Organic Geochemistry 102 (2016) 67–76

Contents lists available at ScienceDirect

Organic Geochemistry

journal homepage: www.elsevier.com/locate/orggeochem

Geochemical characteristics and genesis of natural gas in the Yan'an gas field, Ordos Basin, China

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ARTICLE INFO

Article history:
Received 9 July 2016
Received in revised form 30 September 2016
Accepted 12 October 2016
Available online 19 October 2016

Keywords:
Carbon isotope values
Light hydrocarbon
Coal-derived gas
Carboniferous–Permian
Yan'an gas field
Ordos Basin

ABSTRACT

The Yan'an gas field in the Ordos Basin, China, was discovered in 2014 and contains reserves of up to 100 billion m^3. Its occurrence in the basin contradicts the distribution model of "gas in the north, oil in the south". Upper Paleozoic natural gas in the Yan'an area is dominated by methane, with an average dryness coefficient (C_1/C_{1-4}, %) of 99.5% ($\delta^{13}C_1 = -30.8$ to $-27.5‰$), with minor amounts of $CO_2 = 3.8\%$, $N_2 = 0.5\%$, and ethane ($\delta^{13}C_2 = -37.2$ to $-30.5‰$) and traces of higher hydrocarbons. The gas is predominantly coal-derived originating from Carboniferous–Permian humic hydrocarbon source rocks and minor oil-type gas from sapropelic source rocks. The carbon isotope series includes reversals, with $\delta^{13}C_2 < \delta^{13}C_1$ and rare $\delta^{13}C_3 < \delta^{13}C_2 < \delta^{13}C_1$. The enriched $\delta^{13}C_1$ value is a result of the extremely high thermal maturity, while the depleted $\delta^{13}C_2$ value cannot be explained solely by the simple addition of oil-type gas. The complex carbon isotope reversals result from the combined effects of several secondary reactions under extremely high thermal maturity.

1. Introduction

The Ordos Basin is a petroliferous basin with Paleozoic strata occurring over an area of more than 250,000 km^2. The basin has the largest proven reserves of natural gas, the largest annual output, and the most stable tectonics in China (Liu et al., 2009, 2015; Dai et al., 2014). The Upper Paleozoic stratum is a tight-sand gas pool, where the widely distributed coal-bearing rocks are superimposed with sandstone reservoirs. Tight sand gas accumulations were formed over a large area as the coal-derived natural gas migrated only short distances for efficient trapping and accumulation (Yang and Liu, 2014).

Large-scale gas exploration in the Ordos Basin started in the 1980s when the exploration strategy evolved from targeting structural to lithological traps. Ordovician paleo-weathered crust gas fields, such as the Jingbian gas field, were discovered. The exploration focus moved from Lower Paleozoic carbonate traps to Upper Paleozoic clastic lithological traps in the middle of the 1990s and some clastic lithological gas reservoirs (such as the Yulin gas field) were discovered. Since 2000, exploration has moved to the Upper Paleozoic tight sand gas reservoirs and several (such as the Sulige gas field) were discovered (Yang et al., 2012). The annual average growth of natural gas reserves has exceeded 150×10^9 m^3 in the last 10 years. Since 2007, newly confirmed reserves exceeded 500×10^9 m^3 per year (Yang and Liu, 2014). Large gas fields such as Jingbian, Sulige, Yulin, Daniudi, Shenmu, and Zizhou, occur in the northern parts of the basin and define a regional paradigm for the hydrocarbon distribution of "Paleozoic gas in the north, Mesozoic oil in the south" (Dai et al., 2005; Li et al., 2005; Zhao et al., 2014). With the exception of the Jingbian gas field, for which the reservoir comprises Ordovician carbonate rocks, the large gas field reservoirs consist of Carboniferous–Permian sandstone that produce coal-derived gas (Dai et al., 2005, 2014; Li et al., 2005) and minor oil-type gas. Since 2014, exploration has discovered economic gas flows in several Upper Paleozoic successions in the southeastern Ordos Basin that do not conform to the regional hydrocarbon distribution. Proven reserves had been discovered in the Yan'an gas field, including the YQ2-Y128, Y113-Y133 and Y353-Y145 well areas, with an initial cumulative proven gas reserve of 337.4×10^9 m^3.

The genesis of Ordovician gas in the Jingbian field in the southern Ordos Basin is disputed. The carbon isotope composition of ethane can be used as an indicator of parent material (Dai et al., 2016). Oil-associated gas is typically characterized by $\delta^{13}C_2 = < -28$ to $-29‰$, while the $\delta^{13}C_2$ value of coal-derived gas is $> -28‰$ (Dai et al., 1992, 2014). Ethane in the Jingbian gas field is unusually depleted and $\delta^{13}C_2 < \delta^{13}C_1$. Some studies have suggested that it is a mixture of Upper Paleozoic coal-derived gas and Ordovician oil-type gas, while others have proposed that it

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http://dx.doi.org/10.1016/j.orggeochem.2016.10.008

resulted from the injection of an oil-type gas generated from Carboniferous–Permian marine limestones (Dai et al., 1992, 2014; Zou et al., 2007; Hu et al., 2008).

This study presents the first analysis and discussion of the gas composition, carbon and hydrogen isotope characteristics, light hydrocarbon composition and distribution, genetic type, and carbon isotopic reversal phenomena of the Yan'an gas field. These new data provide a set of reference characteristics and details of unusual aspects of natural gas under over-mature conditions in the Ordos Basin. Since the Lower Paleozoic strata of the Yan'an gas field have not been drilled extensively, the hydrocarbon potential of the source rocks cannot be studied directly sufficiently and can only be inferred from the gas geochemistry.

2. Geological setting

The Yan'an gas field is located in the southern-central part of the Yishan Slope (a first-order tectonic unit) of the Ordos Basin, in eastern Yan'an, Yanchang, and southern Yanchuan counties (Fig. 1). It is bounded by the Yulin–Mizhi gas fields in the north (Zone II), and overlaps the lower Paleozoic gas zone (O_1m_5) in the south of the Jingbian gas field (Zone III). The gas-producing units of this gas field comprise the Carboniferous Benxi Formation (C_2b), middle Permian Xiashihezi Formation (P_2h), and Shanxi Formation sandstones (P_1s; Zhao et al., 2014; Li et al., 2015). The Benxi Formation is composed of tidal flat–barrier island deposits; the reservoir rocks comprise a single barrier island sand bar and sand flat, with a thickness of 2–10 m, which occurs in the southern portion of the field. The Shanxi and Xiashihezi (Member 8) formations represent a lake–delta sedimentary system; the reservoir rocks are composed of 4–20 m thick delta-front, underwater distributary channel sands, with a wide lateral distribution and vertical superposition. Porosity (4.4–5.6%) and permeability (0.6–7.1 mD) of the reservoir rocks are low (Li et al., 2015).

3. Analytical methods

3.1. Sampling

Twenty-seven gas samples were taken from the YQ2–Y128 gas region of the Yan'an gas field (Fig. 1). These were collected in high-pressure cylinders (pressure resistant up to 15 MPa) at pressures of ~5 MPa after the vessels had been repeatedly flushed and refilled.

3.2. Geochemical and stable carbon and hydrogen isotopic analyses

Measurements of gas composition and carbon and hydrogen isotopic ratios were conducted at the PetroChina Research Institute of Petroleum Exploration & Development (RIPED) in Beijing, China. A HP7890A gas chromatograph with a capillary column was used to separate single gas hydrocarbon compositions (PLOT Al_2O_3, 50 m × 0.53 mm). The gas chromatograph temperature was first set at 30 °C, where it was held for 10 min, and then raised to 180 °C at a rate of 10 °C/min.

A mass spectrometer (MS; Thermo Delta V Advantage) was used to analyze carbon isotopes. The initial temperature was set at 33 °C using a GC–C-irm-MS, then raised from 35 °C to 80 °C at a rate of 8 °C/min, and to 250 °C at a rate of 5 °C/min, where it was held for 10 min. Each sample was analyzed three times, yielding an analytical precision of ± 0.3‰. Results are reported relative to the Vienna Pee Dee Belemnite (VPDB). Hydrogen isotopes were analyzed using a Finnigan MAT 253 mass spectrometer using the GC–TC–IRMS method. The gas was separated through a chromatographic column (HP-PLOTQ column, 30 m × 0.32 mm × 20 mm). Analytical precision was ± 3‰, and H-isotope results are reported relative to Vienna Standard Mean Ocean Water.

3.3. Analysis of light hydrocarbons

Light hydrocarbons were analyzed at the Langfang branch of RIPED using a HP5890A gas chromatograph, and a PONA capillary column (50 m × 0.25 mm × 0.5 μm) with helium as the carrier gas. The front of the capillary column was immersed into a liquid nitrogen trap to enrich the low content of light hydrocarbons. After injecting a large volume of gas (about 15–20 ml) over a 20 min period, the cold trap was removed. The eluted light hydrocarbons were analyzed using a FID at 320 °C. The initial temperature was set at 30 °C, where it was held for 10 min, then raised to 70 °C at a rate of 1 °C/min and then to 160 °C at 3 °C/min, and finally the temperature increased from 160 °C to 270 °C at a rate of 5 °C/min, where it was held for 20 min. Light hydrocarbons were qualitatively analyzed using an Agilent PONA gas chromatograph. The standard test mixture contained 53 compounds (from isobutane to *n*-octane). The compounds were quantified from peak areas of individual compounds.

The geochemical parameters of the Upper Paleozoic gas (II) of the Yulin–Mizhi gas fields in the northern Yan'an gas field, and the Ordovician Majiagou Formation gas (III) of the Jingbian gas field in the northwest, were selected for comparison of genetic types. Data and literature sources are listed in Tables 1 and 2.

4. Results

4.1. Natural gas components

The composition of natural gas in the Yan'an gas field is dominated by hydrocarbons (95.7%), of which methane CH_4 accounts for 89.9–97.5% (mean CH_4 = 95.2%), while ethane (C_2H_6) (0.5%) and propane contents are low (Fig. 2). The dryness coefficient (C_1/C_{1-4}, %) averages 99.5% (Table 1), typical of dry gas. Non-hydrocarbon gases include a small amount of CO_2 (1.4–9.1%) and N_2 (0.5%).

The Jingbian gas field is similar to the Yan'an gas field with respect to its dry coefficient values, and CH_4 and CO_2 contents. In the north, the Upper Paleozoic gas of the Yulin–Mizhi gas fields has a low dryness coefficient and CO_2 content (Fig. 2).

4.2. C-isotope compositions

The carbon isotope composition of methane in the Yan'an gas field has $\delta^{13}C_1$ values ranging from −30.8 to −27.5‰, more enriched than that of the Upper Paleozoic gas in the north. The $\delta^{13}C_2$ values range from −37.2 to −30.5‰ (mean $\delta^{13}C_2$ = −34.8‰), which is more depleted than that of the Yulin–Mizhi gas fields (Hu et al., 2008; Zhao et al., 2014). The propane content of the gas is very low, averaging 0.04%, and it has a $\delta^{13}C_3$ value of −37.3 to −30.4‰, which is slightly more depleted than that of the gas from the Jingbian gas field (mean $\delta^{13}C_3$ = −29.3‰; Table 1).

Alkane gases from a single source show a linear relationship between carbon number ($1/n$) and $\delta^{13}C_n$ and the slope change of the regression line can be used to identify whether mixing between different types of gas at different evolutionary stages and biogas occurred, and to monitor the effects of methane seepage (Rooney et al., 1995). Upper Paleozoic gases in the eastern Ordos Basin and gas in the north are typically mature-stage and coal-derived and exhibit a linear relationship between $\delta^{13}C_n$ and $1/n$ suggesting a homogeneous accumulation of gas in this area (Fig. 3). In contrast, the carbon number and isotopic composition