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Geochemical Characteristics of Shale Desorbed Gas in the Shanxi Formation of the Ordos Basin

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ABSTRACT

The Shanxi Formation in the Ordos Basin is an important strata for continental shale gas exploration in China. The study of the geochemical characteristics of its desorbed gas and the main controlling factors of reservoir formation is of great significance for resource potential assessment and development optimization. Based on the core samples from Well Chang96 and Well Yan2156 in the southeastern part of the basin, this paper systematically analyzes the characteristics of desorbed gas from shales in the Shanxi Formation. The research results show that: (1) The shale gas in the Shanxi Formation is mainly high-maturity thermogenic dry gas. The proportion of methane ranges from 80% to 93% (with an average of 80.05% in Member 1 and 84.02% in Member 2). The content of heavy hydrocarbons is extremely low (<0.3%), and the methane coefficient is >0.99. The non-hydrocarbon gases are mainly CO_2 and N_2 (with an average of 14% - 16%), and some are affected by air mixing. (2) The content of desorbed gas is closely related to lithology and organic matter abundance. Carbonaceous mudstone has the highest desorbed gas content, while fine-grained rocks such as mudstone and siltstone have significantly lower desorbed gas content, which is mainly controlled by differences in organic carbon content. (3) The desorbed gas content of shale gas in the Shanxi Formation of the Ordos Basin is low, which restricts resource potential assessment and favorable area prediction. This study provides a scientific basis for the efficient exploration and development of shale gas in the Ordos Basin and contributes to the improvement of the theoretical and technical systems for continental shale gas.

KEYWORDS

Shale Desorbed Gas; Shanxi Formation; Organic Matter Abundance; Ordos Basin.

1. INTRODUCTION

With the global energy structure shifting towards low-carbonization, the development of unconventional natural gases such as shale gas and coalbed methane has become an important direction for ensuring energy security. Shale gas, a self-generated and self-stored natural gas occurring in organic-rich shales, its enrichment laws are controlled by the coupled effects of multiple factors such as the geochemical characteristics of source rocks, reservoir physical properties, and structural preservation conditions. The Ordos Basin, as a typical cratonic superimposed basin, has developed marine-continental transitional organic-rich shales in the Shanxi Formation of the Carboniferous-Permian System, which is an important target strata for continental shale gas exploration. In recent years, breakthroughs have been made in the exploration of continental shale gas in the Shanxi Formation of the Ordos Basin. However, there are still controversies regarding the geochemical characteristics, genetic mechanisms, and reservoir control factors of its desorbed gas, restricting efficient exploration and development. [1-2]

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The Shanxi Formation in the Ordos Basin was formed during the transition period from the epicontinental sea of the North China Craton to the continental environment in the Late Carboniferous-Early Permian. A set of coal-bearing strata mainly composed of dark mud shales and carbonaceous shales were deposited, interbedded with thin sandstone layers and coal seams. The shales in this formation have high organic matter abundance and are mainly of Type III kerogen, with good gas generation potential. The cumulative proven shale gas reserves in the basin can reach 2.7×10^{12} m^3. However, the basin has experienced multiple tectonic movements (Indosinian, Yanshanian, and Himalayan movements), resulting in differential thermal evolution and subsequent transformation of the shales in the Shanxi Formation. The components, isotope compositions, and genetic types of the desorbed gas show significant spatial differences. Existing studies mostly focus on reservoir physical property evaluation or reservoir formation model discussions, while lacking systematic research on the geochemical characteristics of desorbed gas and its response relationship with source rock evolution and tectonic activities, restricting resource potential assessment and favorable area prediction.

The Ordos Basin has defects such as strong heterogeneity of source rocks, poor reservoir physical properties, complex structural preservation conditions, and obvious sedimentary facies control in the Shanxi Formation, increasing the difficulty of shale gas exploration and development. Based on its geological background, this paper uses experimental data to focus on analyzing the characteristics of desorbed gas from shales in the southeastern part of the Ordos Basin, the geochemical characteristics of desorbed gas, and other factors affecting the gas-bearing property of shales in the Shanxi Formation, providing guidance for the efficient exploration and development of shale gas in the basin and promoting the improvement of the theoretical and technical systems for marine-continental transitional shale gas. [3-5]

2. REGIONAL OVERVIEW

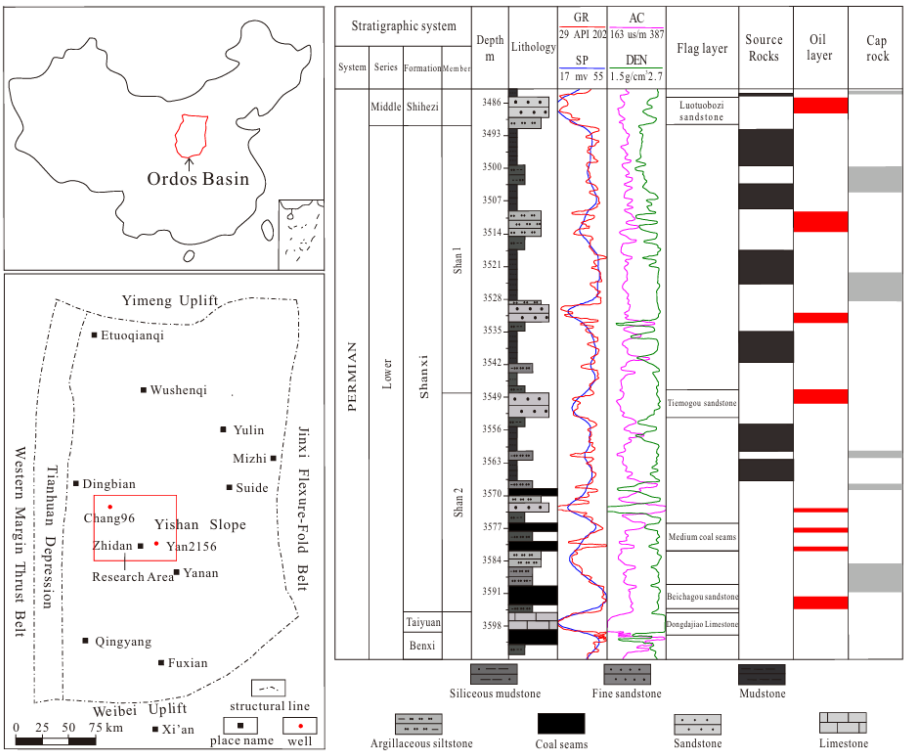


Figure 1. Structural location and stratigraphic comprehensive histogram of the study area

The Ordos Basin is located in the central and northern part of China, spanning five provinces and autonomous regions including Shaanxi, Gansu, Ningxia, Inner Mongolia, and Shanxi, with a total area of approximately 25×10^4 km². It has a relatively stable structure and is the second largest sedimentary basin in China. Its geographical scope extends from the Lvliang Mountains in the east to the Liupan Mountains in the west, from the northern foot of the Qinling Mountains in the south to the southern edge of the Yinshan Mountains in the north, presenting an approximately north-south rectangular outline as a whole. The basement of the basin is the Precambrian metamorphic rock series. The main body belongs to a stable cratonic basin, with a structural pattern of "uplifts around and depression in the middle", and is characterized by weak tectonic activities, complete preservation of strata, and coexistence of multiple energy sources. According to the tectonic evolution stage and deformation characteristics of the basin, the Ordos Basin is divided into six structural units, namely the Yimeng Uplift, the Western Margin Thrust Belt, the Tianhuan Depression, the Yishan Slope, the Western Shanxi Flexure-Fold Belt, and the Weibei Uplift.

The Shanxi Formation (Carboniferous-Permian) in the Ordos Basin generally has a thickness of 30 - 120 meters. Controlled by paleogeomorphology and sedimentary facies, it shows a trend of "thicker in the east and thinner in the west". In the central and southern part of the Yishan Slope, the thickness of the Shanxi Formation is generally 50 - 80 meters, and local areas may thicken or thin due to the influence of paleochannel or swamp microgeomorphology. The lithology of Member 1 is mainly developed with dark mudstone, including grayish-black mudstone and carbonaceous shale, locally interbedded with thin coal seams. Sedimentary structures mainly include horizontal bedding, cross-bedding, and inclined bedding. The lithology of Member 2 is mainly developed with dark gray - black shale, thin-layered siliceous shale, and interlayers of fine-grained quartz sandstone. Sedimentary structures mainly include horizontal bedding and massive bedding.

3. SAMPLES AND EXPERIMENTAL METHODS

In this study, two shale gas wells (Well Yan2156 and Well Chang96) were selected to carry out continuous monitoring of the gas production process at different scales, gas sample collection, and carbon isotope testing and analysis. Twelve shale samples were taken from the core of the first member of the Shanxi Formation in Well Chang96 for on-site sealed tank desorption testing. The main purpose was to explore the methane and ethane carbon isotope fractionation characteristics and main controlling factors during the shale gas desorption process.

Shale core samples were drilled using conventional coring technology for subsequent degassing experiments. After the core was taken out of the barrel, it was cleaned, weighed, and sealed in a tank, and then an on-site desorption experiment was carried out. The experimental process refers to the industry standard of China National Petroleum Corporation, "Determination Method for Shale Gas Content: SY/T 6940—2020". During the coring process, key time nodes such as the start of core lifting, reaching the ground, and tank loading for desorption were recorded to obtain accurate coring time and surface exposure time. The desorption experiment was divided into three stages (with desorption temperatures of 20℃, 65℃, and 90℃ respectively). By conducting staged desorption of the same shale sample under different temperature conditions, the residual gas volume in the shale was reduced. When the desorbed gas volume was less than 5 mL in 2 consecutive hours in a single stage, the stage ended and the next stage was carried out. A water displacement gas collection device was used to measure the gas volume, and a brine glass bottle (150 mL) was used to collect desorbed gas samples. The collected gas volume was approximately 100 - 120 mL, with at least a 2 cm - thick water layer remaining at the bottom. [6-7]

According to the Chinese natural gas standard GB/T13610—2020, "Analysis of Natural Gas Composition - Gas Chromatography Method", a gas chromatograph (GC) was used for natural gas component analysis. Gas chromatography is currently the most commonly used separation and detection method in gas analysis. It separates gas components based on the differences in their

distribution coefficients in the chromatographic column and qualitatively and quantitatively analyzes each component through a detector.

4. DESORBED GAS PRODUCTION CHARACTERISTICS

By conducting staged desorption of the same shale sample under different temperature conditions, the residual gas volume in the shale was reduced. When the desorbed gas volume was less than 5 mL in 2 consecutive hours in a single stage, the stage ended and the next stage was carried out. For example, in Well Yan2156, at a depth of 3599.50 - 3599.61 m, there is black carbonaceous mudstone, and the desorbed gas volume is 3835 mL.

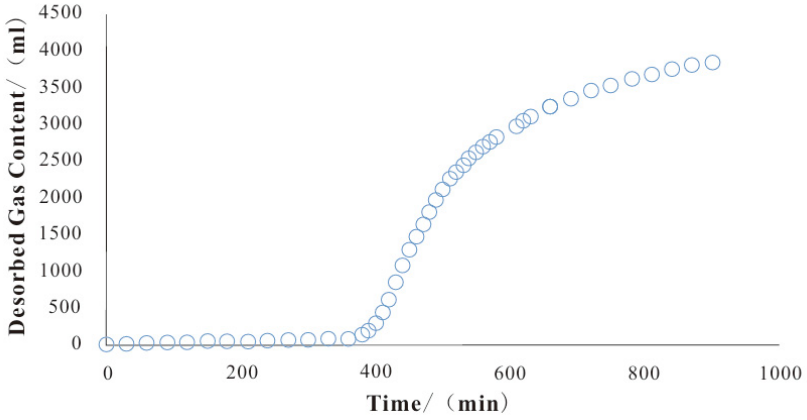


Figure 2. Desorption Results of Mud Shale Samples from the Shanxi Formation in Well Yan2156

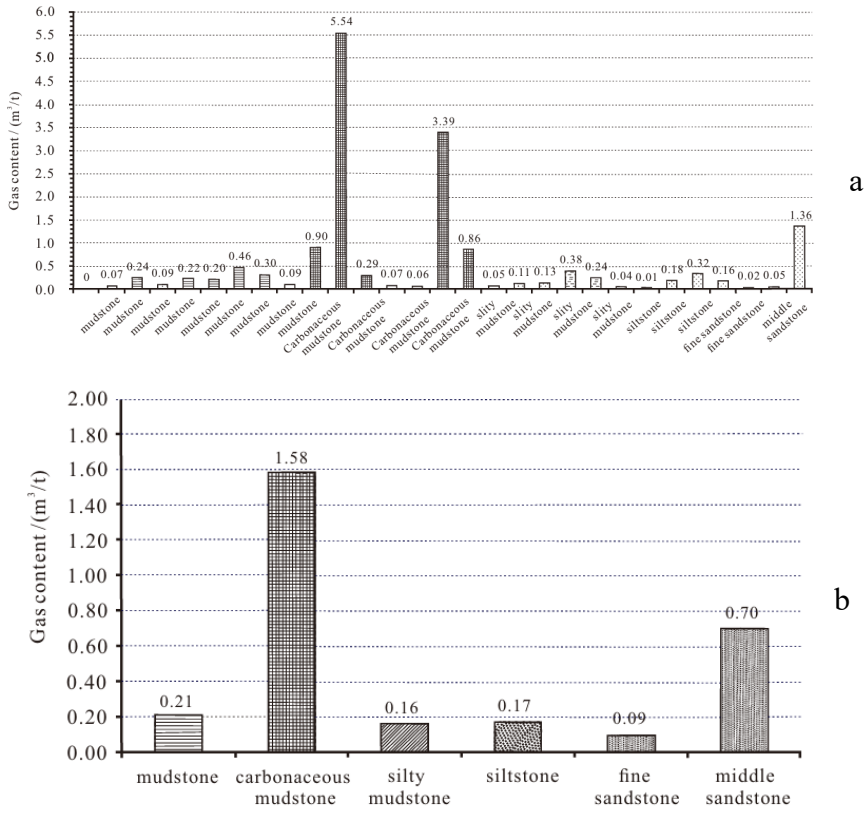


Figure 3. Desorbed Gas Content and Different Lithology Types of the Shanxi Formation in Well Chang96 (2621 - 2670m)

The results show that different lithologies have different desorbed gas contents. Taking Well Yan2156 in the study area as an example, in the well section of the Shanxi Formation (3559 - 3601 m), the desorbed gas content accounts for 29.5% - 84.03% of the total gas production, most of the lost gas is free gas, and the lost gas volume accounts for 10.49% - 64.62% of the total gas production, and the residual gas volume accounts for 0.34% - 17.54% of the total gas production.

The desorbed gas production volume varies with different types of lithologies. In fine-grained sediments, carbonaceous mudstone has the highest desorbed gas content, followed by mudstone, and then siltstone and fine sandstone. Taking Well Chang96 as an example, in the well section of the Shanxi Formation (2621 - 2670 m), specifically, among the desorbed gases of 7 carbonaceous mudstone samples, the content ranges from 0.0678 to 5.539 m^3/t, with an average of 1.58 m^3/t, and only 2 samples reach more than 1 m^3/t (the lower limit of industrial mining index). Secondly, for mudstone, the desorbed gas content of 8 samples ranges from 0.07 to 0.459 m^3/t, with an average of 0.209 m^3/t, and the desorbed gas content of mudstone is very low, with no sample reaching 1 m^3/t. Thirdly, for silty mudstone and siltstone interbedded with mudstone, the desorbed gas content ranges from 0.043 to 0.382 m^3/t, with 6 samples and an average of 0.159 m^3/t. For 3 siltstone samples, the desorbed gas content ranges from 0.013 to 0.318 m^3/t, with an average of 0.17 m^3/t. In coarse-grained fine sandstone and medium-grained sandstone, except for an individual medium sandstone sample with a content of 1.36 m^3/t, the desorbed gas content of most samples is not high, with an average basically ranging from 0.09 to 0.05 m^3/t. [8-10]

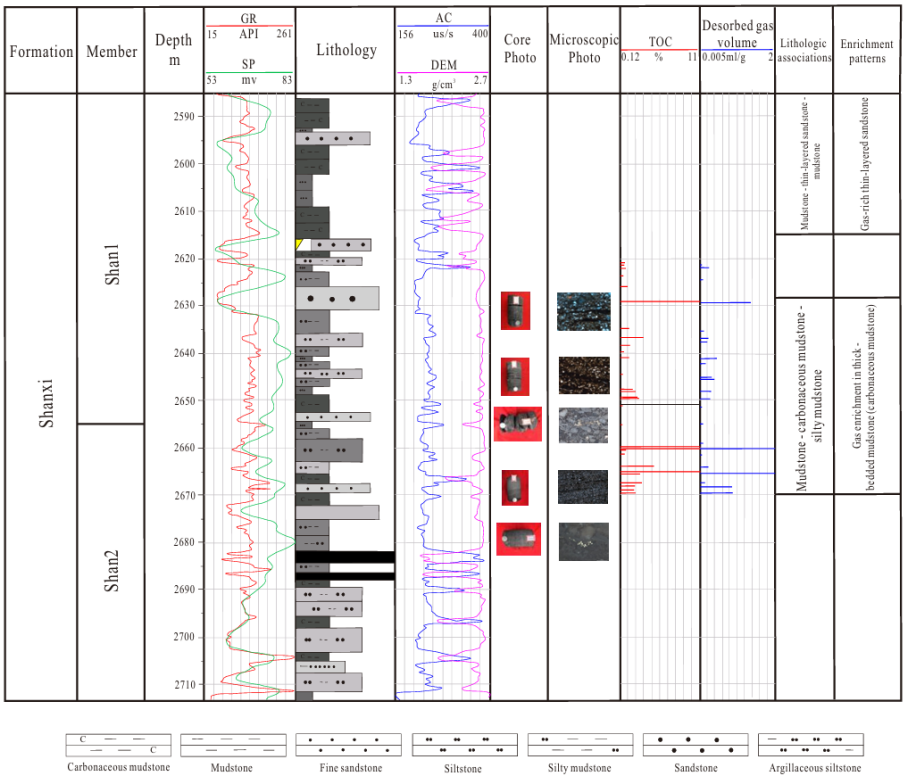


Figure 4. Distribution of shale desorbed gas in the Shanxi Formation of Well Chang 96

In the continental shale gas of the Carboniferous-Permian System in China, the desorbed gas content of mud shales is generally not high. In the Taiyuan Formation and Shanxi Formation mud shales exposed in the North China Platform, the average shale gas content ranges from 0.36 to 0.57 m^3/t, all lower than the industrial mining standard of 1 m^3/t. In the marine-continental transitional mud shales of the Longtan Formation (P_2l) in the Shaoyang Sag, central Hunan, Yangtze Platform, the desorbed gas content ranges from 0.5 to 2.35 m^3/t, with an average of 1.0 m^3/t, and the overall content is not

high. In the study area, according to the desorbed gas of mud shales in the Shanxi Formation studied by Tang Xuan (2016) and this study, the average content is basically 1.11 - 1.3030 m^3/t. Although the average is greater than 1.0 m^3/t, 60% of the samples have a desorbed gas content less than 1.0 m^3/t. Compared with the current shale gas industrial production areas in the Sichuan Basin, such as the Jiaoyeba area, the desorbed gas content of the Wufeng Formation O_3w - Longmaxi Formation S_1l ranges from 0.44 to 5.19 m^3/t, with an average of 1.97 m^3/t. The desorbed gas content of shale gas in the study area is low. Except for carbonaceous mudstone that can be greater than 1.0 m^3/t, most of the contents are very low and cannot reach the industrial mining lower limit. [11-12]

The correlation between the desorbed gas content and lithology is mainly controlled by the organic carbon content. Organic-rich carbonaceous debris adsorbs a large amount of shale gas. In black carbonaceous mudstone and dark gray mudstone, the organic carbon content is high, the adsorbed gas content is high, and the desorbed gas volume is high. On the contrary, in light gray and gray mudstone with low organic carbon content, the adsorbed gas content is low, and the desorbed gas volume is also low.

5. GEOCHEMICAL CHARACTERISTICS OF DESORBED GAS

The mud shale samples taken out of the wellbore were immediately placed in the desorbed gas instrument to desorb the gas. The collected desorbed gas was subjected to gas component analysis. The results are as follows:

(1)Hydrocarbon Gas Composition

In the desorbed gas from mud shales and siltstones in Member 1 and Member 2 of the Shanxi Formation, alkane gases are the main components, mainly methane, with trace amounts of ethane and propane. Secondly, there are non-hydrocarbon gases, mainly CO_2, N_2, O_2, and trace amounts of H_2S and He, etc.

Among the alkane gases, the methane content varies greatly. In Member 1, the methane content ranges from 58.57% to 93.49%, with a main frequency distribution of 85% - 95% and an average of 80.05% (12 samples). In Member 2, the methane content ranges from 74.63% to 92.90%, with a main frequency distribution of 85% - 95% and an average of 84.02% (13 samples). The content of heavy hydrocarbons (the sum of ethane and propane) is low. In Member 1, the content ranges from 0.07% to 1.13%, with a main frequency distribution of 0.15% - 0.25% and an average of 0.27% (13 samples). In Member 2, the content ranges from 0.02% to 0.19%, with a main frequency distribution of 0.0% - 0.05% and an average of 0.08% (13 samples), both less than 5%.

The methane coefficient in the study area is basically greater than 0.99. The average methane coefficients of Member 1 and Member 2 are 0.997 (12 samples) and 0.999 (13 samples) respectively. Combined with the heavy hydrocarbon content, they are all dry gases, consistent with the shale gas taken out of the wellhead.

(2)Non-Hydrocarbon Gas Composition

There are many types of non-hydrocarbon gases, but the ones with the highest content and the most widespread distribution are CO_2 and N_2. In addition, there is a lot of oxygen mixed in, and the trace components include helium, argon, and hydrogen sulfide. Since the desorbed gas equipment does not have a vacuum pumping device, the nitrogen, carbon dioxide, oxygen, helium, and argon in the gas are likely to come from the mixing of the corresponding components in the air.

In Member 1, the non-hydrocarbon content ranges from 1.84% to 40.55%, with a main frequency distribution of 1.84% - 5% and an average of 14.25% (12 samples). In Member 2, the non-hydrocarbon content ranges from 6.94% to 25.35%, with a main frequency distribution of 15% - 20% and an average of 15.9% (13 samples). Compared with shale gas, the non-hydrocarbon content is high, with a wide distribution range and complex components. [13-18]

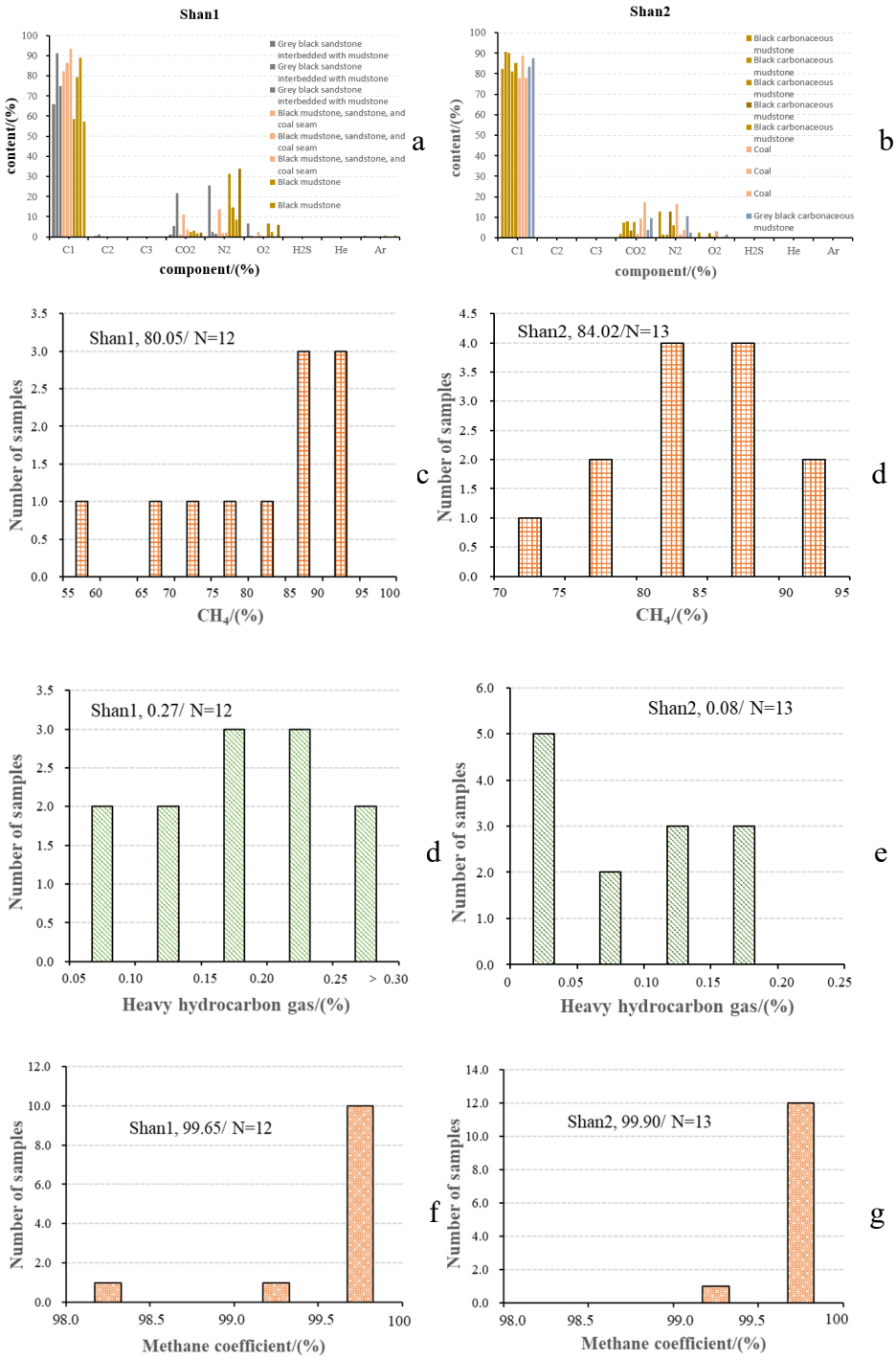


Figure 5. Characteristics of hydrocarbon components of the desorbed gas in the shales of the Shanxi Formation in Well Chang 96

6. CONCLUSION

(1) The shale gas in the Shanxi Formation of the Ordos Basin is mainly high-maturity thermogenic dry gas, and carbonaceous mudstone is the sweet spot target. However, the overall desorbed gas content is low, and the industrial development potential is limited.

(2) The desorbed gas content is positively correlated with TOC. The adsorbed gas in black carbonaceous mudstone accounts for a high proportion, while the gas content in light gray mudstone drops sharply.

(3) In the desorbed gas from mud shales and siltstones in the Shanxi Formation, hydrocarbon gases are mainly methane, and the content of heavy hydrocarbons is extremely low. Among the non-hydrocarbon gases, the contents of CO_2 and N_2 are high, and air components may be mixed in.

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