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Research Article

Comprehensive Evaluation of the Hydrocarbon Preservation Conditions in the Complex Tectonic Area of the Southwestern Sichuan Basin, China

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There are various styles of faults, folds, and unconformity structures in the southwestern Sichuan Basin, which have an important impact on hydrocarbon preservation. Based on the data of regional geological, seismic, formation water characteristics, caprock characteristics, and production, the hydrocarbon preservation conditions of the key horizons (Cambrian, Upper Permian, and Triassic) were analyzed. Southwestern Sichuan Basin margin structure has two obvious tectonic layers (the upper and lower). The upper tectonic layer is dominated by Middle Triassic detachment faults and derived thrust faults, while the lower tectonic layer has concealed structures composed of basement detachment faults and derived thrust faults. There are mainly NE, near-SN, NW, and near-EW faults. The outcrops are in the Middle-Cenozoic strata, changing from old to new from outside the Basin to inside the Basin. There are three main sets of high-quality caprocks, i.e., the mudstone of the bottom of the Xujiahe Formation, the gypsum-salt rocks of the Middle-Lower Triassic, and the Lower Cambrian mudstone. Based on the faults, outcrops, formation water type, mineralization, and caprock characteristics, the hydrocarbon preservation evaluation system was established, which divides into the areas of Class I, II, and III. The distribution range of the favorable areas of different horizons has good inheritance, and the hydrocarbon preservation conditions gradually improve from outside the basin to inside the basin. Class I favorable areas are the most widely distributed and are mainly located within the basin, with the characteristics of a low degree of fault development, relatively new outcropping strata, $CaCl_2$ formation water type, and large caprock thickness.

1. Introduction

The Sichuan Basin is a typical superimposed basin, which has the characteristics of an extremely stable basement, the development of multiple sets of reservoir layers, source rocks, and good sealing conditions with multilevel caprocks. It is rich in hydrocarbon resources, has great exploration potential, and is an important natural gas production [1–7]. However, there are great differences in hydrocarbon enrichment and accumulation of the different strata in the Basin, and the hydrocarbon preservation is important for the oil and gas exploration [8, 9]. Previously, extensive studies have been conducted on hydrocarbon preservation conditions, and evaluation systems for hydrocarbon preservation conditions in different regions and under different tectonic conditions have been established. By analyzing the relationship between the sealing time and performance and of caprocks and faults, He et al. [10] clarified the concept and type of hydrocarbon preservation unit and evaluated the effects of fault characteristics, magmatic activity, and hydrogeological conditions on preservation conditions. Ma et al. [11] established evaluation indicators based on the caprocks and their sealing performance, fault sealing properties, late tectonic strength, hydrogeological conditions, and the chemistry-kinetics of the underground fluid and developed an evaluation system in southern China. Based on the fluid history of hydrocarbon-bearing sedimentary basins, Lou et al. [12] analyzed the response characteristics of the chemical-kinetics behavior of the underground fluids during the evolution of the basin and summarized the failure of the preservation conditions in southern China. Liang et al. [13] comprehensively evaluated hydrocarbon preservation units based on factors such as tectonic movement, accumulation time, regional caprock conditions, hydrogeological conditions, and reservoir organic fluids. Xiao [14] conducted a comprehensive analysis of geological parameters, such as the caprock, fluid chemistry-kinetics, fault development history and sealing properties, cap-source formed trap, and reservoir characteristics, and established an evaluation index system for hydrocarbon preservation in the multicycle superimposed region with syntectonic sedimentation. Wang et al. [15] mainly analyzed the dynamic transformation relationship between the destruction and construction of tectonic effects on hydrocarbon preservation. Li et al. [16] focused on the impact of hydrogeological and geochemical characteristics on hydrocarbon preservation conditions and comprehensively evaluated the hydrocarbon preservation conditions in complex tectonic areas at the basin margin using parameters such as outcrops, caprock sealing properties, formation fluid pressure, tectonic uplift and denudation, and fault distribution characteristics. Zhang et al. [17] analyzed multistage hydrocarbon accumulation under multistage tectonic movement and later transformation and destruction at different levels. In general, the hydrocarbon preservation conditions are affected by the characteristics and assemblages of the source, reservoir rock and caprock, the time of accumulation, tectonic movements and tectonic characteristics, and hydrogeological conditions [18, 19].

The southwestern Sichuan Basin is a typical complex tectonic zone influenced by the Longmen Mountain Thrust Belt in the west, the Daliang Mountain Tectonic Belt in the south, and the Longquan Mountain Tectonic Belt in the east [20–23]. It has experienced the Indosinian-Yanshan-Himalayan tectonic movements, with strong tectonic deformations and multistage transformations, resulting in obvious differences in the hydrocarbon preservation conditions and enrichment levels of the different strata [24–26]. However, research on the tectonic characteristics and hydrocarbon preservation conditions is relatively limited, which is not conducive to hydrocarbon exploration in this area. In this study, according to data of the logging, formation water, and tectonic characteristics of this area, the criteria for the preservation condition evaluation were established, which provides good support for the selection of favorable targets for hydrocarbon exploration in this area.

2. Geological Setting

The study area is located at the southwest margin of the Sichuan Basin and mainly includes the Longmen Mountain piedmont tectonic system, the Daxingchang tectonic system, and the Emei-Wawu Mountain tectonic system. Its northwestern margin is the southern Longmen Mountain Thrust Belt, its southwestern margin is the Kang-Dian uplift zone, and its east side is the Chuanzhong Uplift, with the Jurassic strata being the main outcrops (Figure 1(a)). It has mainly experienced the multistage tectonic movements of the Indosinian-Yanshan-Himalayan period, which can be divided into the four evolutionary stages of the pre-Indosinian Basin uplift, the Indosinian inherited uplift, the Yanshanian multiple episodic uplift, and the Himalayan intense fold uplift. Therefore, the tectonic deformations are extremely complex, forming complex fold and fault structures [27–31]. The surface of the study area consists mainly of some forward or reverse thrust faults that strike almost parallel to the strike of the peripheral orogenic belt and the fold structures associated with the thrust faults. The tectonic axis and faults of the Longmen Mountain piedmont tectonic system are distributed along the northeast-southwest direction, and the trap is characterized by fault-related folded structures controlled by reverse faults. The Daxingchang tectonic system is a fault-controlled block type with Middle Triassic shallow detachment faults. The tectonic axis and faults of the Emei-Wawu Mountain tectonic system are the north-south direction, and the Tongtian faults are relatively well developed. The strata are relatively well developed, the Sinian-Quaternary sedimentary strata are developed above the pre-Sinian crystalline basement, and the Silurian-Devonian strata are absent inside the Basin (Figure 1(b)).

3. Materials and Methods

3.1. Materials. The comprehensive evaluation of hydrocarbon preservation conditions mainly used fault development data, production data, formation water type, and mineralization data of the key horizons. The three-dimensional (3D) contiguous data from southwestern Sichuan were collected to establish three typical structural section types to explain structural systems and faults. More than 30 formation water samples from more than 20 wells (such as Woshen 1, Zhougong 1, Hanshen 1, Gong 2, Gongshen 1, and Ma 1) and the production data of each well were collected, and tests for formation water type and mineralization were performed.

3.2. Methods

3.2.1. Geophysical Interpretation. The seismic data are processed and interpreted by the LANDMAK 2003.12.13 interpretation system using the 10×10 grid density control. The fault characteristics of the key horizons in southwestern Sichuan Basin were described, and the basic characteristic parameters and development characteristics of the faults were obtained [32–36]. Three typical seismic profiles of the margin were established to clarify the tectonic characteristics of different strata in the study area.

3.2.2. Chemical Characteristics of the Formation Water. Formation water ion types and different concentrations of anions and cations were measured using a CIC-D280 ion chromatograph produced by Qingdao Shenghan Chromatography

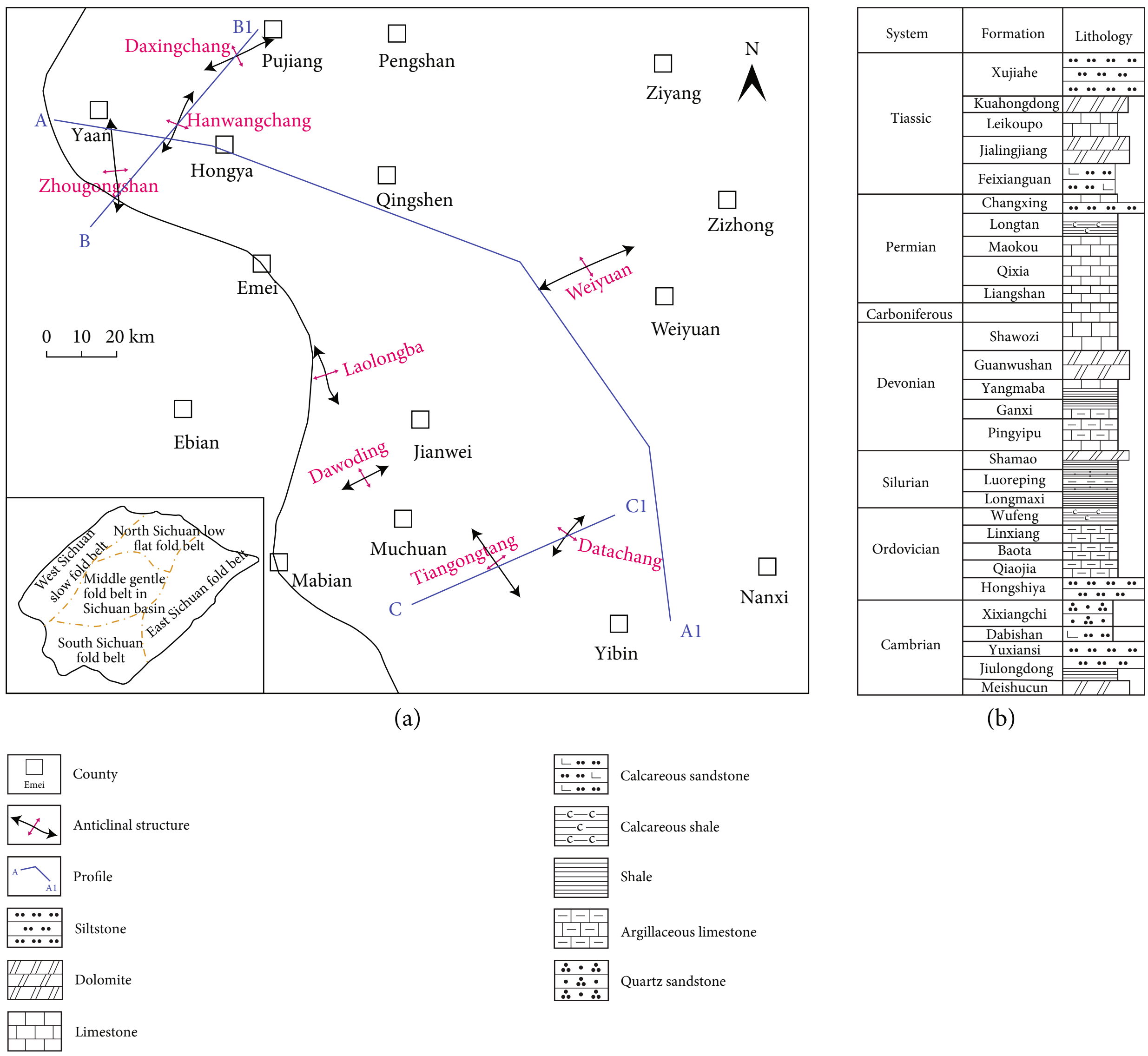


Figure 1: Geological overview of the study area. (a) Tectonic location. (b) Stratigraphic lithology.

Technology Co., Ltd. The chemical composition of formation water was analyzed according to the industry standard (SY/T5523-2016). The geochemical analyses were performed at the State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation (part were from the PetroChina Southwest Oil & Gasfield), and the tests included pH, cation concentration, anion concentration, and total mineralization of formation water mainly used to analyze the type and mineralization of formation water [37].

3.2.3. Comprehensive Evaluation of the Preservation Conditions. Based on the longitudinal structural differences of the different strata in the southwestern Sichuan Basin, there are three key vertical horizons of deep (bottom of Cambrian), middle (bottom of Upper Permian), and shallow (bottom of Triassic). We fully investigated the evaluation systems related to hydrocarbon preservation conditions in China and elsewhere. Based on the current situation and the evaluation parameters (fault development, well-logging data, formation water type, and mineralization), an evaluation system that was adapted to the complex tectonic region in southwestern Sichuan Basin was established [38–40].

4. Results

4.1. Structural Characteristics. The structural development of in southwestern Sichuan Basin margin has two obvious tectonic layers (the upper and lower layers) (Figure 2). The Middle Triassic detachment faults dominate the upper tectonic layer and the derived thrust faults, the lower tectonic layer has concealed structures composed of basement detachment faults and the derived thrust faults, and the preservation conditions of the lower tectonic layer are better than those of the upper layer [32, 33, 41, 42]. In particular, the Longmen Mountain piedmont tectonic system mainly has fault-bend folds and imbricated structures. Due to the

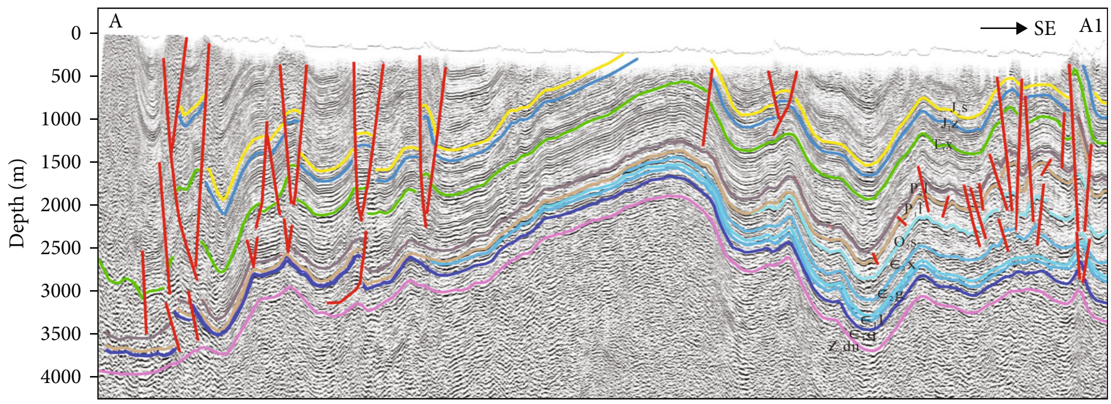


Figure 2: Seismic interpretation profile of the Zhougong Mountain-Weiyuan structure in southwestern Sichuan Basin.

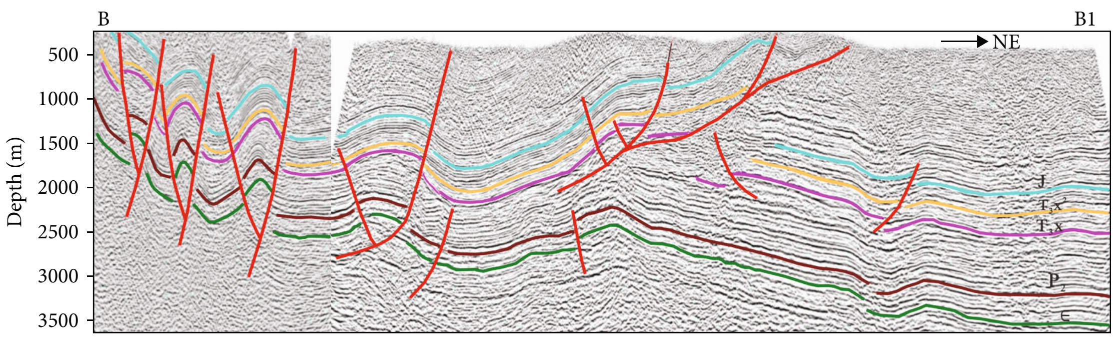


Figure 3: Seismic profile of the Daxingchang tectonic system in southwestern Sichuan Basin.

simultaneous action of the basement detachment surface and the Lower Triassic Jialingjiang-Middle Triassic Leikoupo Formation gypsum-salt detachment surface, two sets of structure systems formed. Multiple thrust faults in the Longmen Mountain piedmont extend to the central Sichuan region, resulting in multiple local fold-thrust deformations with small uplifts and short extensions up to the surface. In addition, multiple basement normal faults were identified on the seismic profile. These normal faults dislocated the Lower Triassic strata. With the compression and deformation of the Longmen Mountain orogenic belt in the later period, some faults were inverted, such as the two thrust faults of the Hanwangchang anticline and the Sansuchang anticline. The Zhougong 1 and Hanshun 1 wells are both located in the high tectonic part of the southwestern Sichuan paleo-uplift. Still, due to the strong superimposed thrust-fold deformation that occurs nearby, the Zhougong Mountain and the southern area are strongly tectonically deformed, and the Tongtian faults were formed at the top of the structure, resulting in poor hydrocarbon preservation conditions. The Weiyuan paleo-uplift influences the area of the Weiyuan gas field. The Aurora-Cambrian strata are all uplifted in high tectonic areas, with no deep faults, and only some small hidden faults have developed, which is conducive to the hydrocarbon accumulation.

The Zhougong Mountain-Hanwangchang area in the southwestern Sichuan Basin mainly manifests as a unified deformation and a steeply standing fault-fold structure in the north-south direction. Most of the faults are Tongtian faults, and preservation conditions are poor. Two sets of tectonic systems developed in the Daxingchang area in the Basin. The shallow layer has the Tongtian faults, with poor preservation conditions; the deep layer is a structured layer with carbonate rocks, few faults, and good preservation conditions (Figure 3).

The tectonic style of the Tiangongtang system is a basement-entangled fault-propagating fold with a large tectonic uplift. The dominating fault on the northern margin outcrops up to the surface, and the overall preservation conditions are moderate. The Datachang tectonic system has a basement detachment fold, and only small concealed faults developed in the fold wing, with good preservation conditions (Figure 4).

Overall, faults in different directions and scales developed in the study area due to the influence of multistage tectonic movement and marginal tectonic units. The overall deformation of the Kangdian uplift zone and the Dalou Mountain has the typical flower-like structural characteristics, the piedmont zone has imbricated thrust deformation, and the tectonic deformation was differentially transmitted to the Basin. The wide and gentle folds mainly developed in the transitional area to the Dalou Mountains; the fold morphology is primarily controlled by the forward thrust fault extending into the Basin. The low-steep fault fold zone in the northwestern part belongs to the Longmen Mountain piedmont tectonic system, and its tectonic axis and faults are

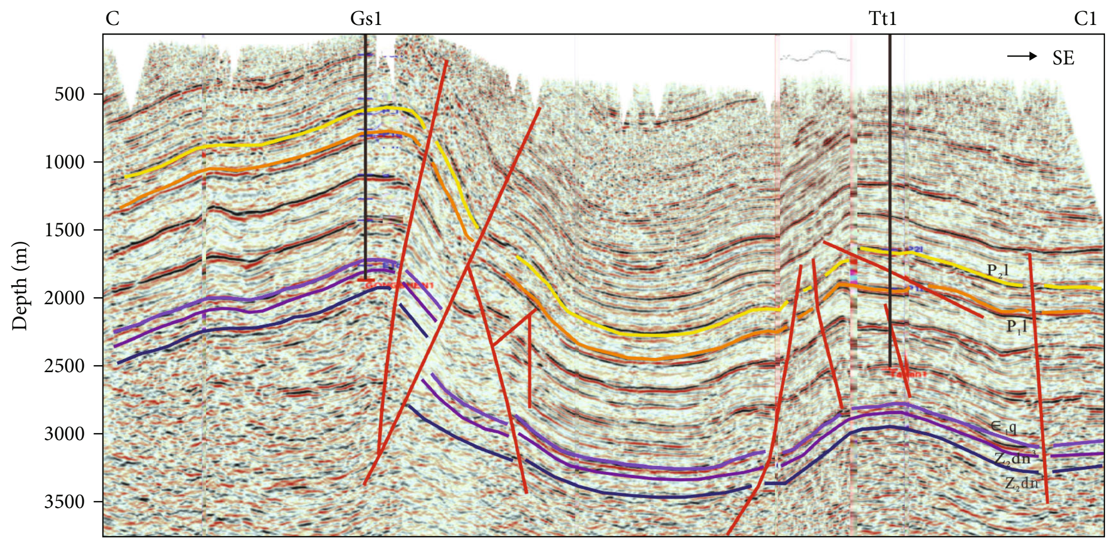
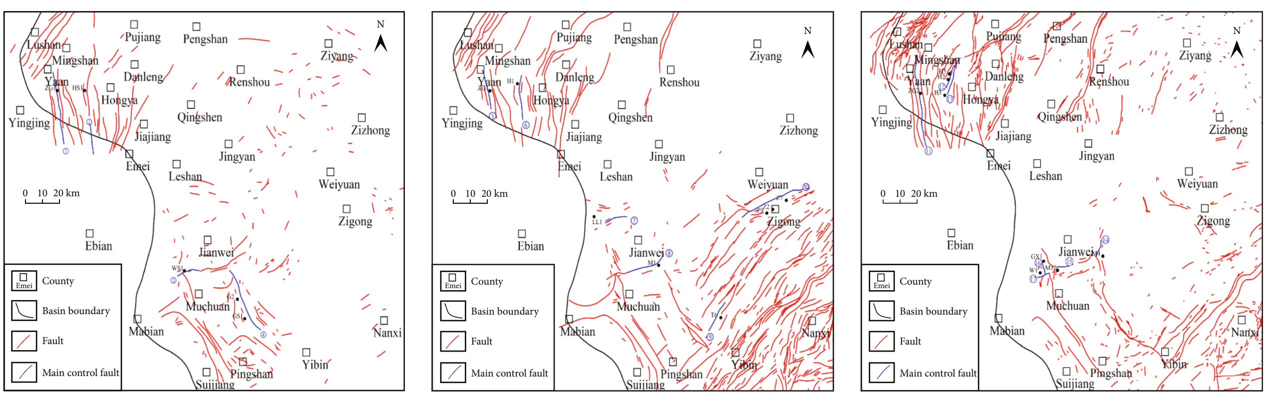


FIGURE 4: Seismic profile of the Tiangongtang-Datachang tectonic system in southwestern Sichuan Basin.



(a) (b) (c)

FIGURE 5: Planar distribution of faults in the key horizons in southwestern Sichuan Basin. (a) Cambrian bottom. (b) Upper Permian bottom. (c) Triassic bottom.

distributed along the northeast-southwest direction, and the development of hydrocarbon traps is closely related to folding. The Emei-Liang Mountain fault-block belt in the central-western region belongs to the Emei-Wawu Mountain tectonic system, which mainly includes the Zhougong Mountain and Hanwangchang structures, and the tectonic axis and faults are the north-south direction. Specifically, the main Cambrian bottom faults include NE-trending, near-SN-trending, NW-trending, and near-EW-trending faults in the southern and northwestern of the area (Figure 5(a)). The dominating fault has an extension length greater than 12 km and a fault distance greater than 600 m. The strikes of the upper Permian bottom faults are in the NE, near-SN, NW and near-EW, and the NE, and near-SN oriented faults are dominant and mainly developed in the southeastern and northwestern of the area (Figure 5(b)). The dominating fault has an extension length greater than 15 km and a fault distance greater than 400 m. The strikes of the Triassic bottom faults still have a good inheritance, and these faults mainly developed in the southeastern and northwestern of the area (Figure 5(c)). The dominating fault has an extension length greater than 20 km and a fault distance greater than 350 m.

4.2. Outcrop Characteristics. The outcrops are important for the preservation conditions. If the Middle Triassic and above strata outcrop on the surface, the preservation of the Upper Paleozoic strata and the strata below are good; if the Silurian-Ordovician strata outcrop, severe denudation is present [12]. If the Lower Triassic Jialingjiang Formation outcrops, the sealing capacity of the gypsum-salt strata may be destroyed. Therefore, the preservation of the Carboniferous and above strata are significantly worsened, and the target strata may be mainly the lower Paleozoic and lower part of the upper Paleozoic. If the Permian-Devonian strata outcrop, the main target strata should be the lower Paleozoic, followed by the lower part of the Upper Paleozoic. If the Silurian-Ordovician strata outcrop on the

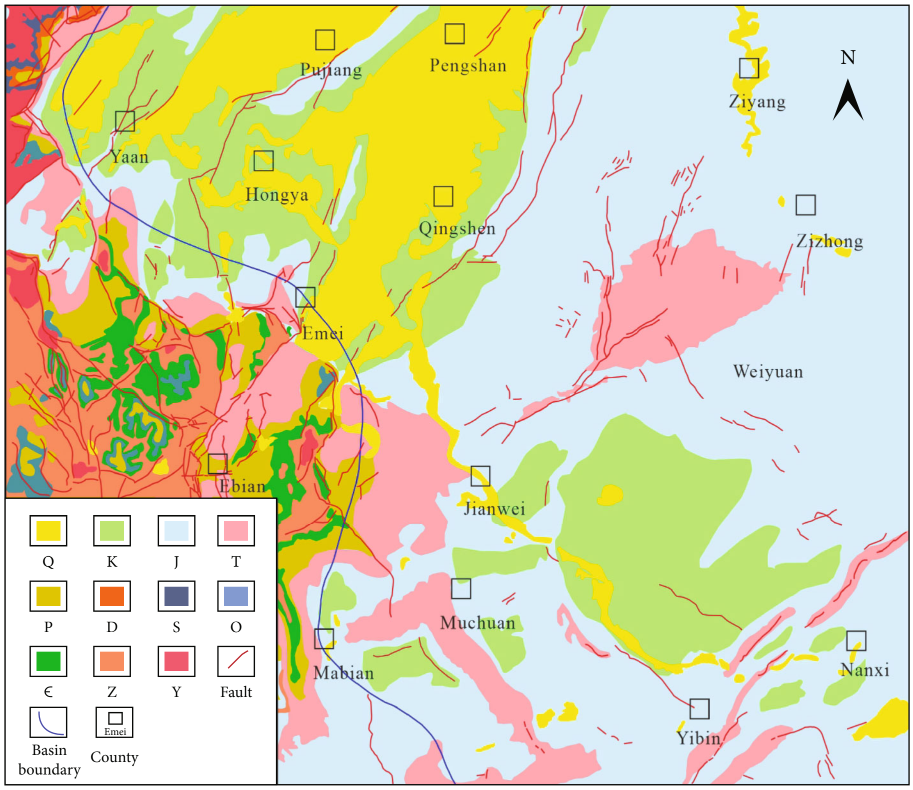


Figure 6: Outcrops in the southwestern Sichuan Basin.

surface, the preservation conditions may have been severely disrupted, and under certain special conditions, the Cambrian-Sinian hydrocarbon reservoirs may remain locally. Large-scale basement and Sinian, Paleozoic, and Triassic strata outcrop in the orogenic belt at the outer edge of the thrust belt and the deformations of the thrust folds are severe. Inside the Basin, the Mesozoic-Cenozoic strata are mainly outcrop; the strata at the edges are old, and those inside are new, and Cambrian-Carboniferous strata are generally absent (Figure 6). For example, the Hanshen 1 well encountered 70-meter-thick Lower Cambrian strata below the Permian and extended into the Sinian Dengying Formation for more than 200 m. The drilling confirmed the absence of Paleozoic and the relatively intact development of Permian-Mesozoic strata; Silurian, Cambrian, and Ordovician strata dominate the outcropping strata in the Zhougong Mountain and southern area.

Moreover, this area is located on the margin of the Sichuan Basin, with frequent tectonic activity, developed faults, and relatively poor preservation conditions. Of the outcropping strata in the Emei-Wawu Mountain tectonic region, most are Cambrian and Ordovician, and a small portion is the Sinian basement type, indicating that the caprock suffered severe denudation, tectonic nappe, tectonic compression, and uplift and that the hydrocarbon preservation conditions are poor. Cenozoic and Mesozoic strata dominate the interior of the Basin. For example, in the case of the strata above the Jurassic strata outcrop on the surface in the Daxingchang tectonic area, the interior of the Basin is less exposed to stratigraphic denudation and tectonic action, and the outcrops are new and better preserved than those on the outer edge of the Basin [43]. Overall, the outcrops in southwestern Sichuan Basin changed from old to new from the edge of the Basin to the inside of the Basin, and the Jurassic, Cretaceous, and Paleogene successively occurred, reflecting the strength of the differential tectonic uplifts and deformations of the orogenic front towards to the Basin. Among them, the Jurassic and Cretaceous are both distributed, constituting the basement background of the Cenozoic tectonic and sedimentary activity. Their preservation conditions are also successively improved.

4.3. Chemical Characteristics of the Formation Water. The metamorphic degree of formation water increases with the depth of the stratum longitudinally, and the salinity gradually increases. The water type changes from $NaHCO_3$ type in an open environment to $CaCl_2$ type in a closed environment [37]. The high mineralization and $CaCl_2$ water type indicate that the formation has a strong sealing capacity and good hydrocarbon preservation conditions; the low mineralization and $NaHCO_3$ or Na_2SO_4 water types indicate that hydrocarbon dissipation channels have been created, the formation water is in contact with the surface water, and hydrocarbon preservation conditions are poor. The differences in the formation water type and mineralization led to large differences in the hydrocarbon preservation conditions (Table 1). For the Gongshen 1 well, the formation water mineralization in the Cambrian is 74.10 g/L, the water

Table 1: Chemical characteristics of shallow and deep formation water in key wells in southwest Sichuan and its relationship with main control faults.

Well	Stratigraphic unit	Fault	Extension length (km)	Fault displacement (m)	Distance to main control fault (km)	Mineralization (g/L)	Water type
Woshen 1	Cambrian bottom	Wo 2	13.65	1000	0.4	0.84	$NaHCO_3$
Zhougong 1		Zhou 2	37.75	1820	0.65	3.58	$NaHCO_3$
Hanshen 1		24	25.97	600	1.2	2.35	Na_2SO_4
Gong 2		Gong 1	36.21	2000	2.4	15.3	$NaHCO_3$
Gongshen 1		Gong 1	36.21	2000	3.1	74.1	$CaCl_2$
Zhougong 1	Bottom of Upper Permian	A	20.94	700	0.9	0.84	$NaHCO_3$
Ma 1		B	24.22	500	1.4	3.58	Na_2SO_4
Han 1		C	23.33	450	1.5	0.878	$NaHCO_3$
Ta 6		E	17.79	100	2.2	35.76	$CaCl_2$
Zi 7		F	38.9	200	3.1	37.43	$CaCl_2$
Gong 2		G	15.71	1000	3.4	6.08	$NaHCO_3$
Laolong 1		H	13.3	200	3.65	21.6	$CaCl_2$
Zi 2		F	38.9	200	4.7	73.44	$CaCl_2$
Zi 9		F	38.9	200	4.9	51.13	$CaCl_2$
Han 2	Triassic bottom	Han 20	5.83	100	0.6	0.72	$NaHCO_3$
Ma 4		Ma 5	9.30	400	3.85	41.43	$CaCl_2$
Han 5		11	7.97	300	0.83	0.81	Na_2SO_4
Gaoxun 1		2	7.05	100	1.1	6.65	Na_2SO_4
Han 3		Han 12	20.67	600	1.6	8.82	$CaCl_2$
Zhougong 2		Zhou 2	48.29	900	1.62	16.66	Na_2SO_4
Wo 1		26	7.7	100	2.1	19.75	Na_2SO_4
Ma 12		Ma 3	7.31	100	4.1	46.68	$CaCl_2$

type is $CaCl_2$, and they are relatively good; for the Zhougong 1 and Hanshen 1 wells, the water types are $NaHCO_3$ and Na_2SO_4, respectively, and they are poor. For the Ta 6 and Zi 7 wells, the formation water mineralization values in the upper Permian are 35.76 g/L and 37.43 g/L, respectively, the water type is $CaCl_2$, and they are relatively good. The formation water mineralization for the Ma 1 well is 3.58 g/L, the water type is Na_2SO_4, and the relatively poor hydrocarbon preservation conditions. For the Ma 4 and Ma 12 wells, the formation water mineralization values in the Triassic are 41.43 g/L and 46.68 g/L, respectively, the water type is $CaCl_2$, and they are relatively good.

In addition, the quantitative relationship between the formation water mineralization of a single well and the distance between the well location and the dominating fault was studied to analyze the influence of the dominating fault on the measured production of the well, thereby analyzing the effect of the fault on the hydrocarbon preservation conditions. The statistical results show that in the Cambrian strata, within 1.5 km from the dominating fault, the mineralization values are less than 15.00 g/L, the water type is $NaHCO_3$, and the preservation conditions are poor; in the range of 1.5-3.0 km from the dominating fault, mineralization gradually increases, and they are moderate, which is the transitional zone for preservation conditions; for the wells with a distance greater than 3.0 km, from the dominating fault the mineralization values are greater than 40.00 g/L, the water type is $CaCl_2$, and they are good, the preservation conditions are good, and the correlation coefficient R^2 of the distance between the salinity and the main fracture is 0.5569 (Figure 7(a)). In the upper Permian strata, within 2 km from the dominating fault, the mineralization values are less than 10.00 g/L, the water type is $NaHCO_3$, and the preservation conditions are poor; in the range of 2.0 to 4.0 km from the dominating fault, the mineralization gradually increases, the water type is Na_2SO_4, and they are moderate; for the wells with a distance greater than 4.0 km from the dominating fault, the mineralization values are greater than 50.00 g/L, the water type is $CaCl_2$, and they are good, the preservation conditions are good, and the correlation coefficient R^2 of the distance between the salinity and the main fracture is 0.5706 (Figure 7(b)). In the Triassic strata, within 2 km from the dominating fault, the mineralization values are less than 20.00 g/L, the main water type is $NaHCO_3$, with the Na_2SO_4 type being occasionally observed, and the preservation conditions are poor; in the range of 2.0 to 5.0 km from the dominating fault, the mineralization values are 20.00-40.00 g/L, the water type is the Na_2SO_4, with the $CaCl_2$ type occasionally being observed, the preservation conditions are moderate, which is the transitional zone for preservation

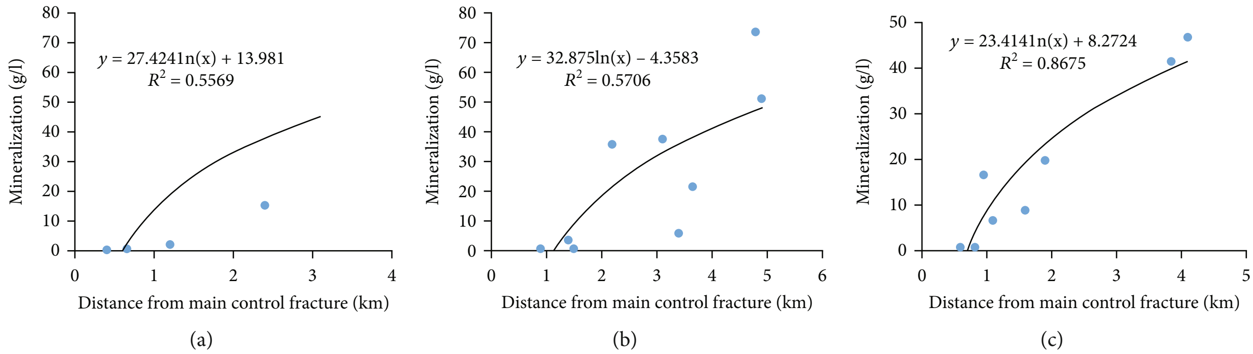


Figure 7: Relationship between the formation water mineralization values of key wells in the southwestern Sichuan Basin and the distance from the dominating fault. (a) Cambrian. (b) Upper Permian. (c) Triassic.

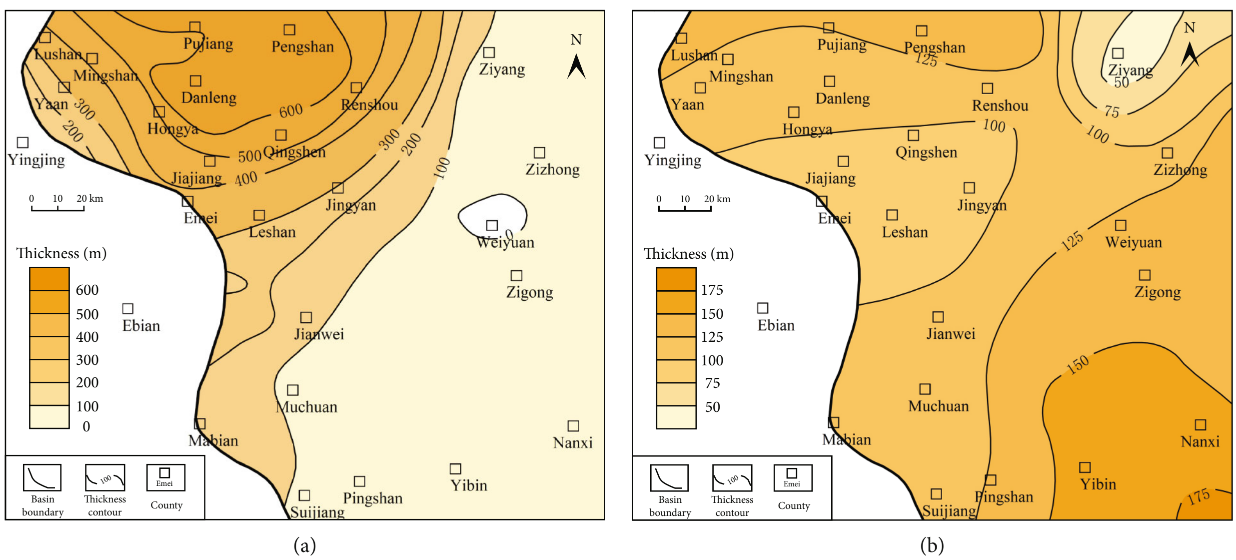


Figure 8: Planar distribution characteristics of the cumulative thickness values of the major caprocks in the Sichuan Basin. (a) Middle and Lower Triassic. (b) Lower Cambrian.

conditions; for the wells with a distance greater than 5.0 km from the dominating fault, the mineralization values are greater than 40.00 g/L, the water type is $CaCl_2$, and the correlation coefficient R^2 of the distance between the salinity and the main fracture is 0.8675 (Figure 7(c)).

4.4. Caprock Characteristics. The sealing performance of the caprock for the underlying reservoirs is an important hydrocarbon preservation condition. Gypsum-salt rock and shale are the two main types of the caprock. A good regional caprock determines hydrocarbon preservation; that is, the greater the thickness of the caprock, the better the hydrocarbon preservation. The main effective regional caprock are mudstones at the bottom of the Xujiahe Formation, Middle-Lower Triassic gypsum-salt rocks, and Lower Cambrian mudstones, and these three types of caprocks are widely distributed with a large thickness value and good sealing performance [44–46]. The thickness of the mudstone at the bottom of the Xujiahe Formation is in the range of 5-90 m, the thickness is generally less than 10 m, and the preservation of the caprock are moderate. The thickness of the Middle Lower Triassic mudstone ranges from 50-600 m and is mainly concentrated in <100 m and 200-300 m, with good sealing performance (Figure 8(a)). The thickness of the Lower Cambrian mudstone is 30-190 m, the thickness is relatively large, generally >50 m, the maximum thickness is >180 m, and they are good (Figure 8(b)). Overall, the regional caprocks inside the southwestern Sichuan Basin are relatively intact, with large thickness values, good sealing properties, and relatively good conditions. For example, the Daxingchang tectonic zone in the Basin is less affected by tectonic activity, and the regional caprock is well preserved. However, the outer edge of the Basin is affected by strong tectonic activity, caprock denudation is serious, and the thickness values of the regional caprock are small. In the Emei-Wawu Mountain structure, a large amount of pre-Sinian basement strata outcrop onto the surface, indicating that the regional caprock is totally damaged, forming a denudation skylight, and most of the hydrocarbons have been lost. In other words, the conditions of the caprock in

Table 2: The comprehensive evaluation system of the hydrocarbon preservation conditions of Cambrian formations.

Evaluation parameters	Evaluation results Class I	Class II	Class III
Distance to dominating fault/km	>3.0	1.5-3.0	<1.5
Fault development	Less distributed, small fault distance, and few cut-through horizons	Widely distributed, medium fault distance, and more cut-through horizons.	Widely distributed, large fault distance, multiple cut-through layers, and deep cut layers
Outcrops	Jurassic–Triassic	Permian-Devonian	Silurian-Sinian
Mineralization ($g\,L^{-1}$)	>40	15-40	<15
Water type	$CaCl_2$	$MgCl_2$, Na_2SO_4	$NaHCO_3$
Caprock	Large thickness and good sealing	Moderately sealed	Small thickness and severe erosion

Table 3: The comprehensive evaluation system for hydrocarbon preservation conditions of the Upper Permian formations.

Evaluation parameters	Evaluation results Class I	Class II	Class III
Distance to dominating fault (km)	>4.0	2.0-4.0	<2.0
Fault development	Less distributed, small fault distance, and few cut-through horizons	Widely distributed, medium fault distance, and more cut-through horizons.	Widely distributed, large fault distance, multiple cut-through layers, and deep cut layers
Outcrops	Jurassic–Triassic	Permian-Devonian	Silurian-Sinian
Mineralization ($g\cdot L^{-1}$)	>50	10-50	<10
Water type	$CaCl_2$ is the dominant type, followed by $MgCl_2$	$MgCl_2$, Na_2SO_4	$NaHCO_3$, Na_2SO_4
Caprock	Large thickness and good sealing	Moderately sealed	Small thickness and severe erosion

Table 4: The comprehensive evaluation system of hydrocarbon preservation conditions of Triassic formations.

Evaluation parameters	Evaluation results Class I	Class II	Class III
Distance to dominating fault/km	>4.0	2.0-4.0	<2.0
Fault development	Less distributed, small fault distance, and few cut-through horizons	Widely distributed, medium fault distance, and more cut-through horizons.	Widely distributed, large fault distance, multiple cut-through layers, and deep cut layers
Outcrops	Jurassic–Triassic	Permian-Devonian	Silurian-Sinian
Mineralization (g/L)	>40	20-40	<20
Water type	$CaCl_2$ is the dominant type, followed by $MgCl_2$	$MgCl_2$, Na_2SO_4	$NaHCO_3$, Na_2SO_4
Caprock	Large thickness and good sealing	Moderately sealed	Small thickness and severe erosion

the southwestern Sichuan Basin gradually improve from the orogenic belt outside the basin to the tectonic stability zone inside the basin.

5. Discussion

5.1. Comprehensive Evaluation System of Preservation Conditions. As mentioned above, hydrocarbon preservation conditions are closely related to tectonic characteristics, outcrop characteristics, formation water characteristics, and caprock characteristics [47–52]. Fold deformation, fault cutting, stratum uplift, denudation, surface water seepage, and destruction of the pressure system are the fundamental causes of the destruction and dissipation of the reservoirs. Formation water type and mineralization are important factors. High mineralization and $CaCl_2$ water type often indicate good hydrocarbon preservation conditions. The outcrops on the surface are also closely related to the hydrocarbon preservation conditions. A good regional caprock determines the hydrocarbon preservation, the greater the

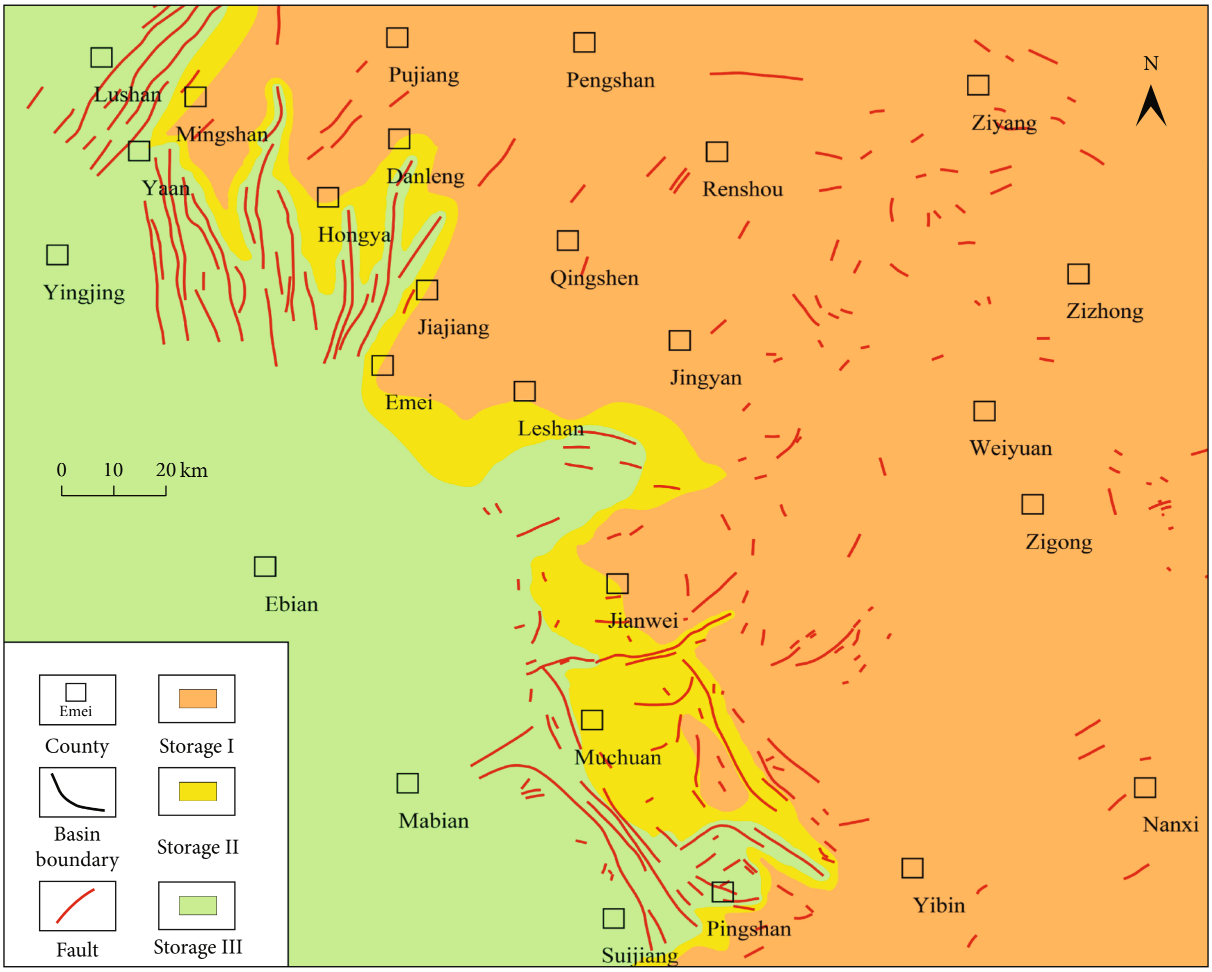


FIGURE 9: Planar distribution of the comprehensive evaluation of hydrocarbon preservation in the Cambrian strata in the southwestern Sichuan Basin.

thickness of the caprock, the better the hydrocarbon preservation conditions. Based on these factors, scholars have conducted comprehensive studies on hydrocarbon preservation conditions in many basins and regions in China and established comprehensive evaluation criteria [53–55]. Based on these studies, we established a comprehensive evaluation system (Tables 2–4), which divides the study area into Classes I, II, and III according to the differences in preservation conditions, with Class I being the area with the best preservation conditions.

5.2. Distribution Characteristics of Areas Favorable for Hydrocarbon Preservation. The preservation conditions of the Cambrian strata are generally good, and the distribution range of Class I areas is large, mainly inside the Basin to the east of Meishan-Hongya-Danling-Emei-Leshan-Ganwei-Pingshan. In the Class I areas, the faults are less developed, the fault distances are small, the formation water mineralization values of the key wells are high (>40 g/L), the water type is $CaCl_2$, and the distances from the dominating fault are >3 km, and the formation pressure coefficient is generally high (>1.3). The Class II areas are distributed close to the edges of Class I areas, with a small distribution range, and they are generally located in the southeastern part of the Emei-Wawu Mountain tectonic system, which is mostly at the edges of the Basin. The main outcrops of Class II areas are the Permian-Devonian strata, with moderate tectonic deformations and some developed small-scale faults. In addition, the formation water mineralization values are high, the water types are $MgCl_2$ and Na_2SO_4, and the hydrocarbon preservation conditions are moderate, with certain exploration potential. The hydrocarbon preservation conditions in the Class III areas are the most unfavorable; the Class III areas are mostly located in the orogenic belt outside the Basin (such as within the Zhougong Mountain and Hanwangchang structures), and the main outcropping strata are Silurian, Cambrian, and Ordovician, and tectonic activity is frequent. The faults are densely distributed and accompanied by the large Tongtian faults; the Zhougong 1 and Hanshen 1 wells produce freshwater in the Sinian system, and the hydrocarbon preservation conditions are poor. The pressure coefficient in the Laolongba tectonic zone is low,

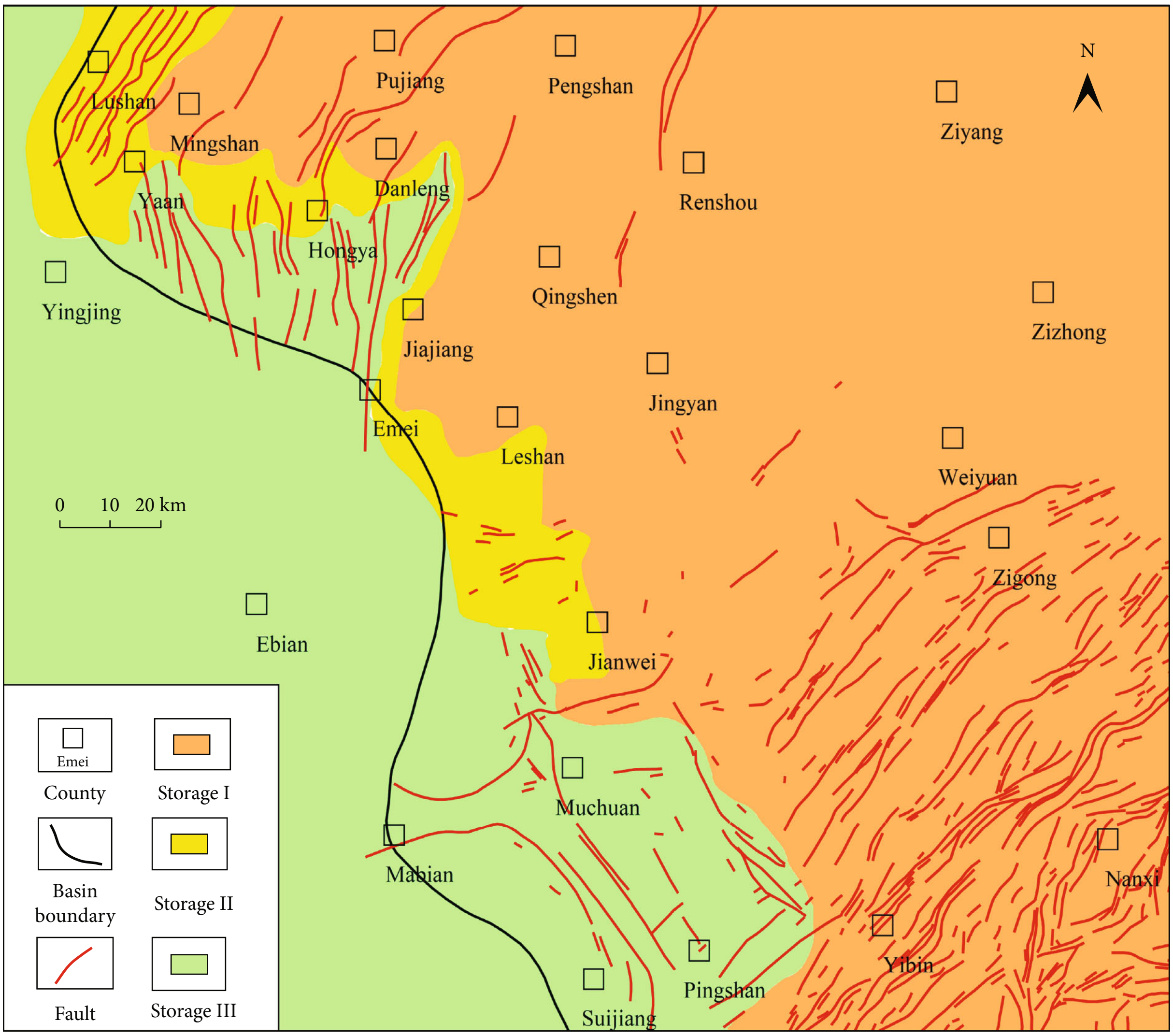


Figure 10: Planar distribution of the comprehensive evaluation of the Upper Permian hydrocarbon preservation in the southwestern part of the Sichuan Basin.

with low local pressure, poor sealing performance [56], and damaged hydrocarbon preservation conditions that are not conducive to hydrocarbon exploration (Figure 9).

The Class I areas of the upper Permian strata in the study area are consistent with the Cambrian strata. These areas are mostly located in the interior of the Basin, with small degrees of fault development, small fault distances, high formation water mineralization values in key wells, and a $CaCl_2$ water type. In addition, the distances from the dominating faults are generally greater than 4 km, and the mineralization values are greater than 50 g/L. The Class II areas are mostly located at the edges of the Basin, the distribution ranges are small, and the extension lengths of the fault are generally greater than 12 km. The distances from the dominating faults Class II areas are generally in the range of 2-4 km, the water type is Na_2SO_4, with the $CaCl_2$ type being occasionally observed, and the mineralization values are between 10 and 50 g/L. The distribution range of the Class III areas is significantly smaller than that of the Cambrian strata, and the Class III areas, which have poor hydrocarbon preservation conditions, are mostly located in the orogenic belt outside the Basin, with extensive fault development. The fault extension lengths are generally greater than 15 km (such as in the Zhougong Mountain area). Wells within 2 km of the faults with fault distances greater than 400 m mainly produce freshwater, mostly the $NaHCO_3$ type, and low mineralization values (Figure 10).

The comprehensive evaluation results of the Triassic strata have the best agreement with those of the upper Permian strata. The Class I areas are mostly in the interior of the Basin to the east of Tianquan-Mingshan-Hongya-Danling-Jiajiang-Leshan-Qianwei-Yibin-Pingshan, with a small degree of fault development, small fault distances, high mineralization values of the formation water in key wells, a $CaCl_2$ water type, distances from the dominating fault generally greater than 4 km, and mineralization values greater than 40 g/L. The Class II areas are less well distributed. They are mainly located along the Danling-Jiejiang-Emei-Muchuan-Pingshan,

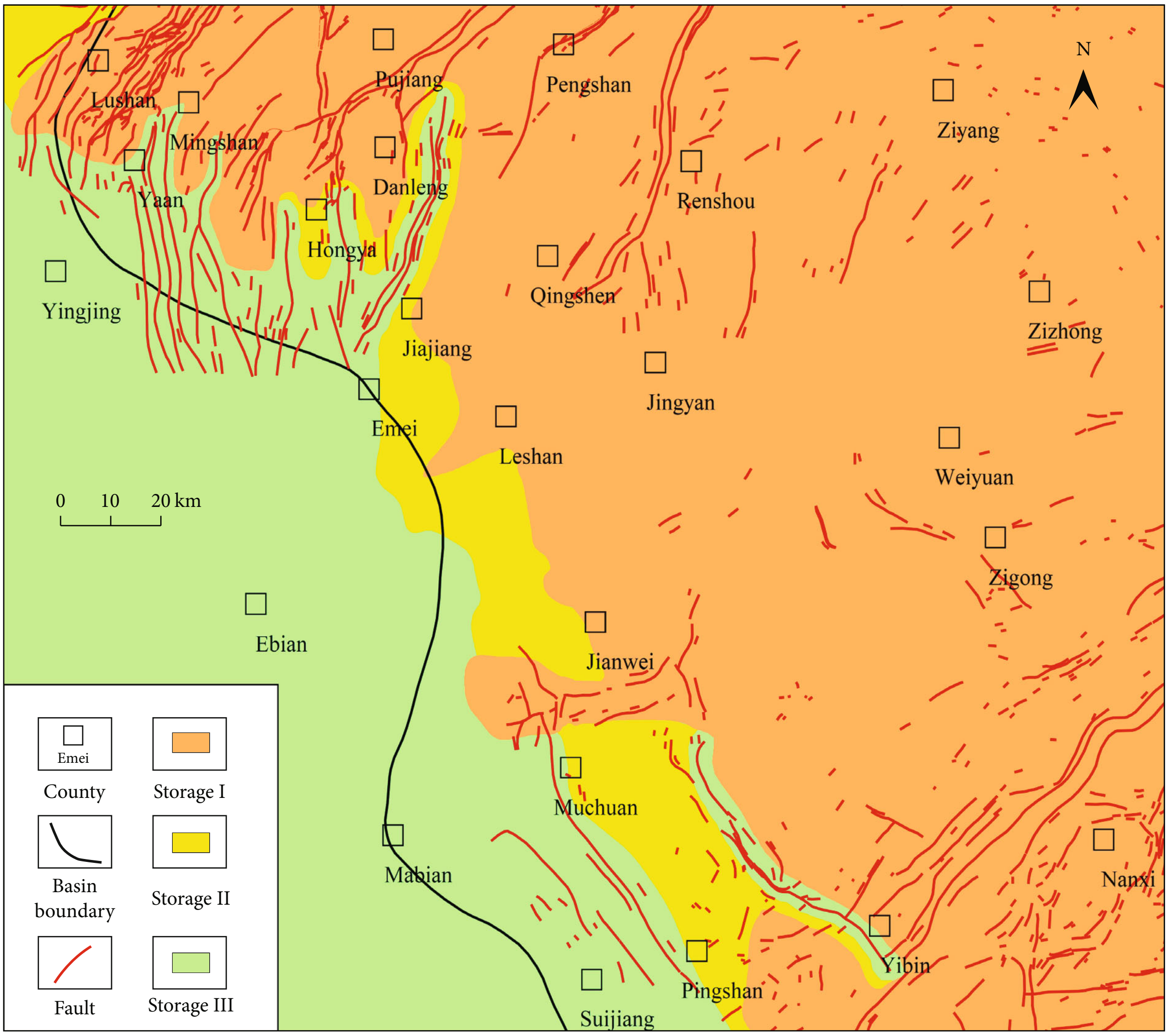


Figure 11: Planar distribution of the comprehensive hydrocarbon preservation evaluation results of Triassic formation in the southwestern part of the Sichuan Basin.

with fault extension lengths greater than 20 km. They are within 2-4 km of the faults with fault distances greater than 350 m, moderate fault developments, medium formation water mineralization, and moderate hydrocarbon preservation conditions. The Class III areas, which have the smallest distribution range, are mainly in the northwestern part and are near the Gong 2 and Gongshen 1 wells. Overall, the Class III areas are within 2 km of faults with fault extension lengths greater than 20 km and fault distances greater than 350 m or is located in a fault-intensive area. The key wells mainly produce the $NaHCO_3$ and Na_2SO_4 water types, with low mineralization values. These areas have poor hydrocarbon preservation conditions (Figure 11).

6. Conclusion

(1) The southwestern Sichuan Basin has two obvious tectonic layers (the upper and lower). Middle Triassic detachment and derived thrust faults dominate the upper tectonic layer. In contrast, the lower tectonic layer has concealed structures composed of basal detachment faults and derived thrust faults. The preservation conditions of the lower tectonic layer are better than those of the upper tectonic layer. The fault strikes of the major horizon formations (Cambrian, upper Permian, and Triassic) have good inheritance

(2) The study area mainly consists of three sets of high-quality caprocks, i.e., Middle-Lower Triassic gypsum-salt rocks, Lower Cambrian mudstones, and mudstones at the bottom of the Xujiahe Formation, and the first two have a large thickness and a high sealing capacity values. When the distances from the fault are large, the formation water mineralization is high, and the water type is $CaCl_2$, the corresponding hydrocarbon preservation conditions are good

(3) The characteristics of the faults, formation water type, outcrops, and caprocks were selected as the most important parameters. Evaluation criteria for the hydrocarbon preservation conditions in key horizons were established, and the classification of hydrocarbon preservation conditions (Class I, II, and III) was completed. Class I areas are the most favorable areas for hydrocarbon preservation. The distribution ranges of the different strata are relatively wide and similar and are mainly located within the Basin. Hydrocarbon preservation conditions progressively improve from outside to inside the Basin

Data Availability

The data used to support the findings of this study are included within the paper.

Conflicts of Interest

The authors declare no conflict of interest.

Authors' Contributions

Cunhui Fan, Huwei Cao, Lifeng Meng, and Haihua Zhu were responsible for conceptualization, methodology, and software acquisition and wrote the original manuscript. Jing Li, Maolong Xia, Jing Liu, and Jing Liang were responsible for data curation and interpreted the results. All authors have read and agreed to the published version of the manuscript.

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