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Lithofacies and pore characterization of the Lower Permian Shanxi and Taiyuan shales in the southern North China Basin

Shuai Tang [a, b, c], Jinchuan Zhang [a, b, *], Derek Elsworth [c], Xuan Tang [a, b], Zhongming Li [d], Xiaorui Du [a, b], Xiaoqun Yang [a, b]

[a] Key Laboratory of Shale Gas Exploration and Evaluation, Ministry of Land and Resources, China University of Geosciences, Beijing 100083, China
[b] School of Energy Resources, China University of Geosciences, Beijing 100083, China
[c] College of Earth and Mineral Sciences, The Pennsylvania State University, University Park, PA 16802-5000, USA
[d] Henan Institute of Geological Survey, Zhengzhou 450000, China

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Marine-continental transitional shales with varied lithofacies are widely distributed in the Lower Permian Shanxi and Taiyuan Formations in the southern North China Basin (sNCB) where they have been subject to frequently changing depositional conditions. Despite their importance, integrative classifications of the lithofacies of such shales are not normalized primarily due to the complex composition of the formations. This work classifies and defines the pore microstructure of the Shanxi and Taiyuan shales (well Mouye-1) from the Zhongmou exploration area. Classification is performed by optical (polarizing) microscopy, X-ray diffraction, and scanning electronic microscopy (SEM) imaging of Ar-ion milled samples, yielding measurements of the total organic carbon (TOC) content, porosity, and nitrogen adsorption. The TOC content is introduced into traditional ternary plots denoting “clay-carbonate-quartz”. Four primary lithofacies are identified from the combined metrics of optical microscopy and inorganic and organic contents. These four divisions comprise silt bearing mudstones, silty mudstones, muddy siltstones, and silty carbonaceous mudstones. The samples exhibit porosities between 1% and 4.5%, with silty carbonaceous mudstones having the highest TOC content and returning the highest porosity. Pores hosted in both the inorganic matrix and organic substrate are imaged by SEM. The predominant and largest pore types are in the inorganic matrix and include inter-particle mineral pores, inter-crystalline mineral pores and secondary denudation pores caused by smectite illitization. The pore size distributions (PSDs) and specific surface areas are recovered from nitrogen gas adsorption using BJH and BET models that reveal a wide range of pore sizes. The pore volumes are predominately associated with larger macro-/mesopores, whereas the specific surface area is primarily from a contribution of smaller micro-/mesopores. Finally the target zone for fracturing and recovery is optimized using these integrated methods for lithofacies description, pore characterization, and petrophysical and geomechanical analysis. This study provides a selective completion strategy to reduce fracturing-treatment expense and improve well productivity.

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1. Introduction

Significant progress has been made in the exploration and development of unconventional shale gas worldwide, especially in North America (Wang and Carr, 2012). The expanded application of horizontal drilling and hydraulic fracture stimulation technology has been shown to be capable of recovering gas at economic and industrial flow rates from unconventional resources that have extremely low porosity and permeability (Mitra et al., 2010). Previous research on lithofacies characterization primarily focused on sandstone and carbonate reservoirs, using descriptions from core data and outcrops (Bridge et al., 2000; Porta et al., 2002). The prediction of lithofacies using logging techniques, seismic volume (Berteig et al., 1985; Wong et al., 1995; Qi and Carr, 2006), and

* Corresponding author. School of Energy Resources, China University of Geosciences, Beijing 100083, China.
E-mail addresses: tangshuaier@163.com (S. Tang), 452224822@qq.com (J. Zhang), elsworth@psu.edu (D. Elsworth), tangxuan@cugb.edu.cn (X. Tang), 771219188@qq.com (Z. Li), 653005823@qq.com (X. Du), yxq@cugb.edu.cn (X. Yang).

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lithofacies modeling in two and three dimensions (Akatsuka, 2000; Yao and Chopra, 2000; Qi et al., 2007) has been well developed for conventional reservoirs. However, lithofacies studies of shales are in their infancy (Zhang et al., 2008; Javadpour, 2009; Curtis et al., 2010; Aplin and Macquaker, 2011; Loucks et al., 2012). As a result, primarily due to the complex composition of the formations, such nascent integrative classifications for shales have not been normalized. In this study, the content of "total organic carbon (TOC)" is introduced into traditional ternary plots of "clay-carbonate-quartz", defining a new tri-partite lithofacies classification based on the relative contents of different minerals. Such a classification of shales aids in design optimization of horizontal wells and stimulation strategies in unconventional reservoirs, where the porosity-permeability characteristics correlate with different lithofacies.

Compared with conventional sand and carbonate reservoirs, shale gas systems, where the unit serves as both source rock and reservoir rock (Jarvie et al., 2007; Hill et al., 2007), exhibit extremely low porosity and permeability (Curtis et al., 2010; Javadpour, 2009). Gas is stored in any of three forms: free gas in pores and fractures, gas adsorbed onto the surface of organic and inorganic matter and gas dissolved in oil and water (Curtis, 2002; Zhang et al., 2004). Pore shapes and extents can be observed by Broad Ion Beam-Scanning electron microscopy (BIB-SEM) (Houben et al., 2013; Klaver et al., 2012, 2015; Yang et al., 2014). This technique can be used to determine the shapes and sizes of pores as a complementary technique in combination with the quantification of the pore structure and pore size distribution derived from Nitrogen Gas Adsorption (N_2GA) (Loucks et al., 2009; Mayka et al., 2013; Milliken et al., 2013). Traditional methods of helium porosimetry (Bustin et al., 2008; Chalmers et al., 2012a) can establish a combined PSD and total porosity, but they are difficult to apply to shales due to the complexity of the pore network microstructures (Curtis et al., 2012; Nelson, 2009) – thus, alternate methods must be used to characterize pore morphology.

Marine shales in southern China have received renewed attention during the past few years, similar to the renewed interest in marine strata in the United States (Zeng et al., 2012; Tian et al., 2013; Wu et al., 2014; Dong et al., 2015; Yang et al., 2016). However, studies associated with transitional gas shales in northern China, which differ significantly from marine shales in terms of the conditions of gas accumulation and organic geochemical characteristics, remain rare (Ding et al., 2013). Since the petrophysical and geomechanical properties vary abruptly both vertically and laterally, the recovery of gas from shales using traditional hydraulic fracturing techniques is significantly influenced by the heterogeneity of the target zone (Boyer et al., 2006). In this study, 35 samples from the Lower Permian Shanxi and Taiyuan Formations (southern North China Basin, Henan Province (Mouye-1 well)) are characterized for lithofacies and pore characteristics. These characterizations include measurements of the inorganic mineral composition, organic geochemical parameters, pore morphology, pore microstructure, total porosity and mechanical properties. The major objectives of this study are to: (1) describe and classify the lithofacies of the Lower Permian Shanxi and Taiyuan Formations through according to their inorganic mineral composition and total organic carbon content; (2) investigate the pore characteristics, such as the porosity, pore types, pore size distribution and specific surface area; and (3) identify the potential target zone for hydraulic fracturing and production by using these integrated data.

2. Geologic setting

The southern North China Basin (sNCB) is located at the junction between the southern part of the North China plate and the southern Qinling-Dabie orogenic belt (Yu et al., 2005; Huang et al., 2005). This belt has a unique and complex tectonic history resulting from its special geotectonic location. The sNCB has experienced long-term multiphase tectonic movements, including compressional thrust tectogenesis (during the Indo-Chinese epoch), strike-slip stretching tectogenesis (during the Yanshan epoch), and extensional faulting depression (during the Xishan epoch). The mutual superposition and reconstruction of these tectonic movements are closely related to oil and gas exploration since they control the preservation and distribution of Permo-Carboniferous hydrocarbon resources in the sNCB (Xu et al., 2004; Lv et al., 2005). The sNCB was developed during the Mesozoic Indo-Chinese epoch and is further divided into five secondary tectonic units. These include the Kaifeng depression, Taikang uplift, Zhoukou depression, Bengbu uplift and Xinyang-Hefei depression (Fig. 1) (Sun, 1996; Wang et al., 1994).

The Zhongmou exploration area lies in the southwest part of the Kaifeng depression and together with the northwest part of the Taikang uplift belongs to the "Mesozoic-uplift & Cenozoic-depression" tectonic evolution pattern. The Lower Permian strata, which comprise the Taiyuan, Shanxi, Lower Shihezi, Upper Shihezi, Pingdingshan and Sunjiagou formations, have been recognized as effective source rock within the research area. However, the Taiyuan and Shanxi Formations are the two major exploration targets, in which the Taiyuan Formation represents transitional deposition from marine to continental facies. Thus it contains lithofacies of mudstone, limestone, sandstone and coal beds resulting from inter-tidal sedimentation to a thickness of 39–140 m. The Shanxi Formation is a delta sedimentary system of tidal, lagoon, peat bog and delta deposits with a thickness of 73–103 m and is dominated by sandstones, sandy mudstones, mudstones and coal beds (Fig. 2). The alternating variation of four different lithologies, including mudstone/shale, coal, sandstone, and limestone, in the Shanxi and Taiyuan Formations of the Lower Permian reflect frequent changes in depositional conditions (Qin, 2005; Zou et al., 2010). Well logs (Fig. 2.) show moderate to high gamma intensity and high resistivity readings for shale, low gamma intensity and high resistivity for coal, low gamma intensity for sandstone and extremely low gamma intensity for limestone. Kerogens in the shales of the two formations are predominantly humic (type III), showing their promising prospect for shale gas.

The Mouye-1 exploration well probes the Lower Permian Shanxi and Taiyuan Formations shales in the Zhongmou exploration area. The exploration well is fully cored throughout these two formations to evaluate the characteristics of the transitional shale gas reservoir in this region via geochemical, mineralogical, petrological, petrophysical and pore microstructural characterization methods and to relate these characteristics to gas potential.

3. Methodology

3.1. Samples

A total of thirty-five core samples from the Lower Permian Shanxi and Taiyuan Formations shales were collected from the Mouye-1 well at depths of 2806.36–2963.00 m using sampling intervals of ~2–3 m. These contained 19 black shale intervals with thicknesses of ~2–8 m (Fig. 2). Detailed information for each shale sample involved, including the stratigraphy, lithology, sample location, and log data, is shown in Fig. 2.

3.2. Methods

The samples were characterized for their geochemical, mineralogical, petrological, petrophysical and pore microstructural

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