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Journal of Natural Gas Geoscience 1 (2016) 383−395

http://www.keaipublishing.com/jnggs

Original research paper

Pore system characteristics of the Permian transitional shale reservoir in the Lower Yangtze Region, China☆

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Received 18 September 2016; revised 11 October 2016
Available online 14 November 2016

Abstract

The Permian shale, a set of transitional shale reservoir, is considered to be an important shale gas exploration target in the Lower Yangtze region. Due to little research conducted on the pore system characteristic and its controlling factors of the shale gas reservoir, SEM, FE-SEM, low-pressure N_2 adsorption, and mercury intrusion tests were carried out on the Permian shales from the outcrop and HC well in the southern Anhui. The results show that the Permian shales mainly consist of organic matter, quartz, illite, calcite, and pyrite, of which pyrite occurs as framboids coexisting with organic matter and the organic matter is distributed in shales in stripped, interstitial, thin film and shell shapes. The basic pore types are inorganic mineral pore (intercrystalline pore, intergranular edge pore, intergranular pore, and interlayer pore in clay minerals) and the organic pore and microfracture, of which organic pore and microfracture are the dominating pore types. In shale, organic pores are not developed at all in some organic grains but are well developed in others, which may be related to the types of and maceral compositions of kerogen. Under tectonic stress, shale rocks could develop mylonitization phenomenon exhibiting organic grains well blend with clay minerals, and produce a mass of microfractures and nanopores between organic matter grains and clay minerals. Mercury intrusion tests show that the shale is mainly composed of micropore and transition pore with high porosity, good pore connectivity and high efficiency of mercury withdraw, while the shale that mainly dominated by mesopore and macropore has a low porosity, poor pore connectivity, and low efficiency of the mercury withdraw. The volume percentage of mesopore and marcopore is increasing with the increase of quartz, and that of micropore and transition pore has a decreased tendency along with the increase of soluble organic matter (S1). Organic matter is the main contributor to the specific surface area. However, clay minerals could significantly inhibit the numbers of the microscopic pore and specific surface area due to the clay minerals being mainly dominated by illite and chlorite.

Keywords: Transitioanal facies; Pore system; Specific surface area; Permian; Lower Yangtze region

1. Introduction

Shale gas consists of free gas that's existing in the matrix minerals-related pores and fractures, adsorbed gas on the surface of micropores in organic matter and clay minerals, and dissolved gas in bitumen and water [1]. It has been made known that the organic pores are the most important reservoir space, and that the shale gas content is increasing with the increasing TOC [2,3]. In addition to organic pores, the

☆ This is English translational work of an article originally published in *Natural Gas Geoscience* (in Chinese).The original article can be found at: 10.11764/j.issn.1672-1926.2016.07.1332.

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Peer review under responsibility of Editorial office of *Journal of Natural Gas Geoscience*.

http://dx.doi.org/10.1016/j.jnggs.2016.11.004

inorganic pores and microfractures also play an important role in the gas storage and migration. The shale gas reservoir dominated by inorganic pores is rare, such as Haynesville shale gas reservoir, and the dominated pore type is matrix mineral pore with a relatively high content of free gas, therefore, has a certain significance of shale gas exploitation.

The shale gas exploited in North America mostly exists in marine shale gas reservoirs. Only Lewis shale gas is produced in the transitional shale reservoir, and its total porosity and gas content are obviously lower than that of marine shale reservoir [4]. There are several sets of transitional organic-rich mudstones that developed in China. The Permian transitional shales, with great thickness, high TOC (generally greater than 2%), and moderate high maturity (R_O is about 1.3%–3.0%) [5,6] are widely distributed in the Lower Yangtze region, and are considered have good shale gas geological conditions. The researchers have used a variety of techniques, such as low-pressure N_2 adsorption, mercury intrusion, and nuclear magnetic resonance, to study the pore structure characteristics of the Permian transitional shales, and some knowledge has been obtained. TOC is the main contributor of micropores, and clay minerals have limited contribution to pore system [7,8], whereas fractures may also be an important provider to pore space for these Permian shales [9]. Wang et al. [10] and Yuan et al. [11] investigated the pore characteristics of transitional shales of the Upper Permian Longtan Formation in Guizhou province and the Upper Carboniferous Shanxi Formation, respectively, and found that the main pore types are intergranular pores between mineral grains and shear fractures in interlayered sandstones and organic pores are not well developed. Hence, it is very necessary to systematically study the characteristics and possible controlling factors of microscopic pore system of transitional shales.

In this paper, we conducted the scanning electron microscopy (SEM), field emission scanning electron microscopy (FE-SEM), low-pressure N_2 adsorption, and mercury intrusion experiments to study the pore morphology of the Permian transitional shales in the Lower Yangtze region, and summarize the characteristics of pore system and discuss their controlling factors. This not only has important reference significance for investigating the shale gas potential of the Lower Permian, but it also provides a good reference for evaluating the transitional shales in other regions in China.

2. Geological setting

The tectonic evolution of the Lower Yangtze Platform experienced two stages: the continental margin of the Late Sinian to the Late Triassic, and the continental margin of the western Pacific after the Indosinian movement; they formed two large tectonic units, the Su-Wan structural belt and the Jiangnan uplift [12]. The study area is located in the southern Anhui in the Lower Yangtze region. This area covers the South Anhui-South Jiangsu depression with an area of about 12,000 km^2. The Paleozoic sedimentary-tectonic evolution of the Lower Yangtze Platform indicates that there are several sets of high-quality hydrocarbon source rocks in the Paleozoic strata in southern Anhui. A set of transitional facies organic-rich shale of the Permian is distributed in this region. The Permian is divided into the Xixia Formation (P_1x), Gufeng Formation (P_2g), Longtan Formation (P_3l), and Dalong Formation (P_3d) from bottom to top. The Permian shale has a moderate buried depth and is rich in organic matter, which is considered as a favorable shale gas exploration layer [5]. However, this region has undergone multi-phase strong tectonic reconstruction since the Indosinian period. The destruction of the Paleozoic strata in southern Anhui by the tectonic activity would affect the storage space and the gas storage of shale gas reservoirs, which may be a factor of controlling the gas-bearing capacity of shale [13]. The shale samples studied in this paper were collected from HC well in Wuhu area and Pingdingshan outcrop profile in Chaohu area (Fig. 1). These samples show that the thickness of the Permian strata is large and the organic matter is high. And hence the Permian shales in southern Anhui were selected as an object to study the pore system characteristics.

3. Samples and experiments

3.1. Samples

Fourteen core samples from the Longtan and Gufeng formations were taken from the HC well in the Wuhu area, with the sampling depth ranging from 109.9 m to 275.1 m (Table 1). Three outcrop samples from the Gufeng Formation were collected from the Pingdingshan profile in the Chaohu area (Table 1). The TOC value, Rock-eval, and mineral compositions were analyzed for all the samples. Several samples were selected to carry out SEM and FE-SEM analysis. The samples from the HC well were also measured by low-pressure N_2 adsorption and mercury intrusion techniques.

3.2. Experiments

The fresh section of shale was made perpendicularly to the shale bedding and was analyzed by S-4800 SEM instrument produced by Hitachi Company in Japan to observe the shale compositions and their occurrence states. Meanwhile, the shale samples were cut into slices of about 0.5 cm × 0.5 cm and then subjected to argon ion polishing. The treated samples were used to observe microscopic pore structure by Helios 650 FE-SEM manufactured by FEI Company. The maximum resolution of this instrument is 0.8 nm. In order to prevent electron beam damaging the surface of the sample, a lower acceleration voltage (2.0 kV) and the working distance of 3.0–3.6 mm were set in the experiment.

Porosity and pore size distribution were measured using Autopore 9510 porosimeter produced by Micromeritics Company. The pressure was continuously increased from 0.01 MPa to 413 MPa, and the corresponding pore diameter was varying from 120 μm to 3 nm. The pore size classification was adopted the decimal scheme [14], consisting micropore (<10 nm), transitional pore (10–100 nm), mesopore and macropore (>100 nm).