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Original research paper

Geochemical characteristics and origin of natural gas reservoired in the 4th Member of the Middle Triassic Leikoupo Formation in the Western Sichuan Depression, Sichuan Basin, China

Xiaoqi Wu*, Yingbin Chen, Guangxiang Liu, Huasheng Zeng, Yanqing Wang, Ye Hu, Wenhui Liu

Wuxi Research Institute of Petroleum Geology, Petroleum Exploration and Production Research Institute, SINOPEC, Wuxi, Jiangsu 214126, China

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Abstract

The gas exploration in the 4th Member of the Middle Triassic Leikoupo Formation (T_2l^4) in the Western Sichuan Depression has achieved a continuous breakthrough in the recent years. However, the gas origin and source remain controversial. The study on the geochemical characteristics indicates that the T_2l^4 gas in the Western Sichuan Depression is typically dry. Its dryness coefficient is generally higher than 0.99. The $\delta^{13}C_1$ and $\delta^{13}C_2$ values range from −35.1‰ to −29.3‰ and −34.8‰ to −31.9‰, respectively, with the exception of one gas sample from Well PZ1 with the $\delta^{13}C_2$ value of −26.4‰. The δD_{C1} value ranges from −164‰ to −136‰. The gas souring index is positively correlated with the $\delta^{13}C_2$ value in comparison to the $\delta^{13}C_1$. The T_2l^4 gas has experienced heavy alkane-dominated TSR instead of the methane-dominated TSR. The T_2l^4 gas in the Western Sichuan Depression generally displays a GSI value lower than 0.01 with the exception of two gas samples from Well PZ1 (0.036, 0.04); they indicate extremely low TSR alteration extent. Gas origin identification points out that the T_2l^4 gas in the Western Sichuan Depression is mainly oil-type gas that has reached the secondary gas cracking stage. The CO_2 in the T_2l^4 gas that has high $\delta^{13}C$ values are mainly inorganic. They are mainly derived from the interaction between acidic fluids and carbonate reservoirs.

Keywords: Western Sichuan Depression; Leikoupo Formation; Natural gas; Geochemical characteristics; Genetic types

1. Introduction

The Western Sichuan Depression is one of the most important exploration sites in Sichuan Basin in China. The natural gas exploration in this area has achieved significant progress in the recent years. On one hand, the exploration concentrates on the terrigenous layers of the Upper Triassic Xujiahe Formation (T_3x) and the Jurassic strata, and for this reason, several medium- to large-sized gas fields including the Xinchang (XC) gas field have been discovered [1−4]. One the other hand, the exploration focuses on the marine stratum of the Middle Triassic Leikoupo Formation (T_2l). Although the gas pool in the Zhongba (ZB) gas field in the northern part of the Western Sichuan Depression was discovered in 1972 within the 3rd Member of T_2l (T_2l^3) [5,6], the subsequent exploration in T_2l had made little progress until 2006. Gas exploration in the 4th Member of T_2l (T_2l^4) as carried out by SINOPEC has achieved a continuous breakthrough in the central part of the Western Sichuan Depression since 2006. In addition, the gas production test on Wells CK1, XS1, PZ1, YaS1, and YS1 have achieved commercial gas flow suggesting the favorable prospect of gas exploration in T_2l [7,8]. The Leikoupo Formation has become the new hotspot stratum in the gas exploration in the Western Sichuan Depression.

* Corresponding author.
E-mail address: xqwu@163.com (X. Wu).
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The studies on the geochemical characteristics of natural gas indicate that the T_2l^3 gas in the ZB gas field is mainly oil-type gas derived from the Permian source rocks. It is partially mixed with coal-type gas derived from the T_3x coal-measure source rocks [6,9]. The characteristics and controlling factors on the development of the T_2l^4 karst reservoirs in the central part of the Western Sichuan Depression [8,10] as well as the exploration potential [7,11] have been widely studied. Although the hydrocarbon potential of the T_2l source rocks [12] and the source of the T_2l^4 gas from Wells CK1 and PZ1 [13] have been roughly analyzed, there is no consensus on the origin and source of the T_2l^4 gas. The number of exploration wells has increased in recent years. Thus, favorable conditions have been provided for relevant studies.

The origin of the H_2S-bearing gas is one of the research hotspots for the marine natural gas [14,15]. The H_2S-enriched gas in the marine strata in the northeastern Sichuan Basin is generally believed to have been altered by the thermal sulfate reduction (TSR) [16−21]. The high H_2S contents in the T_2l^3 gas from the ZB gas field in the western Sichuan Basin is also considered to be derived from the TSR alteration [6]. The T_2l gas from wells such as Well CK1 and Well XS1 in the Western Sichuan Depression generally contains H_2S. However, it has been weakly studied. Therefore, the authors intend to analyze the geochemical characteristics of T_2l^4 gas in the Western Sichuan Depression and further demonstrate the genetic types of the T_2l^4 gas based on the comparison with the T_2l^3 gas from the ZB gas field and T_3x and the Jurassic gas from the XC gas field.

2. Geological setting

The NE-trending Western Sichuan Depression refers to the foreland basin which was formed in the Late Triassic period within the Western Sichuan Basin. The said depression's western boundary is the Longmenshan thrust belt with the eastern boundary being in the Longquan Mountain area. The Western Sichuan Depression has experienced multi-stage tectonic evolution as a result of the multi-period structural deformation of the periphery mountain system. This aforementioned phenomenon provides the favorable basis for the hydrocarbon migration, accumulation, and trap generation [22]. The study area locates at the central part of the Western Sichuan Depression, and it is generally divided into six secondary structural units, i.e., Dayi-Anxian Structural Belt, Xinchang Structural Belt, Zitong Sag, Chengdu Sag, Zhixinchang Structural Belt, and Zhongjiang-Huilong Structural Belt (Fig. 1). The wells with high-yield gas flow from the T_2l discovered to date are mainly located at the Xinchang Structural Belt (Wells CK1, XS1) and the Dayi-Anxian Structural Belt (Wells PZ1, YS1, YaS1) (Fig. 1). The Middle Triassic Leikoupo Formation (T_2l) in the Western Sichuan Depression is unconformably covered by the Upper Triassic Xujiahe Formation (T_3x), and it is divided into four members from bottom up, namely the 1st (T_2l^1), 2nd (T_2l^2), 3rd (T_2l^3), and 4th (T_2l^4) members, respectively. The top T_2l carbonate rocks in the Western Sichuan Depression have generally experienced denudation and karstification due to the effect of the early Indosinian movement at the end of the Middle Triassic period. The karst pore-type reservoirs on top of the T_2l are mainly distributed at the upper sub-member of T_2l [7,8]. In addition, natural gas is mainly enriched in this set of reservoirs; the T_2l^4 in the ZB gas field has been denuded, and natural gas is mainly enriched in the T_2l^3 reservoirs [5,9].

3. Geochemical characteristics of natural gas

The T_2l^4 gas in the Western Sichuan Depression has been analyzed in the Wuxi Research Institute of Petroleum Geology, Petroleum Exploration and Production Research Institute in SINOPEC. This is to accurately identify chemical, carbon, and hydrogen isotopic compositions. The chemical composition of gas samples was determined using an Agilent 7890A gas chromatograph (GC) that's equipped with a flame ionization detector and a thermal conductivity detector. The stable carbon isotopic composition of the natural gas was measured using a Finnigan MAT-253 mass spectrometer. The stable hydrogen isotopic composition of the alkane gases was measured by means of the Thermo Scientific Delta V Advantage mass spectrometer (GC/TC/IRMS). The analytical methods utilized were referenced from Dai et al. [1]. The analytical results are listed in Table 1. Based on the comparison between the T_2l^3 gas in the Zhongba (ZB) gas field and T_3x and the Jurassic gas in the XC gas field, the geochemical characteristics of the T_2l^4 gas in the Western Sichuan Depression were successfully and comprehensively analyzed.

3.1. Chemical composition

The CH_4 content of the T_2l^4 gas in the Western Sichuan Depression ranges from 89.19% to 99.63% with the content of heavy hydrocarbons being extremely low (Table 1). The C_3H_8 content is lower than 0.1% and it is too low to be detected in several gas samples. Similarly, both the C_4H_{10} and C_5H_{12} were hardly detected in all of the T_2l^4 gas samples (Table 1). The T_2l^4 gas is typically a dry gas, and it has a dryness coefficient (C_1/C_{1-5}) generally higher than 0.99 (Fig. 2a). This is evidently different from T_3x and the Jurassic gas in the XC gas field, which displays a positive correlation between the C_1/C_{1-5} ratio (<0.97) and the CH_4 content (Fig. 2a). The C_1/C_{1-5} ratio and the CH_4 content of the T_2l^4 gas in the Western Sichuan Depression are significantly higher than those of the T_2l^3 gas in the ZB gas field, respectively (Fig. 2a).

The nonhydrocarbon gas in the T_2l^4 gas in the Western Sichuan Depression is mainly composed of CO_2, N_2, and H_2S. The N_2 content is generally lower than 1.5%, whereas the CO_2 content ranges from 0 to 9.48% (Table 1). The T_2l^4 gas in the Well PZ1 has an H_2S content ranging from 3.5% to 3.72%. Meanwhile, the T_2l^4 gas in the Western Sichuan Depression contains a trace amount of H_2S that is generally lower than 1% (Table 1). This value is noticeably lower than the H_2S content of the T_2l^3 gas in the ZB gas field (1.78%−8.34%). The T_2l^4 gas is also different from the T_3x-J gas in the XC gas field as it has no H_2S (Fig. 2b). Since the nonhydrocarbon content in the

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