Distribution and characteristics of paleo-oil reservoirs in Cambrian Longwangmiao Formation in Anyue area of Sichuan Basin, China

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Abstract: The Anyue gas field is a giant marine gas field with the largest reserves of a single reservoir and the oldest strata in China. In this area, the proved gas reserves in the Cambrian Longwangmiao Formation are \(4,404 \times 10^8\) m\(^3\), which are believed to originate from crude oil cracking according to substantial evidences. The paleo-oil reservoirs in the area have been destroyed, and their fluid properties, scale and other characteristics are unclear, despite of the distribution preliminarily determined. In this paper, the paleo-oil reservoirs in the Cambrian Longwangmiao Formation in the Moxi–Gaoshiti area were analyzed thoroughly through conventional microscopic observation, together with quantitative grain fluorescence (QGF), total scanning fluorescence (TSF), and micro-laser Raman analysis. The study results indicate that the Longwangmiao Formation contains bitumen, which is mainly distributed in four types of pore space, i.e. vein-like fractures, dissolution pores, intergranular pores, and intercrystalline pores. The bitumen in vein-like fractures was formed mostly in relation to hydrocarbon migration, while the bitumen in dissolution pores, intergranular pores and intercrystalline pores was formed by in-situ cracking of petroleum, mostly as a result of thermal alteration. The QGF index suggests the existence of paleo-oil reservoirs in certain scale in the study area, and the high QGF-E intensity indicates the property of residual bitumen. The laser Raman spectroscopy reveals the maturity of the extensive solid bitumen in reservoir rocks. The well-cross section illustrates that the paleo-oil reservoirs are mainly layered, have experienced mostly in-situ cracking, and match with the present gas reservoirs.

1 Introduction
The Anyue gas field in the Sichuan Basin was discovered in 2013, and it was a new historic breakthrough of gas exploration in China. This discovery ended the stagnation of gas exploration in the Sinian–Cambrian of the Sichuan Basin since 1964 when the Weiyuan gas field was confirmed. In the Anyue gas field, the proved gas reserves in the Cambrian Longwangmiao Formation are \(4,404 \times 10^8\) m\(^3\), making it a monolithic field with the largest size of single reservoir discovered to date in China. The gas reservoir in the Longwangmiao Formation (or Longwangmiao gas reservoir) is characterized by large burial depth, old geologic age and multiple stages of tectonic activities, leading to complex and unique hydrocarbon accumulation process and mechanism. Many studies have demonstrated that the natural gas in the Longwangmiao gas reservoir of the Anyue gas field is a typical dry gas, dominantly hydrocarbon gas [1,2]. Coupled with isotopic signature, the gas is confirmed having originated from crude oil cracking. In addition, a large number of drilling and logging data reveal the extensive distribution of residual solid bitumen, which also implies the development of paleo-oil
reservoirs that ultimately evolved into gas reservoirs. Therefore, understanding the occurrence and spectrum of solid bitumen in the reservoir is conducive to identify the characteristics of paleo-oil reservoirs and the distribution of present-day gas reservoirs. In this paper, the characteristics of the paleo-oil reservoirs in the Cambrian Longwangmiao Formation in the Anyue area of the central Sichuan Basin are investigated through microscopic observation, together with quantitative grain fluorescence (QGF), total scanning fluorescence (TSF) and micro-laser Raman analysis, so as to provide reference for subsequent exploration in the study area.

2 Geological setting
The Anyue gas field is located in the central area of the Sichuan Basin and the eastern axis of the Leshan–Longnüsi paleo-uplift. With an area of $2.7 \times 10^4$ km$^2$, the gas field radiates from the Gaoshiti–Moxi area to the Guang'an County in the east, the Dazu County in the south, and the Nanbu County in the north. The Leshan–Longnüsi paleo-uplift is an inherited paleo-uplift controlled by the basement uplift. It initiated from the rigid uplift basement in the central Sichuan Basin during the Jinning and Chengjiang periods, and finally shaped before the Permian after the synsedimentary uplifting and denudation uplifting in the Tongwan, Xingkai, and Caledonian periods [1,2]. Its core resides at the high part of the paleo-uplift; the unified giant structural trap is developed and the later structure is relatively stable. The grain bank on carbonate platform is dominant, and its distribution is mainly controlled by paleo-geomorphology during the sedimentary period. The paleo-geomorphic highland is conducive to the deposition of grain bank, and it may aggrade longitudinally to form thick grain bank bodies. The Longwangmiao Formation is a set of high-quality regional reservoir rocks with the gas sourced from the underlying Lower Cambrian, and it constitutes three good reservoir–seal assemblages with the overlying Gaotai Formation tight carbonate with gypsum-salt, which serves as the direct seal, and the Cambrian Xixiangchi Formation–Triassic mudstone, sandstone, carbonate and gypsum-salt with thousands of meters of thickness, which act as the regional seal [3] (Figure 1).

![Figure 1. Location map of study area in the Sichuan Basin, China.](image)

3 Methodology and experiment

3.1 Microscopic observation and Microscopic Laser Raman Analysis
In this study, the samples were observed using the AX10 Zeiss polarizing microscope ($\times 100$) to determine the occurrence and distribution characteristics of the solid bitumen in the dolomite. Content of the solid bitumen in the rock is measured as well. We used the HORIBA Raman spectrometer to observe the thin sections of samples. The composition of a material can be identified depending on the characteristic peaks, which are variable for different components [4].

3.2 Grain fluorescence experiment
Workflow of the grain fluorescence experiment is showed in (Table 1). The QGF spectrum can be characterized by five parameters: QGF intensity, QGF index, QGF ratio, maximum
wavelength ($\lambda_{\text{max}}$), and half-peak width ($\Delta \lambda$). The QGF index, the most important parameter, is generally greater than 4 for oil layer, and less than 4 and presents a relatively flat curve close to the baseline for water layer. However, there is no definite QGF index threshold to discriminate between oil layer and water layer. Controlled by the oil property, reservoir property and inclusion development, the QGF index threshold is different from area to area, so it should be determined for specific circumstance. Similarly, the half-peak width $\Delta \lambda$ increases with the decrease of the API density of crude oil.

The quantitative grain fluorescence on extract (QGF-E) represents the fluorescence characteristics of hydrocarbon adsorbed on the surface of reservoir grains. It is generally believed that the fluorescence intensity is greater than 40 pc (optical count) for oil layer, and less than 20 pc for water layer. Liu et al. proposed that the oil-water contact should be judged with consideration to QGF and QGF-E spectral signatures for the specific area, and usually an evident inflection point can be observed in the distribution of QGF and QGF-E near the oil-water contact [5].

The $R_1$ of the TSF spectrum reflects the ratio of tricyclic aromatics to monocyclic aromatics in crude oil and can be used to characterize the maturity, density and aromatics composition of crude oil. The larger the $R_1$, the lower the maturity of crude oil, and the higher the density of crude oil [6]. In the TSF plot, a single peak indicates a unique oil source, while a double peak may imply two different oil sources.

![Workflow of rock sample QGF and QGF-E analysis](image)

**Figure 2.** Workflow of rock sample QGF and QGF-E analysis

4 Results and discussion

4.1 Types and occurrence of bitumen

Abundant bitumen is endowed in the Lower Paleozoic Cambrian Longwangmiao Formation in the Sichuan Basin. It is diverse in types by morphology and distribution according to the observation under the polarizing microscope. The thin sections of the core reveal that the bitumen is mainly distributed in vein-like fractures (Figure 3a), dissolution pores (Figure 3c), intergranular pores (Figures 3b and 3f), and inter-crystalline pores (Figures 3d and 3e).
4.2 Characteristics of the Cambrian Longwangmiao Formation paleo-oil reservoir

The grain fluorescence experiment was conducted on 66 samples from four wells (17 samples from GS17, 16 samples from MX39, 11 samples from GT2, and 22 samples from MX13). Microscopic observation and laser Raman spectroscopy analysis were performed on some of the samples. Due to page limitation, this paper takes MX39 well as an example to illustrate the research results.

The QGF index for Well MX39 is 3.4–90.9 (Figures 4 and 5), with high values concentrated in the intervals of 4,486.35–4,865.35 m and 4,889.55–4,897.05 m, indicating that paleo-oil reservoirs are well developed in these two intervals. The QGF-E intensity ranges from 9.2 pc to 42.8 pc, suggesting weak response of residual oil. $R_1$ is 0.74–1.45, indicating that the crude oil cracking was sufficient, and the evolution degree of bitumen is high, with the paleo-oil reservoirs completely destroyed and cracked into gas. According to the laser Raman spectroscopy scanning of bitumen, the Raman peak is observed at about 1316.71 m and 1603.72 m, and displays the characteristics of Raman peak of bitumen (Figure 6). Moreover, the widths of peaks D and G of the Raman spectrum are relatively narrow, reflecting a high degree of thermal evolution and indicating that the residual bitumen basically has no potential for gas generation. The half-peak width $\Delta \lambda$ ranges from 90.2 to 117.7, indicating that the paleo-oil reservoir was mainly charged with condensate. The TSF plot also reflects the high maturity of the reservoir and shows less obvious features of double peak. It is speculated that the paleo-oil reservoir might have undergone a certain degree of gas washing or water washing during its adjustment and reworking process.
5 Restoration of paleo-oil reservoir in Longwangmiao Formation

According to the bitumen distribution, QGF, TSF and micro-laser Raman spectroscopy of the Longwangmiao Formation reservoirs of key wells (GS17, MX39, GT2 and MX13) in the study area, the profile distribution and characteristics of paleo-reservoir in the Longwangmiao Formation were preliminarily clarified (Figure 7). This study has confirmed the idea of layered distribution, and revealed a certain thickness of paleo-oil reservoir in the Longwangmiao Formation of Well GT2 through experiements, but Wei et al. denied the existence of paleo-oil reservoir. The layered paleo-reservoirs have a good correspondence with the present layered gas reservoirs. Moreover, there is a regular distribution relationship between the present gas layer and the paleo-oil layer, which are inherited to a certain extent at relatively high structural parts. In the paleo-oil reservoirs of Well GS17 and Well MX13 which are drilled at structural highs, gas generated from in-situ oil cracking was mostly accumulated in situ, the gas volume generated by thermal cracking of crude oil is much larger than the oil volume, and gas is more likely to dissipate than oil. The in-situ accumulation at this position indicates that the later adjustment and reworking had little effect on the reservoir, and the preservation conditions are good. The present gas layers accumulate near the paleo-oil reservoirs. In Well MX39 and Well GT2, located at the structural lows, certain paleo-oil reservoirs were accumulated, but their preservation conditions were destroyed due to the later tectonic movements. As a result, most of the gas migrated along the dominant pathways (e.g. faults) and then accumulated in favorable traps, such as those on the structural highs; some of the gas was lost, and only a small part remained in place to form a thin gas layer or dry layer.

Figure 7. Well-cross sections of present gas reservoirs and paleo-oil reservoirs in Longwangmiao Formation, Anyue area, Sichuan basin.

6 Conclusions

(1) Bitumen is universally developed in the Longwangmiao Formation in the Moxi-Gaoshiti area, with an overall high maturity. However, there may also be a small amount of bitumen with relatively low evolution degree, resulting in high values of QGF-E and R1. The QGF index corresponding to the
paleo-oil reservoir in the Longwangmiao Formation is relatively large, and the paleo-oil reservoirs are distributed in layers.

(2) The paleo-oil reservoirs in the Longwangmiao Formation of the Moxi-Gaoshiti area generally contained condensate–light oil. The crude oil, with high maturity, might be cracked under high temperature and high pressure to form large gas reservoirs.

(3) The paleo-oil reservoirs of the Longwangmiao Formation at structural highs in the Moxi–Gaoshiti area match well with the present gas reservoirs, and gas generated by in-situ oil cracking mostly accumulated in situ. At structural lows, the preservation conditions were destroyed due to tectonic movement, making the gas migrate; as a result, poor gas accumulation conditions appeared at the structural low positions.

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