. The Sha-2 gas reservoir can be divided into three types of combinations based on its two migration patterns, i.e., seepage and diffusion, and is dominated by the miscible phase of the water-soluble phase and free phase. The Sha-1 reservoir can be divided into two types of combinations based on its main migration pattern, i.e., seepage, and is dominated by the free phase.

3) In the early accumulation stage, the source rocks entered the hydrocarbon expulsion threshold with limited hydrocarbon expulsion and the gas gathering near the source, while the low-maturity natural gas penetrated into the Sha-3 reservoir first and the Sha-2 gas reservoir partially. In the middle-late accumulation stage, the source rocks entered the period of hydrocarbon expulsion peak with sufficient hydrocarbon expulsion, while the high-maturity natural gas and the high-salinity formation water of the Xujiahe Formation penetrated into the Sha-3, Sha-2, and Sha-1 reservoirs in a hybrid phase state from the lower part to the upper part along the faults.
4) From the lower part of the Sha-3 gas reservoir to the upper part of the Sha-1 gas reservoir, the feature of natural gas changes from early-late continuous filling to late single filling, the lateral migration distance of oil and gas gradually becomes shorter, and the gas-rich range of the gas reservoirs gradually decreases.

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 authors.

AUTHOR CONTRIBUTIONS

JD is the first author and corresponding author of this manuscript who contributed to this work his general idea and experiment analysis, geochemical characteristics of the natural gas study, and in charge of discussion and migration pattern of natural gas and dynamic evolution process of accumulation. SL is the second author and corresponding author, who contributed to this work by providing technical guidance, research geological background, and accumulation difference of Shaximiao Formation gas reservoirs. SY is the third author, who contributed to this work by studying and analyzing organic–inorganic geochemical tracer indexes, such as methane carbon isotope composition. Engineer QL is the fourth author, mainly responsible for data statistics and graphics compilation. CW is the fifth author, and his main contributions are experimental samples and analytical method study.

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Conflict of Interest: JD, SL, SY, and QL were employed by the Exploration and Development Research Institute of SINOPEC Southwest Oil and Gas Company.

The remaining author declares 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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