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Classification and controlling factors of organic pores in continental shale gas reservoirs based on laboratory experimental results

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ABSTRACT

This study aims to document the classification and controlling factors of organic pores distributed in the continental shale reservoir of the Chang-7 Member of the Yanchang Formation in the Ordos Basin. More than 105 sample blocks were collected from the continental shale gas reservoirs of the Chang-7 Member from 18 separate wells located in central and southern Ordos Basin. Samples were etched via argon ion polishing in preparation for imaging using core plugs and drill cuttings. Next, an environmental scanning electron microscope Quanta 250 FEG was used to scan the micropores; these results are presented in the Samples section. The Quanta 250 FEG can also be used to analyze the media of micropores via energy dispersive spectroscopy. Detailed pore structure parameters were calculated by analyzing the adsorption and desorption isotherms of the samples. Specimen results indicate that all organic pores developed in type-II kerogen and combined with different thermal evolution stages of organic hydrocarbon expulsion can be divided into either 1) oil outlet pores, 2) gas outlet pores, or 3) gas pore groups. Most organic pores are irregular, bubble-like, elliptical, and elongated. Pore diameters are primarily less than 1 μm, with median values ranging from 0.1 μm to 0.2 μm. Relatively small oil outlet pores, ranging from 10 nm to 150 nm, are always concave or elliptical when isolated. Gas outlet pores with diameters ranging from several tens of nanometers to hundreds of nanometers are elliptical, spherical, or ellipsoidal. Numerous randomly aggregated and dispersed gas outlet pores that form gas pore groups emerge and are partially connected to a certain extent.

The controlling factors of organic pores in the study area are vitrinite reflectance and the rock brittleness index. Particularly, thermal evolution controls the development of organic pores through different vitrinite reflectances (*Ro*) with specific total organic carbon (%) of shale. In addition, relative brittleness indexes combined with the degree of diagenesis and evolution are calculated using a mineral constituent method. The results show a positive correlation between the gas pore groups distribution and the rock brittleness index based on the relationship between relative brittleness indexes and the number of organic pores in the samples.

1. Introduction

Pore characteristics are used as important indicators to evaluate reservoir conditions and the recovery effect and to reflect reservoir performance and the occurrence and transport mode of hydrocarbon, especially in shale reservoirs with low porosity and permeability and complex pore structures (Mastalerz et al., 2013). Given the initial discovery of organic pores through ion milling and scanning electron microscopy (SEM) (Loucks et al., 2009), numerous studies have focused on the classifications and genesis of pores in shales (Jarvie et al., 2007; Milner et al., 2010; Curtis et al., 2010; Loucks et al., 2012; Zou et al., 2012; Heller et al., 2014; Fu et al., 2015). The International Union of Pure and Applied Chemistry (IUPAC) proposed another pore classification system in 1994, which is significant to quantitatively describe and evaluate the characteristics of shale pore structures. Specifically, the micropore size is defined as less than 2 nm, the mesopore size is between 2 and 50 nm, and the macropore size is larger than 50 nm. Zou et al. (2010) initially found nanoscale pores of less than 1 μm in a shale gas reservoir in China through nano-CT digital core and SEM

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imaging technologies. The authors also classified the pores in the shale gas reservoir into micrometer-scale pores (with diameters that range from 1000 μm to 1 μm) and nanometer-scale pores (with diameters less than 1 μm); such classification greatly improved research accuracy (Zou et al., 2012b). Pores in Barnett and Woodford shale are divided into preserved floccules, organopores, porous fecal pellets, pore-preserved fossil fragments, intraparticle pores, and microfractures (O'Brien and Slatt, 1990). In addition, the Maquoketa shale was explored, and mudrock pores were classified into silicate pores, carbonate pores, and organopores (Schieber, 2010). Three pore types are also found in a shale gas reservoir in the Sichuan Basin: 1) organic pores, 2) mineral pores, and pores that are classified as a combination of organic and mineral pores. In accordance with the qualitatively observed occurrence of pores (Nie and Zhang, 2011), a classification of an "occurrence-integrated structure" was established (Yu, 2013). A pore classification that consists of three major matrix-related pores, that is, interparticle pores, intraparticle pores, and organic matter pores, was presented (Loucks et al., 2009, Jarvie et al., 2012). In the Barnett and Woodford shale, a classification of pores, which included porous floccules, pore spaces observed between the floccules, pores found within organic matter, porous fecal pellets, preserved fossil fragments, microchannels within shale matrix, and microfractures, was presented (Slatt and O'neal, 2011). However, these studies did not focus on analyzing pore types and the controlling factors in continental shale gas reservoirs. The observed organic pores within all pores analyzed are clearly important in shale reservoirs, and such pores also control the adsorbed natural gas content. Pore characteristics that are distributed in shale reservoirs have been investigated extensively since their discovery, and the pore characteristics of continental and marine shale reservoirs have certain differences. Understanding the development of organic pores in continental shale reservoirs is essential to evaluate the resources of the shale (oil and gas) and forecast the enriched targets.

This study aims to present and discuss the classification and major controlling factors of organic pores in the continental shale reservoir of Chang-7 Member of Yanchang Formation in Ordos Basin. First, a summarized classification combined with the morphology and genesis of all organic pores in the selected samples is presented. Second, the pore characteristics, including the size, morphology, and structure, of the different pores in the selected samples are described. Finally, the major controlling factors of organic pores in continental shale gas reservoirs are analyzed.

2. Geological setting and samples selection

Ordos Basin, the location from which the samples in this study were collected, is briefly introduced in this section. Located in the western margin of the North China platform, the Ordos Basin is both a multi-cycle composite basin and a continental petroliferous basin with stable Paleozoic subsidence, Mesozoic depression, and altered Cenozoic surroundings (Yang et al., 2012). Shale layers are located in the Benxi and Shanxi Permo-Carboniferous formations, and the Chang-7 and Chang-9 Members of Mesozoic Triassic Yanchang Formation. The Yanchang Formation was deposited in a sedimentary environment, consisting of a deep to moderately deep lake. The Yanchang Formation has exploration potential, given its enriched hydrocarbon resource rocks and the extensive presence of source rock, reservoir rock, and seal rock assemblages. The shale layer in Chang-7 is an important shale exploration targets, where the lithology of is mostly composed of a dark gray and black mudshale and a dark mudstone mixed with charcoal (iron). The layer thickness is relatively large, and the maximum value is larger than 100 m (Fig. 1). The present geotemperature is between 49.0 and 93.6 °C (Li et al., 2013; Yao et al., 2014).

3. Experimental methods

3.1. Samples

The continental shale gas reservoirs in this study are primarily found in the central and southern basins of the Chang-7 Member of the Yanchang Formation. This region is regarded as an "L"-shaped development zone that includes Dingbian, Huachi, and Fuxian (Zhou et al., 2013). More than 105 block samples were collected in this research from the core lengths totaling 399.04 m from 18 wells, and 83 pieces of casted thin sections were fabricated (Table 1). The average clay mineral content of the shale samples was approximately 49%, while the average content for quartz, feldspar, pyrite, and carbonate minerals were approximately 27.4%, 14%, 5.1%, and 4.5%, respectively. The target shale was primarily composed of Type-II organic matter, with the total organic carbon (TOC) content primarily larger than 2.0%, and the vitrinite reflectance (*Ro*) varied from 0.6% to 2.2% (Zhou et al., 2013). Combined with compaction, cementation, and dissolution, some authors (Er et al., 2013) suggest that the diagenesis evolution of the Chang-7 Member of the Yanchang Formation was in stage A of the middle diagenetic evolution.

3.2. Experimental approach

First, the surfaces of the samples were etched via argon ion polishing and the samples were prepared for imaging using core plugs and drill cuttings. Second, an environmental scanning electron microscope (ESEM) Quanta 250 FEG was used to scan the micropores presented in the Samples section. The ESEM was also used to analyze the media of micropores via energy dispersal spectroscopy. The characteristics of and division between organic pores were examined based on these experiments. In addition, the amount of corresponding adsorption was measured with the use of nitrogen as adsorbed gas at a constant temperature, which increased the gas pressure. Hence, the adsorption isotherms of the shale samples were obtained by plotting the relationship between adsorption and relative gas pressure. By contrast, the desorption isotherms of the shale samples were obtained by plotting the relationship between desorption and decreasing relative gas pressure. Detailed pore structure parameters were calculated by analyzing the adsorption and desorption isotherms of the samples.

4. Classification of organic pores

4.1. Classification of organic pores

The characteristics of organic pores in the Chang-7 Member study area are described in this section. In 2009, Loucks et al., found that the Barnett shale contained organic pores, which developed in the organic matter that is present gas-bearing shale. Organic pores are crucial in generating shale gas. In this experiment, the development media of porosity is identified, and organic pores are observed through spectroscopy experiments.

These organic pores positively influence the accumulation, migration, and preservation of shale gas. Understanding the development of different organic pores in organic matter located within shale is crucial to predicting the hydrocarbon storing capacity of shale reservoirs. Combined with characteristics and genesis, organic pores can be divided into oil outlet pores, gas outlet pores, and gas pore groups (Fig. 2).

(1) Oil outlet pores. In this experiment, when the thermal evaluation is relatively low but is larger than 0.5%, the fluid oil/gas phase that exists mainly comprises thermogenic shale oil. The presence of isolated oil outlet pores that are concave