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Formation and Distribution of Tight Sand Gas Reservoirs in the Sichuan Basin, China

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Abstract

Located in the central west of China, the Sichuan Basin is abundant in natural gas resources. It is the earliest basin where natural gas was discovered and utilized in the world. After more than 60 years' exploration, many gas fields have been found in the Paleozoic - Mesozoic carbonate and clastic formations. The basin has become a critical production base in China for its cumulative proved recoverable gas reserves of more than 8,000×10^8 m^3, and gas production over 150×10^8 m^3 in 2010. During the past decade, many tight gas reservoirs have been found in the Xujiahe coal measures of the upper Triassic continental deposits. Based on lithology, this suite of formation can be divided into six members from bottom to top. The source rocks are the coal beds and carbon-bearing mudstones in Xu1, Xu3 and Xu5 members with relatively high organic carbon contents and type III kerogen; the reservoir rocks are the tight sandstones in Xu2, Xu4 and Xu6 members. The source rocks and the reservoirs distribute alternatively and widely in "sandwiched" structure, providing favorable conditions for natural gas accumulating near source. As the formations are gentle and lack of structural traps, the lithologic gas reservoirs dominate the Xujiahe tight sandstones. Both coal-measure source rocks and sandstone reservoir distribute in strong heterogeneity, leading to thin gas-layers in the reservoir, poor continuity in plane, and varying full-up ratio and gas saturation in the gas reservoir. Within the 80,000 km^2 area, the Xujiahe Formation has the features of widespread gas-bearing beds and local gas enrichment. The current high-yield gas wells are mainly distributed in the tectonic highs or fractured zones in the areas with effective source-reservoir assemblages. The resources assessment is made considering the tight gas accumulating intensively into reservoir. It reveals the favorable gas-bearing area up to 6×10^4 - 7×10^4 km^2 and the estimated recoverable gas reserves of 2×10^{12} - 3×10^{12} m^3 in the Xujiahe Formation.

Key words: Sichuan Basin; Tight sandstone; Coal measures; Tight gas; "Sandwiched" structure; Resources

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INTRODUCTION

Located in the southwestern China, the Sichuan Basin is prolific in natural gas. Extensive exploration began from the 1950s, to find structural and fractured gas reservoirs initially. However, most of the discovered gas reservoirs were small. In the past decade, along with the progress of exploration and development technologies, many lithologic-stratigraphical reservoirs were discovered, making the gas reserves up to several hundreds to thousands billions of cubic meters. The discoveries of some large gas fields (such as Puguang and Luojiazhai) in marine carbonate reservoirs represent significant breakthroughs of exploration in the Sichuan Basin. Recently, Guang'an, Hechuan and other 10^8 m^3-level gas fields were found in the Xujiahe continental tight sandstones, with 3P gas reserves more than trillion cubic meters, which made this formation the critical target in the Sichuan Basin and even China. The tight gas exploration area and scale are still expanding.

1. GEOLOGIC SETTING

The formations in the Sichuan Basin are complete, from Proterozoic Sinian to Cenozoic Quaternary. In particular, the marine facies dominate the middle-lower Triassic and formations below, and the continental facies control upper Triassic and formations above. In this basin, there are six suites of regional gas source rocks, and the discovered gas reservoirs distribute in nearly 12 series of strata, of which over one-third are in the Xujiahe Formation of upper Triassic with reserves more than 6,000×10^8 m^3. This formation has been developed for nearly half a century[1,2]. Those gas fields discovered initially are covered in the Longmenshan front structural belt in the western Sichuan Basin, consisting of small structural and fractured gas reservoirs. In recent years, with the further exploration and research, many large gas fields have been acquired, such as Bajiaochang, Guang'an and Hechuan in the central Sichuan, Zhongba and Pingluoba in the western Sichuan, Longgang in the northern Sichuan, Jiulongshan in the northwestern Sichuan, and Baimamiao in the southwestern Sichuan, forming a giant gas province with trillion-m^3 gas reserves (Figure 1). Following the Triassic Feixianguan Formation and Permian Changxing Formation, Xujiaohe Formation has become another growth point of natural gas in the Sichuan Basin[3]. It can be said that the Xujiahe gas coverage extends almost everywhere in this basin, indicating the further potential of gas exploration[4,5].

A suite of continental clastic coal-bearing formation covering the whole basin was developed in the Xujiahe Formation, upper Triassic. It can be divided into six members from bottom to top. Xu1, Xu3 and Xu5 members are major source rocks and cap rocks, consisting of black shale and mudstone, interbedded with siltstone, sandstone, coal bed or coal seam; they are mature-high mature, under the stage of gas generating. Xu2, Xu4 and Xu6 members are major gas reservoirs, containing grey medium-fine sandstone, interbedded with thin muddy shale, showing poor properties. Above source rocks and reservoirs are overlapped with each other vertically, in extensive and alternative distribution[1,6-8] (Figure 1).

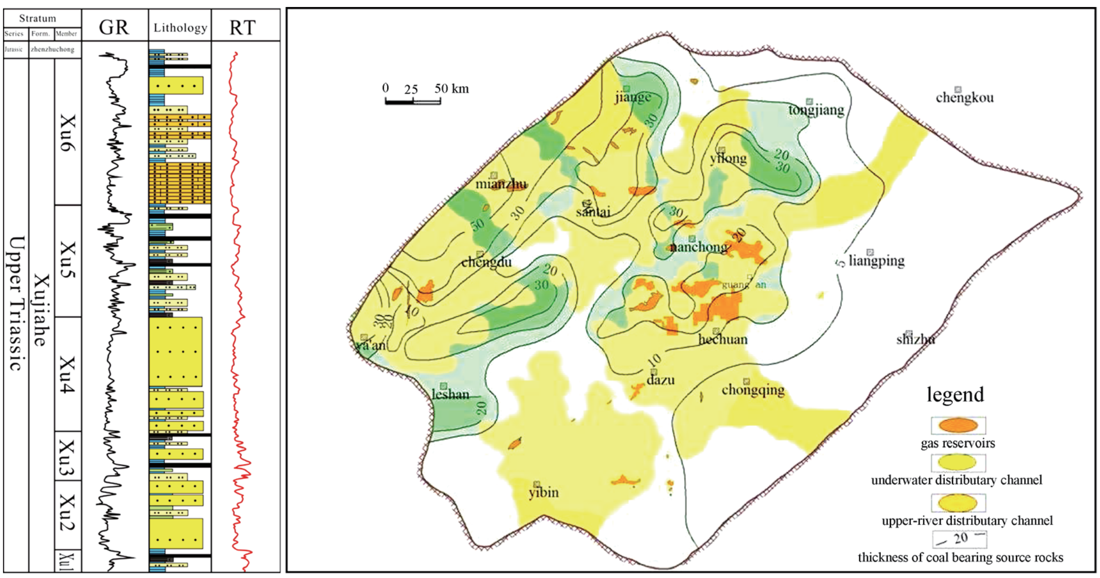


Figure 1
Stratigraphic Profile and Distribution Map of Gas Source Rocks and Reservoir of Xujiahe Formation, the Sichuan Basin

2. GAS ACCUMULATING CHARACTERISTICS AND FORMING CONDITIONS

2.1 Geologic Features of Natural Gas in the Xujiahe Formation

The studies have proved that the heterogeneity of source rocks and reservoirs causes the distinct distribution of Xujiahe tight gas in different areas. In contrast with other basins, such as the western Canadian Basin where tight gas is also called "continuously accumulated gas"[9,10], the Xujiahe Formation tight gas reservoir is much different and special in the following aspects.

2.1.1 Gas Reservoirs Are Distributed in Patched Form

The source rocks of Xujiahe Formation are mainly dark mudstone, carbon-bearing mudstone and coal bed. The lateral change of deposit environment led to the plane distribution unbalance of the source rocks. Generally, the dark mudstone is thicker, increasing from southeast to northwest, and averagely 40-150 m in Xu1, Xu3 and Xu5 members; the coal bed and carbon-bearing mudstone are relatively thinner. According to the analysis of geochemical data, the average organic carbon content in the Xujiahe dark mudstone is 1.95%[5,11]; the organic carbon content in the carbon-bearing mudstone is generally more than 10%, with hydrogen index over 100 mg/gTOC, and the organic carbon content in the coal bed is more than 60%, with hydrogen index over 150 mg/gTOC, which is different from abroad source rocks[12-19]. Thermal simulation reveals the hydrocarbon potentials of various gas source rocks in the Xujiahe Formation as: coal bed, 97 mg/g; carbon-bearing mudstone, 15 mg/g; mudstone, only 2.4 mg/g, slightly lower than that of basins abroad. Because of the high organic carbon contents and hydrocarbon generation potentials, the carbon-bearing mudstone and coal bed are the major gas source rocks in Xujiahe Formation. Their thickness variation can be used to qualitatively judge the plane distribution of gas source kitchens and gas generation intensity.

We investigated the thickness of coal bed and carbon-bearing mudstone in near 100 wells within this basin, and drawn a plan distribution map of strata depending on the changes of sedimentary facies (Figure 2). In short, the average thicknesses gradually increase from Xu1 to Xu5, and from central Sichuan to western Sichuan. Particularly, the thickness of coal bed is 5-15 m in central Sichuan, and 10-20 m in western Sichuan; the thickness of carbon-bearing mudstone is bigger, namely 10-20 m in central Sichuan and 20-30 m in western Sichuan. From the view of series of strata, the coal bed and carbon-bearing mudstone of Xu1 member are relatively limited in distribution, mainly in central Sichuan Basin (including Bajiaochang, Yingshan and Hechuan-Anyue areas, with smaller thickness of 3-6 m) and western Sichuan Basin (including Zhongba and its southern areas, with bigger thickness of 5-15 m), only 1-2 m in other areas. In contrast, the coal bed and carbon-bearing mudstone of Xu3 member are vast, covering most areas of the Sichuan Basin. In the middle and southern parts of the western Sichuan Basin, Xu3 member is up to 10-30 m thick, or over 40 m in Zhongba-Mianyang area. In the central Sichuan Basin, Xu3 member is mainly observed in Yilong-Guang'an, Weiyuan and Leshan areas, with thickness of 3-8 m generally (Figure 2). The coal bed and carbon-bearing mudstone of Xu5 member distribute in the eastern and northern parts of the central Sichuan Basin and the southern part of the western Sichuan Basin, with general thickness of 10-20 m, up to 20-30 m Longgang, Bajiaochang and Mianzhu areas.

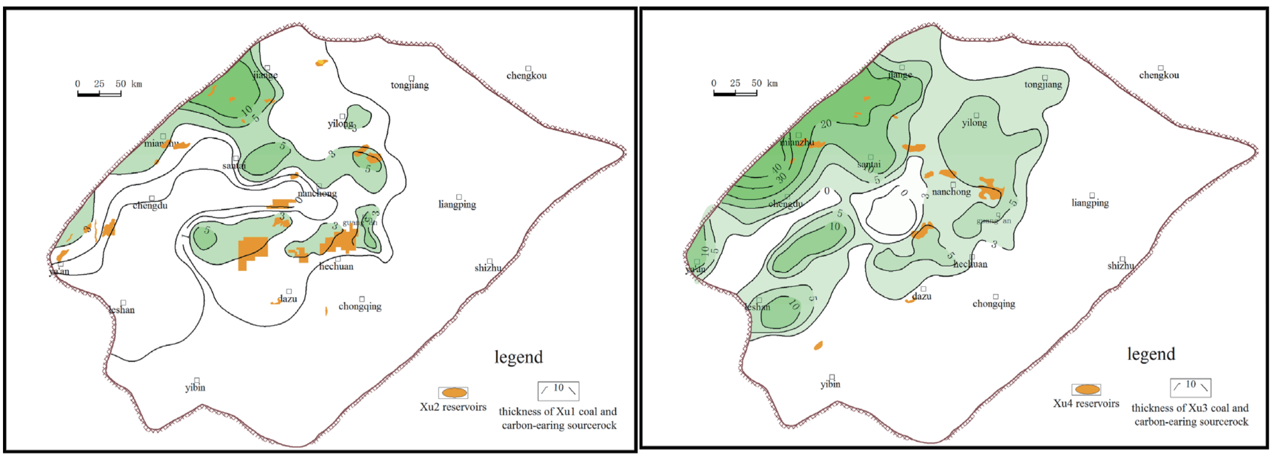


Figure 2
Distribution Map of Gas Source Rocks and Gas Reservoirs of Xu1 (Left) and Xu3 (Right) Members in the Sichuan Basin

It can be seen that the plane heterogeneity of major source rocks in the Xujiahe Formation caused the great variation of drainage area and intensity, and the strong heterogeneity of the reservoir made the natural gas expelled from source rocks hard to migrate laterally when it entered the reservoir, so the Xujiahe gas reservoirs distributed in patched form, not everywhere in the basin.

2.1.2 Gas Reservoirs Have Poorer Internal Continuity

The Xujiahe sandstone reservoir in the Sichuan Basin is mainly shallow braided river delta deposit, showing the features of wide lake basin, shallow water body and dispersing water system. The river channels are frequently redirected, overlapped and converged, with wide facies belt; there are many mono-stage river channels in limited size, while the multi-stage river channels are superimposed, converged and laterally connected to form sandstone composites which are sill-like macroscopically and heterogeneous microscopically. During original deposition, this suite of sand body was laterally connected and interbedded with coal measures; the original water body was more acidic, with stronger diagenesis after being buried and more loss of porosity as the result of cementation. Therefore, the connectivity of and between effective sand bodies with accumulation capacity became poorer; some sand bodies even became tight rocks as the result of cementation and failed to act as valid reservoir. Therefore, the gas reservoirs became less connected due to different physical properties. Moreover, the barriers in the reservoir divided a gas field into several gas reservoirs; each gas reservoir is independent, but multiple reservoirs are overlapped vertically, leading to wide gas-bearing scope on the plane, showing "patched" distribution in local areas.

Guang'an is one of the major gas fields discovered in the Xujiahe Formation, with major payzones in Xu4 and Xu6 members. Based on the logging data and core analysis, there are six reservoir intervals interpreted in Xu6 member, which belong to gas layer, gas-water layer and gas-bearing water layer. These intervals are separated by tight sandstone or mudstone, thus single gas layer is thinner (generally 4-12 m) with area of 51-218.5 km^2. The physical properties of the intervals (consisting of medium sandstone and medium-fine sandstone) are better, with porosity of 10% - 11.8%, permeability of 0.68 - 0.9 mD, and displacement pressure of 0.34 - 1.32 MPa. In contrast, the physical properties of the barriers (consisting of tight sandstone or mudstone, intensive and thick as 4-13 m) are poorer, with porosity of 2.8% - 5.5%, permeability of 0.01 - 0.05 mD, and displacement pressure of 0.94 - 8.38 MPa. Such barriers also exist in Xu4 member of Guang'an gas field and other gas reservoirs in the central Sichuan Basin, leading to discontinuous gas reservoir (Figure 3). Based on sand body thickness, sedimentary microfacies, test pressure, gas testing and other data, the Xu4 member of Guang'an gas field can be divided into 35 - 60 relatively independent gas storage units. These units are independent, with respective pressure system. In macroscopic viewpoint, these units are interlapped to form the giant $1,000 \times 10^8$ m^3 Guang'an gas field.

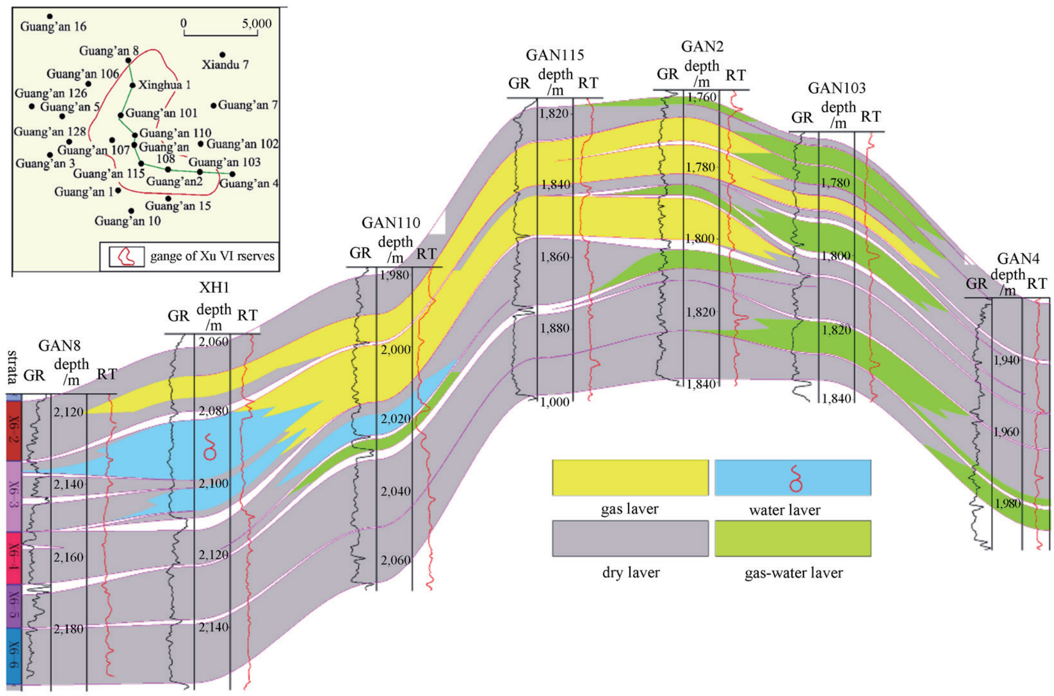


Figure 3
Vertical Reservoir Separation of Xu6 Member in the Guang'an Area

Table 1
Features of Xujiahe Gas Reservoir in the Central Sichuan Basin

Gas field	Trap type	Gas bearing area (km^2)	Number of gas reservoirs	Thickness of gas layer (m)	Full-up ratio(%)
Xu6 in Guang'an area	Lithologic-Structural	200.8	15 - 25	8 - 13	55 - 67
Xu4 in Guang'an area	Structural-Lithologic	415.6	28 - 35	5 - 10	21 - 46
Xu2 in Hechuan area	Lithologic-Structural	1,058.3	24 - 30	5 - 15	52 - 61
Xu2 in Tongnan area	Lithologic	278.8	16 - 20	4 - 12	26 - 42
Xu4 in Moxi area	Structural	26.25	5 - 8	10 - 20	55 - 58

2.1.3 The Gas Reservoir's Full-up Ratio Is Lower, and Gas Saturation Changes Much

According to the dissection on the discovered Xujiahe gas reservoirs in the central Sichuan Basin, it can be seen that the gas reservoir's general full-up ratio is lower; the reservoir at structural lows usually produce water, but the reservoir at structural highs shows better gas-bearing capacity even though it has poor properties. The statistics of full-up ratio of Xujiahe gas reservoir in the central Sichuan Basin are shown in Table 1. It is found that the full-up ratios of Xu2, Xu4 and Xu6 members are only 30% - 60%; the structural or lithologic-structural gas reservoirs have biggest full-up ratio, up to 56% - 61%, while the structural lows, with visibly poor gas-bearing capacity, only show full-up ratio of about 30%. Insufficient gas source is the major reason for low full-up ratios of Xu2, Xu4 and Xu6 members. At structural highs, the gas abundance becomes much better. According to the reservoir charging mechanism, under the buoyancy, gas would firstly charge the reservoir top in closely contact with cap rock, and then expand downward and outward. If the gas source is sufficient, the gas may fully charge the whole trap[20,21].

The inhomogeneity of gas source kitchen and reservoir and the difference of structural amplitude also result in the big variation of gas saturation in the Xujiahe gas reservoirs. The Xu6 gas reservoir in Guang'an area shows favorable properties, with average porosity of 10% - 11.8%, and permeability of 0.68 - 0.9 mD. Gas saturation in Guang'an 2 well field at the structural highs can be up to 55%, without gas produced, while the average gas saturation in Guang'an 101 well field at the structural lows is only 42%, with both gas and water produced or more water and less gas produced. These well fields are not much different in physical properties. In Tongnan area, natural gas is mainly distributed in the upper Xu2 member where the physical properties are poor (average porosity: 7.9%, average permeability: 0.2 mD, gas saturation: over 50%); but the reservoir in the lower Xu2 member with better physical properties is mainly gas-bearing water layer, with average porosity of 9.2%, average permeability of 0.4 mD, and gas saturation of 60% - 75%, which is well related to the thinner gas source kitchen in the lower Xu2 member, dominant dark mudstone and insufficient gas supply.

2.2 The Forming Conditions Demonstration of Tight Gas Reservoirs

During the past few years, we have intensively and effectively studied the major controlling factors of gas accumulation in the Xujiahe Formation, including fine description of source-reservoir-caprock, distribution and evaluation of major gas source kitchen, conditions and features of high productivity and enrichment of gas reservoirs.

2.2.1 "Sandwiched" Source-Reservoir-Caprock Assemblage, With Advantage for Near-Source Gas Accumulation

As described earlier, the gas source rocks are mainly distributed in Xu1, Xu3 and Xu5 members, containing coal bed and carbon-bearing mudstone and distributing in 8×10^4 - 12×10^4 km^2 coverage. For single layer of coal bed and carbon-bearing mudstone, the thickness is 5 - 20 m, and the gas generation intensity is 5×10^8 - 20×10^8 m^3/km^2. The reservoir rocks are mainly Xu2, Xu4 and Xu6 tight sandstones, with average porosity of 5% - 10%, and average permeability of 0.01 - 0.5 mD. This tight sandstone reservoir may distribute in an area up to 11×10^4 - 14×10^4 km^2, with single layer thickness of 10 - 30 m generally. The gas source rocks of Xu1, Xu3 and Xu5 members closely and intensively contact with the reservoirs of Xu2, Xu4 and Xu6 members, with direct contact area of 8×10^4 - 11×10^4 km^2, forming large-scale interbedded "sandwiched" structure. Moreover, because of the frequent lake surface cycling of Xujiahe shallow lake basin during a short period, sandstone also deposited in the source rocks of Xu1, Xu3 and Xu5 members; similarly, mudstones developed in each reservoir. This made the source rocks and reservoirs not only overlapped extensively, but alternate in each suite of assemblage, expanding the contact area between the source rocks and reservoirs. Thus, the hydrocarbon expulsion efficiency is improved, gas is more possibly to accumulate in each effective sandstone layer, and the gas reservoir coverage is also broadened (Figure 4).

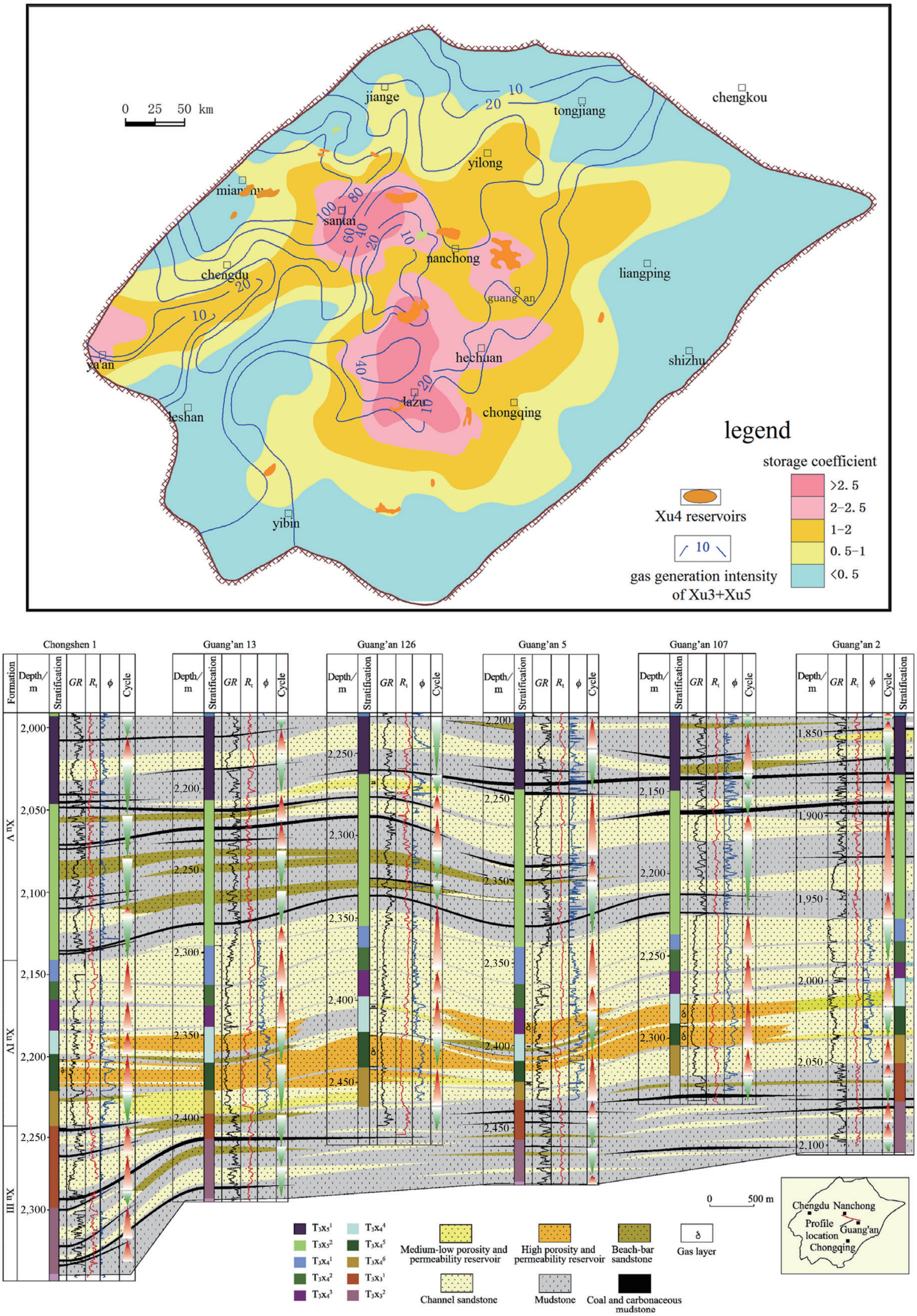


Figure 4
Plane (up) and Profile (Down) Distribution of the "Sandwiched" Source-Reservoir-Caprock Assemblage in the Xujiahe Formation

Under the "sandwiched" source-reservoir-caprock assemblage, natural gas generated in the source rocks expels and then charges intensively the upper and lower adjacent reservoirs and the reservoirs in the source rocks. Because of the gentle structures, high tightness and strong heterogeneity of the Xujiahe Formation, natural gas is difficult to migrate and accumulate massively after entering the reservoir, but accumulate in sandstones with better physical properties near gas source kitchen. This can be illustrated by the following aspects. Firstly, the natural gas is extremely different in the western Sichuan and the central Sichuan. In Zhongba and Pingluoba areas of the western Sichuan, the Xu2 gas reservoirs have higher methane contents, with dry coefficient of 0.95 - 0.97 and methane carbon isotope of -33‰ - -36‰, which reflects the higher gas maturity, corresponding to the high evolution of gas source kitchen in this area. But in most central Sichuan, the gas reservoirs have lower methane contents, with dry coefficient of 0.86-0.93, and methane carbon isotope of -38‰ - -42‰, which reflects the lower gas maturity, corresponding to the low evolution of gas source kitchen in this area. This means that the natural gas in western Sichuan depression didn't laterally migrate into the central Sichuan in large scale. On the other hand, the natural gas in the central Sichuan also mainly accumulated near source. For example, Xu2 gas reservoirs in Hechuan area have 4% higher methane contents, 3% lower ethane contents, and 0.3% - 0.4% higher methane and ethane carbon isotope than those of Tongnan area, showing their apparent gas source differences.

2.2.2 Effective Source-Reservoir Assemblage Distribution Controlled Gas Accumulation and Enrichment

The Xu4 and Xu6 gas reservoirs in Guang'an area are in different series of strata in the same area. Their composition and isotope are very different. In Xu4, the methane content is 90% - 95%, ethane content is 3% - 6%, methane carbon isotope is -38 - -36‰, and ethane carbon isotope is -26‰ - -22‰; in Xu6, the methane content is 87% - 93%, ethane content is 5% - 8%, methane carbon isotope is -42‰ - -39‰, and ethane carbon isotope is -29‰ - -25‰. These features indicate that the maturity of Xu4 is higher than that of Xu6, and they originated from different gas sources. The Xujiahe Formation is of "self-generation and self-accumulation"[20]. According to the geochemical parameters and maturity of gas source rocks in this area, natural gas in Xu4 member is mainly from the underlying Xu3 gas source rock, and Xu4 and Xu3 constitute a suite of independent source-reservoir assemblage; but natural gas in Xu6 member is mainly from the underlying Xu5 gas source rock, and they belong to another source-reservoir assemblage.

(a) Distribution of Effective Source-Reservoir Assemblage
Taking Xu3 and Xu4 source-reservoir assemblage as example, the statistics and analysis are made on the sand/mud ratios of the Xujiahe Formation drilled by more than 200 wells. It is concluded that in most areas of the northwestern Sichuan and some areas of the central-southern Sichuan, the sandstone thickness in Xu3 member is over 25 m, and average sand content is more than 20% (Table 2). Therefore, the sandstone-mudstone in the Xu3 member can constitute an effective source-reservoir assemblage. In the Xu4 member, the mud contents in formations of Ziyang area in southwestern Sichuan and southeastern Sichuan are over 25% or 30% - 40% generally, indicating that there are thicker mudstones developed in Xu4 member, which are continuously distributed in profiles. For example, in Well Siyi1 in north-western Sichuan, the Xu4 member is 242 m thick, with mud content of 50%; coal bed and carbon-bearing mudstone developed in the nearly 100m-thick mudstone, forming source-reservoir assemblage with interbedded sandstone. Moreover, the Xu3 pure mudstones with lower sand content and the overlying Xu4 sandstones form the Xu3 + Xu4 source-reservoir assemblage (Figure 5). For example, in Zi5 well field, the Xu3 member is mainly composed of muddy source rock, but the Xu4 member contains sandstone by 90% plus, which jointly constitute the favorable source-reservoir assemblage.

Table 2
Thickness and Sand/Layer Ratio of Xu3 Member in the Sichuan Basin

Well name	Strata thickness (m)	Sandstone thickness (m)	Mudstone thickness (m)	Sand content (%)
Jiepai1	130	92	38	29
Yu1	165	100	65	60
Longfeng1	647	446	201	69
Chongshen2	101	31	70	31
Tongnan103	74	38.6	35.4	52

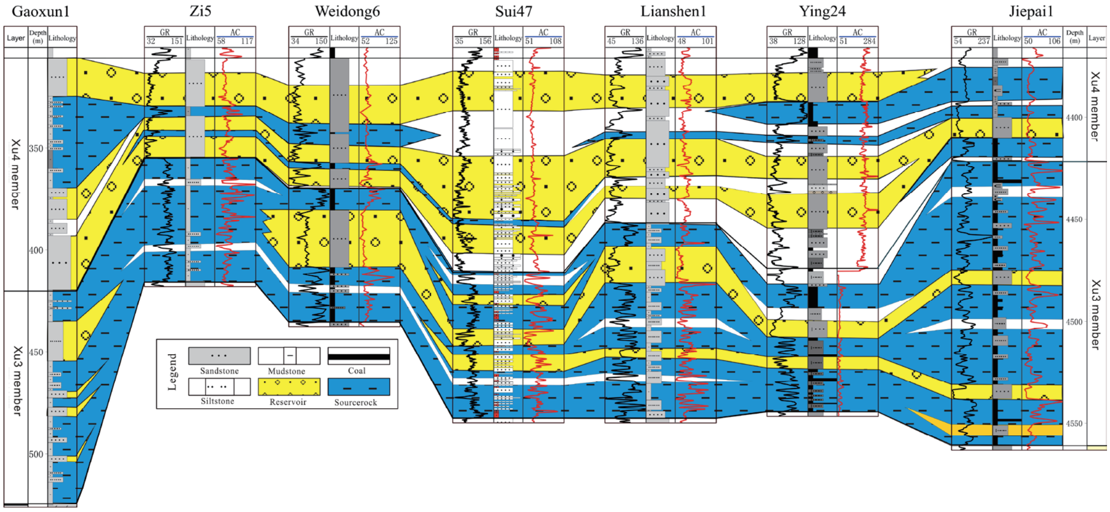
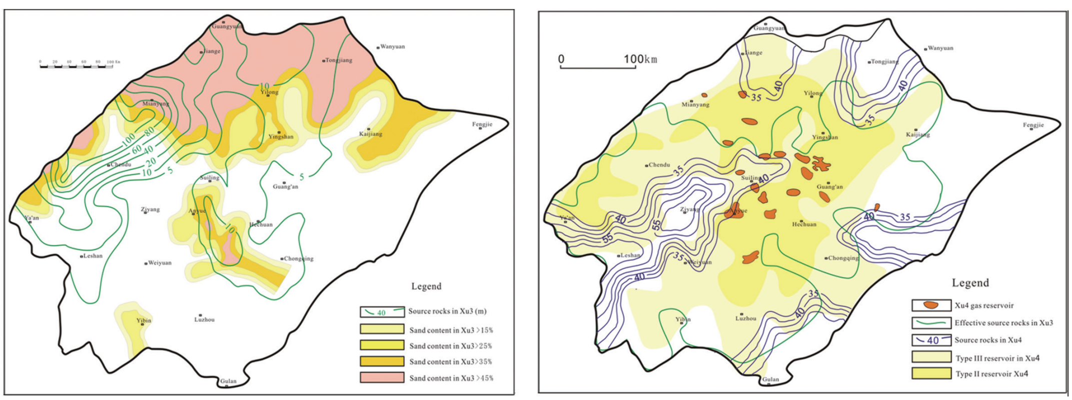


Figure 5
Distribution Section of Effective Source-Reservoir Assemblage of Xu3 + Xu4 Members

(b) Control of Effective Source-Reservoir Assemblage on Gas Accumulation

In plane, the differently distributed source-reservoir assemblage controlled the formation of natural gas reservoirs in Xu3 and Xu4 members. The effective source-reservoir assemblage of Xu3 member is distributed in the northwestern Sichuan. If the sand contours of more than 25% are superimposed on the thickness contours of Xu3 mudstone source rocks, it can be seen that the discovered wells are mainly distributed in the areas where sand contents are over 25%, and generally no discovery in the areas where sand contents are less than 25%. Studies show that in the areas with lower sand contents, the predelta or lacustrine deposits are dominant, and single sand layer is thin, generally 1-3 m; as a result of strong compaction and cementation due to thick overlying and underlying mud layers and poor physical properties, such sand layers could not be effective gas-bearing reservoir. Therefore, it is more probable to accumulate hydrocarbons in the superimposed zones where sand contents are over 25% in Xu3 member (Figure 6a).

In the areas where there are favorable sand reservoir and mudstone contents more than 35%, better source-reservoir assemblage can be formed. In the superimposed zones where there are purer Xu3 mudstone and overlying Xu4 favorable reservoir, the Xu3 source rocks can supply gas for Xu4 reservoir. As shown on Figure 6b, the discovered gas reservoirs and gas-bearing structures in the Xu4 member are mainly distributed in the source-reservoir superimposing zones, including such large gas fields as Guang'an, Chongxi and Moxi. But in the areas of Xu4 member where plays are distributed, if there is no Xu4 mudstone and Xu3 source supply (such as Yanting and Yingshan), the source conditions should be considered. Better reservoir may have higher water saturation. For example, the Bajiaochang reservoir feature higher water saturation, with obvious bottom water; the Xu4 member in Yingshan area shows better properties, with poor gas-bearing capacity.



a. Source-reservoir assemblage of Xu3 member **b. Source-reservoir assemblage of Xu4 member**

Figure 6
Distribution of Source-Reservoir Assemblages of Xu3 and Xu4 Members

(c) Gas Enrichment and High Production Are Controlled by Structural High and Fracture Development

Controlled by near-source accumulation, it is difficult for natural gas to massively migrate and enrich in the Xujiahe reservoirs, but near the zones with high gas generation intensity. In this way, the gas layers are widely distributed and thin, with lower full-up ratio. Thus, it is very important to discover high-production wells for effective and economic development of gas reservoirs. According to the fine dissection of gas reservoirs and study on dynamic development, gas enrichment and high production are controlled by structural highs and fracture development. If reservoir rocks match well with structural highs and fractures, gas saturation and single well production would be relatively higher; but, the case will be lower in structural lows. For example, in Xu6 reservoir in Guang'an and Xu2 reservoir in Hechuan, the high-production wells are mainly located at structural highs, generally without water produced. The gas reserves may be 3×10^8 - 5×10^8 m^3/km^2 at structural highs, but only 1×10^8 - 3×10^8 m^3/km^2 at structural lows. The gas production is 32.2×10^4 m^3/d and 26.22×10^4 m^3/d respectively at structural highs of Xu6 member in Guang'an and Xu2 member in Hechuan, but only 2×10^4 - 3×10^4 m^3/d at structural lows. In view of single wells, Well Guang'an19 is located at structural highs, producing gas of 30×10^4 m^3/month initially and stabilizing for 10 years; after 30 years, its present gas production is still over 10×10^4 m^3/month, without apparent change of gas layer pressure; on the contrary, when gas production decreased in later period, the gas layer pressure increased somewhat, indicating that the gas reservoirs are large, with high energy and gas abundance.

On the other hand, in most well fields with fractures, there were obvious circulation loss and gas show during drilling, and gas production was higher during gas testing. For example, in Well Guang'an106, the Xu4 member is located at structure slope, with fractures. The gas production in testing was 7.1×10^4 m^3/d, without water observed. Thus, the fractures improve the permeability and storage volume of the reservoir, and contribute to economic reservoirs formed at structural lows and structural highs. In the central Sichuan Basin, there are three fracture systems in N-W, N-E and nearly E-W trend. They are closely related to deep faults at matrix[22] and twisting movement induced by tectonic compression since the end of Cretaceous, and distribute in belts apparently. The fractures were formed in two stages: Yanshanian period, when fractures were mainly distributed in N-E, in Xu2 and Xu4 members, with intensity decreased upward, and Himalayan period, when fractures were mainly distributed in the central-northern areas of the central Sichuan Basin, basically secondary faults and fracture systems derived from twisting activity, in Yingshan, Chongxi-Guang'an and Wusheng-Pengxi faulted zones (mainly shear fractures, partly filled). The Yanshanian fractures provided migration channels for gas that was generated and expelled at the end of later Jurassic; but during uplifting, both Yanshanian and Himalayan fractures acted as migration channels, providing critical spaces for gas to enrich (Figure 7).

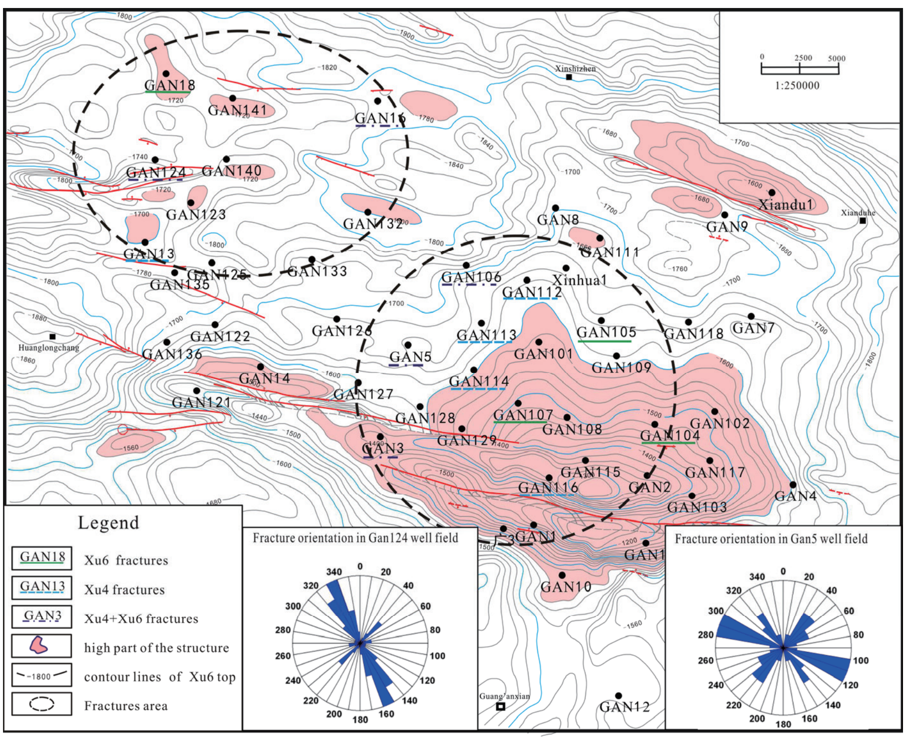


Figure 7
Directions and Features of Fractures in Guang'An Area

3. EVALUATION OF TIGHT GAS RESOURCES

Just as above mentioned, the accumulation process of tight gas in the Xujiahe Formation was controlled by the effective and tightly-contact source-reservoir assemblages. To evaluate gas resources, considering the distribution of gas source kitchen in coal measures, especially the coal bed and carbon-bearing mudstone with high gas generation intensity, we overlaid favorable reservoir rocks that are closely contacted and structures. Taking Xu4 member as an example, the thickness distribution map of coal bed and carbon-bearing mudstone of Xu3 member that are closely contacted with Xu4 member are overlaid with the map of plays of Xu4 member to form the source-reservoir evaluation map, by taking the distribution of mudstone in Xu4 member into account. The effective gas source rocks of Xu3 member are mainly distributed in the western Sichuan Basin and the north and south of central Sichuan Basin, with thickness of 5 - 30 m. But, the source rocks of Xu4 member are mainly distributed in western Sichuan Basin (Table 3, Figure 8), north of central Sichuan Basin and certain areas of southern Sichuan Basin, with general thickness of 15 - 60 m (80 - 100 m in local areas of western Sichuan Basin). In the overlying areas of above two source rocks, the effective gas source rocks of Xu4 reservoir are developed. Xu4 reservoir is widespread, mainly in Jinhua-Guang'an-Dazu zone of the central Sichuan Basin, with storage coefficient over 1.5 - 2, and porosity over 6%; after superimposed with structures, it can be divided into 4 types of gas plays. Type I is mainly in Santai and Dazu zones, where source rocks and reservoir are thick and tightly contacted; especially, the source rocks in Xu4 member are better developed, with area of 2.1×10^4 km^2. Some gas fields including Moxi, Guang'an and Bajiaochang have been discovered in this area, with gas resources of 1.1×10^{12} m^3. Type II is mainly in Ya'an and Yingshan zones, with area of 8,000 km^2. The source rocks in Ya'an zone are buried more deeply, and source rocks in Yingshan zone are thinner, with better developed faults and poorer preservation conditions. Generally, source-reservoir assemblages are better developed, with gas resources of about $6{,}000\times10^8$ m^3. Using the above method, we evaluated the gas resources of the whole Xujiahe Formation. The results reveal favorable gas-bearing area of 6×10^4 - 7×10^4 km^2, gas resources of 5×10^{12} - 6×10^{12} m^3, and recoverable gas reserves of 2×10^{12} - 3×10^{12} m^3.

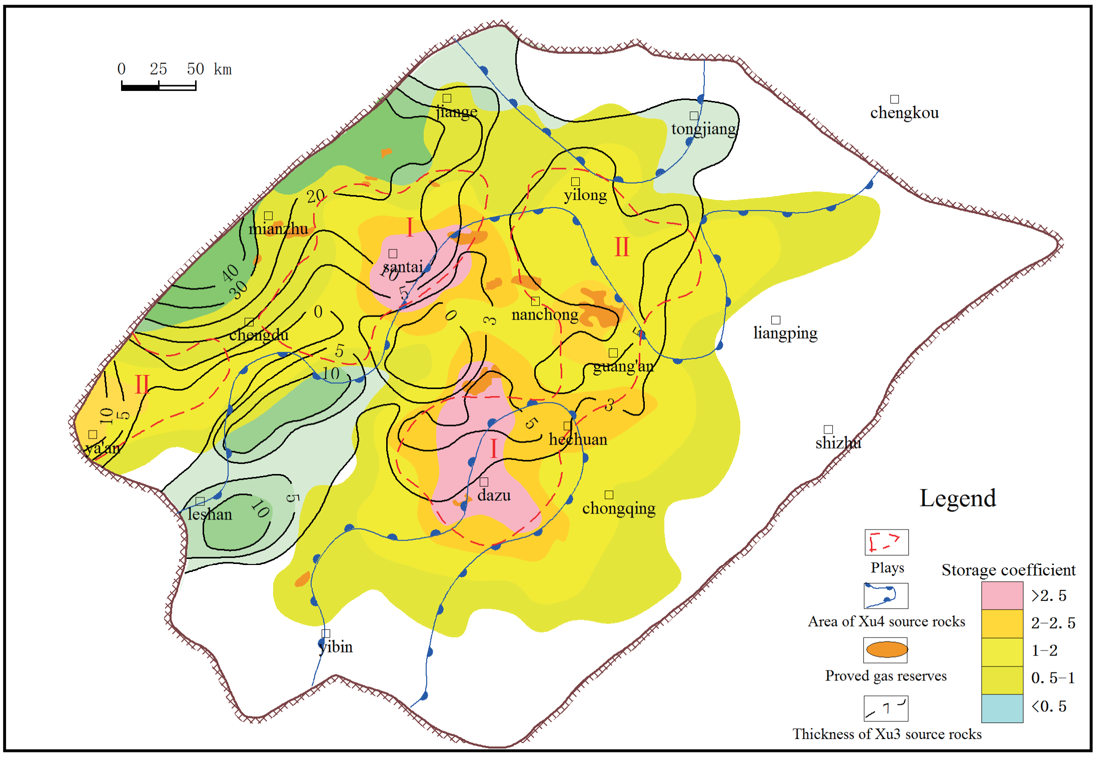


Figure 8
Comprehensive Evaluation Map of Gas Plays in Xu4 Member

Table 3
Resources Evaluation and Favorable Plays of Xu4 Member

Structure types	Favorable plays	Area (km^2)	Total amount of gas (10^{12} m^3)	Accumulation efficiency	Resource amount (10^{12} m^3)	Recoverable reserves (10^{12} m^3)
Sag	Chengdu-Mianzhu	12,228.9	26.17	0.03	0.53	0.212
slope	Laoguanmiao-Bajiaochang	9,703.6	48.48	0.06	1.71	0.684
	Pingquan	7,622.1	11.41	0.03	0.23	0.092
structure with Low amplitude	Yilong-Guang'an	13,207.4	16.53	0.05	0.54	0.216
	Pengxi-Weidong	12,524.7	13.24	0.06	0.45	0.18
Structure developed	Yaan-Pingluoba	2,927.2	5.47	0.04	0.14	0.056
		Total amount			3.60	1.44

4. DISCUSSION

Based on the anatomy of typical gas reservoirs in Xujiahe formation, the paper analyzed the distribution characteristics of gas reservoirs: Gas reservoirs are distributed in large scale with patched form, with strong heterogeneity planely, and gas saturation changes a lot. Because of deficiency of gas kitchen in Xujiahe formation, and close contact with reservoirs to source rock in a large area, the effective source-reservoir assemblage control the formation and distribution of natural gas accumulation. As the reservoirs are low porosity and low permeability and strong heterogeneity, natural gas is less likely accumulating with massively lateral migration and gathering, but mainly filling in the near surface in the reservoir adjacent to the source rock. The gas enrichment zone are mainly distributed in the structure with high position and fissure developed. This understanding has proved in exploration and development practice in Guang'an, Hechuan gas field, which has important reference for the Xujiahe gas exploration in future.

CONCLUSIONS

(a) The tight gas reservoir in the Xujiahe Formation is characterized by widely distributed coal measures interbedded with fluvial sandstones; the close contact between source rocks and reservoir provides rich conditions for gas accumulation. Most gas generated in source kitchens can be preserved in strata, without much loss. Therefore, tight gas includes conventional gas, adsorbed gas in source rocks and entrapped gas in tight sandstone.

(b) Tight gas scale is mainly controlled by the distribution of effective source-reservoir assemblages. There are several effective source-reservoir assemblages in the "sandwiched" source-reservoir-caprock assemblages of the Xujiahe Formation. They are wide, leading to extensive and broad tight gas coverage.

(c) The peculiarity of the tight gas in the Sichuan Basin is reflected in the facts that the inhomogeneity of the gas source kitchens led to different gas sources and near-source charging. Though reservoir is widely distributed, gas-bearing capacities are much unbalanced. It has more differences with typical tight gas reservoirs (such as those of the upper Paleozoic in the Ordos Basin and abroad near-continuous gas accumulation).

(d) Because of the above features, the tight gas exploration in the Xujiahe Formation may be more difficult. However, the gas resources are potential and prospective. The gas plays of the Xujiahe Formation are mainly in the Jiange-Penglai zone in western Sichuan Basin, and certain zones in central and southern Sichuan Basin, with 6×10^4 - 7×10^4 km^2 of favorable areas, recoverable gas reserves of 2×10^{12} - 3×10^{12} m^3. The gas resources are still very potential.

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