Distribution law of helium in Leshan-Longnvsi paleo-uplift in Sichuan Basin, China

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Abstract. The Weiyuan and Anyue large gas fields discovered on the Leshan-Longnvsi paleo-uplift in Sichuan Basin have the oldest marine gas reservoir discovered in China so far, and Weiyuan is also the first gas field to utilize helium resources in China. The Helium in natural gas of Leshan-Longnvsi paleo-uplift belongs to crust-derived helium formed by radioactivity, and its content distribution shows obvious regularity. The content of helium is highly correlated with the age of reservoir in the same gas field, and the helium content is gradually increased from the top to the bottom. However, the content of helium in natural gas presents significantly different in various tectonic units. The content of helium in Anyue gas field developed on Gaoshiti-Moxi structure is very low. The average contents of Sinian and Cambrian are 0.0356% and 0.0078%, respectively. The content of helium in Weiyuan gas field developed on Weiyuan structure is relatively higher, and the average contents of Sinian and Cambrian are 0.28% and 0.18% respectively. The high helium content of natural gas in Weiyuan gas field is related to the large-scale granite body developed on the basement on the one hand and the water-soluble gas accumulation on the other hand. The main gas reservoirs in the Weiyuan gas field and adjacent areas are located in the Sinian system. From the slope area to the high point of the Weiyuan structure, the helium content has increased significantly. With the tectonic movement of the Himalayan period, the Weiyuan area is greatly uplifted, causing structural traps. Natural gas dissolved in the water, including helium gas, is decomposed by decompression, and the released gas is trapped, then released gases accumulated in traps and thus formed Weiyuan gas field with high content of helium.

1. Introduction

The Leshan-Longnvsi paleo-uplift lies in the southwest of Sichuan Basin, which is a large nose-shape and the largest paleo-uplift in Sichuan Basin. Weiyuan and Gaoshiti-Moxi structure are developed on this paleo-uplift. Weiyuan gas field has been discovered in Sinian System Dengying Formation on Weiyuan structure in 1964, which was the largest and oldest gas field discovered at that time, and its proved reserves is $408.61 \times 10^8$ m$^3$. After the discovery of Weiyuan gas field, exploration was carried out in the Weiyuan and Ziyang areas around the Sinian reservoir of the paleo-uplift and the Slope area. Only 3 industrial gas wells in the Ziyang area north of the Weiyuan gas field were discovered, and the Ziyang small gas field was obtained with controlled reserves of $102 \times 10^8$ m$^3$ (Figure 1). Anyue large gas field was discovered in Gaoshiti-Moxi structure in 2011, whose reservoirs are Dengying
Formation of the Sinian and Longwangmiao Formation of the Cambrian, which marked that natural gas exploration had great breakthrough in Leshan-Longnvsi paleo-uplift. At present, the gas reserves of Sinian and Cambrian in Gaoshiti-Moxi structure have exceeded trillion cubic meters [1].

The major gas reservoirs of Weiyuan gas field are distributed in Dengying Formation of Sinian (Z2d), and there are also several small gas reservoirs in Xixiangchi Formation of Cambrian (∈ 2+3x) and Lower Permain (P1). Dengying Formation of Sinian and Longwangmiao Formation (∈ 1l) of Cambrian are major reservoirs in Anyue gas field. Natural gas in studied area is mainly composed of hydrocarbons, non-hydrocarbon gases consisted of CO₂, N₂, H₂S and a small amount of noble gas. Natural gas was mainly from high-over mature source rock of Qiongzhusi Formation of the Lower Cambrian [2]-[3].

2. Geological background

2.1. Structure

The Leshan-Longnvsi paleo-uplift is a long-term inherited development of the NEE direction giant paleo-uplift, which slopes from the southwest to the northeast [6]. The strata under Permian, especially Dengying Formation and Cambrian System, were subjected to the erosion caused by Tongwan movement (570Ma) and Caledonian movement(439Ma), which made contribution to two series high...
quality reservoirs combined with Karstification and provided good reservoir conditions for formation of gas field. Sichuan Basin has experienced differential uplifting since Late Cretaceous, which caused the high-point of the Leshan-Longnvsi paleo-uplift migrate to the current Weiyuan gas field, with uplift amplitude about 4000m [7]. The tectonic deformation was relatively weak in the eastern area of the paleo-uplift, therefore, Gaoshiti-Moxi structure has a gentle structure and its lifting amplitude is about 2500m [7][8].

2.2. Formation
The strata of Leshan-Longnvsi paleo-uplift can be distinguished into 6 systems in descending order as follows, Jurassic, Triassic, Permian, Ordovician, Cambrian and Sinian. Cambrian consist of Xixiangchi Formation of middle-upper system (∈2+3x), Gaotai Formation of middle system(∈2g) and Longwangmiao Formation (∈1l), Canglangpu Formition(∈1c), Qiongzhusi Formation of Lower system(∈1q). The strata of Sinian can be divided into Dengying Formation(Z2d) and Doushantuo Formation(Z1d) from top to bottom. Dengying Formation is dominated by algae dolomite. The lithology of Doushantuo Formation are mainly dolomite, accompanying with dark mudstone.

The major source rock in the study area is the Lower Cambrian Qiongzhusi Formation, its lithology is mainly composed of black mudstone and shale with the thickness of tens of meters, the average content of TOC is 1.95%, which is now in high-over maturation [9].

2.3. Types of gas reservoir
Weiyuan gas field is located at the highest part of paleo-uplift, in which Dengying Formation reservoir belongs to anticline block massive gas reservoir with abundant bottom water, but its fullness coefficient was only 26.3%. The Gaoshiti-Moxi structure where the Anyue gas field is located is relatively flat. The Longwangmiao Formation develops complete traps on Gaoshiti-Moxi structure. The gas and water distribution is controlled by reservoirs and local structures, and is called tectonic-lithologic gas reservoirs. Upper gas reservoir of Dengying Formation is structure-strata complex gas field, and lower is structural gas field with bottom water system [9].

3. Distribution law of helium

3.1. As the age of the reservoir becoming older, the content of helium increases
The content of helium is related to the age of reservoir both in Weiyuan and Anyue gas field. It means that the older the age of reservoir, the higher the content of helium (Figure 2). The average content of helium in Dengying Formation of Weiyuan gas field is 0.28%, Xixiangchi Formation and Lower Permian is 0.18% and 0.056% respectively. In Anyue gas field, the average content of helium in lower Dengying Formation (Z2d) is 0.05%, and upper (Z2d4) is 0.017%, and Longwangmiao Formation (∈1l) is 0.0078%.
3.2. Helium is often enriched in higher part along the same reservoir
Since Anyue gas field has flat structure, the variation of the helium is not obvious with amplitude of structure in this area. However, the content of Helium is closely related to the amplitude of structure in Weiyuan structural belt. There are two gas fields called Wiyuan and Ziyang gas field in Weiyuan structural belt at present. The tectonic movement that occurred after the Late Cretaceous caused the Weiyuan gas field to rise much larger than the Ziyang gas field and became a new high point in the Weiyuan structural belt. A huge rising slope was formed between Ziyang and Weiyuan gas fields. The content of Helium in Dengying Formation increases gradually from Ziyang gas field to Weiyuan gas field. The average content of Helium in Ziyang gas field, Weiyuan gas field and transition belt is 0.027%, 0.277%, and 0.205%, respectively (Figure 3).

4. The enrichment of helium is related to granite basement and water-soluble gas
Anyue gas field shows the characteristics of lean helium, by contrast, Weiyuan gas field is rich in helium. Previous studies show that helium in Weiyuan gas field belongs to crust source radioactivity genesis[2], it is typical crust-source helium. Helium was from the radioactive decay of uranium and thorium, but the exact source of helium is difficult to determine. Helium may come from Qiongzhusi Formation source rock with high content of uranium and thorium, or may originate from granite basement under the gas field. Judged from natural gas accumulation conditions, Dengying and Longwangmiao formations of Anyue gas field are similar to Weiyuan gas field. They have the same source rock and similar reservoir, but the helium content of the later exceeds that of the former by more than an order of magnitude, therefore, we conclude that helium is unlikely to come from source rock or reservoir themselves.

There is granite body under Sinian system of Weiyuan structural belt [13], but Gaoshiti-Moxi structure doesn't, which may be the primary cause of helium-rich natural gas in Weiyuan gas field. The huge granite body with radioactive uranium and thorium under Sinian underwent radioactive decay that caused the formation of helium, and then the helium accumulated in Weiyuan gas field in some way. However, Ziyang and Weiyuan gas field are all situated on granite basement, why the content of helium in Ziyang area is low, but that of Weiyuan area is relatively high? We believe that this is related to the special accumulation process of Weiyuan Gas Field - water-soluble gas degassing into reservoirs.

The decay of uranium and thorium in the basement granite produces helium, and the helium dissolves in the water. Since tectonic uplift greatly caused by Himalayan movement, helium desolvented from water, and accumulated in the trap together with natural gas. Not only is helium, but the alkane gas in the Weiyuan gas field is also derived from water-soluble gas. It is not that the natural gas that people once thought is from the lateral migration from the Ziyang area. The isotope of methane carbon released from water is relatively less negative [14], degassing and accumulation of water-soluble gas has caused methane carbon isotope in Weiyuan gas field to be less negative than Ziyang gas field [15]. With Himalayan movement in the end of Cretaceous, Weiyuan gas field experienced tectonic uplift of great amplitude, and it led to formation of structural traps and release of gas (include helium) from water, then the released gas accumulated in the traps, forming helium-rich Weiyuan gas field.

Weiyuan gas field has favorable geological conditions for the formation of water-soluble gas (including helium) and degassing and gas accumulation for extracted gas, such as reservoir with large area of primary water which is favorable for slow solution of helium and preservation of water-soluble gas. Besides, Himalayan movement resulted in large-amplitude uplift; it is favorable for degassing of water-soluble gas and accumulation of desolvent gas in traps.

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