Journal of Natural Gas Science and Engineering 36 (2016) 597–616

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

Logging assessment of tight clastic rock reservoir fractures via the extraction of effective pore aspect ratios: A case study of lower Permian strata in the southern Qinshui Basin of eastern China

Shuai Yin [a, b, c], WenLong Ding [a, b, c, *], Wen Zhou [d], Yuming Shan [d], Ruyue Wang [a, b, c], JianJun Liu [e], Yang Gu [a, b, c]

[a] School of Energy Resources, China University of Geosciences, Beijing 100083, China
[b] Key Laboratory of Strategic Evaluation of Shale-gas Resources, Ministry of Land and Resources, Beijing 100083, China
[c] Key Laboratory of Geological Evaluation and Development Engineering of Unconventional Natural Gas Energy, Beijing 100083, China
[d] College of Energy Resource, Chengdu University of Technology, Chengdu, Sichuan 610059, China
[e] Research Institute of Petroleum Exploration and Development of Huabei Oilfield Lit., PetroChina, Renqiu, Hebei, 062550, China

A R T I C L E I N F O

Article history:
Received 25 July 2016
Received in revised form
28 October 2016
Accepted 2 November 2016
Available online 4 November 2016

Keywords:
Optimized algorithm
Differential equivalent medium theoretical model
Effective pore aspect ratio
Coal measure strata
Southern Qinshui Basin

A B S T R A C T

Research on tight gas enrichment in coal measure strata is contentious worldwide. Gas logging anomalies are very common in the upper Paleozoic coal-bearing strata in the Southern Qinshui Basin of eastern China. The distribution characteristics of these free gases are closely related to the degree of fracture development. The rock pore aspect ratio (α) can reflect the morphology of rock pores and fractures. In this paper, we use full wave logging data to propose a new logging assessment method for tight clastic rock reservoir fractures via the extraction of effective pore aspect ratios. The basic concept is as follows: (1) we extract the rock matrix mineral modulus and dry rock modulus of the rocks using an optimized algorithm, and (2) we invert the effective pore aspect ratio of coal measure strata using the theoretical model of a differential equivalent medium. The research results show that the studied clastic rocks in coal measure strata are very tight, with porosity levels that are generally less than 5%, and sections in which fractures have formed often correspond to relatively low α values of less than 0.1. The microfracture-bearing sections identified based on α inversions correspond well to the sections with fractures at the core scale. Thus, this method can be used to identify fractured sections at the core scale. For sandy mudstone, microfractures mainly exist in sandy intervals, and α is negatively related to rock porosity and positively related to shale content. Regardless of lithology, i.e., sandstone, mudstone or coal, the communication and transport capacity of fracture systems are greater than those of the pore system, and coal-derived gas reservoirs form when there are good gas sources, transportation systems, fracture systems and preservation conditions. Similar to the formation mechanism of fractures in rocks, α is also derived from mechanical mechanisms, and this study shows that the inversion process is effective in characterizing the degree of fracture development in tight clastic rocks in coal measure strata based on elastic rock properties.

1. Introduction

Large gas fields in China are mainly composed of coal-derived gases. By 2011, 48 large gas fields had been discovered, 31 of which are coal-derived gas fields (Dai et al., 2014; Zou et al., 2012). Due to their close proximity to source rocks and complex gas accumulation characteristics, tight gas accumulations in coal measure strata are a contentious topic (Guo et al., 2015; Liang et al., 2014; Lin et al., 2015; Su et al., 2005; Zhao et al., 2015). Coal-bearing strata developed in the Qinshui Basin of eastern China during the Carboniferous-Permian. The upper Carboniferous Taiyuan Fm. and the lower Permian Shanxi Fm. currently form the main development sections for coalbed methane (Dai et al., 2014). The study of pore-fracture structures constitutes the basis for the reasonable development of coalbed methane and tight gases, and further study is

* Corresponding author. School of Energy Resources, China University of Geosciences, Beijing 100083, China.
E-mail address: dingwenlong2006@126.com (W. Ding).

http://dx.doi.org/10.1016/j.jngse.2016.11.001
1875-5100/

critical to seismic inversion, physical simulation and well block optimization (Armstrong et al., 2015; Ding et al., 2012, 2013; Desbois et al., 2011; Farrell et al., 2014; Li and Zhang, 2010; Vernik and Kachanov, 2009; Vernik and Hamman, 2010; Wang et al., 2016; Zeng and Liu, 2010; Zhang et al., 2015). In the southern area of the Qinshui Basin, logging anomalies in tight sandstone are very common in the coal measure strata of the Taiyuan, Shanxi and the Xiashihezi Fms. according to the reexamination of gas logging operations in partial wells (Liang et al., 2014). Although this region presents considerable tight clastic gas exploration potential, exploration here has been limited. These natural gases belong to coal-derived gases (free gases) sourced from superimposed coal seams. The hydrocarbons migrated short distances via diffusion and fractures, forming a broad distribution area of variable enrichment levels. Drilling has shown that the degree of fracture development is the main factor affecting the differential accumulation of hydrocarbons. It is thus of great importance to conduct further research on pore and fracture morphologies associated with the transport and conservation of coalbed methane or coal-derived gases (Yao and Li, 2012).

The evaluation of a rock pore-fracture system mainly involves the inversion of the microscale α parameter. In addition to the significant effects of rock physical properties and gas-bearing capacities, elastic rock properties are also considerably affected by microfractures, which form through mechanical processes. Microfractures in rocks generally have apertures smaller than 50 μm and relatively small pore aspect ratios; thus, microfractures can only be observed under a microscopic (Zhang et al., 1990). Microfractures constitute a significant component of the evaluation of reservoir sweet spot areas in tight clastic rocks, but due to the small scale of microfractures, this parameter is very difficult to quantify (Lama and Vutukuri, 1978). Previous research has only focused on using CT testing techniques to characterize the distributions and enrichment degrees of microfractures (Menendez et al., 1996). However, these tests are generally quite expensive and cannot determine quantitative relationships between microfracture and core fracture parameters, whereas logging inversions can obtain high-resolution fracture parameters at different vertical scales, thereby guiding reservoir prediction and fracturing.

Several methods can be used to invert the α value of a medium that contains fractures. Generally speaking, these methods require knowledge of the rock matrix mineral and dry rock moduli (Berryman, 1992; Hudson, 1981; Mavko et al., 1998). Thus, we first extract the rock mineral matrix and dry rock moduli. The mineral component content method (Yong and Zhang, 2007) uses the identification results of microscopic mineral components or logging interpretation results to identify the rock matrix mineral and dry rock moduli based on the mineral contents of the rock. This method is limited by the fact that it is very difficult to obtain accurate and continuous mineral component contents of stratigraphic rocks unless one employs reliable elemental capture spectroscopy (ECS) tools to interpret the mineral component contents of the vertical stratigraphy. The differential equivalent medium theoretical method (Li and Zhang, 2010) involves conducting finite differential analyses of the effective medium modulus formula proposed by Berryman and Berge (1996) and exploring the relationships between the pore aspect ratio α and the rock matrix minerals, dry rock moduli and porosity. When α is unknown, this method is constrained. By referencing reasonable variables, the optimized algorithm can predict the rock matrix mineral and dry rock moduli with continuous results, and the reliability of the results can be confirmed by comparing the results obtained via different methods (Lin et al., 2013).

Several methods, such as the Biot consistency theoretical method, the Hudson fracture medium inversion method and the differential equivalent medium theoretical method, can be used to invert the α values of rocks (Berryman, 1992; Berryman and Berge, 1996; Hudson, 1981; Mavko et al., 1998; Tang et al., 2013). The difference among these methods lies in the fact that the variable fracture density ε must be known when predicting α using the Biot consistency theoretical method and the Hudson fracture medium inversion method. However, the differential equivalent medium theoretical method does not require knowledge of ε to predict α. Thus, when parameter ε is unknown, the differential equivalent medium theoretical method produces more reliable results when inverting the α of rocks.

Because rock fractures are found at all scales, these inversion methods share a common defect: certain differences exist between the effective α values obtained through these methods and the real values (Li and Zhang, 2010). However, inversion results can still represent the overall distribution of pore-fracture morphologies in rocks. Therefore, we propose adopting a combined model of optimized algorithms in addition to the differential equivalent medium theoretical method to perform α inversion in coal measure strata. When the extracted rock matrix mineral and dry rock moduli are reliably known, the inversion of α via this method is regarded as reliable.

2. Geological setting

The study area examined in this paper is situated in a well block of coalbed methane in the southern area of the Qinshui Basin. The coalbed methane capacity in this area is relatively high, and the daily gas production rate of high-yield wells is frequently greater than 2000 m^3. The study area includes the Zhengzhuang Block, the Fanzhuang Block and the Panzhuang Block (Fig. 1a and b).

According to the interpretation results of the latest seismic data, high-angle normal faults are present in this area (Fig. 1c). The majority of these faults strike NE and NNE, with a minority striking N-S and WNW, and extend over short distances with small fault throws. Yanshanian folds oriented in the NNE and N-S directions and Himalayan folds oriented in the NW direction are the major fold structures. The elevation of the terrain is generally high in the southeast and low in the northwest.

The stratigraphy of the southern Qinshui Basin from the base to the surface is shown in Fig. 2. The No. 3 coal seam is the main layer containing coalbed methane in this region, as the reservoir and hydrocarbon source rocks lie at the bottom of the Shanxi Fm. and are composed of high-rank anthracite (R_o>3.5%). The macroscopic coal lithotype of the No. 3 coal seam is bright coal, which cannot be separated by hand due to its high firmness. The No. 3 coal seam is mainly found at a depth of 500–1000 m and has a thickness of 5–8 m and a gas content exceeding 15 m^3 t^{-1}. It also exhibits negative pressure, low permeability and strong heterogeneity.

As tight clastic gas reservoirs are always adjacent to source rocks and the gas migrates only short distances to form reservoirs (Lin et al., 2015), the logging inversion data used in this study were primarily obtained from coal measure strata of the Shanxi Fm. These strata were deposited in a peat swamp environment during a marine regression from north to south, with the main sedimentary system being an shallow delta sedimentary system in an epicontinental sea. The delta system can be divided into an upper delta plain, a lower delta plain and a submarine delta plain.

3. Databases

3.1. Core description and sampling

Stratigraphic, drilling, and logging data from 50 wells and coring, gas logging and fracturing data from typical wells were