RESEARCH ARTICLE

Hydrocarbon Preservation Conditions and Evaluation of the Maokou Formation in the Leshan-Yibin Area, Southern Sichuan Basin, China

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Abstract

The southern Sichuan Basin is rich in natural gas and is a key area for hydrocarbon exploration. Due to multi-phase tectonic movements, structural characteristics and preservation conditions are critical for gas accumulation. Focusing on the Middle Permian Maokou Formation in the LY area, this study analyzes the regional and local structural framework to assess structural features and their impact on preservation conditions. Using indicators such as deformation intensity, caprock properties, formation water chemistry, and pressure coefficients, an evaluation system is established to identify favorable exploration zones. Results show that the LY area lies in the southern Sichuan low-steep structural belt, dominated by NE- and NWW-trending systems. Structural styles include back-thrust combinations, fault-propagation folds, and pop-up structures. Back-thrust and pop-up structures severely compromise preservation, while fault-propagation folds with small blind faults favor accumulation. Favorable preservation areas are mainly in Ziliujing and Kongtan, characterized by stable geology, thick caprocks, and younger exposed strata, indicating good sealing. Overall, the Maokou Formation exhibits favorable hydrocarbon accumulation conditions.

Keywords: structural characteristics, preservation conditions, Maokou Formation, evaluation system, favorable area optimization, LY area.

1 Introduction

The Sichuan Basin is a large petroliferous basin in southern China, hosting multiple vertically stacked hydrocarbon-bearing assemblages. Each assemblage has its specific distribution range and favorable

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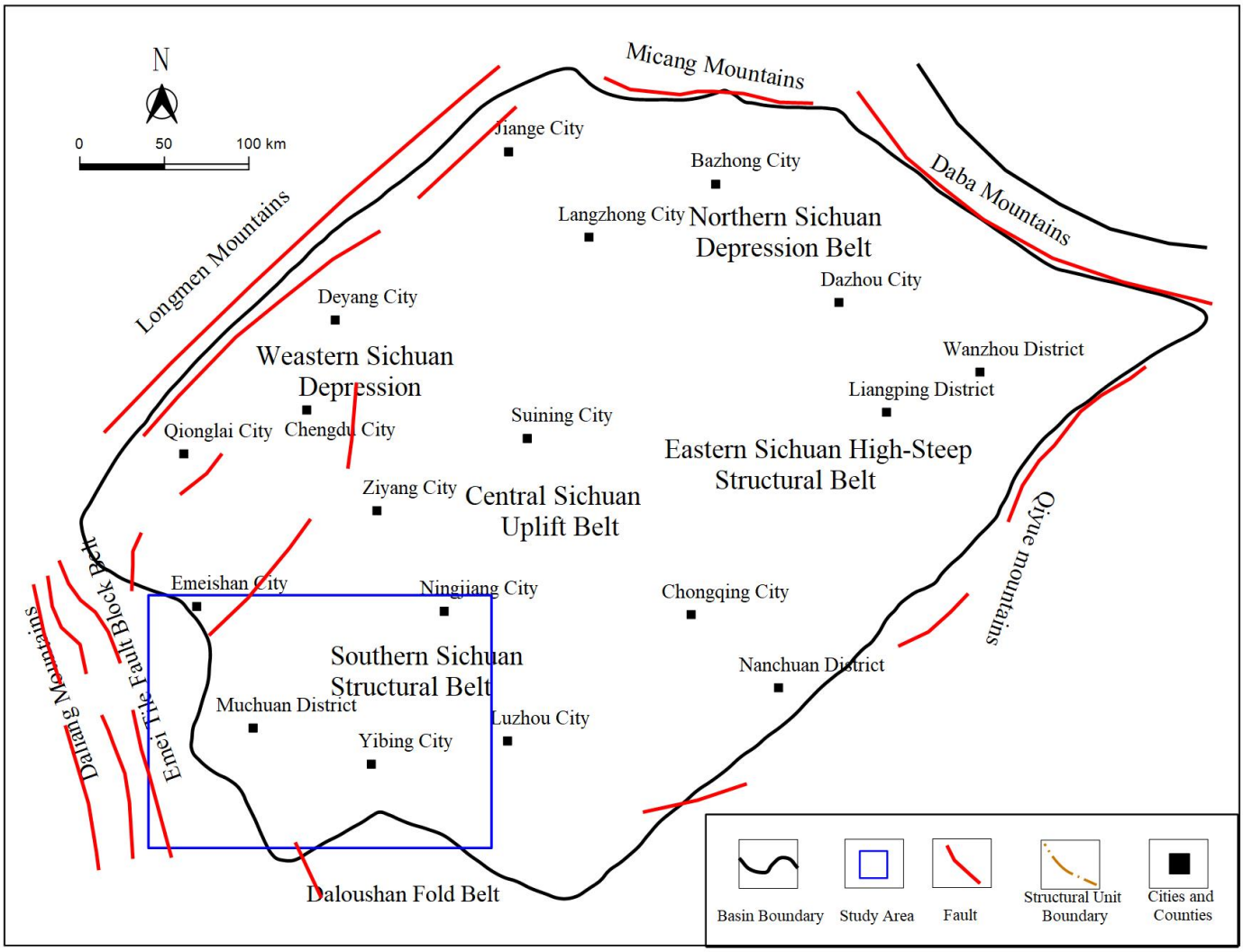

Figure 1. Tectonic location of the study area.

play fairways, demonstrating the basin's substantial hydrocarbon resource potential. The Sichuan Basin developed on the Upper Yangtze Craton and experienced three main Phanerozoic stages: the Sinian to Middle Triassic marine platform stage, the Late Triassic to Eocene foreland basin stage, and the Oligocene to recent tectonic basin stage [1–5]. It is rich in hydrocarbon resources, has a long history of exploration and development, and features multiple sets of source rocks and several source-reservoir-cap assemblages.

The LY area, located in the southern Sichuan Basin, is a key region for hydrocarbon exploration. Among its targets, the Middle Permian Maokou Formation serves as a primary exploration interval in southern Sichuan, possessing favorable conditions for hydrocarbon accumulation [6, 7]. Following more than 50 years of exploration and development, several gas reservoirs have been discovered, including Shengdengshan, Yanggaosi, and Ziliujing, which primarily utilize karst fracture-cavity systems as reservoir spaces. The proven natural gas reserves reach 812×10^8 m^3, with cumulative gas production of 650×10^8 m^3 [8, 9]. These significant exploration achievements demonstrate the excellent exploration and development potential of the Middle Permian Maokou Formation in the southern Sichuan region.

The study area borders the western plunging segment of the Huayingshan fold belt to the north, adjoins the Yunnan-Guizhou Plateau and the Daloushan fault-fold belt to the south, and lies adjacent to the Xianshuihe large strike-slip fault zone to the west. Situated in a region influenced by the superimposition and interaction of different tectonic belts, the structural deformation is exceptionally complex, which significantly controls the gas reservoir distribution and preservation conditions of the Middle Permian Maokou Formation. Conducting further

research on the structural characteristics of the LY area to clarify their impact on hydrocarbon preservation, combined with a comprehensive analysis of the regional hydrocarbon accumulation conditions, is of great importance for guiding future hydrocarbon exploration deployment.

2 Geological Setting

The Sichuan Basin is primarily divided into five tectonic units: the northern Sichuan depression belt, the central Sichuan uplift belt, the western Sichuan depression belt, the eastern Sichuan high-steep structural belt, and the southern Sichuan low-steep structural belt [10, 11]. The LY area is located on the southern margin of the Sichuan Basin and is tectonically positioned within the southern Sichuan low-steep structural belt, where large-scale folds are well developed. This area connects with the Daliangshan and Emei-Washan fault-block belt to the west, borders the Daloushan fold belt to the south, and adjoins the Huayingshan fold belt to the east [12]. Being a zone where different tectonic belts interact and superimpose, the structural deformation in this area is relatively complex (Figure 1).

Two major structural systems are mainly developed in the study area. The first is a NE-trending structural belt, primarily distributed in the Shuanglong-Luochang area in the central part of the study area. This NE-trending system represents the extension of the western plunging segment of the Huayingshan fold belt and exhibits a linear distribution pattern in plan view. The second is a NWW-trending structural belt, typically represented by the northwestern part of the Changning anticline and structures such as Tiangongtang and Wuzhishan in the northwestern region. The morphology of the NWW-trending belt differs significantly from the NE-trending belt. Its formation is mainly controlled by the Xianshuihe fault zone on the western side of southern Sichuan and the Daloushan fold belt to the south.

3 Samples and Methods

This study integrates seismic, well log, and production test data from over 30 exploration wells within the LY area. The methodological workflow consists of three primary components:

3.1 Seismic Interpretation and Structural Analysis

Three-dimensional seismic reflection data covering approximately 8,000 km² were utilized to delineate the structural framework of the Middle Permian Maokou Formation. Key seismic profiles across representative structures (e.g., Wuzhishan, Tiangongtang, and Dengjingguan) were interpreted using Petrel software. Fault geometry, cutting depth, and combination styles were characterized based on seismic reflection terminations and strata deformation patterns to establish the regional structural model.

3.2 Geochemical and Hydrogeological Analysis

Formation water chemistry data, including salinity and ionic composition (Sulin classification), were collected from 20 key wells targeting the Maokou Formation. The relationship between water chemistry parameters and the distance to major faults was analyzed via linear regression to assess stratigraphic sealing integrity. Additionally, pressure coefficient data were compiled from drill stem tests (DST) and well log calculations to evaluate the preservation environment.

3.3 Evaluation System Establishment

A comprehensive evaluation matrix was developed by integrating structural deformation intensity (fault throw and order), caprock thickness distribution (derived from drilling and seismic inversion), exposure strata age, and formation fluid characteristics. Classification thresholds for favorable, moderate, and unfavorable zones were determined by synthesizing regional empirical standards with statistical correlations from well performance data in the study area.

4 Results

4.1 Fault Characteristics

Located on the southern margin of the Sichuan Basin within the southern Sichuan low-steep structural belt, the LY area has undergone multiple phases of tectonic superimposition and reworking, resulting in a complex fault system characterized by distinct orientations, zonation, and stratification. The distribution, cutting depth, and combination patterns of faults not only control the regional structural framework but also profoundly influence the hydrocarbon preservation conditions of the Middle Permian Maokou Formation.

4.2 Fault Distribution Characteristics

Based on seismic interpretation results, faults in the study area exhibit clear directional and zonal characteristics in plan view. Two main fault systems, NE-trending and NWW-trending, are developed and interweave in space to form a complex fault network

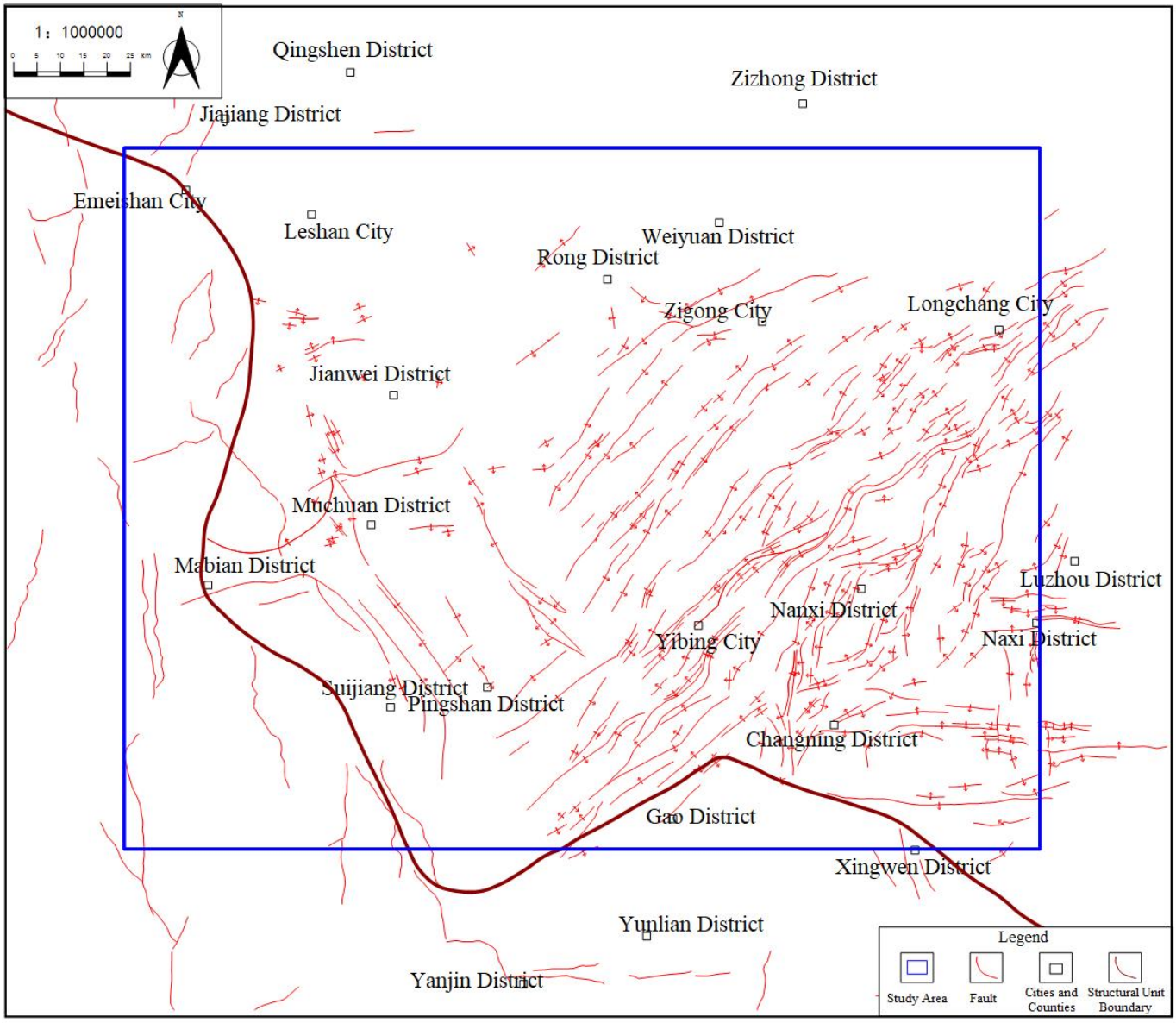

Figure 2. Plan view showing the distribution of Middle Permian faults in the study area.

(Figure 2). The NE-trending fault system is the most developed in the study area and is widely distributed in the Shuanglong-Luochang area in the central part. This system extends northeastward to the western plunging segment of the Huayingshan fold belt and converges southwestward toward the basin margin. The faults in this group display linear to zonal distribution patterns with relatively large scales. Their lengths generally range from 10 to 30 km, with some master faults exceeding 50 km, such as the Ziliujing-Dengjingguan fault belt and the Qingshanling fault belt. In plan view, NE-trending faults are often arranged in parallel or en echelon patterns, with branch faults developing locally and forming broom-shaped or feather-shaped combinations. The formation of this fault group is primarily controlled by compressional tectonics during the Late Mesozoic to Early Cenozoic foreland basin evolution stage, representing the westward structural response of the Huayingshan fold belt. The NWW-trending fault system is mainly developed in the Wuzhishan-Tiangongtang structures in the northwestern part of the study area and the northwestern limb of the Changning anticline in the south, displaying a nearly E-W to NWW orientation. These faults intersect or connect obliquely with the NE-trending faults at high angles. This fault group is relatively smaller in scale, with lengths generally ranging from 5 to 15 km. The faults exhibit discontinuous or lenticular distributions, with dense

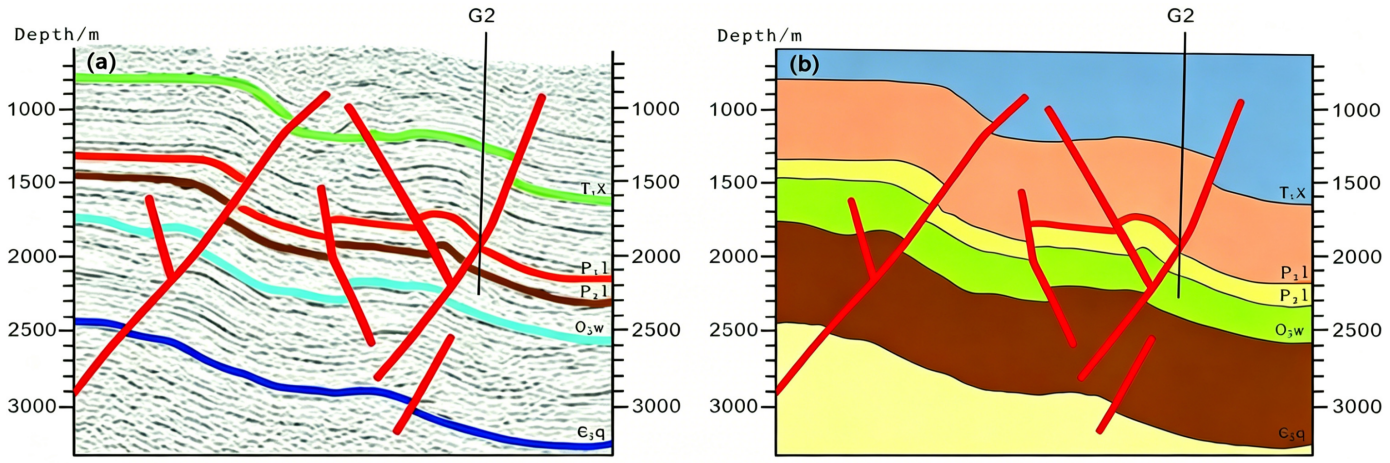

Figure 3. Seismic interpretation (a) and corresponding geological model (b) of back-thrust uplift across the G2 profile.

secondary fault zones developed locally, such as on the southern limb of the Wuzhishan structure and the northern limb of the Tiangongtang structure. The formation of NWW-trending faults is closely related to the combined action of the Xianshuihe strike-slip fault zone on the western basin margin and the Daloushan fault-fold belt on the southern margin, resulting from the basin-margin strike-slip-compressional tectonic stress field.

Interpretation of seismic profiles reveals that fault development in the study area exhibits obvious stratification and heterogeneity in the vertical direction, with significant differences in development intensity, cutting depth, and activity across different structural layers. In the deep structural layer (Sinian to Cambrian), fault development is relatively concentrated and mainly manifested as basement-involved thrust faults with steep fault planes. These faults mostly terminate upward within the Cambrian or at the base of the Ordovician, with some master faults extending upward to the base of the Permian, forming the main body of deep structural deformation. Such faults often exhibit long-term activity and serve as important pathways for transmitting regional tectonic stress to shallower levels. In the middle structural layer (Ordovician to Permian), fault development is most complex and comprises both secondary branches inherited from deep-seated major faults and intraformational detachment faults and accommodation faults. These faults are predominantly characterized by high-angle thrusting or strike-slip-thrusting. The stratigraphic intervals they cut are mainly from the Ordovician Wufeng Formation to the Permian Maokou Formation. Some master faults cut upward through the Triassic Leikoupo Formation or Xujiahe Formation, forming breakthrough faults, such as in the G2 well area of the Tiangongtang structure and the D17 well area of the Dengjingguan structure. These breakthrough faults directly compromise the sealing integrity of the overlying regional anhydrite-bearing caprock and act as primary pathways for hydrocarbon dissipation. In the shallow structural layer (Triassic to Jurassic), fault development is relatively limited. These faults are mostly terminal splays or accommodation faults extending upward from deeper levels and are characterized by small throws and short lengths. Some faults terminate within the Xujiahe Formation without breaching the surface. However, in areas with intense basin-margin tectonics, such as the Wuzhishan structure and the northern limb of the Changning anticline, shallow faults are still relatively well developed and locally form surface rupture zones, reflecting intense tectonic exhumation and uplift.

Overall, the vertical fault development in the study area exhibits a layered characteristic of "concentrated in the deep, complex in the middle, and weakened in the shallow." The cutting depth of faults progressively increases from the basin interior toward the basin margin. Breakthrough faults are mainly developed in the basin-margin structural belt and the piedmont transitional zone, whereas stable intra-basin areas are characterized by small-scale intraformational faults, which are conducive to hydrocarbon preservation.

4.2.1 Fault Combination Styles

Based on structural interpretation of seismic profiles, the fault combination styles in the study area are diverse and can be mainly categorized into three types: back-thrust uplift, fault-propagation fold, and pop-up structure [13]. The impact of these different styles on hydrocarbon preservation conditions varies

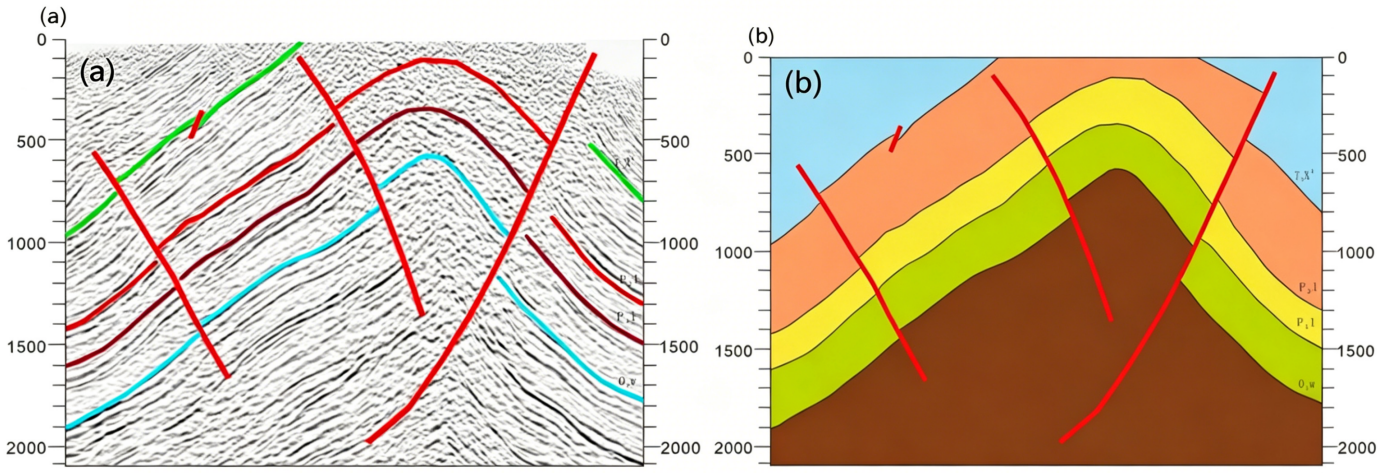

Figure 4. Seismic interpretation (a) and corresponding geological model (b) of fault-propagation fold.

significantly.

(1) *Back-thrust uplift*

This style is mainly characterized by two or two groups of oppositely dipping thrust faults acting together to form back-thrust fault blocks or back-thrust fault uplifts. Typical structures include the Dengjingguan and Qingshanling structures. Seismic profiles reveal deep-seated thrust faults with opposite dips that converge upward, forming Y-shaped or V-shaped combinations (Figure 3). This configuration leads to intense uplift and erosion of the overlying strata, cutting through the regional anhydrite-bearing caprock and severely damaging hydrocarbon preservation conditions. Tests from wells D17 and D18 in the Maokou Formation within the Dengjingguan area both produced water with low salinity, confirming the destructive effect of this combination style on preservation conditions.

(2) *Fault-Propagation Fold*

This style is the most developed structural style in the study area and is widely distributed in structures such as Wuzhishan, Tiangongtang, Changning, and Lianhuasi. The deformation mechanism involves basement-involved thrust faults propagating upward, with fault displacement gradually decreasing and being transformed into fold deformation, forming asymmetric anticlines characterized by steep forelimbs and gentle backlimbs. Faults mostly terminate within the fold core or forelimb. Some master faults cut upward into the Xujiahe Formation or reach the surface, leading to caprock failure, as observed in the Wuzhishan and Lianhuasi structures. However, if the fault scale is small and does not breach the caprock, it is conducive to hydrocarbon accumulation and preservation. An example is the area with small-scale fault development in the northeastern part of the Tiangongtang structure, where faults are mostly confined within the Cambrian-Ordovician section without affecting the overlying strata, resulting in relatively good preservation conditions (Figure 4).

(3) *Pop-Up Structure*

This style is mainly characterized by deep-seated thrust faults branching upward to form multiple secondary faults, collectively forming a pop-up fault block or pop-up anticline. Typical structures include the southern limb of the Dengjingguan structure and the northern limb of the Qingshanling structure. Seismic profiles show deep master faults bifurcating upward into multiple branch faults, forming Y-shaped or broom-shaped combinations (Figure 5). This configuration results in intense deformation and uplift of the overlying strata, destruction of the regional caprock, and consequently poor hydrocarbon preservation conditions. This style is mostly developed in areas with intense basin-margin tectonics and, together with the back-thrust combination style, constitutes the main destructive fault system in the study area.

In summary, the fault combination styles in the study area are closely related to hydrocarbon preservation conditions. Back-thrust combinations and pop-up structures are often associated with intense uplift and caprock failure, which are detrimental to hydrocarbon preservation. Within the fault-propagation fold style, large-scale master faults similarly compromise preservation conditions, whereas smaller-scale blind faults are favorable for hydrocarbon accumulation and preservation. Stable intra-basin structural areas, characterized by few faults or only small-scale intraformational faults, represent favorable zones for

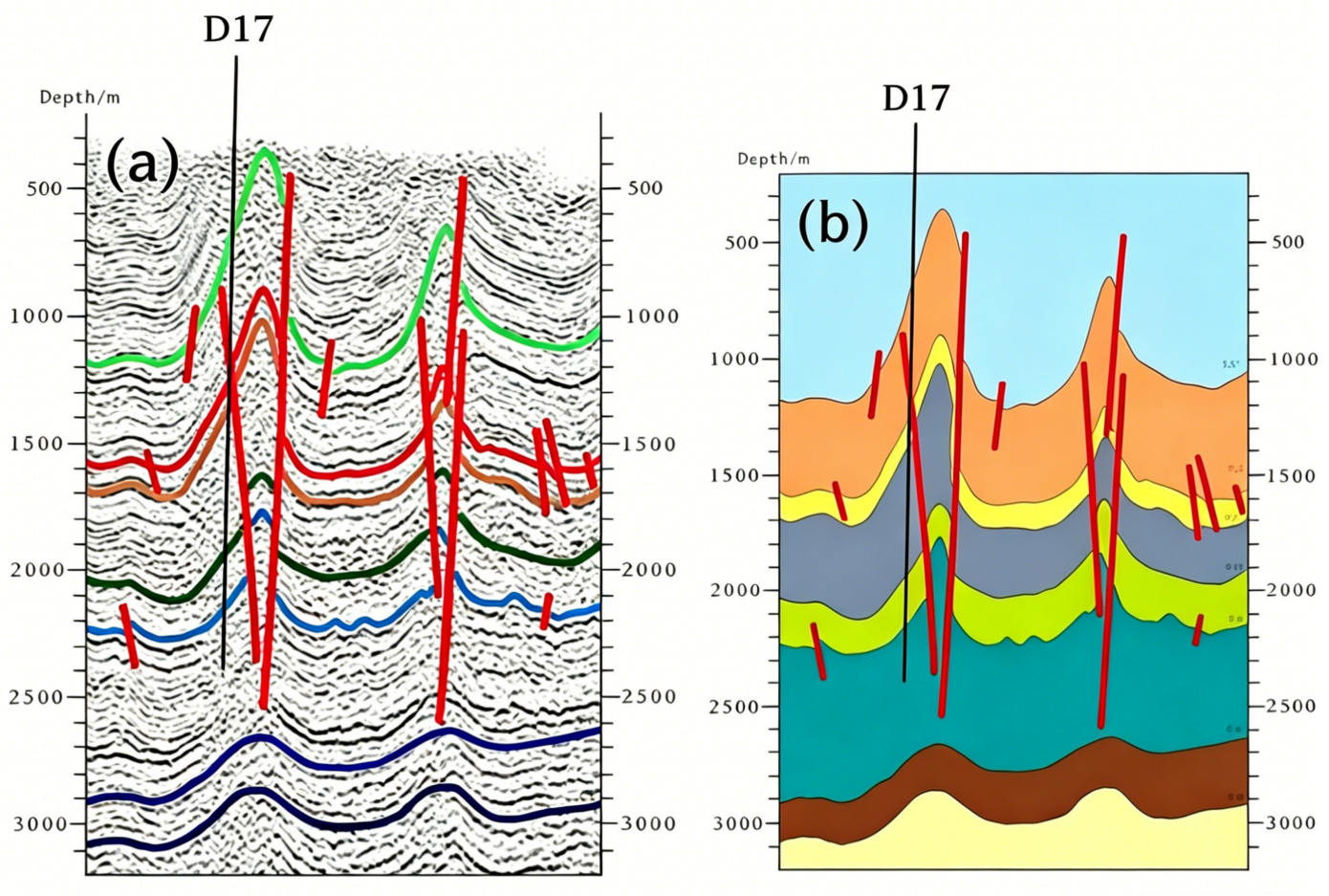

Figure 5. Seismic interpretation (a) and corresponding geological model (b) of pop-up structure across the D17 profile.

hydrocarbon preservation.

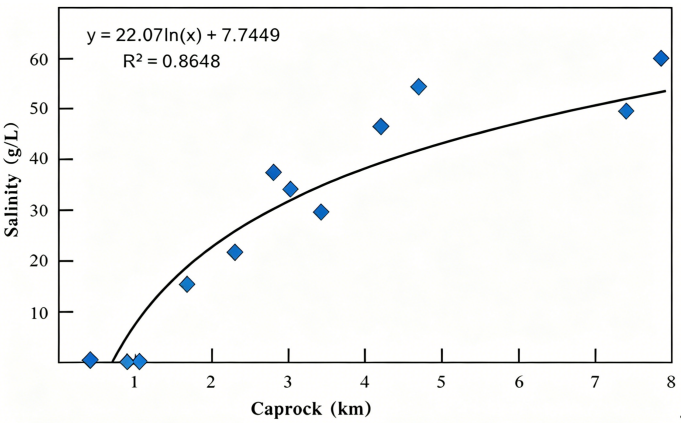

Figure 6. Relationship between salinity characteristics of key wells and distance from faults in the study area and its vicinity.

4.3 Hydrocarbon preservation conditions analysis

4.3.1 Formation water chemical characteristics

Based on the analysis of drilling data from typical structures in the LY area of southern Sichuan, the study statistically classified the formation water chemical characteristics and test results from the Middle Permian Maokou Formation in 20 key wells across structures such as Guanyinchang, Tiangongtang, Datachang, Ziliujing, Dengjingquan, and Kongtan (Table 1). In the Guanyinchang structure, the formation water from the Maokou Formation in wells Y11, Y20, and Y21 is all of the $NaHCO_3$ type, indicating unfavorable water type conditions. The formation water salinities are all less than 15 g/L, representing low salinity values. Furthermore, the gas production rates from these wells are all less than $1.5 \times 10^4\ m^3/d$. This suggests that the hydrocarbon preservation conditions in wells Y11 and Y20 are significantly influenced by master faults, leading to a compromised subsurface sealing environment, hydrocarbon dissipation, and consequently poor preservation conditions. In the Ziliujing structure, well Z2 tested gas at a rate of $195.4 \times 10^4\ m^3/d$ from the Third Member to the First Member of the Qixia Formation, with a salinity of 70.36 g/L. Well Z6 tested gas at $8.1 \times 10^4\ m^3/d$ from the Second Member (sub-member b to c) of the Maokou Formation, with a salinity of 76 g/L. The formation water type in both wells is $CaCl_2$. In contrast, well ZS1 tested

trace gas in the First Member (sub-member b to a) of the Qixia Formation and the Fourth to Second Member of the Maokou Formation, with salinities of 0.12 g/L and 0.1 g/L, respectively, and the water type is Na_2SO_4. From the drilling and test results in the Ziliujing structure, it can be observed that wells with better hydrocarbon preservation conditions tend to yield higher test production, and vice versa. In the Datachang area, multiple wells produce gas from the Middle Permian Maokou Formation. Among them, well T2, characterized by high salinity and a $CaCl_2$ water type, exhibits significantly better hydrocarbon preservation conditions than wells T8, T9, and T16, and its test production is also markedly higher. This further confirms the overall good hydrocarbon preservation conditions of the Middle Permian Maokou Formation in this area and suggests a positive correlation between test production and preservation conditions. The Dengjingguan area is characterized by the development of breakthrough faults, resulting in generally poor preservation conditions. Wells D17 and D18 in this area have low salinities and both tested water, reflecting compromised hydrocarbon preservation conditions. In the Kongtan area, wells K10 and K27 both tested gas. Well K10 tested gas at a high rate of 75.2×10^4 m^3/d. Formation water salinities in this area are generally high, and the water type is $CaCl_2$, indicating favorable hydrocarbon preservation conditions.

Based on the actual drilling situations of the aforementioned typical wells and statistics of their distances from master faults, the study observed that when a well is located close to a master fault, the salinity tends to decrease, and conversely, it increases with greater distance [14–16]. This indicates a certain linear relationship between the two variables. The study clarified this relationship by analyzing the trend of the regression curve (Figure 6). The results show a correlation coefficient of 0.8648, which is close to 1 and indicates a strong positive correlation. Specifically, the

Table 1. Water chemical characteristics of key wells in the study area.

Structure	Well	Horizon	Salinity (g/L)	Water Type	Test Result ($10^4m^3/d$)	Distance from Master Fault (km)
Tiangongtang	G2	Second Member (sub-member a) of Maokou Fm.			Water produced	1.1
Guanyinchang	Y11	Fourth to Third Member of Maokou Fm.	0.6	$NaHCO_3$	1.44	0.4
	Y20	Fourth to Second Member of Maokou Fm.	0.62	$NaHCO_3$	0.03	1.1
	Y21	Third to Fourth Member of Maokou Fm.	0.7	$NaHCO_3$	12.66	0.1
Datachang	T2	Fourth Member of Maokou Fm.	90.12	$CaCl_2$	7.85	6.5
	T9	Fourth Member of Maokou Fm.	1.91	$NaHCO_3$	1.51	1.1
	T16	Fourth Member of Maokou Fm. to First Member (sub-member b) of Qixia Fm.	2.42	Na_2SO_4	1.84	3.2
	T8	Second Member (sub-member c) of Maokou Fm.	24.2	Na_2SO_4	3.02	3.02
Ziliujing	Z2	Third Member of Maokou Fm. to First Member of Qixia Fm.	70.36	$CaCl_2$	195.4	5.2
	Z6	Second Member (sub-member b to c) of Maokou Fm.	76	$CaCl_2$	8.1	4.55
	ZS1	First Member (sub-member c) of Maokou Fm. to First Member (sub-member a) of Qixia Fm.	0.12	Na_2SO_4	Trace gas	1.05
		Fourth to Second Member (sub-member b) of Maokou Fm.	0.1	Na_2SO_4	Trace gas	1.05
Dengjingguan	D17	First Member (sub-member c) of Maokou Fm. to Second Member of Qixia Fm.	0.446	$CaCl_2$	Water produced	0.2
	D18	Second Member (sub-member a) of Maokou Fm. to Liangshan Fm.	1.359	$CaCl_2$	Water produced	2.18
Kongtan	K10	Fourth Member of Maokou Fm.	46.6	$CaCl_2$	75.2	9.6
	K27	Fourth to Second Member (sub-member b) of Maokou Fm.	21.63	$CaCl_2$	6.64	2.3
	K31	Second Member (sub-member c) to Fourth Member of Maokou Fm.			0.23	1.58
Nanjing	J16	Third to Second Member (sub-member b) of Maokou Fm.	66.55	$CaCl_2$	Water produced	2.8
	J11	Second Member (sub-member b) of Maokou Fm.	34.4	$CaCl_2$	3.2	4.7
	J14	Second Member (sub-member b) of Maokou Fm.	37.82	$CaCl_2$	Trace gas	2.8
Lianhuasi	L2	Fourth to Second Member (sub-member a) of Maokou Fm.	80	$MgCl_2$	Water produced	2.5
	L3	Fourth to Third Member of Maokou Fm.	15.45	$MgCl_2$	Water produced	1.68
	L4	Second Member (sub-member c) of Maokou Fm.	0.34	Na_2CO_3	Water produced	0.9

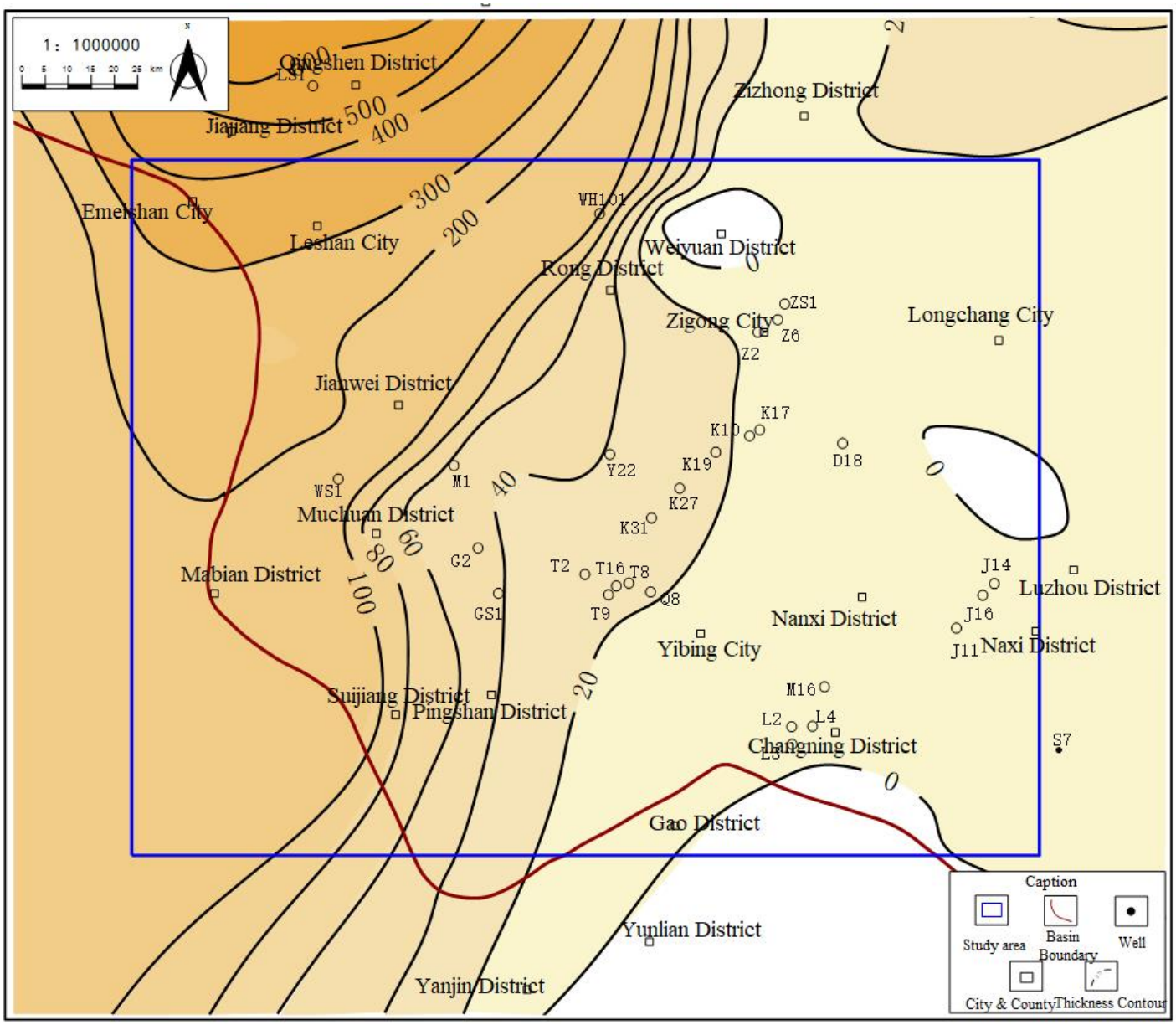

Figure 7. Thickness distribution of the Leikoupo Formation anhydrite-bearing caprock in the study area.

farther a well is from a breakthrough fault, the more likely the water type is $CaCl_2$, and the salinity values are higher, suggesting good stratigraphic sealing and undisturbed hydrocarbon preservation conditions. Conversely, wells closer to breakthrough faults often display water types such as Na_2SO_4 or $NaHCO_3$ with lower salinity values. This may indicate that, due to stratigraphic uplift and erosion, the strata are in a semi-closed or open state, and the hydrocarbon preservation conditions have been compromised.

4.3.2 *Stratigraphic Exposure and Caprock Integrity*

The Sichuan Basin features favorable conditions for marine carbonate hydrocarbon accumulation, including a relatively stable tectonic environment, multiple sets of regional source rocks with significant generation potential, widespread distribution of layered or quasi-layered reservoirs, and clustered distribution of stratigraphic-lithologic traps. Exploration practices indicate that while the Permian Maokou Formation was an early key exploration target in the Sichuan Basin, only a number of small gas fields primarily characterized by fractured reservoirs were discovered in southern Sichuan for many years [17–20]. Subsequently, with the deepening understanding of dissolution cavities distributed along fractures and continuous exploration efforts, several high-yield gas wells were drilled in the Middle Permian Maokou Formation in the southern Sichuan Basin, revealing promising natural gas exploration prospects in this interval. The thickness of the regional Leikoupo

Formation caprock in the study area ranges from 0 to 600 m, with an average thickness of 300 m. Thick areas are mostly distributed in the Leshan and Qianwei areas in the northwestern part of the study area. In the Weiyuan, Changning, and northern Luzhou areas within the region, the overlying Leikoupo Formation anhydrite-bearing caprock has been completely eroded due to exhumation, resulting in a total loss of sealing capacity. The Datachang structure within the study area represents a relatively high-value area for caprock thickness, exhibiting strong sealing capacity, favorable for hydrocarbon preservation. Multiple gas wells in the Maokou Formation within this area have achieved commercial gas flows. Low-thickness areas are mainly distributed in the Changning, Yibin, and Luzhou areas, where caprock thickness is generally less than 20 m, representing relatively low-thickness zones with weaker sealing capacity. Overall, apart from partially eroded areas, the Leikoupo Formation anhydrite-bearing caprock in the study area is widely distributed and exhibits good continuity. Caprock thickness gradually increases from the southeast toward the northwest, with a corresponding enhancement in sealing capacity (Figures 7 and 8) [21, 22].

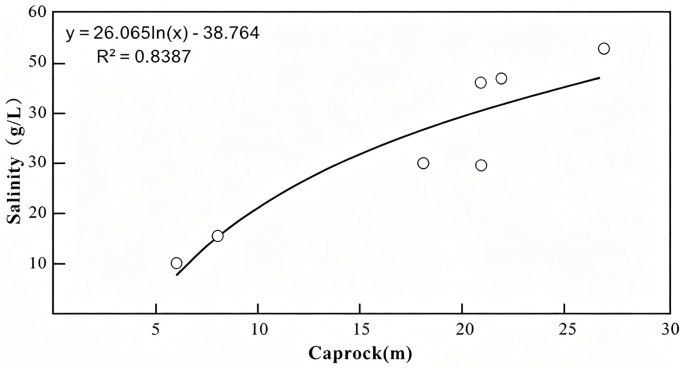

Figure 8. Relationship between salinity of key wells and caprock thickness in the study area.

4.3.3 Pressure Coefficient Analysis

Generally, when the formation pressure coefficient is close to hydrostatic pressure (i.e., pressure coefficient $\approx$ 1.0), it indicates that the formation fluid is in a relatively balanced state. If the caprock sealing is good and the structure is stable, hydrocarbons are easily preserved. However, if the pressure coefficient deviates significantly from the normal value (overpressure or underpressure anomaly), it may reflect changes in the preservation conditions of the hydrocarbon reservoir. Generally, the presence of abnormally high pressure (pressure coefficient > 1.3) indicates the existence of sealed compartments where significant hydrocarbon generation is still occurring, favoring hydrocarbon accumulation and preservation [23–25]. Conversely, the appearance of abnormally low pressure (pressure coefficient < 1.1) could be a sign of crustal uplift, cessation of hydrocarbon generation, and substantial natural gas dissipation, indicating compromised hydrocarbon preservation conditions.

In the study area, high-pressure zones for the Middle Permian are mainly located in structurally stable intra-basin areas such as Yibin, Luzhou, and Zigong. Multiple gas wells have been successfully tested in structures like Datachang and Guanyinchang within these zones, indicating good stratigraphic sealing and favorable hydrocarbon preservation conditions (Figure 9). Abnormally low-pressure zones are primarily distributed in basin-margin areas such as Mabian, Suijiang, and Pingshan. These areas exhibit intense tectonic activity and a high degree of deep major fault development. Furthermore, gas wells in structures such as Tiangongtang and Dawoding within these zones have mostly been unsuccessful exploration wells in the Permian, suggesting that the hydrocarbon preservation conditions in these structures have been compromised and hydrocarbons may have dissipated. The formation pressure coefficients generally show a gradual increase from the intensely deformed basin-margin areas toward the tectonically stable intra-basin areas in the southern Sichuan region.

5 Discussion

5.1 Methodology for Evaluating Preservation Conditions

Based on the preceding discussion of individual factors affecting preservation conditions, the hydrocarbon preservation conditions within the study area are influenced by factors such as tectonic deformation intensity, surface stratigraphic exposure, formation water chemistry, formation pressure coefficient, and caprock conditions [13, 26–30]. The impact of tectonic activity on hydrocarbon preservation can be either positive or negative, which primarily depends on the intensity of the tectonic activity. Intense tectonic movements leading to folding and faulting that damage caprocks, stratigraphic uplift and erosion, and the destruction of stratigraphic sealing are major causes of hydrocarbon dissipation and compromised preservation conditions (Table 2). Low-intensity tectonics can generate source-connected faults that effectively link source rocks and reservoirs, facilitating hydrocarbon migration. The age of

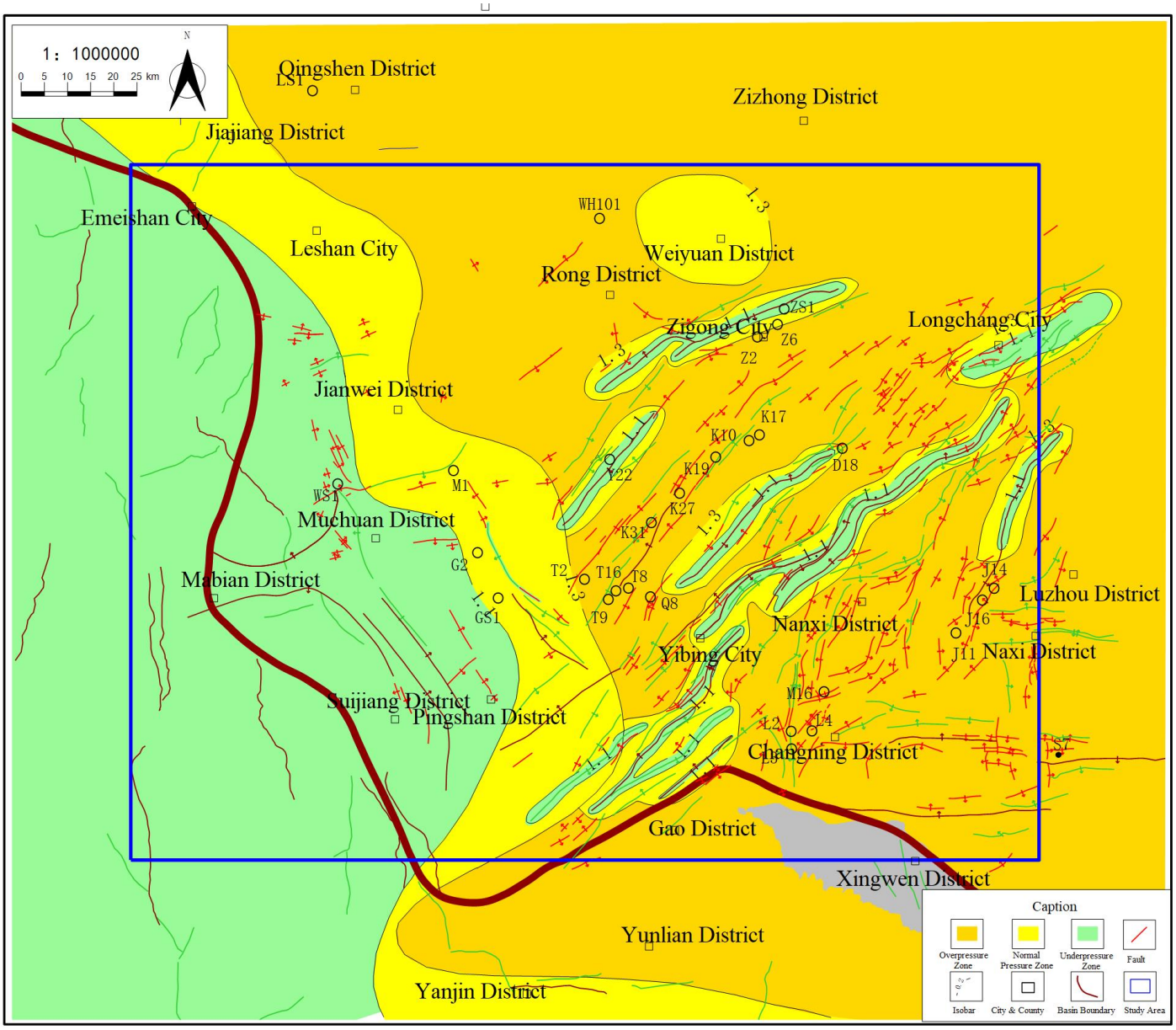

Figure 9. Distribution of formation pressure coefficients for the Middle Permian in the study area.

Table 2. Comprehensive evaluation system for hydrocarbon preservation conditions of the Maokou Formation in the study area.

Evaluation Parameter		Evaluation Result		
		Favorable Zone	Moderate Zone	Unfavorable Zone
Tectonic Intensity	Fault Development Degree	Small throw, short extension, sparse distribution	Moderate throw, relatively widespread	Large throw, long extension, cuts multiple layers
	Fault Order	Third-order faults	Second-order faults	First-order faults (master faults)
	Distance from Master Fault (km)	4	2-4	2
Exposed Strata		Q-J	T-C	S-Z
Regional Caprock		Thick, good sealing	Moderate sealing	Thin, severely eroded
Hydrogeology	Salinity (g/L)	>40	20-40	<20
	Sulin Water Type	$CaCl_2$	$MgCl_2$, Na_2SO_4	$NaHCO_3$
Pressure Coefficient		High-pressure zone (>1.3)	Normal-pressure zone(1.1-1.3)	Low-pressure zone (<1.1)

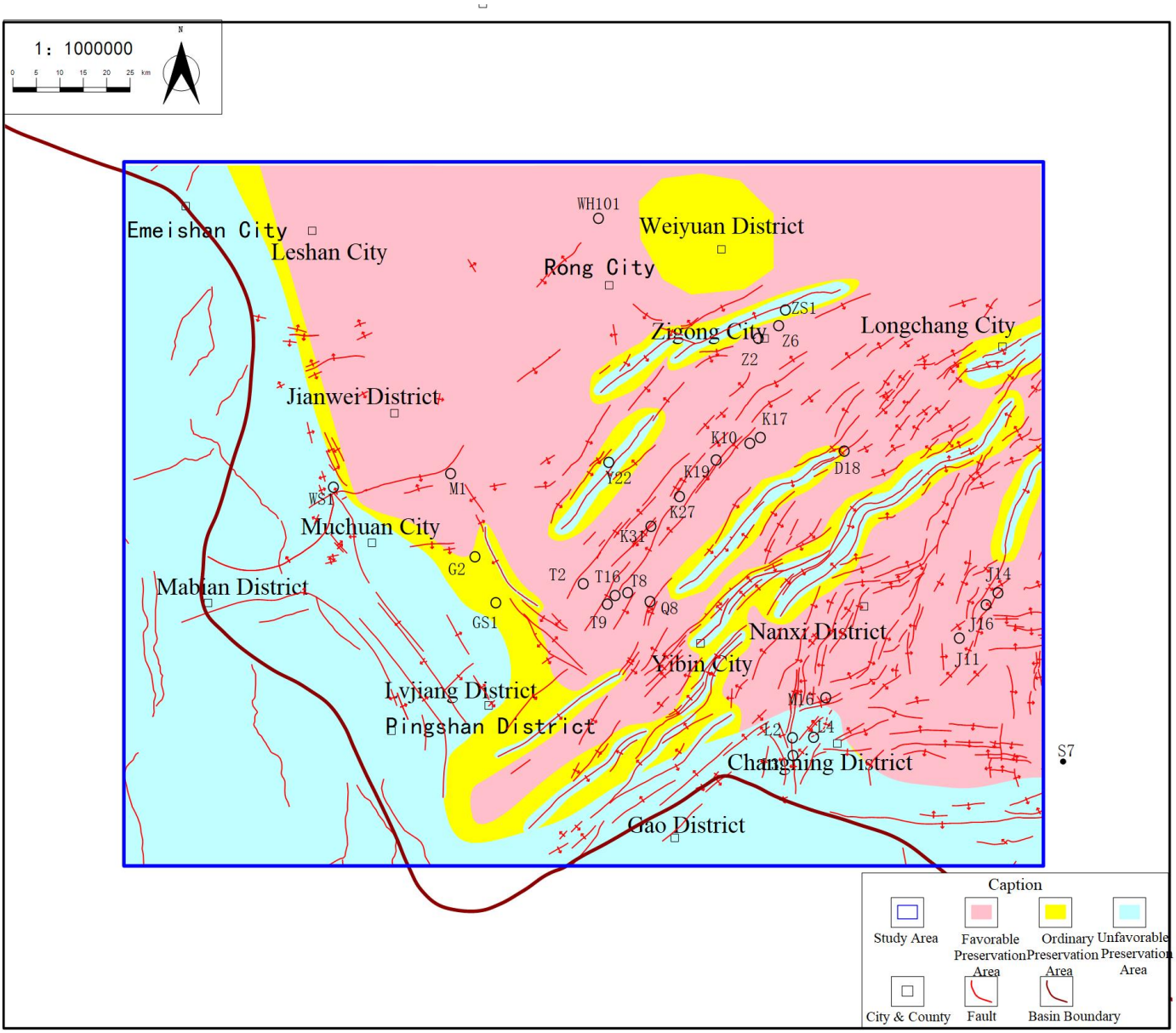

Figure 10. Evaluation results of hydrocarbon preservation conditions for the Maokou Formation in the study area.

exposed surface strata can reflect the quality of hydrocarbon preservation conditions: exposed younger strata indicate low erosion intensity and favorable preservation conditions, whereas exposed older strata suggest intense erosion and poor preservation conditions. A competent regional caprock is one of the crucial conditions for effective hydrocarbon preservation: when the caprock lithology consists of gypsum-salt layers and the thickness is greater, hydrocarbon preservation conditions are better. Formation water chemical characteristics can indirectly reflect the quality of hydrocarbon preservation conditions: formation water type and salinity are direct indicators of preservation conditions. In a closed preservation environment, salinity tends to be high (typically > 40 g/L), and the water type is predominantly $CaCl_2$. Similarly, the magnitude of the formation pressure coefficient is an important factor in assessing stratigraphic sealing: areas with better stratigraphic sealing are often located in high-pressure zones (formation pressure coefficient > 1.3). Integrating the actual geological conditions of the study area, the study established a comprehensive evaluation system for hydrocarbon preservation conditions specific to the Middle Permian Maokou Formation (Table 2).

5.2 Results of Preservation Condition Evaluation

Through the comprehensive evaluation of influencing factors, including tectonic deformation intensity,

stratigraphic exposure, caprock conditions, formation water chemical characteristics, and pressure coefficient in the study area, the study classified the area into favorable, moderate, and unfavorable preservation zones. Favorable preservation zones are mainly located in the Leshan-Changning area toward the basin interior. These zones are characterized by tectonic stability, low development of first-order faults, thick and continuous regional caprock, surface outcrops mostly consisting of Jurassic and younger strata, formation water salinity values $>$ 40 g/L, formation water type predominantly $CaCl_2$, and high formation pressure coefficients. Some areas also feature high-yield wells, classifying them as favorable preservation zones. Moderate preservation zones are distributed in the transitional area from the basin margin to the basin interior. These zones feature development of second-order faults, moderate regional caprock thickness, salinity values ranging between 20 and 40 g/L, and formation water types predominantly $MgCl_2$ or Na_2SO_4. Unfavorable preservation zones are mostly located in basin-mountain junction zones, such as the Mabian, Suijiang, and Pingshan areas. These zones exhibit intense tectonic activity, development of first-order faults, destroyed and thin regional caprock, exposed strata of Silurian and older systems, salinity less than 20 g/L, common $NaHCO_3$ formation water type, and low formation pressure coefficients, indicating poor hydrocarbon preservation (Figure 10).

6 Conclusions

(1) The LY area is situated in the southern Sichuan low-steep structural belt and is characterized by complex and diverse structural types. Significant differences in hydrocarbon enrichment and accumulation exist among different structural types and stratigraphic levels. The study area mainly develops two structural systems: NWW-trending and NE-trending. The former is typically represented by the Tiangongtang and Wuzhishan structures, whereas the latter is mainly distributed in the Shuanglong-Luochang area. The formation of these systems is primarily controlled by the Xianshuihe fault zone to the west and the Daloushan fault-fold belt to the south of the basin.

(2) Through comprehensive structural interpretation of typical profiles in the northwestern, central, and southeastern segments of the LY area, the northwestern segment exhibits distinct structural layering and characteristics of fault-propagation folds. Structures such as Wuzhishan and Tiangongtang in this region are thrust-nappe structures controlled by deep-seated thrust faulting. The shallow structures have been modified and influenced by deep structures, causing faults to cut through to the surface and severely damaging hydrocarbon preservation conditions.

(3) Integrating evaluation indicators such as tectonic deformation intensity, surface stratigraphic exposure, caprock conditions, formation water chemical characteristics, and pressure coefficient, the study established and applied an evaluation system for preservation conditions in the study area. Favorable preservation zones are mainly distributed in intra-basin structures such as Ziliujing, Kongtan, and Nanjing. These areas are essentially devoid of first-order faults, exposed strata are mostly Jurassic and younger, the caprock is thick and well distributed, the distance from master faults is generally $>$ 4 km, formation pressure coefficients are relatively high, and some areas exhibit high-yield wells.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

Chao Geng is affiliated with the Shunan Gas Mine, PetroChina Southwest Oil & Gasfield Company, Luzhou 646001, China. The authors declare that this affiliation had no influence on the study design, data collection, analysis, interpretation, or the decision to publish, and that no other competing interests exist.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

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