Research article

Accumulation conditions and enrichment patterns of natural gas in the Lower Cambrian Longwangmiao Fm reservoirs of the Leshan-Longnüsi Palaeohigh, Sichuan Basin

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Received 12 January 2014; accepted 25 March 2014
Available online 1 November 2014

Abstract

As several major new gas discoveries have been made recently in the Lower Cambrian Longwangmiao Fm reservoirs in the Leshan-Longnüsi Palaeohigh of the Sichuan Basin, a super-huge gas reservoir group with multiple gas pay zones vertically and cluster reservoirs laterally is unfolding in the east segment of the palaeohigh. Study shows that the large-scale enrichment and accumulation of natural gas benefits from the good reservoir-forming conditions, including: (1) multiple sets of source rocks vertically, among which, the high-quality Lower Paleozoic source rocks are widespread, and have a hydrocarbon kitchen at the structural high of the Palaeohigh, providing favorable conditions for gas accumulation near the source; (2) three sets of good-quality reservoirs, namely, the porous-vuggy dolomite reservoirs of mound-shoal facies in the 2nd and 4th members of the Sinian Dengying Fm as well as the porous dolomite reservoirs of arenaceous facies in the Lower Cambrian Longwangmiao Fm, are thick and wide in distribution; (3) structural, lithological and compound traps developed in the setting of large nose-like uplift provide favorable space for hydrocarbon accumulation. It is concluded that the inheritance development of the Palaeohigh and its favorable timing configuration with source rock evolution are critical factors for the extensive enrichment of gas in the Lower Cambrian Longwangmiao Fm reservoirs. The structural high of the Palaeohigh is the favorable area for gas accumulation. The inherited structural, stratigraphic and lithological traps are the favorable sites for gas enrichment. The areas where present structures and ancient structures overlap are the sweet-spots of gas accumulation.

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Keywords: Sichuan Basin; Leshan-Longnüsi Palaeohigh; Sinian-Early Cambrian; Hydrocarbon accumulation; Sweet spot; Source rock; Structural adjustment

1. Introduction

Discovered at the beginning of 1970s in the Sichuan Basin, the Leshan-Longnüsi Palaeohigh is a large nose-like synsedimentary and denuded Palaeohigh that was developed in Early Cambrian and fell into a pattern in Pre-Permian [1], with the axial line starting from Leshan in the west and terminating at Longnüsi in the east. Calculated by the full denuded area of Silurian, the area of the Palaeohigh is 6.25 × 10^4 km². The exploration of the Sinian-Lower Palaeozoic in the Leshan-Longnüsi Palaeohigh commencing in 1950s, resulted in the discovery of the first integral large gas field in China — Weiyuan gas field in 1964 on the slope at southwest flank of the Palaeohigh, where Sinian Dengying Fm is the major pay. But after that, although the Sinian-Lower Palaeozoic of the Palaeohigh had been the key point of concern and under constant exploration, no major discovery had been made until 2010 (Fig. 1).
Well Gaoshi 1 in the east segment of the Palaeohigh tested a gas flow of $102 \times 10^4$ m$^3$ a day in the 2nd member of the Sinian Dengying Fm in July 2011; later, Well Moxi 8 tapped a gas flow of $191 \times 10^4$ m$^3$ per day in the two sets of reservoirs in the Lower Cambrian Longwangmiao Fm in September 2012. To this point, after strenuous efforts, the petroleum exploration of the Sinian-Lower Palaeozoic in the Leshan-Longnûsi Palaeohigh finally harvested the major discovery in Sinian and historical breakthrough in the Cambrian Longwangmiao Fm, forerunning the new page of Sinian-Lower Palaeozoic exploration in the Palaeohigh. With the rapid and efficient exploration in the past two years, a super-huge gas reservoir group with multiple gas pay zones vertically and cluster pools in the plane is unfolding in the east segment of the Palaeohigh, where the proved gas reserves have exceeded $4400 \times 10^8$ m$^3$.

2. Good geologic conditions for gas accumulation in Sinian-Cambrian

2.1. Good hydrocarbon source conditions represented by multiple sets of source rocks

There developed multiple sets of source rocks of two categories in the Sinian-Cambrian of the Sichuan Basin, mud shale category including Sinian Doushantuo Fm mudstone, Deng III member mudstone, Cambrian Qiongzhusi Fm shale and Canglangpu Fm mudstone; carbonate category includes Dengying Fm argillaceous dolomite. Among them, Doushantuo Fm mudstone, Deng III member mudstone and Qiongzhusi Fm shale have higher abundance, with an average TOC of 2.06%, 1.19% and 1.88% (Table 1) respectively, and are in high-overmature stage; whereas the average TOC of Canglangpu Fm mudstone and Dengying Fm argillaceous dolomite is only 0.91% and 0.61% respectively.

The Sinian-Cambrian source rocks are thick, and premium source rocks are widespread across the basin. The Lower Cambrian argillaceous source rocks are 140 m thick on average, and $15 \times 10^8$ km$^2$ in area in the basin (Fig. 2); Sinian Deng III member mudstone, 10–30 m thick, covers an area of $7 \times 10^4$ km$^2$ in the basin; while Doushantuo Fm mudstone, 10–30 m, covers an area of $5 \times 10^4$ km$^2$ in the basin. Apart from large distribution area, the hydrocarbon generation intensity and quantity of source rocks are also large.

Taking Lower Cambrian argillaceous source rocks as an example, the hydrocarbon generation intensity ranges from 0 to $160 \times 10^8$ m$^3$/km$^2$, $40 \times 10^8$–45 $\times 10^8$ m$^3$/km$^2$ on average (Fig. 3). More importantly, Cambrian source rocks are very thick at the structural high of the Palaeohigh, especially, the Lower Cambrian argillaceous source rocks on the west side of Gaoshiti, with an average thickness of 400 m and gas generation intensity of $140 \times 10^8$ m$^3$/km$^2$, providing good source conditions for the formation of near-source gas reservoirs in the Palaeohigh area.

Table 1

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Stratigraphy and lithology</th>
<th>TOC</th>
<th>$R_o$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cambrian</td>
<td>Canglangpu Fm mudstone</td>
<td>0.51%–1.56%/0.91% /</td>
<td>0.50%–7.56%/1.88% /</td>
</tr>
<tr>
<td></td>
<td>Qiongzhusi Fm shale</td>
<td>3.18%–3.90% /</td>
<td>1.83%–3.90%</td>
</tr>
<tr>
<td>Sinian</td>
<td>Deng III member mudstone</td>
<td>0.50%–4.73%/1.19% /</td>
<td>3.16%–3.21% /</td>
</tr>
<tr>
<td></td>
<td>Dengying Fm argillaceous dolomite</td>
<td>0.20%–3.67%/0.61% /</td>
<td>1.97%–3.46% /</td>
</tr>
<tr>
<td></td>
<td>Doushantuo Fm mudstone</td>
<td>0.56%–4.64%/2.06%</td>
<td>2.08%–3.82%</td>
</tr>
</tbody>
</table>

Note: For TOC the figures before and after the N-dash stand for range value, while those after the oblique line stand for average value.
2.2. Multiple sets of high quality reservoirs are superimposed vertically and in a wide distribution laterally

Oil and gas shows are universal in Sinian-Cambrian, and dissolved vugs are generally seen in cores. Taking Gaoshiti-Moxi in the east segment of the Palaeohigh as an example, two sets of high-quality dolomite reservoirs, the Dengying Fm and the Longwangmiao Fm, have been discovered.

2.2.1. Multiple reservoirs vertically are developed with large total thickness

1) Fracture-vug type reservoirs predominate the Sinian Dengying Fm, and mound-shoal complex-related algae clotted dolomite and algae arenitic dolomite are the major types of reservoir rocks. The reservoir core has an average porosity of 3.86% and maximum porosity of 9.88%, and a permeability of $0.0054 - 9.3 \text{ mD}$, $2.12 \text{ mD}$ on average.
reservoirs, mainly developed in Deng II and IV members, feature multiple layers and big total thickness. The reservoirs drilled in Deng II member and Deng IV member are 28–340 m and 47.75–148.23 m thick and 93.36 m and 88.54 m thick on average respectively.

2) Pore (vug) type reservoirs predominate in the Longwangmiao Fm, and grain shoal dolarenite is the major type of reservoir rock. The reservoir core has an average porosity of 4.78% and maximum porosity of 18.48%, and a permeability of 0.0005–78.5 mD, 4.24 mD on average. The reservoirs change greatly in thickness, and the thick ones are mainly distributed in Moxi area, where the reservoir thickness of individual well ranges from 3.1 to 64.5 m, and 39.1 m on average.

2.2.2. Superimposed and joined together, the reservoirs are in a wide distribution

The large area superimposition of reservoir facies and denudation resulted in the superimposed and joint wide distribution of Sinian-Lower Palaeozoic reservoirs.

1) The development and distribution of Sinian reservoirs are controlled by the superimposition and reworking of mound-shoal facies and hypergenic denudation. Influenced by multiple episodes of Tongwan movement, the Dengying Fm was universally affected by the weathered crust karstification in the epidiagenetic stage, the reservoirs were universally developed and in joint and large-area distribution. Based on the preliminary forecasting results (Fig. 4), the distribution area of Deng IV member reservoir (more than 50 m thick) reaches 2200 km² in Gaoshiti-Moxi area; furthermore, if the bottom of Deng IV member gas layer in Well Moxi 22 (5230 m SS) is taken as a boundary in the east and the Deng IV member pinchout as a boundary in the west, the gas bearing area of Deng IV member calculated is 7500 km².

2) The development and distribution of Longwangmiao Fm reservoirs are controlled by grain shoal body and denudation, especially, the hypergenic karstification at the end of Caledonian in the Palaeohigh area has a strong effect on the reservoir development. The coupling of large area grain shoal and dissolution along bedding in epidiagenetic stage gave rise to high quality reservoirs in a large area. Based on the preliminary prediction results (Fig. 5), the distribution area of Longwangmiao Fm reservoirs (more than 20 m thick) is 6510 km² in the Weidong-Gaoshiti-Moxi-Longnûsi area.

2.3. Various types of traps developed in the large nose-like uplift setting provide favorable space for hydrocarbon accumulation

Many types of traps are developed in the large nose-like Leshan-Longnûsi Palaeohigh setting (Fig. 6). Deng II member in the Weiyuan area at structural high of the Palaeohigh developed a structural gas reservoir with a uniform GWC; whereas Deng II member in the Ziyang structure in the slope zone has gas accumulation in lithologic traps. At the east segment of the Palaeohigh, the trap types of Deng II member and Deng IV member are different in Gaoshiti-Moxi area, the gas-bearing thickness of Deng IV member is much larger than the structural height, the gas-bearing area is not controlled by the local structural traps; whereas in the updip direction on the west side of Gaoshiti-Moxi area, owing to the pinch-out of Deng IV member, stratigraphic barrier is formed, and Wells Moxi 22 and Guangtan 2 confirm that there is water in the structural low in the down dip direction of nose of the nose-
3. Key factors controlling the large-area hydrocarbon enrichment in Sinian-Cambrian

Excellent geologic conditions are only the foundation, and the quality of coupling relation or configuration of the reservoir-forming elements (geologic conditions) is the key to the gas accumulation in a large area [2]. The key factors for large area of enrichment of hydrocarbon in Sinian-Cambrian in the region are the coupling of reservoir-forming elements and their evolution.

3.1. Wide contact of sources and reservoirs, multiphase unconformities and fault systems provide effective channels for oil and gas migration

As mentioned above, there developed 3 sets of high-quality argillaceous source rocks and 2 sets of high-quality reservoirs in the Sinian-Cambrian strata, and both hydrocarbon source and reservoir layers are distributed over a large area. From the perspective of source-reservoir contact relationship, 2 types of source-reservoir assemblages exist in the region, i.e., “source and reservoir side by side” and “source below reservoir”, and they contact with each other extensively. For instance: a. affected by long term weathering and denudation in episode II of Tongwan movement, the top of the Dengying Fm was widely denuded, giving birth to a great number of karst monadnocks and karst platforms, which resulted in the extensive contact and continuous butt joint of Lower Cambrian Qiongzhusi Fm mud shale and Deng IV member reservoir laterally, making it convenient for the oil and gas generated in the Lower Cambrian Qiongzhusi Fm mud shale to migrate into the Deng IV member reservoir in a short distance laterally, so they make “source and reservoir side by side” (new-source and old-reservoir) type from the perspective of “source-reservoir assemblage”; and b. lower Cambrian mud shale (the Qiongzhusi Fm and the Canglangpu Fm) lies below and contact widely with the Longwangmiao Fm reservoir, representing “source below reservoir” type.

The regional unconformities developed at top Sinian and the Dengying Fm Deng II member and the faults cutting into the source beds are the effective channels for oil and gas migration. Oil and gas can not only, in structural high, directly migrate upward into and accumulate in reservoirs along the faults, but also, in structural low, be introduced into the regional unconformities or reservoirs by faults, then migrate towards structural high in a long distance, accumulate and form reservoirs.

3.2. Long hydrocarbon generation and discharge history, and continuous hydrocarbon supply ensure abundant gas source for the palaeohigh

The alternating uplift-and-depression palaeostructural pattern of the Sinian-Lower Palaeozoic strata in the Sichuan Basin results in different hydrocarbon source evolution stages at different tectonic positions in different geologic epochs [3–6], and the phase state of hydrocarbon was different.
laterally. Taking the Lower Cambrian Qiongzhusi Fm source rocks as an example: before Permian deposition, source rocks in the depression area, more than 0.8% in $R_o$, entered the oil window first, and the oil and gas generated migrated towards the structural high of the uplift along the transport system composed of unconformities and fractures; prior to Triassic Xujiahe Fm deposition, source rocks in the depression area, more than 1.4% in $R_o$, entered gas generation stage, while source rocks at structural high of the Palaeohigh were still in oil generation stage, the gaseous hydrocarbon migrated from the depression area towards the structural high of the uplift, and the palaeo-oil reservoirs in the structural high of the Palaeohigh were gas-invaded; prior to Jurassic sedimentation, the amplitude of the Luzhou Palaeohigh increased, source rocks in the depression area, more than 1.4% in $R_o$, entered continuous gas generation stage, but the structural high of the Palaeohigh was still in the oil generation stage; in Himalayan, the Sinian-Lower Palaeozoic source rocks in the Basin, more than 1.6% in $R_o$, entered the gas-generation stage. On the whole, the hydrocarbon source became mature gradually from the depression area to the uplifted area, the hydrocarbon generation and discharge history is long and the hydrocarbon supply is continuous, which ensures the abundant gas source supply for the Palaeohigh area.

3.3. Multiphase structural adjustment and oil-gas evolution form the present widely-distributed multi-type gas reservoir group under the large palaeohigh background

The Leshan-Longnosi Palaeohigh experienced Caledonian, Hercynian-Indosinian, Yanshanian and Himalayan tectonic evolution and adjustment, and the late Caledonian, Indosinian and Yanshanian were the three important hydrocarbon generation and discharge periods. The palaeostructural evolution and the hydrocarbon generation and discharge history coupled well, favorable for the oil and gas enrichment in a large area in the Palaeohigh setting (Fig. 5): a. Caledonian is a period for the forming of the Palaeohigh and the oil generation for the first time, however, owing to the uplifting of the whole basin resulted from the Caledonian movement, the oil generation stopped, and the palaeo-oil reservoirs in the structural high were destroyed; b. in Indosinian, the Leshan-Longnosi Palaeohigh maintained the palaeostructural pattern of Caledonian, the Sinian and Lower Cambrian source rocks in the axial part of the Palaeohigh entered oil generation peak for the second time, the oil and gas migrated towards the top of the uplift zone and the upper slope, and bigger palaeo-oil reservoirs were formed in Ziyang paleotrap, Anyue paleotrap, Weiyuan palaeoslope and different types of traps in Moxi – Gaoshiti region; c. in Yanshanian, compressed by the Chuanxi depression, the axis of the Palaeohigh shifted from Ziyang to the direction of Weiyuan, and the structural high of Moxi-Gaoshiti also shifted on a small scale towards the southeast; as the source rocks basically entered gas generation stage, the oil in the palaeo-oil reservoir was cracked to gas substantially [7–8], this period became the critical period for natural gas accumulation; and d. Himalayan is the critical period for the violent deformation of Sinian-Lower Palaeozoic structures and the adjustment of gas reservoirs; in this period, the Weiyuan anticline became the highest position of the present structure of the Palaeohigh, the Ziyang paleotrap disappeared and became a slope area, the Moxi-Gaoshiti structure was stable, but high-angle compresso-shear faults were developed. As the tectonic deformation occurred, the trap types changed, the gas reservoirs were adjusted, and the present widely-distributed multi-type gas reservoir group under the large palaeohigh background was finally formed — the Ziyang palaeostructure gas reservoir is changed into a stratigraphic-lithologic gas reservoir, the Weiyuan gas reservoir becomes a structural gas reservoir, and the Moxi-Gaoshiti gas reservoirs become a structural, stratigraphic-structural and structural-lithologic gas reservoir group.

4. Oil and gas enrichment rules

The gas accumulation condition analysis shows that the Sinian-Lower Palaeozoic strata in the Leshan-Longnosi Palaeohigh have the conditions for forming a large gas reservoir group that has multiple series of reservoirs vertically and cluster pools in lateral direction. The formation and development of the large Palaeohigh played an important controlling role in the natural gas accumulation, and established the foundation for the forming of large natural gas enrichment zones, specifically: a. multiphase structural uplifting prior to Permian resulted in the formation of unconformities in the Palaeohigh area or even the whole Sichuan Basin as well as the development of large area of karst reservoirs in the Palaeohigh area, which provides the hydrocarbon accumulation with places and migration channels; b. the existence of the Palaeohigh allowed the source rocks to mature gradually from the depression area to the uplifted area, and further extended the hydrocarbon generation and discharge period, which is favorable for the long-term and continuous oil and gas charge, enrichment and accumulation in uplifted area; and c. the inherited development of the Palaeohigh only resulted in weak structure deformation in the Moxi-Longnosi zone at the east segment of the Palaeohigh, and the superimposition of palaeo-present structures is good and favorable for the accumulation and preservation of oil and gas, with violent tectonic deformation only happened to Weiyuan and Ziyang areas.

Based on the above factors, the enrichment of Sinian-Cambrian natural gas in the Leshan-Longnosi Palaeohigh is characterized by: a. the strong control of Palaeohigh, and the structural high is the most favorable area for gas accumulation; b. in the setting of wide distribution of the reservoirs, the palaeo-present structural superimposed area is the best sites for natural gas accumulation; and c. the lithologic traps developed in the structural high of the Palaeohigh and nowadays located in the slope zone have the potential of forming lithologic gas reservoirs owing to the enrichment of natural gas at early stage. In a word, the structural high of the Palaeohigh is the prospective area of gas accumulation, the
inherited structures and strata as well as the lithosomes in its setting are the sites for gas enrichment, and the proximal palaeo-present structural superimposed areas are the sweet spots for the enrichment of gas.

5. Conclusions

1) The Sinian-Cambrian strata in the Leshan-Longnüsi Palaeohigh have excellent natural gas accumulation conditions: multiple sets of pervasive hydrocarbon source rocks are developed, especially, massive Cambrian high-quality source rocks are developed at the structural high of the Palaeohigh; multiple sets of high-quality reservoirs are superimposed vertically and in a wide distribution; and various types of traps are developed in the inherited large nose-like uplift setting.

2) The configuration of reservoir-forming elements and the coupling of their evolution are the key to a large area of enrichment of oil and gas in Sinian-Cambrian strata of the Palaeohigh: sources and reservoirs contact each other widely; the Palaeohigh evolution matches the source rock evolution; and the inherited structural evolution at east segment of the Palaeohigh is the key to the effective preservation of oil and gas reservoirs during the high evolution period.

3) The structural high of the Palaeohigh is the prospective area of gas accumulation; the inherited structures and strata as well as the lithosomes in its setting are favorable sites for gas enrichment; all the factors jointly give birth to the large gas reservoir group with multiple gas pay zones vertically and in clusters laterally at the east segment of the Palaeohigh.

References