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Evaluation of coal texture distributions in the southern Qinshui basin, North China: Investigation by a multiple geophysical logging method

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ABSTRACT

Coal texture is indicative of coal mechanical strength, which is important not only for evaluating coalbed methane (CBM) reservoir permeability but also for evaluating the possibility of coal and gas outbursts in underground coal mining. This paper begins with a foundation of a geophysical logging-based coal texture evaluation method that compares the digital logging data with the results from 108 coring samples. Then, the method was applied to the analyses of coal textures in 39 CBM wells, the results of which are discussed in terms of the vertical distribution of coal textures in the study area. Finally, a ternary diagram based on thickness proportions of coal textures was used to identify reservoir compartments in the Zhengzhuang field of the southern Qinshui basin. The results show that undeformed coals are easily distinguished from cataclastic and granulated coals because of the high DEN and GR of undeformed coals. Meanwhile, cataclastic coal has lower response values of AC and LLD than granulated coal, which can be used in identifying cataclastic from granulated coal. A multiple geophysical logging method combining the log data of DEN, GR, AC, and LLD was provided for predication of the coal textures in the Zhengzhuang field. The predicated results show that the coal seam can be vertically divided into three to eight sub-layers, with a typical interbedded pattern of undeformed and cataclastic coals on the upper and lower parts and granulated coal in the middle at a relatively large thickness. The study area is divided into four major regions and 11 sub-regions based on the classification of coal texture types. The undeformed coal-dominated region is located in the southwestern part of the study area, indicating a low permeability in the coal reservoir. The granulated coal-dominated region is mainly in the northern and eastern parts of the study area and has resulted from deep burial and multi-period structural activities. The cataclastic coal-dominated region is in the middle of the study area; the coal reservoir in this region is possibly the most favorable for CBM production.

1. Introduction

The Qinshui basin is the most important coalbed methane (CBM) production area in China, with in-place CBM resources of approximately 3.28×10^{12} m^3, which has excelled in the commercial development of CBM (Cai et al., 2011; Liu et al., 2014; Lv et al., 2012; Su et al., 2005; Xu et al., 2014). The Qinshui basin has evolved from the Late Paleozoic basement to the end of the Mesozoic (Su et al., 2005). Coalification and thermogenic gas generation were influenced in the basin by a tectonic–thermal event during the Jurassic to Cretaceous Yanshanian Orogeny, which resulted in anthracite coal with a vitrinite reflectance of 2.2–4.5% (Lv et al., 2012; Su et al., 2005). The gas content in this basin is high and is mainly controlled by the structural and hydrodynamic geology (Liu et al., 2014; Lv et al., 2012; Song et al., 2012). The coal reservoir permeability is relatively low (0.047–1.337 mD) (Li et al., 2011) and changes during the production process (Tao et al., 2012). The production performance of CBM reservoirs is mainly controlled by the geological structure and hydrogeology (Sang et al., 2009; Tao et al., 2012).

Coal texture is representative of coal mechanical strength, which is important not only for evaluating coal reservoir permeability but also for evaluating the possibility of coal and gas outbursts in underground coal mining (Fu et al., 2009a; Li, 2001; Li et al., 2012; Meng et al., 2011a,b; Pan et al., 2012; Wang et al., 2013). Coal texture types, with an increasing degree of coal deformation, can be classified as undeformed, cataclastic, granulated, and mylonitized (Fu et al., 2009a; Xue et al., 2012). Original sedimentary structures are preserved in the undeformed coal, whereas mylonitized coal is strongly deformed due to extreme tectonic activity. To our knowledge, a quantified description of coal textures has not been undertaken in the southern Qinshui basin.

Geophysical logging provides insight into the variability of the physical and chemical properties of coal by using acoustical, electrical, and radioactive detection (Hatherly, 2013; Roger, 2005; Yegireddi and Uday, 2009). Typical geophysical logs of coals show low natural gamma responses, low density, low sonic velocity, and high resistivity (Karacan, 2009a,b; Roger, 2005; Yegireddi and Uday, 2009; Zhou and

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Yao, 2014). It has been shown that geophysical logs can identify coal textures (Frodsham and Gayer, 1999; Fu et al., 2009a,b; Scholes, 1993) because coals with typical textures return a variety of responses from geophysical logs (Fu et al., 2009a; Peng et al., 2008; Teng et al., 2013; Yegireddi and Uday, 2009). For example, the increasing degree of coal deformation can result in a decrease in acoustic velocity (Peng et al., 2008) and an increase in resistivity (Fu et al., 2009a; Peng et al., 2008; Teng et al., 2013). The available research suggests that multiple geophysical logging responses of coal textures may be different for coals with various coal rank and petrologic characteristics. Thus, whether a geophysical logging method can be used for forecasting coal texture in a specific field needs to be evaluated.

This paper provides an advanced quantitative method for identifying the coal textures of anthracite coal by integrating the geological logging data of 39 CBM wells and 108 cores of the No. 3 coal seam. Both vertical and regional distributions of coal textures were evaluated, the results of which were used to compartmentalize the CBM reservoirs in the Zhengzhuang field in the southern Qinshui basin.

2. Geological setting

The Qinshui basin is a large synclinorium basin with bilateral symmetry (Fig. 1), which is surrounded by the Taihang Mountain in the east, the Huo Mountain in the west, the Wutai Mountain in the north, and the Zhongtiao Mountain in the south (Cai et al., 2011; Su et al., 2005). Structures in the basin are relatively simple with a few internal secondary folds (Cai et al., 2011). The Zhengzhuang field is located in the southern Qinshui basin (Fig. 1), which shows multi-period tectonic stresses (Cai et al., 2011; Li et al., 2011; Su et al., 2005; Tao et al., 2012). During the Indosinian period (250 Ma), folds with an E–W strike were formed, and extensional tectonics such as normal faults with a NE–SW strike were developed under the early compressive tectonic stress parallel to the normal fault strike (Liu et al., 2014). In the Yanshan period (208 Ma), the basic tectonic shape was formed under a NW–SE compression stress. Magmatic activity developed on the northern and southern ends of the basin, which led to an abnormally high geothermal field (Wei et al., 2007). A characteristic of the Himalayan period (65 Ma) was a NNE–SSW compression stress, resulting in a few secondary folds striking NW in the study area, formed under nearly horizontal and compressive stresses (Liu et al., 2013, 2014). In general, the Zhengzhuang field is a NW plunging syncline with the Sitou fault in the southeast and with open boundaries in the north and west (Fig. 1). The strata are wide with a gentle dip of 2–7° and an average of 4°. The Sitou and Houchengyao faults in the NE–SW direction are the main faults with some concomitant minor faults. Gentle and parallel folds are widespread, with axial NNE–SSW striking near N–S (Cai et al., 2011).

The study area consists of the Carboniferous Benxi and Taiyuan Formations, Permian Shanxi, Shihezi and Shiqianfeng Formations, and Triassic to Quaternary deposits (Lv et al., 2012; Tao et al., 2012; Wei et al., 2007). The Taiyuan and Shanxi Formations, with a combined average thickness of 150 m, are the two main coal-bearing strata (Lv et al., 2012; Su et al., 2005). The No. 15 coal seam of the Taiyuan formation and the No. 3 coal seam of the Shanxi Formation are the most continuous and stable coal seams, with thicknesses of 1–6 m and 3–7 m, respectively. The No. 3 coal seam is currently the target seam for CBM development in the Qinshui basin, which is also selected as the focus of this paper. The No. 3 coal seam is within the anthracite rank (Su et al., 2005). The present burial depth of the coal seam ranges from 600 to 1200 m, and increases from SE to NW parts in the field. The gas content ranges from 10 to 37 m^3/t, and the gas saturation is 56–80% in the study area (Lv et al., 2012; Su et al., 2005).

3. Methodology

A total of 108 coal cores of the No. 3 coal seam were sampled from the exploration wells of Z1, Z4, Z6, Z7, Z8, Z9, Z12, Z13, Z14, Z15, Z16, Z17, Z34, Z35, Z36, Z37, Z38, and Z39 (see locations in Fig. 1) and were examined for the purpose of identifying coal textures. For each well of the No. 3 coal seam with a thickness of approximately 6 m, an average of five to eight core samples were analyzed. The natural gamma (GR), deep resistivity (LLD), density (DEN), and sonic–interval transit time (AC) log curves were chosen for identifying the coal texture. The log curve depth was calibrated to the core depth based on the log response prior to using the geophysical logging data. The details for the calibration method were presented by Fu et al. (2009b). The digital logging data of GR, LLD, DEN, and AC were then extracted with a vertical identification of 0.1 m, and the data were compared with the coal texture results identified from the core description. Finally, a quantified relationship between coal textures and the logging responses was developed. This relationship was applied to evaluate the coal textures of the No. 3 coal seam of other CBM wells that have only the digital logging data but no coring data.

4. Results and discussion

4.1. Coal texture characterization by core description

Results from the core description of the 108 coal cores show that the textures of the No. 3 coal seam are mainly undeformed, cataclastic, and granulated coals, with none of the mylonitized texture. The macroscopic and microscopic characteristics of the three coal types are shown in typical coal core samples (Fig. 2). Undeformed coals commonly preserve an intact and massive coal texture (Fig. 2a), in which the plant tissue of vitrinite and inertinite groups has well-preserved bedding structures and unaltered organic pores (Fig. 2b). Exogenous fractures resulting from tectonic stresses rarely can be found in undeformed coals. Cataclastic coals are easily broken into large fragments (Fig. 2c), which retain the same endogenous fracture as those in undeformed coals, and they also have interconnected exogenous fractures (Fig. 2d). Granulated coals are easily broken into small fragments and even powders (Fig. 2e). Tectonically generated pores and fractures are common in granulated coals (Fig. 2f).

4.2. Coal texture identification by geophysical logging data

4.2.1. Logging responses of coal textures

The identification of coal textures was performed in 18 wells, and only two of the wells are given in Fig. 3 as examples. The No. 3 coal seam of well Z4 includes 5 m of coals and 50 cm of interlayered carbonaceous-shale. From the bottom to top, six coal core samples (a thickness of approximately 30 cm for each core) including granulated, undeformed, granulated, undeformed, cataclastic, and undeformed coals were identified in sequence. From the bottom to top for the Z17 well, five coal core samples were identified for undeformed, cataclastic, granulated, cataclastic, and cataclastic coals. As shown in Fig. 3, the logging curves of GR and DEN present a fingerlike shape for the granulated coal locations, where the logging values obtain the minimum. In contrast, the logging curves of LLD and AC show a sharp variance for the granulated coal locations, where the logging values obtain the maximum.

Moreover, the logging response values of undeformed, cataclastic, and granulated coals were averaged for the Z4 and Z17 wells, and the results are shown in Fig. 4. The values of the LLD and AC logs have an increasing trend with the increasing degree of coal deformation from undeformed coal to granulated coal, whereas the values of the GR and DEN logs exhibit a decreasing trend.

The logging responses of coal textures agree well with previous studies on bituminous (Fu et al., 2009a) and anthracite coals (Peng et al., 2008) in China. Fig. 5 shows the vertical variations in coal texture, coal maceral composition, porosity, and cleat density of the coring samples in wells Z4 and Z17. This figure indicates that coal petrological composition and physical characteristics are different in coals with different