Exploration potential of Zhaoxian shale gas of Carboniferous Benxi Formation in Ordos Basin

Jinhua Fu\textsuperscript{1,3}, Xinshan Wei\textsuperscript{2,3}, Daojun Huang\textsuperscript{2,3}, Hui Zhang\textsuperscript{2,3,*}, Yani Jia\textsuperscript{2,3}, Yan Liu\textsuperscript{2,3}, Wenxiang Liu\textsuperscript{2,3}

\textsuperscript{1} PetroChina Changqing Oilfield, Xi’an 710018, China
\textsuperscript{2} Research Institute of Exploration and Development, PetroChina Changqing Oilfield, Xi’an 710018, China
\textsuperscript{3} National Engineering Laboratory for Exploration and Development of Low Permeability Oil and Gas Fields, Xi’an 710018, China

*Corresponding author’s e-mail address: zhanghui01_cq@petrochina.com.cn

Abstract. In recent years, the domestic study on shale gas has been affected greatly by significant research achievements of overseas marine-facies shale gas exploration and development. In order to study exploration potential of Zhaoxian shale gas of Carboniferous Benxi Formation in Ordos Basin, the petrology, organic geochemistry and gas-bearing capacity of Zhaoxian shale samples from Benxi Formation were investigated. Based on these parameters, the exploration potential of these shales were estimated by applying mathematical statistics and analysing logging response characteristics. Results showed that the Zhaoxian shale was located in the lower part of the Benxi Formation, it was formed in a marine sedimentary environment with a thickness of 15-30m, logging was characterized by higher gamma anomalies and high compensation neutrons. The brittle minerals were mainly quartz, carbonate rock and pyrite, with an average of 36.9%, and a maximum of 50.9%. The total organic carbon (TOC) content was greater than 1% in general and the average value was 2.8%. Organic matter type of the shale samples was mainly type II\textsubscript{2} and a few samples were of type II\textsubscript{1} organic matter. Vitrinite reflectance values (1.82% on average) showed that shale samples were at mature-high mature stage, which enables good pyrolysis gas generation. The desorbed gas content ranged between 0.34~2.01 m\textsuperscript{3}/t with an average of 0.99 m\textsuperscript{3}/t. All the evidences indicate that Zhaoxian shale from Carboniferous Benxi formation was of great potential for shale gas exploration.

1. Introduction

Based on the success of shale gas exploration and development in North America [1-4], Shale gas has become one of the hot spots of unconventional natural gas exploration [5-11]. In recent years, the domestic study on shale gas has been affected greatly by significant research achievements of overseas marine-facies shale gas exploration and development. Zhaoxian shale is a set of dark-gray melanic shale (Figure 1) developed in the upper part of Benxi Formation of Upper Carboniferous in the Zhaoxian section of Linxian County, Luliang City, Shanxi Province, with a thickness of 3 to 5 m and developed horizontal bedding. The outcrop at the edge of the basin and the drilling data in the basin confirmed that the shale was shallow marine deposits with high TOC. Logging was characterized by higher gamma anomalies and high compensation neutrons (Figure 2). The gas testing was abnormally high and showed that these were favorable accumulation intervals for shale gas.
2. Sedimentary characteristics and environment

The cumulative thickness of the Zhaoxian shale in the Benxi Formation of the Ordos Basin was mainly distributed between 15 and 30 m, and up to more than 40 m in some areas, which was characterized by being thick in the east and west, thin but stable in the middle. According to the lithofacies characteristics, the Benxi Formation can be divided into two intervals. The lower part was mainly composed of gray-white aluminous rock, aluminum mudstone and clay rock. The Zhaoxian shale was located in the lower part of the Benxi Formation. The maximum content of clay minerals could be up to 74.6% and the average value was 63.1%, showing that the samples were rich in clay minerals. The brittle minerals were mainly quartz, carbonate and pyrite, with an average of 36.9%, and the maximum of 50.9% (table 1).

The boron content of Zhaoxian shale was 121-470ppm, which indicates that it was formed in the super salt water environment. The Sr/Ba ratio ranged between 0.71 and 3.90, with the average value of 1.66, both of which were greater than 0.7, suggesting marine sedimentation.
3. Organic geochemical characteristics

3.1 Abundance of organic matter

The TOC of the Zhaoxian shale was generally high (Figure 3), and the TOC peak was between 2.0 and 3.0%, with an average of 2.8%. 70.0% of samples were of TOC content greater than 1.0%, and 44% of the samples have TOC greater than 2%. According to [12], the TOC content of mud shale reaching 0.5% can be used as the lower limit of gas-producing shale, while the TOC content of favorable gas-producing shale should be greater than 2.0%. Zhaoxian shale belongs to the type with high organic matter abundance.

Table 1. Whole rock X-ray diffraction analysis of Zhaoxian shale from well Mxxx of Ordos Basin

| No. | Bottom depth (m) | Quartz (%) | Feldspar (%) | Carbonat (%) | Pyrite (%) | Clay mineral (%) | Brittle minerals (%) |
|-----|------------------|------------|--------------|--------------|------------|-----------------|---------------------|
| 49  | 2112.86          | 27.9       | 0            | 1.6          | 4.2        | 66.3            | 33.7                |
| 51  | 2119.01          | 37.2       | 2.2          | 0            | 0          | 60.6            | 39.4                |
| 54  | 2125.4           | 30.4       | 0            | 3.1          | 0          | 66.5            | 33.5                |
| 55  | 2130.42          | 32.5       | 2            | 7.6          | 8.8        | 49.1            | 50.9                |
| 56  | 2133.26          | 1.1        | 1.1          | 5.6          | 17.6       | 74.6            | 25.4                |
| 57  | 2135.78          | 4.5        | 18.5         | 15.4         |            | 61.6            | 38.4                |
| average |             | 63.1       | 36.9         |              |            |                 |                     |

![Figure 3. TOC histogram of shale in Benxi Formation of Upper Paleozoic, Ordos Basin](image)

3.2 Types of organic matter

The kerogen of Zhaoxian shale were mainly composed of sapropel amorphous and inert components, with a sapropel amorphous range of 67-70%. The kerogen type index (TI) ranged from 34 to 41. The standard of kerogen type was: Ti of type I ≥ 80; Ti of type II 1 was 40 to 80; Ti of type II 2 was 0 to 40; Ti of type III was smaller than 0. The organic matter type of Zhaoxian shale was mainly type II 2 (table 2).
Table 2. Maceral composition of kerogens in Zhaoxian shale, well MXXX.

| No. | Bottom depth (m) | Sapropel amorphous% | Vitrinite % | Inertia group % | TI | Type |
|-----|------------------|----------------------|-------------|-----------------|----|------|
| 45  | 2102.2           | 70                   | 1           | 29              | 40.3 | Ⅱ 1 |
| 48  | 2109.3           | 67                   | 2           | 31              | 34.5 | Ⅱ 2 |
| 52  | 2121.01          | 67                   | 1           | 32              | 34.3 | Ⅱ 2 |
| 55  | 2130.42          | 68                   | 0           | 32              | 36.0 | Ⅱ 2 |

3.3 Thermal mature degree of organic matter
The vitrinite reflectance of organic matter in the Zhaoxian shale ranged between 1.7 and 2.0% and the average value was 1.82%. It was in the high to over-mature stage, during which large amount of gas could be generated.

4. Gas-bearing characteristics
The on-site analytical gas content of the Zhaoxian shale was 0.34-2.01 m³/t, with an average of 0.99 m³/t (due to the closed coring, no lost gas was calculated). Wang Shejiao et al. [13] showed that the gas content of Benxi formation in well M35 ranged from 0.45 to 0.74 m³/t through the analysis of gas content of sealed coring. This indicated that the Zhaoxian shale of Benxi Formation has a great potential for natural gas exploration.

Table 3. Gas content of Zhaoxian shale in Benxi Formation in the M××× well

| No. | Bottom depth (m) | Lithology                  | Desorption gas (m³/t) | Residual gas (m³/t) | Total gas (m³/t) | Coring mode |
|-----|------------------|----------------------------|-----------------------|---------------------|-----------------|-------------|
| 43  | 2097.1           | carbonaceous mudstone      | 1.89                  | 0.12                | 2.01            | Airtight coring |
| 44  | 2099.48          | dark gray mudstone         | 1.45                  | 0.16                | 1.61            | Airtight coring |
| 49  | 2112.86          | dark gray mudstone         | 0.18                  | 0.16                | 0.34            | Airtight coring |
| 50  | 2116.17          | dark gray mudstone         | 0.66                  | 0.04                | 0.70            | Airtight coring |
| 51  | 2119.01          | dark gray mudstone         | 0.5                   | 0.21                | 0.71            | Airtight coring |
| 56  | 2133.26          | dark gray mudstone         | 0.49                  | 0.06                | 0.55            | Airtight coring |

5. Exploration potential
The Zhaoxian shale was formed in a marine sedimentary environment, with a thickness of 15-30m. Its effective shale (TOC>1%) has a thickness of 10m, with the distribution area of more than 5×10⁴ km², and a moderate buried depth of 1600-4400m. The organic matter abundance was high (TOC > 2%, accounting for 44%). The organic matter type was favorable for gas generation (mainly type Ⅱ2),
which was in a large gas-generation mature stage ($R_o > 1.7\%$). The gas content was between 0.34–2.01 m$^3$/t. The Zhaoxian shale had great potential for shale gas exploration.

Acknowledgements
This work was supported by funds from the PetroChina Changqing Oil field Company (Grant No. 2020-10) and State Key Laboratory of Organic Geochemistry, GIGCAS (Grant No. SKLOG202015).

References
[1] Bowker K 2007 AAPG Bulletin 91 523–533.
[2] Curtis J 2002 AAPG Bulletin 86 1921–1938.
[3] Ewing T 2006 AAPG Bulletin 90 963–966.
[4] Montgomery S, Jarvie D, Bowker K and Pollastro R 2005 AAPG Bulletin 89 155–175.
[5] Dong D, Zou C, Dai J, Huang S, Zheng J, Gong J, Wang Y, Li X, Guan Q, Zhang C, Huang J, Wang S, Liu D and Qiu Z 2016 Journal of Natural Gas Geoscience 1 413–423.
[6] Dong D, Zou C, Yang H, Wang Y, Li X, Chen G, Wang S, Lü Z and Huang Y 2012 Acta Petroleii Sinica 33 107–114 (in Chinese with English abstract).
[7] Tang X, Zhang J, Ding W, Yu B, Wang L, Ma Y, Yang Y, Chen H, Huang H and Zhao P 2016 Earth Science Frontiers 23 147–157 (in Chinese with English abstract).
[8] Wang S, Chen G, Dong D, Yang G, Lü Z, Xu Y and Huang Y 2009 Natural Gas Industry 29 51–58 (in Chinese with English abstract).
[9] Zou C, Dong D, Wang S, Li J, Li X, Wang Y, Li D and Cheng K 2010 Petroleum Exploration and Development 37 641–653.
[10] Zou C, Dong D, Wang Y, Li X, Huang J, Wang S, Guan Q, Zhang C, Wang H, Liu H, Bai W, Liang F, Lin W, Zhao Q, Liu D, Yang Z, Liang P, Sun S and Qiu Z 2015 Petroleum Exploration and Development 42 753–767.
[11] Zou C, Dong D, Wang Y, Li X, Huang J, Wang S, Guan Q, Zhang C, Wang H, Liu H, Bai W, Liang F, Lin W, Zhao Q, Liu D, Yang Z, Liang P, Sun S and Qiu Z 2016 Petroleum Exploration and Development 43 182–196.
[12] Zhang J, Jin Z, Yuan M 2004 Natural Gas Industry 24 15–18 (in Chinese with English abstract).
[13] Wang S, Li D, Li J, Dong D, Zhang W and Ma J 2011 Natural Gas Industry 31 40–46 (in Chinese with English abstract).