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Investigation of pore structure and fractal characteristics of organic-rich Yanchang formation shale in central China by nitrogen adsorption/desorption analysis

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A B S T R A C T

The Chang-7 of the Upper Triassic Yanchang Formation in the Xiasiwan area, located in the southwest of the Ordos Basin in central China, was investigated for its shale gas potential, which is the continental shale gas reservoir and still under exploration. In this study, sixteen shale samples were collected from four wells in Ordos Basin, and their geochemistry, pore structures and fractal characteristics was investigated by X-ray diffraction (XRD) analysis, total organic carbon (TOC) analysis, low-pressure N_2 adsorption/desorption analysis and fractal analysis. The relationships between TOC, mineralogical compositions and pore structure parameters were investigated, and the relationships between TOC, mineralogical compositions and fractal dimensions also were discussed. The results showed that shales have TOC contents ranging from 3.89 to 5.11%, and the major mineralogical compositions of shales are quartz and clay minerals. The clay minerals contents are between 12.37 and 61.55%, the quartz contents are between 17.10 and 72.33%, and there is a negative relationship between TOC and quartz contents in shales. The total pore volume is in the range of 0.001215–0.007495 cm^3/g and the specific surface area is between 0.38 and 3.03 m^2/g. The total pore volume and specific surface area of shale investigated are much less than those of the marine shales. The organic matter and clay minerals have a positive influence on total pore volume and specific surface area, whereas quartz has an opposite influence. The fractal dimensions are large and the values are between 2.5777 and 2.6280, which increase with the increase of the total pore volume and specific surface area, and the decrease of the average pore size. The fractal dimensions show positive correlations with the contents of TOC and clay minerals, whereas there is negative relationship between the fractal dimensions and quartz contents.

1. Introduction

With the increasing demand of global energy and the improving of advanced techniques, the unconventional reservoirs (including tight sands, coal bed methane, and shale oil and gas) have gradually been the focus of exploration and development in many countries besides United States (including Canada, China, Europe and others countries) (Chen et al., 2011; Clarkson et al., 2012a), especially in China (Li et al., 2012). Shale gas, as one kind of unconventional oil and gas reservoirs, is an important energy supplement. According to “The nation survey and evaluation of shale gas resource and favorable area selection”, issued by the Ministry of Land and Resources of the People's Republic of China, the geological reserves of shale gas reservoirs are estimated to be approximately 134×10^{12} m^3 in China and 19.9×10^{12} m^3 in the Ordos Basin, central China (MLR, 2012). Some studies also suggested that there is a great development potential of shale gas resources in the Ordos Basin (Ding et al., 2013; Liu et al., 2013; Jiang et al., 2014). The shale gas reservoir from the Upper Triassic Yanchang Formation in Xiasiwan area in the Ordos Basin of central China was distinguished from marine shale gas reservoirs in southern China and abroad, because it occurred in continental shale (Liu et al., 2013; Jiang et al., 2014). In April 2011, Shaanxi Yanchang Petroleum successfully drilled the Liuping-177 well, the first continental shale gas well in China, and the production was successful, demonstrating that the continental shale gas reservoirs in China were high-profile (Liu et al., 2013; Jiang et al., 2014).

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Shale is the heterogeneous porous media, the porosity and the pore size with random distribution are important parameters for characterizing the pore structure of shale. The understanding of porosity, pore size and its distribution in shale is critical (Ross and Bustin, 2008, 2009; Loucks et al., 2009; Clarkson et al., 2013), which is of practical significance for studying adsorption mechanism for gas in shale and desorption, diffusion and percolation for gas in shale. There are various measurements to investigate the characteristics of complex pore structure in shale. The pore geometries and pore sizes in shale can be observed by scanning electron microscopy, field emission scanning electron microscopy, transmission electron microscopy, CT-scan and focused ion beam scanning electron microscopy (Bernard et al., 2012; Chalmers et al., 2012a,b; Loucks et al., 2009, 2012; Wei et al., 2013; Yang et al., 2013a). Low-pressure gas adsorption analyses, mercury injection capillary pressure, nuclear magnetic resonance and small-angle neutron scattering can be used to investigate qualitative pore shapes and statistic characteristics of pore size distribution. And they can also be used to obtain total pore volume and specific surface area (Chalmers and Bustin, 2007; Ross and Bustin, 2007, 2009; Strąpoć et al., 2010; Chalmers et al., 2012a,b; Clarkson et al., 2012b, 2013; Saidian et al., 2014; Tian et al., 2013; Wu et al., 2013; Yang et al., 2013b, 2014). Among these, low-pressure nitrogen (N_2) adsorption analysis have been proven to be an effective method to characterize pore structures in shales (Chalmers and Bustin, 2007; Ross and Bustin, 2007; Strąpoć et al., 2010; Chalmers et al., 2012a; Clarkson et al., 2012b, 2013; Tian et al., 2013; Wu et al., 2013; Yang et al., 2013b, 2014), and N_2 adsorption data had also been used to investigate the fractal characteristics of pores in coals or carbons (Kaneko et al., 1991; Liu et al., 2005; Yao et al., 2008). There are a few reports on the fractal characteristics of marine shales (Yang et al., 2014), and no reports on the fractal characteristics of continental shales.

Compared with the extensive investigations on marine shale gas reservoirs in North America and south China (Chalmers and Bustin, 2007; Ross and Bustin, 2007; Strąpoć et al., 2010; Chen et al., 2011; Chalmers et al., 2012a; Clarkson et al., 2012b,2013; Chen et al., 2013; Tian et al., 2013; Wu et al., 2013; Yang et al., 2014) or marine–continental shale gas reservoirs in China (Wang et al., 2014a,b), studies on continental shale gas reservoir in Ordos Basin of central China have only received attention in recent years (Liu et al., 2013; Yang et al., 2013a,b), and there are relatively few achievements on the research. Among the shale plays in China, the continental shales from the Chang-7 of the Upper Triassic Yanchang Formation in the Ordos Basin are regarded as one of the current shale plays (Li et al., 2012).

The mission of this article is to investigate the pore structure in shales from the Chang-7 of the Upper Triassic Yanchang Formation in Xiasiwan area in the Ordos Basin of central China using low-pressure N_2 adsorption/desorption analysis. Meanwhile, the fractal dimension used to investigate the fractal characteristics of shale pore system was from N_2 adsorption data with the fractal Frenkel–Halsey–Hill (FHH) method. The relationships between TOC, mineralogical compositions and pore structure parameters were discussed, and the relationships between TOC, mineralogical compositions and fractal dimension also were discussed. It was anticipated that our results might be significant to explore continental shale gas reservoirs in the field.

2. Geological setting

The study area is located in Xiasiwan area in the southeast Ordos Basin of central China (Fig. 1a), the most favorable exploration and exploitation target districts in China where continental shale gas resources were found (Wang et al., 2012). The Ordos Basin was a Paleozoic intracratonic sag basin, which has undergone multiple

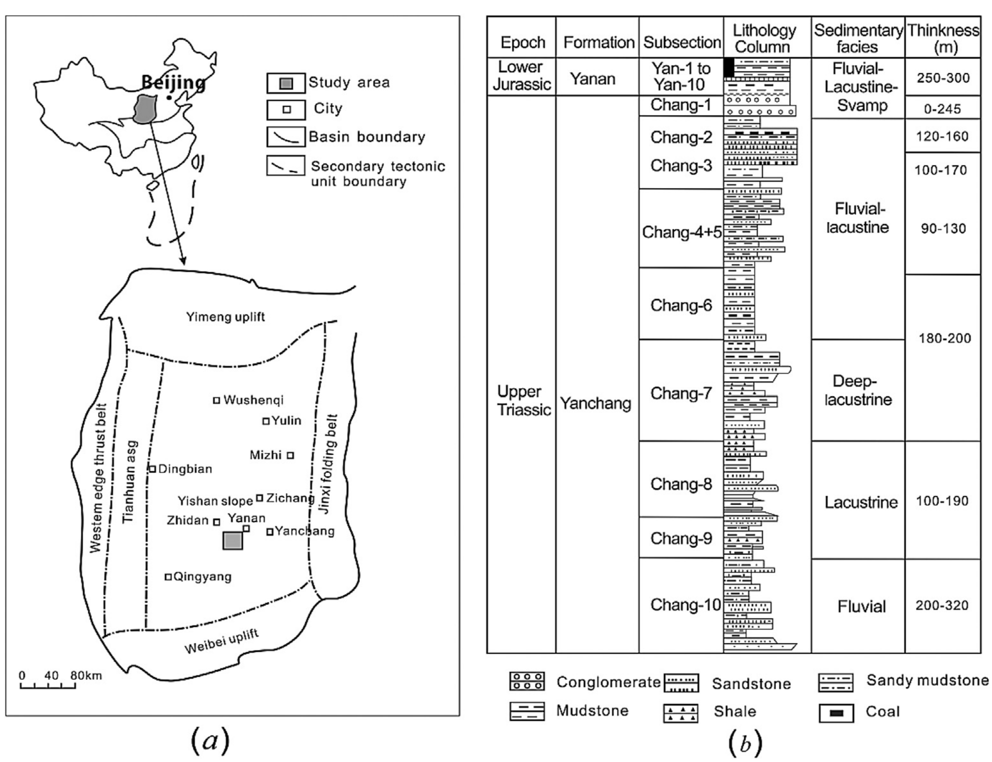

Fig. 1. (*a*) Location of the study area in the southeast Ordos Basin, central China; (*b*) Upper Triassic and Lower Jurassic stratigraphy and depositional environment (simplified from Ding et al., 2013; Duan et al., 2008).