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Original research paper

Formation conditions, accumulation models and exploration direction of large-scale gas fields in Sinian-Cambrian, Sichuan Basin, China☆

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Abstract

According to comprehensive research on forming conditions including sedimentary facies, reservoirs, source rocks, and palaeo-uplift evolution of Sinian-Cambrian in Sichuan Basin, it is concluded that: (1) large-scale inherited palaeo-uplifts, large-scale intracratonic rifts, three widely-distributed high-quality source rocks, four widely-distributed karst reservoirs, and oil pyrolysis gas were all favorable conditions for large-scale and high-abundance accumulation; (2) diverse accumulation models were developed in different areas of the palaeo-uplift. In the core area of the inherited palaeo-uplift, "in-situ" pyrolysis accumulation model of paleo-reservoir was developed. On the other hand, in the slope area, pyrolysis accumulation model of dispersed liquid hydrocarbon was developed in the late stage structural trap; (3) there were different exploration directions in various areas of the palaeo-uplift. Within the core area of the palaeo-uplift, we mainly searched for the inherited paleo-structural trap which was also the foundation of lithological-strigraphic gas reservoirs. In the slope areas, we mainly searched for the giant structural trap formed in the Himalayan Period.

Keywords: Large-scale gas fields; Formation condition; Accumulation model; Exploration direction; Sinian-Cambrian

1. Introduction

The NE-trending rhombic tectonic sedimentary basin, namely the Sichuan Basin, has an area about 180,000 km^2, and this was developed on the basis of the stable Yangtze craton Presinian metamorphic basement; it is China's major petroliferous basin, where there are more than 20 sets of hydrocarbon bearing series in total [1], among which the Sinian-Cambrian is the major natural gas producing formation. Since the Sinian, thick sedimentary rocks have been deposited and dominated by marine carbonate and clastic rock strata, with a total thickness of 6000−12,000 m [2]. The Sinian-Middle Triassic strata are marine sediments dominated by carbonate rocks whose thickness is approximately 5000 m. In 1964, the oldest producing layer in the Sinian Dengying Formation in Sichuan Basin was discovered within the Weiyuan gas field. The proved geological reserves of Weiyuan gas field is 400 × 10^8 m^3 [3]. Subsequently, during the 1970s and the 1990s, a series of explorations was conducted aiming at the Sinian-Cambrian layers. Such explorations included drillings in 11 structures in several locations such as the Longnvsi, Anpingdian, Ziyang, etc, as well as drilling wells, e.g. Well Ziyang 1, Well Ziyang 3, and Well Ziyang 7 of the Sinian in the Ziyang paleo-structural traps during 1993−1997. Thus, obtaining industrial gas with the flow of (5.33−11.54) × 10^4 m^3/d, whose estimated and prognostic natural gas reserves were 102 × 10^8 m^3 and 338 × 10^8 m^3, respectively.

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In the beginning of the year 2000, some explorations for the Cambrian Longwangmiao Formation and Xixiangchi Formation in the Weiyuan gas field succeeded. However, no major breakthroughs [4–6] was made up to the year 2010. High expectations were then oriented to the Sinian-Cambrian in Sichuan Basin, in order to continuously conduct exploration and research activities. This where we believed that the palaeo-uplift of Leshan-Longnvsi has been controlling the Sinian-Cambrian accumulation. Not to mention, the forming conditions within the palaeo-uplift range were good enough to form large gas fields [7–9]. Constrained by the limited data in the early stages, our research has been focused on the palaeo-uplift cores of [4–9] the structures in the locations Weiyuan, Ziyang, and Longnvsi where our understanding of the basin-wide reservoir accumulation conditions were not systematic. In addition, only a small number of researches on the differences of accumulations of various parts of the palaeo-uplift [10,11] have been conducted. During the past two years, with great discovery taking place with the Sinian-Cambrian exploration [11] of the Gaoshiti-Moxi structure in the middle Sichuan region there were new progresses [11–23] for the whole study on Sinian sedimentary facies, reservoir, accumulation and structural evolution, etc., but they were based on specific results of each special research. In this paper, comprehensive research was conducted on forming conditions including sedimentary facies, reservoirs, source rocks, and palaeo-uplift evolution of Sinian-Cambrian. It is concluded that large-scale inherited palaeo-uplifts, large-scale intracratonic rifts, three widely-distributed high-quality source rocks, four widely-distributed karst reservoirs, and oil pyrolysis gas were all favorable conditions for large-scale and high-abundance accumulation; diverse accumulation models were developed in different areas of the palaeo-uplift. In the core area of the inherited palaeo-uplift, “in-situ” pyrolysis accumulation model of paleo-reservoir was developed. On the other hand, in the slope area, pyrolysis accumulation model of dispersed liquid hydrocarbon was developed in the late stage structural trap. Within the core area of the palaeo-uplift, we mainly searched for the inherited paleo-structural trap which was also the foundation of lithological-strigraphic gas reservoirs. In the slope areas, we mainly searched for the giant structural trap formed in the Himalayan Period. The research results play a great role in guiding further explorations on the Sinian-Cambrian gas reservoirs in Sichuan Basin, it is also helpful and important for its practical significance to large-scale palaeo-uplift reservoir explorations in China. Due to the remarkably low level of awareness of paleo-sedimentary facies and the controlling factors of the accumulation of the Sinian-Cambrian in Sichuan Basin, results have also played an important role to theoretical significance for systematical research.

2. Formation conditions of large-scale gas fields

2.1. Large-scale palaeo-uplift of long-term inherited development

A large scale palaeo-uplift developed in Sichuan Basin, namely the Leshan Longnvsi palaeo-uplift, which has been recognized as a large inherited palaeo-uplift by the industry consensus [24]; which has controlled the Sinian-Cambrian basin natural gas gathering and accumulation [25]. Before the Cambrian Longwangmiao Formation deposited, the top surface area of the Sinian in mid-Sichuan was expressed as the “uplift” structural framework, and its core part of the uplift is located in Gaoshiti-Moxi area; before the Ordovician was deposited, the Sinian top surface was still developing to be a palaeo-uplift. The Gaoshiti-Moxi core area of the palaeo-uplift is around about 20,000 km^2 (Fig. 1)a. Prior to Permian deposition, ridge pattern on the Sinian top surface was more evident right before the upper Triassic Xujiahe Formation was deposited (Fig. 1)b. Throughout the Himalayan period, due to the structural events, the Weiyuan-Ziyang area was further uplifted where the Sinian top surface uplift performance in Weiyuan-Ziyang was more obvious; the uplift's high position in the Gaoshiti-Moxi area has essentially unchanged and is continuously inheriting development till today (Fig. 1)c. Long-term uplift paleogeomorphologic pattern has controlled the hydrocarbon source rock, reservoir development, large-scale paleo-reservoir formation, pyrolysis in the later stage, and accumulation in reservoirs especially the core portion of the Gaoshiti-Moxi area which has been developing in the long run since Sinian till present. This provides a favorable environment for large gas field formation.

Present structural features of the Sinian top surface in the Sichuan Basin are shown in the Weiyuan-Ziyang area and the Gaoshiti-Moxi area within the core of the uplift as a result of the long-term inherited development. It has an area of about 40,000 km^2. In the mid-part, there was a relatively low portion where the core part is divided into two relatively independent large structural traps, namely the Weiyuan-Ziyang and Gaoshiti-Moxi. The Weiyuan structural trap area in Sinian's top surface is 1200 km^2, and the area of the Gaoshiti-Moxi Sinian structural traps, from the top to the −5010 m closed contour, is 3545 km^2. Large gas fields have been found in the two structures and have become the most favorable exploration target areas. In the periphery of the core there is a palaeo-uplift slope with an area of about 80000 km^2. Before the Himalayan Period, main parts of the slope were expressed as monocline, where the structural traps were not yet developed. For the duration of the Himalayan Period, due to strong structural movement structural traps was formed on a large part of the slope, with a total area of approximately 4000 km^2 it's mainly distributed in the eastern and southern Sichuan areas, such as Deng Jingguan structure in southern Sichuan area where the Sinian top surface structural traps' area is 100 km^2; it has an amplitude of 350 m. Another is the Jiufeng Temple structure located in the eastern Sichuan, where the Sinian structural traps' top surface area is 280 km^2 and its amplitude is 650 m (Fig. 1)c.

2.2. Large scale intracratonic rift

Once the Well Gaoshi 1 Obtaining commercial gas flow, Shugen Liu et al. [26] and Yong Zhong et al. [27] have put forward that the Xingkai taphrogeny occurred in the Sichuan

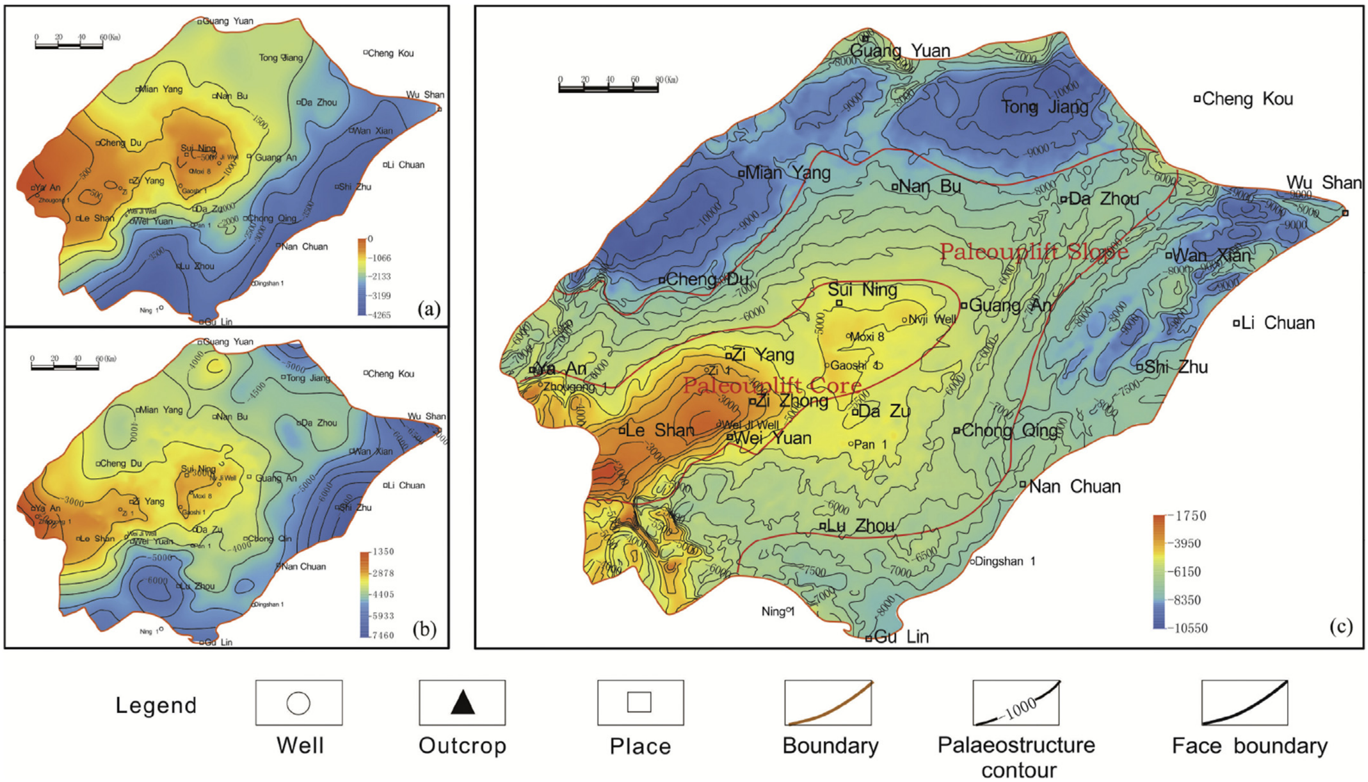

Fig. 1. Structural maps of Sinian top surface in Sichuan Basin during different periods (a)Before Permian; (b) Before Late Triassic Xujiahe Period; (c) Present.

Basin during the period of the late Proterozoic and early Cambrian. In the early Cambrian period, the tensile groove of Mianyang-Lezhi-Longchang-Changning has been formed and it has been controlling accumulation and distribution of Sinian-lower Paleozoic oil and gas in the Sichuan Basin. This paper argues that a large rift was developed under the tensional background within the upper Yangtze Craton, this took place during the Sinian and Early Cambrian period These arguments are somehow different in the aspects of formation time, as well as evolution processes and formation causes of the rift groove proposed by Shugen Liu et al. [26]. According to the basin-wide drilling data and the latest data of Well Gaoshi17, the horizon of Sinian-Cambrian was calibrated and explained in detail. A large scale intracratonic rift (Fig. 2a) was then developed on both the western side of Gaoshiti-Moxi area and the eastern side of Weiyuan-Ziyang area. The rift is located in Mianyang-Changning area, and its overall distribution direction is from north to south throughout the Sichuan Basin. Its western side is steep, but the eastern side is steeper in comparison. The narrowest part within the region is located in Zizhong having a width of about 50 km; the widest belt in the southern and northern region is more than 100 km both gradually widened towards their terminus. From the comparison of charts, we can see that the Cambrian sedimentary thickness within the rift is large, over covering the sinian on both side of the rift. The Sinian sedimentary and Dengying Formation No.3 and No.4 members are rather thin in thickness. The rift continues to affect the development of the strata till the period of Cambrian Changlangpu deposition (Fig. 2b). Large-scale intracratonic rift has controlled the Sinian-Cambrian development of hydrocarbon source rocks, reservoirs, and preservation and accumulation conditions. Rifting development of thick source rocks of the Cambrian, as well as the rifting development on both sides of the thick layers of Sinian platform-edge high-energy shoal facies mound and the argillaceous source rocks within the rift has a lateral sealing effect on the reservoir formed by the body of the mound beach. In short, large scale cratonic rift has important controlling effect on the oil and gas reservoirs accumulation of the Sinian-Cambrian Dengying Formation and Longwangmiao Formation in Sichuan Basin.

2.3. Three widely distributed high-quality source rocks

After the Weiyuan gas field was found, extensive research on its natural gas sources has been conducted. The research has generally considered that the Sichuan Basin natural gas came from the “intrusion” of the Sinian-Cambrian source rocks, and the reservoir mainly gathered in the Sinian top weathered crust reservoirs [28,29]. Through the research on the outcrop of the peripheral edges and underground Sinian-Cambrian source rocks, conclusions have been acquired. Besides the shale source rocks of Lower Cambrian, Qiongzhusi Formation were developed in the Sichuan Basin, mudstone of Doushantuo Formation, as well as the quality mudstone source rocks (Table 1) of the No.3 member of the Dengying Formation has been developed. Three sets of hydrocarbon source rocks were in the over-mature stage, and are widely developed

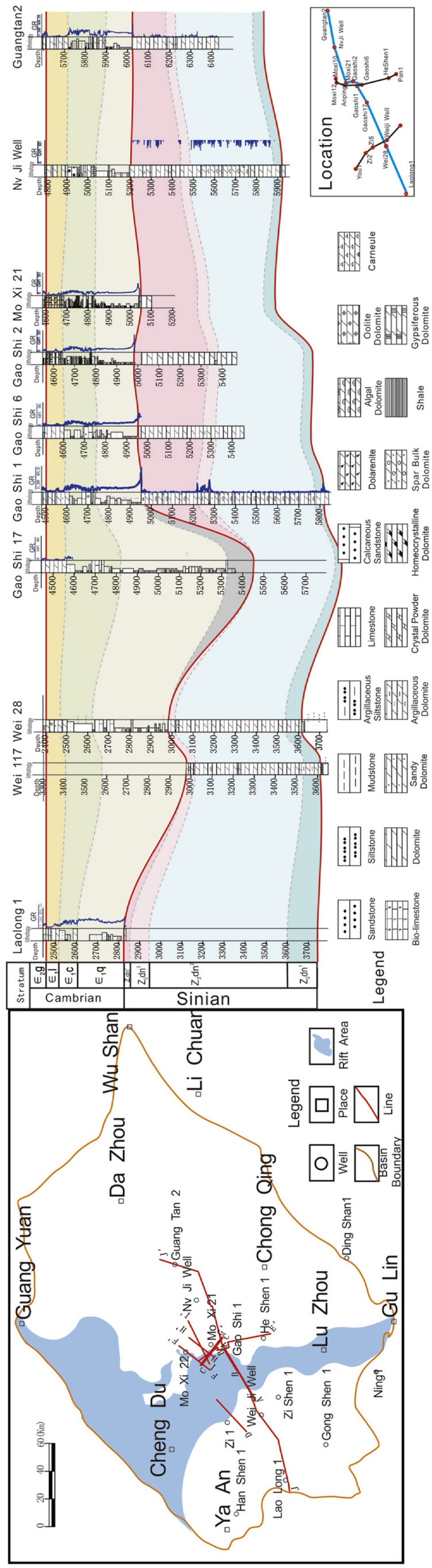

Fig. 2. Boundaries and filled characteristics of intracratonic rift (a) Boundaries; (b) Filled characteristics.

in the basin-wide areas. This provides sufficient gas source for the formation of large gas field.

The Cambrian argillaceous source rocks of Qiongzhusi Formation is one of the best source rocks in Sichuan Basin [10] and is quite abundant. The residual organic carbon content (TOC) of the 443 samples was between the range 0.50% and 8.49%, with an average of 1.97%. The distribution values of Kerogen carbon isotope was between −33.3‰ and −31.1‰, with an average of −32.1‰, belonging to the sapropelic. Equivalent vitrinite reflectance (R_O) was distributed between 1.84% and 2.42%, being in the over-mature and gas formation stage (Table 1). Its thickness is high and generally in the range of 100–400 m. The thickness of the hydrocarbon source within the rift is more than 200 m (Fig. 3), the distribution area is large, and the strength of gas generation is greater than 50,000 km in the area of two billion square meters [4]. The source rocks of the Qiongzhusi Formation drilled by Well Gaoshi 17 had better quality formation having a thickness of 500 m, effective source rocks thickness of 300 m. The residual organic carbon content (TOC) of the 34 samples was distributed between 0.50% and 6.00%, with an average of 2.2%. The value of kerogen carbon isotopes was distributed between −33.3‰ and −31.4‰, with an average of −32.2‰. The averaged equivalent vitrinite reflectance was 2.12%, belonging to the over-mature gas formation stage.

2.4. Four widely distributed karst reservoirs

The development of the Sinian-Cambrian sedimentary and quality reservoir was controlled by the gentle palaeogeomorphologic background in Sichuan Basin. The four widely-distributed effective karst reservoirs have been developed for No.2 and No.4 members of Sinian Dengying Formation, as well as the Cambrian Longwangmiao and Xixiangchi Formations. A large area of the stacked reservoir development provided the effective reservoir space for the formation of large gas fields.

The reservoirs of the Dengying Formation No.2 and No.4 members are similar, they are large scale karst reservoirs formed through dissolution of the beaches and dolomites within the platform. The reservoir space is mainly the caves, intergranular dissolved pores, etc., whose average porosity was about 3.2% and average permeability was 1.0×10^{-3} μm^2. The overall performance is low on porosity and permeability characteristics. The No.2 member of the Well Gaoshiti 1 drilling sample was the Powder-fine crystalline dissolved pore algae dolomite, algae micritic dolomite, gray powder crystal dolomite, etc. The No.4 member samples were in the color range black to gray, and they are developments of the dolomite caves' fine crystalline. Fine quartz, breccia, and cave cloud rocks can be dissolved in cavities. The sample number of full diameter porosity was 14, and the porosity distribution is at the range of 1.82%–8.59%, with an average of 4.71%. The sample number of full diameter permeability is 9, and the permeability distribution is in the range of 0.018×10^{-3} μm^2 and 3.48×10^{-3} μm^2, with an average of 0.84×10^{-3} μm^2. The development of the

Table 1
Characteristics of major source rocks.

Horizon	Rock type	Sample quantity	TOC/%	Equivalent *Ro*/%	Kerogen carbon isotope/‰	Type of organic matters
Cambrian Qiongzhusi Formation	Shale	443	0.50–8.49/1.97	1.84–2.42	−33.3–−31.1	Sapropelic
Sinian Dengying No.3 member	Mudstone	67	0.50–4.73/0.87	3.16–3.21	−33.4–−28.5	Sapropelic
Sinian Doushantuo Formation	Mudstone	95	0.50–14.17/2.91	2.08–3.82	−31.2–−30.7	Sapropelic

Cambrian Longwangmiao Formation of the beaches within the platform is under the same gentle palaeogeomorphologic pattern control. The developments of high-energy particles are stacked on each other in the area with relatively high palaeogeomorphology in which the dissolution cavities are developed, the particles are relatively coarse, and the thickness of the beach body single layer is great. Reservoir space is dominated by intergranular dissolved pores, inter-crystal dissolved pores, and the developed small sized and medium sized caves. Average porosity was at 4.8% and the average permeability was 4.7×10^{-3} μm^2 (Fig. 4). For example, the stratum thickness of the Well Moxi 8 drilling samples of the Longwangmiao Formation was 99 m in the color range of gray to dark gray, and the dolomite reservoir thickness was at 52 m, with an average porosity of 3.67% and permeability average of 4.75×10^{-3} μm^2.

The restricted platform within the Cambrian sedimentary basins in Xixiangchi Formation is significantly deposited. The beach's particles and dolomite were widely distributed within the small thin multi-layers. Reservoir spaces were dominated mainly by intergranular dissolved pores, inter-crystal dissolved pores, micro-cracks, etc.; the average porosity was 4.5%, the average permeability was 0.4×10^{-3} μm^2. Evidences show that the performance was low porosity and permeability characteristics wise. For example, reservoir thickness of the Well Guangtan 2's samples from the Xixiangchi Formation was 43.9 m, and was mainly composed of dolomite sand crumbs. The average porosity of all the 74

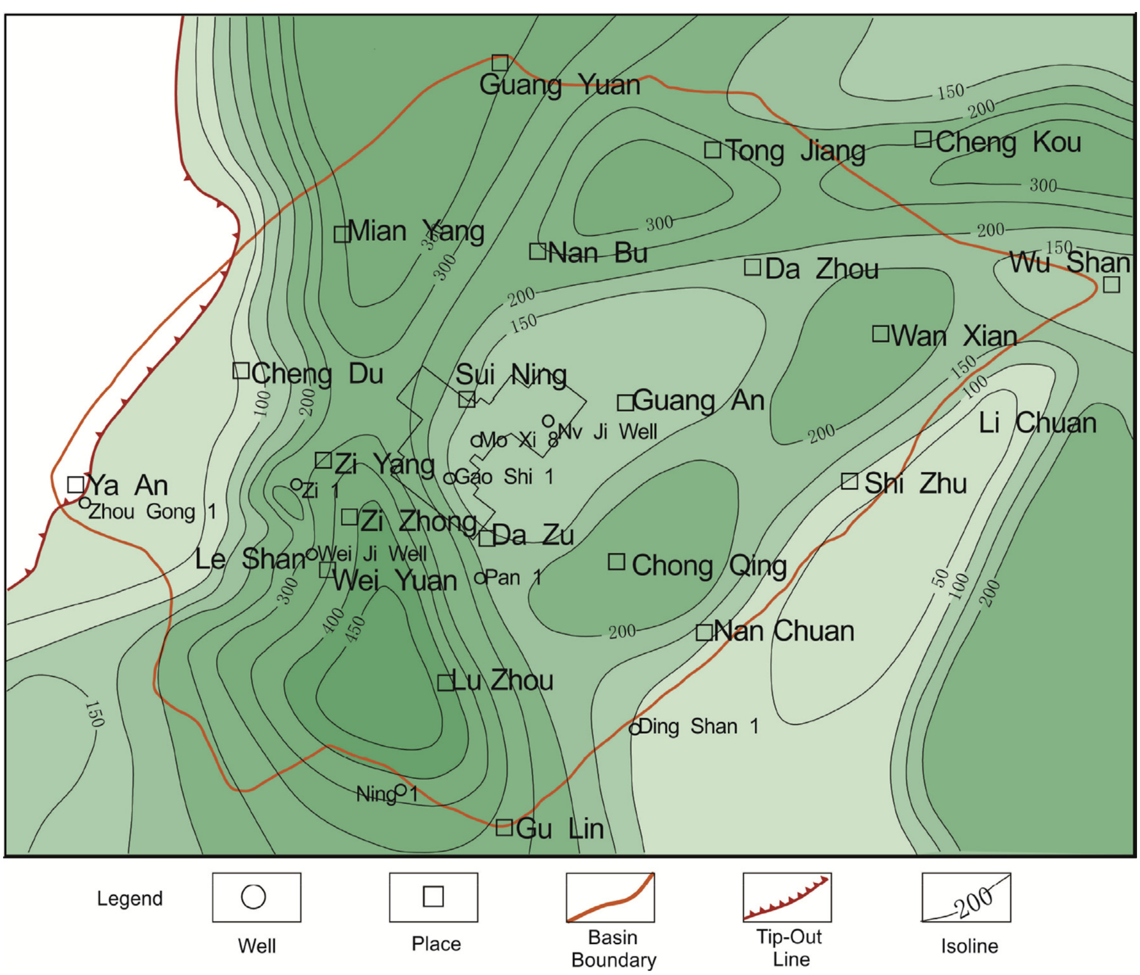

Fig. 3. Isopach of source rocks in Cambrian Qiongzhusi Formation in Sichuan Basin.

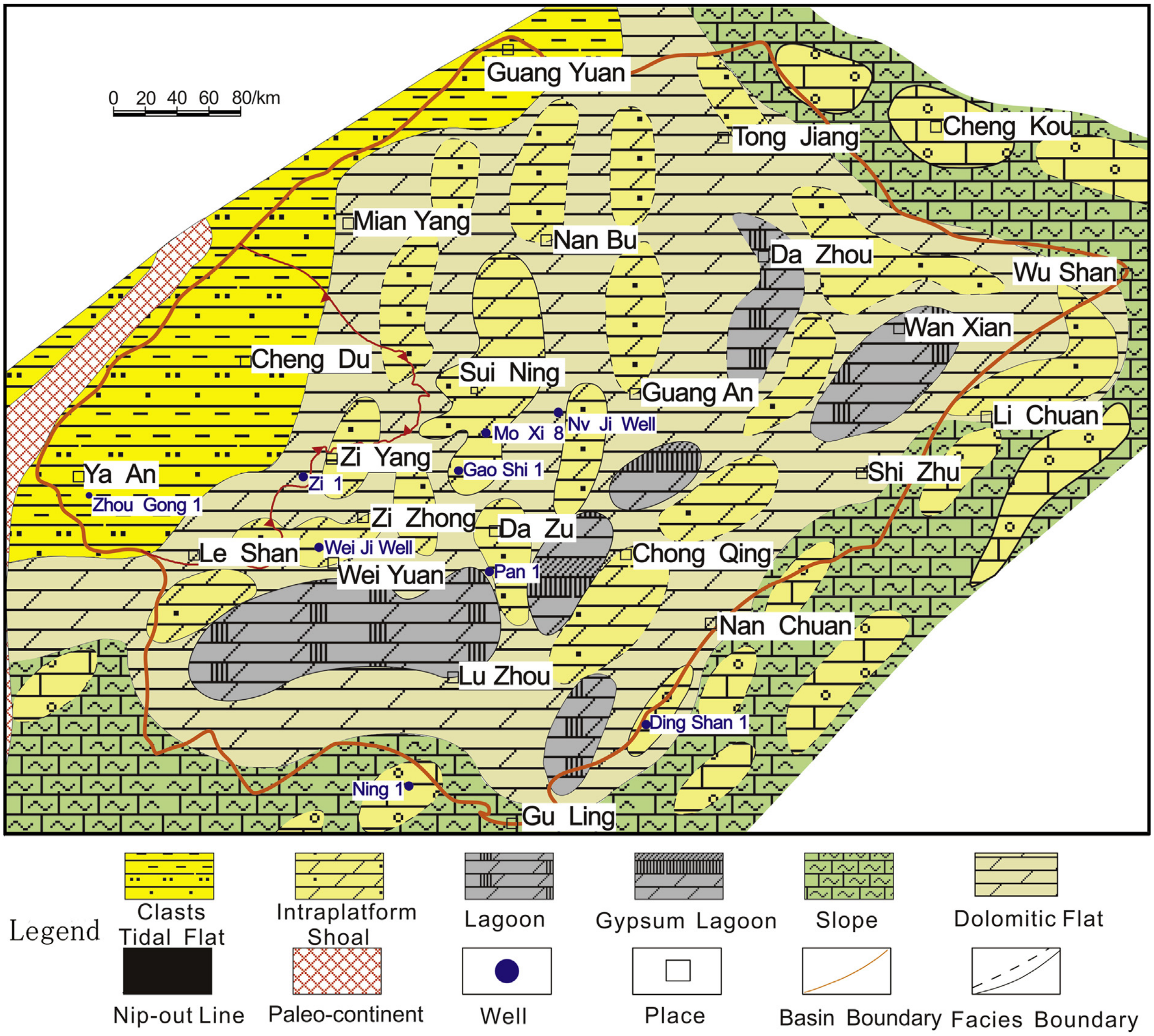

Fig. 4. Lithofacies and paleography map of Cambrian Longwangmiao Formation in Sichuan Basin.

samples was at 4.7% and their average permeability was at 0.43×10^{-3} μm^2.

2.5. Protopetroleum's pyrolysis gas

According to four aspects, namely the components, light hydrocarbons, heavy hydrocarbons, and the asphalt of the Pay formation found in the natural gas of Sinian-Cambrian, the natural gas can be determined primarily from the protopetroleum's pyrolysis gas [17]. Since Prinzofer proposed to apply the ln C_1/C_2-ln C_2/C_3 diagrams to discriminate whether the natural gas belongs to the initial kerogen pyrolysis gas or protopetroleum's secondary pyrolysis gas, the method was then preferred to be used widely in China [17]. In the Gaoshiti-Moxi, Weiyuan Sinian, and Cambrian of the Sichuan Basin the gas ratio of C_1/C_2 changed insignificantly, whilst the C_2/C_3 ratio changed to a great extent being characteristics of the pyrolysis gas characteristics (Fig. 5). The use of new technologies for the light hydrocarbon analysis has facilitated success in detecting light hydrocarbons in natural gas

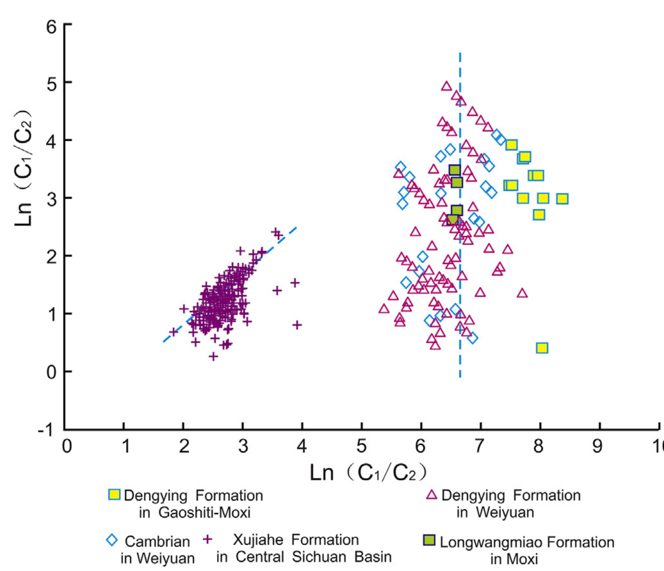

Fig. 5. Relationship of ln (C_1/C_2) to ln (C_2/C_3) of natural gas in Sichuan Basin.

compositions of Gaoshiti-Moxi, Weiyuan, where the observable fact that the natural gas is composed of C_6−C_7 isoparaffins, and having higher naphthenic content is a shared characteristic to pyrolysis gas. For example, compounds with high abundance of C_8−C_{12} have been detected in Well Gaoshi 1 drilling samples from No. 2 and No.4 members' natural gas of the Gaoshiti Dengying Formation, and these compounds were intermediates from the process of pyrolysis gas. A large number of developed reservoir bitumen had more intuitive evidence, and the abundance of reservoir bitumen has gradually decreased from the high parts of the uplift to the slope parts within the basin [10].

3. Natural gas accumulation models

3.1. Accumulation processes

Hydrocarbon-generation evolvement history research on source rocks was Obtained from Well Gaoshi 1. It showed that hydrocarbon generation of the Sinian source rocks began in the Middle-late Cambrian; further on, these were uplifted by the eventual impacts of the Caledonian Movement. The buried depth of hydrocarbon source rocks became shallow where the basic process of hydrocarbon generation stopped. The buried depth of Permian hydrocarbon source rocks were deep, this started another production of hydrocarbons. Oil generation continued until the Triassic period. The Permian−Triassic period was the main period of oil reservoir formation and preservation. During the period of Late Triassic-Cretaceous, protopetroleum pyrolysis occurred a lot forming a large number of crude oil pyrolysis gas (Fig. 6). The accumulation processes of Cambrian and Sinian source rocks were similar, except that the period of crude oil generation and pyrolysis were relatively late. The main period of oil generation was the Permian−Triassic period, yet crude oil started to retain its original state whilst pyrolysis during the Jurassic-Cretaceous period. All through the Himalayan period, when structural adjustments incurred, the gas accumulation was dominated within the structural traps.

Besides accumulation of natural gas reservoirs being related to source rocks' evolution, it was also related to the space-time matching of the key factors related to structural

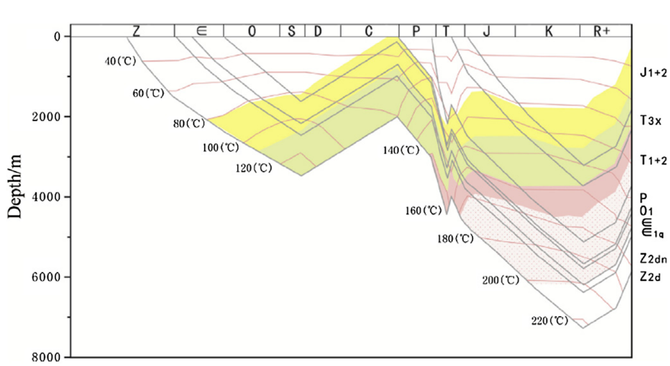

Fig. 6. Thermal evolution and oil and gas charging history of Sinian source rocks.

evolution, reservoir evolution, and more. The Dengying Formation was affected by the movement of Tongwan, where the overall formation is uplifted and exposed forming weathering crust karst reservoir for No.2 and No.4 members of Dengying Formation, in large distributions.

The reservoir was basically formed before the deposition of the Cambrian period that caused the core and slope regions of palaeo-uplift to develop. The Longwangmiao Formation development of the multi-stacked contiguous distribution of beach particles in the late stage experienced being superimposed by the widely distributed karst formation of dolomite reservoir in the basin during all three periods, namely syngenesis, supergene, and burial forming; the formation time is prior to the deposition of Permian. The development of the large area of the karst reservoir can be observed prior to the period of production of the primary raw hydrocarbon source rocks. The weathering crust karst reservoir provided a good space for its large area of oil and gas accumulation. Palaeo-uplift evolution and accumulation is closely related to the long-term inherited development. It has provided the point area of migration and accumulation of oil and gas. The core part development has inherited large structural traps providing conditions for hydrocarbon accumulation and preservation. Slope site reservoirs have been developed, but it lacked structural traps for oil and gas accumulation. Thus, it became difficult bring them together into the oil reservoir within the early stages. However, it can be used as a transport channel for oil and gas from the source rock to the core of the structural traps. During the Himalayan period, a large number of dispersed liquid hydrocarbons within the reservoir can be gathered to accumulate in the late stage of the structures; source rock can be cracked to gas.

3.2. Accumulation models for paleo-reservoirs "in-situ" pyrolysis and accumulation

Sinian-Cambrian natural gas has been found in the Sichuan Basin wherein crude oil was mainly cracked into gas. The long-term large-scale inherited structural traps have been developed in the Gaoshiti-Moxi area of the palaeo-uplift's core part. From the hydrocarbon production of source rocks to oil reservoir cleavage until present time, all the structural traps of the palaeo-upliftcore are continuously developing. Although there are some insignificant changes in terms of shape, size, and amplitude; No.2 and No.4 members of the Sinian Dengying Formation as well as the Cambrian Longwangmiao Formation's reservoir space remains available for source rocks to produce hydrocarbon. Based on the analysis of the structural development features of natural gas in the Gaoshiti-Moxi, evolution of hydrocarbon production from source rocks, and the evolution of palaeo-uplift, paleo-structure, and evolution of structural traps, etc., we can conclude that the vast gas reservoirs of the Gaoshiti-Moxi was "in-situ" cracked and gathered into oil reservoirs (Fig. 7a).

Prior to the Cambrian sedimentary, the karst reservoir has been formed in the No.2 and No. 4 members of Sinian Dengying Formation. Prior to the Silurian sedimentary, the

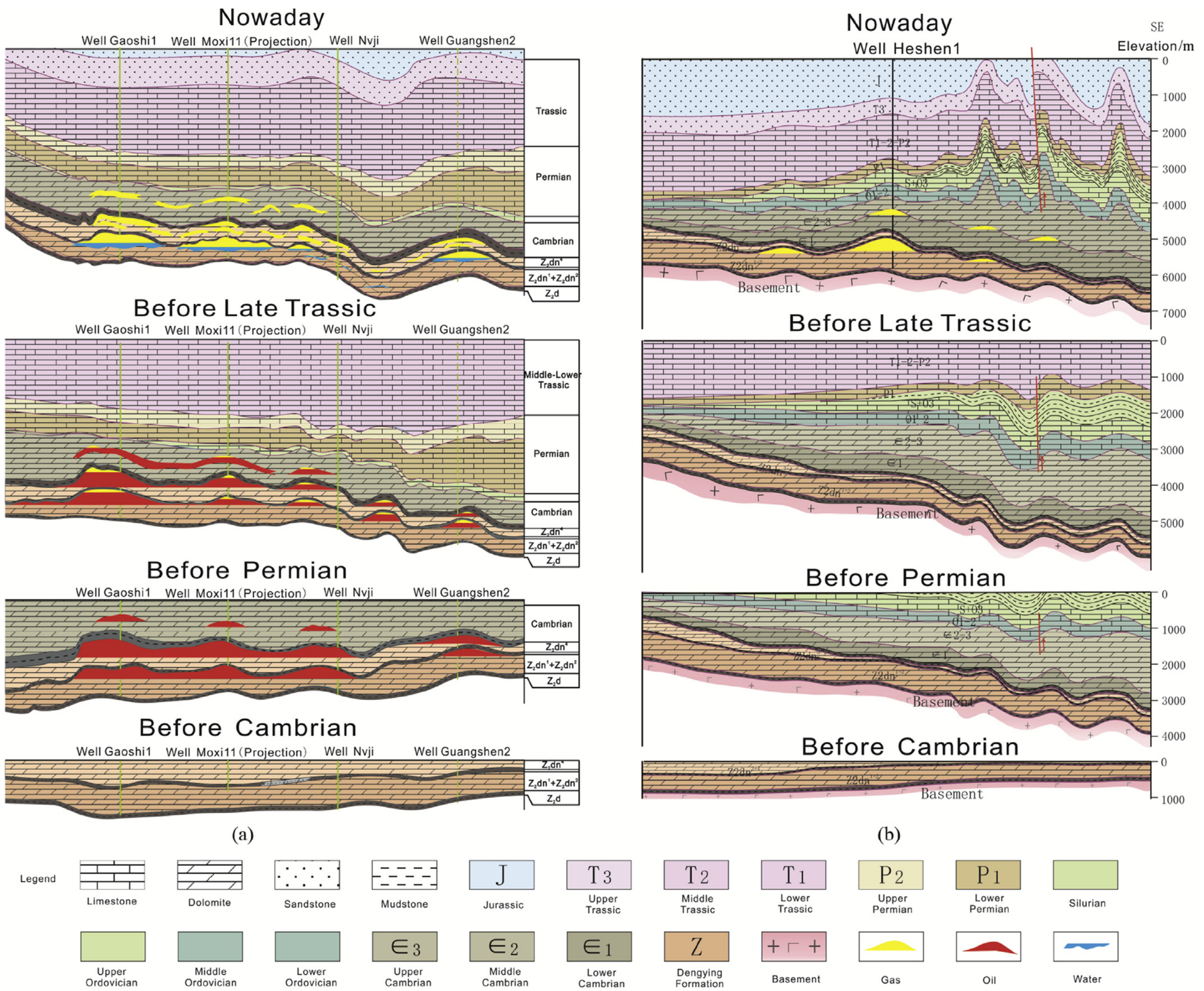

Fig. 7. Sinian-Cambrian natural gas accumulation models in the Sichuan Basin (a)In situ pyrolysis accumulation model; (b) Late stage structural accumulation model.

reservoir has been formed in the Cambrian Longwangmiao Formation, and oil generation has started for the Sinian Doushantuo Formation. The 3rd member of mudstone of the Cambrian shale, mudstone of Qiongzhusi Formation, and the Sinian, Cambrian structural oil reservoir has been formed in the structural traps of the palaeo-uplift core. Prior to the Silurian and right after the Permian sedimentary the palaeo-uplift strata were eroded due to the structural uplift. The structural liability of the Gaoshiti-Moxi brought about the Cambrian Xixiangchi Formation. Oil generation of the hydrocarbon source rocks were put to a stop. All these erosions caused certain degree of damage to the oil reservoir. After the Permian began deposition, along with the increasing depth, source rocks began oil generation. The oil continued to be gathered within the Gaoshiti-Moxi structural traps. Triassic's deposition distribution to the paleo-reservoir had the most significant amount. The Upper Triassic sedimentary reservoir's temperature exceeded 160 °C due to further increased depth. When the oil reservoir began pyrolysis, forming oil and gas reservoirs during the Late Triassic-Cretaceous periods increased in temperature to more than 200 °C due to its depth. The reservoir was completely cleaved to form a dry gas reservoir. Today the Sinian-Cambrian dry gas reservoirs are formed from the "in-situ" pyrolysis of the paleo-reservoirs.

3.3. Dispersed liquid hydrocarbon pyrolysis accumulation model in late structural traps

The reservoir development model for paleo-reservoirs "in-situ" pyrolysis and in long-term accumulation inherited the palaeo-uplift core structural traps. However, the large area of the palaeo-uplift site was the long-term uplift ramp slope; which refers to the hydrocarbon migration channel. Therefore, it was difficult to form a paleo-reservoir. In the Himalayan period, many structural traps in eastern and southern Sichuan region were developed. The reservoirs, core reservoirs of No. 2 and No. 4 members of the Sinian Dengying Formation, Cambrian Longwangmiao, and the Xixiangchi Formation reservoir were similar in slope portion as mentioned before. The reservoir space is available in the beginning of hydrocarbon generation from the source rocks. Analysis conducted in terms of the characteristics of the natural gas field developed purse structures, hydrocarbon evolution in source rocks, and palaeo-uplift evolution. It is concluded that purse field structure can represent the structural dispersed liquid hydrocarbon pyrolysis accumulation during the Himalayan period (Fig. 7b).

Prior to the Cambrian sedimentary, like the palaeo-uplift core, the No. 2 and No. 4 members of the Dengying Formation of Sinian reservoir has been formed. Prior to the Silurian sedimentary, the Cambrian Longwangmiao Formation reservoir has been formed. The Sinian Doushantuo Formation, the mudstone of the No. 3 member, and the mudstone of Qiongzhusi Formation started oil generation until the Himalayan period. Since there were no structural traps for the palaeo-uplift slope, the Cambrian and Sinian structural reservoirs were not formed. Hence, the “in-situ” pyrolysis gas reservoirs were not developed. A lot of liquid hydrocarbon was saved for the hydrocarbon migration channel, and a large number of liquid hydrocarbons that were not timely discharged were also saved within the source rocks. During the Himalayan period, since dramatic changes in structure occurred, a large number of structural traps in both the eastern and southern Sichuan region have been formed. The dispersed liquid hydrocarbon within the Sinian and Cambrian reservoir and source rocks generated natural gas. The said gas was gathered in the Himalayan structural traps to form the dry gas reservoirs. The dispersed liquid hydrocarbon was cracked and gathered into reservoirs, this accumulation model was confirmed by the Well Heshen 1 on the purse field structure. The characteristics of the Sinian natural gas from Well Heshen 1 were similar to those in Gaoshiti-Moxi area. A huge quantity of developed asphalt within the slope belt reservoir and within the argillaceous source rocks were direct evidences showing that dispersed liquid hydrocarbon was cracked into gas.

4. Exploration directions

4.1. Palaeo-uplift cores

The palaeo-uplift core has been provided with developed structural, stratigraphic, and lithologic trap conditions. The palaeo-uplift core gas reservoir was formed by the paleo-oil reservoirs “in-situ” pyrolysis. Therefore, high abundance were the characteristics of structural gas reservoirs; which was the focus of exploration. Searching for paleo-inherited structural traps were the keys. Only inherited paleo-structural traps were developed, the paleo-oil reservoir can be formed to create pyrolysis gas reservoirs. Exploration direction of the field searched for paleo-inherited structural traps within the of 40000 km^2 range around the palaeo-uplift core, besides the Gaoshiti-Moxi structure, Weiyuan structure, and Longnvshi structure; a large number of paleo-inherited structural traps have also developed. Currently, multiple structural traps have been developed in the gentle structural zone on the eastern side of the Gaoshiti-Moxi structure. Multiple large structural traps in Weiyuan-Ziyang area may be developed, and large structural traps may be developed in relatively low-lying structures between the Gaoshiti-Moxi and Weiyuan; these were the focus to be explored. Meanwhile, the field has lithologic reservoir development conditions, from the view of structural evolution and reservoir evolution, the paleo-reservoirs range is larger than that of the present Gaoshiti-Moxi and Weiyuan structural traps. The following two categories of lithologic gas reservoirs may be developed:

(1) Carbonate reservoir heterogeneity is strong, in the developed areas of paleo-structural traps and in the undeveloped areas of structural traps, lithologic traps can be formed by the lithologic lateral sealing the Ziyang area is one example.
(2) During the Caledonian period, the strata were uplifted and erosion incurred. Stratigraphic pinch-out was formed because of the erosion caused by the development of the Sinian Dengying Formation No.4 member as well as the Cambrian Longwangmiao Formation. The stratigraphic traps may be developed to form a gas reservoir. Thus, forecasting the lithologic changing belt and stratigraphic pinch-out belt was the exploration focus of lithostratigraphic gas reservoirs.

4.2. Palaeo-uplift slopes

Palaeo-uplift slopes' gas reservoir is formed by pyrolysis of the dispersed liquid hydrocarbon in the late stages, a large number of structural traps were formed in the eastern and southern Sichuan region during the Himalayan period. There were large numbers of dispersed liquid hydrocarbons within the reservoir of the structural traps and in the vicinity of source rocks, after the Himalayan structural trap formed these dispersed liquid hydrocarbons will continue to pyrolyze forming gas accumulations of the natural gas reservoir in structural traps. Searching for a large Himalayan structure is the key for such gas reservoir exploration. Since the quantity of the dispersed liquid hydrocarbon is smaller compared to that of the paleo-pyrolysis gas reservoir the accumulated gas quantity was also small. Therefore, the required areas and amplitudes of the structural traps were somehow smaller. This can increase gas reservoirs' abundance and economy. Exploration directions in this area were large structural traps with high amplitudes. There were over 20 structural traps in the range of 80000 km^2 around the palaeo-uplift slopes, with the development area greater than 50 km^2, and evaluation and implementation of these structural traps became the focus of exploration.

5. Conclusions

(1) The favorable conditions for the formation of Sinian-Cambrian large-scale and high-abundance oil and gas reservoirs in Sichuan Basin were long-term accumulation of large-scale inherited palaeo-uplifts, stable and gentle paleo-structural backgrounds, three widely-distributed high-quality source rocks, four widely-distributed karst reservoirs, and oil pyrolysis gas.
(2) There is a large-scale inherited palaeo-uplift developed in the Sinian-Cambrian in Sichuan Basin where diverse accumulation models were developed in the various areas of the palaeo-uplift. In the core area of the inherited palaeo-uplift, "in-situ" pyrolysis accumulation model of paleo-reservoir dominated. While in the slope area, pyrolysis accumulation model of dispersed liquid hydrocarbon dominated in the late stage structural trap.
(3) The exploration directions in the palaeo-uplift were all different. Within the core area of the palaeo-uplift, we mainly focused on the inherited paleo-structural traps where the foundation of lithological-strigraphic gas reservoirs coexists. Whilst in the slope areas, we mainly focused on giant structural traps within the Himalayan Period.

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Conflict of interest

The authors declare no conflict of interest.

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