Geological controls on prediction of coalbed methane of No. 3 coal seam in Southern Qinshui Basin, North China

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ABSTRACT

In order to better understand the geological controls on coalbed methane (CBM) in Southern Qinshui basin (SQB), North China, geological surveys and laboratory experiments, including coal petrology analysis, proximate analysis and methane adsorption/desorption, were conducted. Results show that the coals from the SQB contain 0.59–3.54% moisture, 3.5–15.54% ash yield, 73.62–88.92% fixed carbon and 2.14–4.04% hydrogen, with C/H ratios in the range of 19.96–36.25. The vitrinite reflectance (R_v) ranges from 1.95 to 3.49%. The coals are composed of 18.5–97.4% vitrinite and 2.4–81.4% inertinite. The geologic structures, coal-bearing strata and coal depositional environment were studied by both field geological research and laboratory tests. A positive relationship is found between CBM content and basin hydrodynamics, in which CBM easily concentrates in the groundwater stagnant zone because of the water pressure. Furthermore, integrated geographical information system (GIS) and analytical hierarchy fuzzy prediction method (AHP) were used to evaluate the CBM resources in the SQB. The results show that the amount of CBM associated with the No. 3 coal seam in the SQB is 3.62×10^11 m^3. The CBM resource concentration (gas-in-place per square kilometer) in the SQB is in the range of (0.72–2.88)×10^8 m^3/km^2, with an average of 1.21×10^8 m^3/km^2, which decreases from Zhengzhuang coal district to Shitou fault and from Fanzhuang coal district to the margins of the basin. The best prospective targets for CBM production are likely located in the southwest/northwest Zhengzhuang and central Hudi coal districts.

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1. Introduction

Coalbed methane (CBM) resources are abundant in the Southern Qinshui basin (SQB) of Northern China. Exploitation of CBM from coal seams will benefit to mining safety and greenhouse gas emission (Karacan et al., 2008, 2011). In addition, with the decline in conventional natural gas reserves and increased demand and price of gas, industry shows great interest in the CBM resources of this basin, which requires accurate estimation of CBM potential and recoverable reserves to assist in development of gas industry. Although many CBM exploration and basic research projects have been initiated, thus far most are concerned with the CBM reservoir evaluation of the basin. Only a few preliminary studies on the methane occurrence and gas content (GC) of the coal beds have been conducted in the Qinshui basin.

The SQB includes the Zhengzhuang, Fanzhuang and Panzhuang coal districts, which cover an area of 2922 km^2. Previous studies estimated that the gas in place (GIP) in this basin is about 3.28×10^12 m^3. Because of this significant gas potential, the SQB is considered favorable for CBM exploration and development (Su et al., 2005). Among the 8 existing production wells, the highest CBM production is around 16,000 m^3/d per well, and the average is 1500–3000 m^3/d per well.

The SQB is becoming the fastest development district of CBM industry in China. The total coal thickness of the basin has an average of 15 m. Vitrinite reflectance of coals ranges from 2.2% to 4%. Langmuir volume and pressure are in the range of 28.08–57.1 m^3/t and 1.91–3.47 MPa, respectively. Both Langmuir pressure and Langmuir volume correlate significantly with coal rank (Pashin, 2010). In the SQB, the GC of coal is generally high, ranging from 10 to 37 m^3/t (Chen et al., 2007; Zou et al., 2010).

Although many studies related to the geological background of the SQB and some primary evaluations of CBM reservoirs have been conducted (Su et al., 2005; Wei et al., 2007), existing data are insufficient for evaluating the CBM production potential and for selecting the future target area. In this paper, the data from CBM fields and laboratory study are integrated to evaluate the CBM resources in the SQB, using the software “Mapinfo professional 8.5” (Bloom et al., 1996) based on Geographic Information System (GIS) (Roberts et al., 1991; Thoen, 1995) and analytic hierarchy process (AHP) mathematical models (Bryson and Mobolurin, 1994; Saaty, 2007).

2. Geological setting

2.1. Tectonics of the basin

The Qinshui basin, one of the Mesozoic basins evolved from the Late Paleozoic Northern China’s Craton Basin, is surrounded by the
uplifts of Taihang Mountain, Huo Mountain, Wutai Mountain, and Zhongtiao Mountain (Fig. 1). After the uplift and erosion during the Triassic Indosinian and Jurassic-Cretaceous Yanshanian Orogenies, the Qinshui basin was separated from the North China Craton Basin as a separate, complex syncline with axial striking at NNE–SSW. The SQB, with an area of 2922 km², is located at the jincheng coal district of the Qinshui basin dual syncline (Fig. 1). The northern boundary of SQB connects the central Qinshui basin. In general, the SQB is horse-shoe shaped, with a dip of 3–13° and an orientation of 5°NW. Structures within the SQB are relatively simple. A few faults and folds with axial striking of NNE–SSW and near N–S are common (Fig. 2). Previous studies have demonstrated that the faults in the SQB were formed by NW–SE compressional stress during the Jurassic-Cretaceous Yanshanian Orogeny (Qin et al., 2001).

2.2. Coal-bearing strata in SQB

The majority of the North China Craton Basin was exposed and subjected to erosion from Silurian to Mississippian time but subsided and was carapaced with sediments of Pennsylvanian to Triassic age, which include the Pennsylvanian Benxi (C2b) and Taiyuan formations (C3t), the Permian Shanxi (P1s), Xiashihezi (P1x), Shangshihezi (P2s) and Shiqianfeng (P2sh) formations, and Triassic deposits. The Taiyuan and Shanxi formations are the main coal-bearing strata, with an average thickness of 150 m (Fig. 3).

The main CBM reservoirs of the SQB are No. 3 coal seam of the Shanxi formation and No. 15 coal seam of the Taiyuan formation. Total thickness of these two coal seams ranges from 7 m to 16 m.

The thickness of coal-bearing strata of the Shanxi formation is in the range of 27.17–98 m, with an average of 46.78 m. The percentage of coal-bearing layers is 13.57% in this formation. The No. 3 coal seam of the lower Shanxi formation, which is the focus of this study, has relatively stable structure and is also the main minable coal seam. Coal thickness of the No. 3 coal seam in the SQB ranges from 2.3 to 7.37 m, with an average of 6.11 m. The coal seam has only a few organic-poor mudstone bands that are commonly less than 0.35 m thick. The roof of No. 3 coal seam is the K8 siltstone with an average thickness of 2.2 m, which is also favorable for CBM preservation.

3. Samples and methods

3.1. Coal sampling and laboratory experiments

A total of 22 fresh block samples were obtained from 9 underground mines in the SQB. Fig. 2 shows the sampling locations of these coals. Most coal samples were large blocks with a volume of about 30 × 30 × 30 cm³. Samples were directly collected from coal mines following the Chinese Standard Method GB/T 19222-2003, and were carefully packed and taken to the laboratory for experiments.

The helium porosity and air permeability were analyzed using the routine core analysis methods by the Chinese Oil and Gas Industry Standard SY/T 5336-1996. From each coal block, a cylindrical core with 2.5 cm in diameter (length >2.5 cm) was cut parallel to the bedding plane. The porosity was measured using the helium expansion method. And the air permeability was determined using a bubble flowmeter by flowing air through the core sample, which can be defined by Darcy’s equation as follows:

$$
\kappa = \frac{2Q_0 \mu L P_0}{A (P_1 - P_2)}
$$

where $\kappa =$ air permeability, (m²); $Q_0 =$ volumetric rate of flow at reference pressure, (m³/s); $\mu =$ air viscosity, (Pa·s); $L =$ length of coal sample, (m); $P_0 =$ reference pressure, (Pa); $A =$ cross-section area of core sample, (m²); $P_1 =$ upstream air pressure, (Pa); $P_2 =$ downstream air pressure, (Pa). The permeability was calculated, when the bubble rate was steady, using the flow rate, mean pressure drop across the sample and sample dimensions (2.5 cm in length, 2.5 cm in diameter) in Darcy equation.

Vitrinite reflectance ($R_o,m$), coal composition and micro-fracture analyses were carried out on polished slabs of about 30 × 30 mm² following the Chinese standard GB/T 6948-1998. These analyses were
performed on the Laborlxe 12 POL microscope with the MPS 60 photo system manufactured by Leitz Company of Germany. Ash yield, moisture content of coals and methane adsorption isotherm experiments were performed at the Gas Research Center, Langfang Branch of Research Institute of Petroleum Exploration and Development following Chinese standard GB/T 212-2001 and GB/T 19560-2004, respectively.

3.2. AHP model for evaluating CBM resources

AHP can help decision makers to rank multiple-attributes of parameters by deriving priorities (Satty, 1990), and by incorporating qualitative and quantitative aspects of a complex problem (Harker and Vargas, 1987; Hatton and Fardell, in press). A three-level AHP evaluation model was used in this study for evaluating the CBM potential in the SQB. The details of this evaluation model, including the evaluation of parameters, mathematical methods and uncertainties have been discussed in detail in literature (Liu et al., 2009; Yao et al., 2008a, 2009a,b). The goal of the AHP evaluation model is to identify a comprehensive evaluation score V (the favorability index, in the range of 0–1.0) that defines the favorability degree for CBM production potential. Higher score in the first level indicates more favorable CBM production potential. The second level represents the three different types of evaluation-criteria: the CBM generation capacity (V1) with a weight of 0.3, the CBM preservation capacity with a weight of 0.4 (V2) and the CBM economical exploitation potential with a weight of 0.4 (V3). These three criteria are decomposed into eight technically alternative parameters (subcriteria). All weights in the current hierarchy in the AHP model are assigned based on the field tests and experience of geologists. Modeling calculation is done with the software “MapInfo professional 8.5” in a Geographic Information System (GIS). The purpose of the structured model is to transform qualitative preference relationships into appropriate numeric representations. This approach maximizes the knowledge acquisition from experts on the basis of degree of belief in various propositions or the probability of these propositions. It implicitly (through qualitative assessments) and explicitly (through pair-to-pair comparisons of vague intervals) provides the levels of preference relationships (Brysona and Mobolurin, 1999). Evaluation result of each parameter (e.g., coal thickness, GC) for each block was obtained by fuzzy mathematics and vector stacking calculations in the GIS, and then was synthesized to predict the favorable targets for CBM exploration and development.

4. Results and discussions

4.1. Factors influencing CBM concentration in SQB

4.1.1. Sedimentary characteristics and coal seam distribution

The North China Craton was subaerially exposed and experienced erosion from Silurian to Mississippian, and then subsided to form sedimentary basins from Pennsylvanian to Triassic, during which coal-bearing strata of the Pennsylvanian Taiyuan formation and the Permian Shanxi formation in the SQB were deposited. Their average thickness is about 150 m.

In general, the Shanxi formation was deposited from shallow deltaic environments. Peat swamps developed in a deltaic plain consisting of distributary channels and flood basins (Su et al., 2005). Warm moist climate, plentiful coal-forming plants and flat landscape led to deposition of the thick, stable, and widespread No. 3 coal seam. The coal thickness of No. 3 coal seam in the SQB ranges from 2.3 to 7.37 m, with an average of 6.11 m (Fig. 4). After the accumulation of the No. 3 peat swamp, river channels prograded toward the southern part of the basin and cut the northern delta plain into separated flood plains. The thinning and pinch-outs of the No. 3 coal seam toward the north were due to the incision of distributary channels in the deltaic plain. During late Permian, the peat swamp developed only locally, which resulted in the thin and discontinuous Nos. 1 and 2 coal seams. The roof of these three coal seams is siltstone and sandstone, and the thickness is about 2 m. The roof sealing capability of No. 3 coal seam is generally low.

4.1.2. Tectonics and CBM preservation

4.1.2.1. Tectonic evolution and CBM preservation.

CBM generation occurred during coalification, which was controlled by tectonic evolution, burial history and paleo-geothermal heating of the coal seam. The SQB coal experienced the following four evolution stages: slow, fluctuant, fast and terminate stages. The slow evolution stage corresponds to Hercynian–Indosinan orogeny with slow subsidence. In the late Paleozoic, the North China platform was a unified and stable epi-continental basin. During the Triassic, the North China platform experienced differential
subsidence and formed various sub-basins. In most sub-basins, continuous Permian-Triassic strata were deposited. Based on the balanced heat flow, the coal-bearing strata gradually increased in temperature with increasing burial depth. At the bottom of the Shanxi formation, the temperature increased from 45 °C in late Permian stage to around 130 °C in the late Triassic (Fig. 5).

*Fig. 3. Stratigraphic column of the Permo-Carboniferous coal-bearing strata in the SQB.*

<table>
<thead>
<tr>
<th>Strata system</th>
<th>Group thickness (m)</th>
<th>Column</th>
<th>Marker bed and coal seam</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Permian</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shanxi Formation (P₃)</td>
<td>37.01–72</td>
<td>K₈</td>
<td></td>
<td>Bright coal, stable coal seam, often with 1 or 2 thin mudstone interbeds.</td>
</tr>
<tr>
<td></td>
<td>46.53</td>
<td>K₇</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper Pennsylvanian</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Taiyuan Formation (C₂)</td>
<td>46.58–56.15</td>
<td>K₆</td>
<td></td>
<td>Semi-bright coal, occasionally with one thin mudstone interbed.</td>
</tr>
<tr>
<td></td>
<td>50.5 (Group III)</td>
<td>K₅</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>46.58–56.15</td>
<td>7#</td>
<td></td>
<td>Semi-bright coal, coal seam is stable, occasionally with mudstone. It is exploitable locally.</td>
</tr>
<tr>
<td></td>
<td>50.5 (Group III)</td>
<td>8#-1</td>
<td></td>
<td>With one mudstone interbed and exploitable.</td>
</tr>
<tr>
<td></td>
<td>50.5 (Group III)</td>
<td>8#-2</td>
<td></td>
<td>With one mudstone interbed and exploitable.</td>
</tr>
<tr>
<td></td>
<td>50.5 (Group III)</td>
<td>9#</td>
<td></td>
<td>Semi-bright coal, coal seam is stable and exploitable, with sulfur locally.</td>
</tr>
<tr>
<td></td>
<td>50.5 (Group III)</td>
<td>10#</td>
<td></td>
<td>Extremely unstable.</td>
</tr>
<tr>
<td></td>
<td>50.5 (Group III)</td>
<td>11#</td>
<td></td>
<td>Semi-bright coal, coal seam is unstable.</td>
</tr>
<tr>
<td></td>
<td>50.5 (Group III)</td>
<td>12#</td>
<td></td>
<td>Fragile, occasional with one mudstone interbed, and unstable.</td>
</tr>
<tr>
<td></td>
<td>50.5 (Group III)</td>
<td>K₃</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50.5 (Group III)</td>
<td>13#</td>
<td></td>
<td>Semi-bright coal, the coal structure is simple and the coal seam is stable.</td>
</tr>
<tr>
<td></td>
<td>50.5 (Group III)</td>
<td>K₂</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.34–41.37</td>
<td>15#</td>
<td></td>
<td>Semi-bright coal, the coal seam often contain 0–5 mudstone interbeds. The coal seam is exploitable in the whole Southern Qinshui basin.</td>
</tr>
<tr>
<td></td>
<td>19.0 (Group I)</td>
<td>K₁</td>
<td></td>
<td>Locally with thin coal-bearing mudstone.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16#</td>
<td></td>
<td>Semi-bright coal.</td>
</tr>
</tbody>
</table>
strata experienced low temperature thermal maturation, and heat evolution rate was low. Ro increased by 0.0001%/Ma. Therefore, by the end of the Permian, thermal evolution of organic matter is generally low, with only lignite formed. In the Triassic, accelerated rate of thermal evolution of coal resulted in increase in vitrinite reflectance at 0.0003%/Ma, and a rank of medium volatile bituminous coal was achieved. At this stage, coal was slowly warming; coal rank was slowly increasing; and the paleo-geothermal field is normal. CBM generated at this stage is the biogenic gas, which was not preserved due to shallow burial depth. But the porosity and permeability of coal reservoir are generally high due to low compaction from overlying rocks. Coalification is subject to the geothermal metamorphism.

The fluctuant evolution stage corresponds to the late Indosinian-early Yanshanian orogeny with fluctuations in the burial history. In this stage, frequent uplift and subsidence occurred in North China. Fluctuated geothermal flows had influences on coal-bearing strata (Ruppert et al., 2010). Although coalification kept more or less stable in this stage, the permeability was improved by the geothermal fluctuations. However, no CBM of this stage could be preserved due to thermal fluctuations.

The fast evolution stage corresponds to the mid- and late-Yanshanian orogeny when the burial depth of coal seams significantly reduced. Coalification during this stage was mainly influenced by high heat flow from magmatic intrusions. More gas and pore volumes were generated during this stage and the porosity was obviously improved. However, local magmatic intrusion and differential deposition caused coalification heterogeneity, resulting in coal metamorphic zonation (Cardott, in press). In the southern part of the study area, abnormal magmatic intrusions created paleo-geothermal gradient as high as 5.5 °C/100 m, with some areas even up to 8 °C/100 m or higher. Such magmatic activities were favorable for CBM generation and coalification. By the end of the Cretaceous, coal in the SQB reached the rank of anthracite.

The terminate evolution stage corresponds to the Himalayan orogeny with the burial depth of coal seams continuously decreased. During this stage, the coal-bearing strata were continuously uplifted and eroded in the study area. Burial depth of coal seams became shallow and temperature of coal-bearing strata decreased. By the end of the Himalayan orogeny, coalification terminated. Coal modification during this stage is unfavorable for CBM preservation.

4.1.2.2. Structural setting and CBM concentration. In the modern SQB, a few faults and folds with axial striking NNE–SSW and near N–S are common (Fig. 6). These structures induce slight coal deformation. The coal reservoir permeability is relatively high, with maximum values approaching 1 mD. In particular a case when strong deformation caused coal mylonitization, coal reservoir has low permeability (Yao and Liu, 2009). Previous studies indicated that the folds in the SQB were formed by NW–SE compressional stress during the Jurassic–Cretaceous Yanshanian Orogeny (Qin et al., 2001). The two tensile non-sealing faults caused serious CBM loss. The gas contents of coals around the faults are lower than those away from the faults.

In the SQB, the GC of coal is generally high, ranging from 10 to 37 m³/t (Fig. 7). The highest GC is present in the deep part of the SQB basin. The gas saturation is 56–100% (generally lower than 80%). In these synclines, fractures and micropores favorable for CBM concentration are abundant due to the structural stress. Because of well-developed coal reservoir porosity (<5%, which include cleat porosity and matrix porosity), permeability (<1 mD) and good roof-sealing capability, appropriate
coal thickness (>5 m), moderate burial depth (600–1000 m), and conditions conducive to methane accumulation, the syncline areas of the SQB such as central Zhengzhuang and southeast Duanshi coal districts (Fig. 7) are ideal for CBM exploration and development.

Based on the well data and experiments, the GC of the SQB is in the order of syncline (GC for well Js7 is 24 m$^3$/t) > slope of syncline (GC for well 0402 is 18.35 m$^3$/t) > slope of anticline (GC for well 0801 is 16.41 m$^3$/t) > anticline (GC for well Zs15 is 12.67 m$^3$/t) >

Fig. 6. Comprehensive map and cross section of structure, gas content and burial depth of coal seam in the SQB.

Fig. 7. Gas content and hydrodynamics of No. 3 coal seam in the SQB, arrows show direction of groundwater flow.
central of normal fault (GC for well Zs31 is 10.08 m³/t) > surrounding normal fault (GC for well Zs39 is 1.8 m³/t), if only structure patterned are considered (Fig. 6).

4.1.3. Hydrodynamics and CBM accumulation
The hydrodynamic connection of the No. 3 and No. 15 coal seams is separated by multiple impermeable layers (Fig. 3). Groundwater recharge, migration, and discharge are similar in both No. 3 and No. 15 CBM reservoirs, as have been confirmed in previous studies (e.g., Qin et al., 2001). Therefore, the discussion hereafter will focus on the hydrodynamic features of the No. 3 CBM reservoir.

The roof of No. 3 coal seam is siltstone in most areas (2–5.5 m thick). There is hydrodynamic connection through fractures within the coal seam, which can be regarded as a single aquifer. Groundwater migration in the aquifer is controlled by tectonics, topography, and precipitation. The Shitou fault divides the drainage system. In the eastern part, the groundwater recharges from Fanzhuang–Panzhuang areas, while in the western part, the groundwater recharges from the northwest and southwest Mabi and Qinsu coal districts, as well as from the Shitou fault toward the Zhengzhuang coal district of the basin. In recharge and discharge areas, groundwater flow reduces CBM content. In the deep groundwater retention area, CBM flows with groundwater and re-accumulates in the deep zone under the water pressure (Fig. 7). The GC of the stagnant area of groundwater (e.g., GC for well Zs58 is 36.89 m³/t; GC for well js7 is 24.07 m³/t) is higher than that of surrounding ground water.

4.1.4. Reservoir condition and related CBM

4.1.4.1. Coal composition and coal rank. Coal composition analysis shows that high-rank coals in the SQB are dominated by maceral assemblage of vitrinite and subordinate inertinite. Liptinite is no longer microscopically recognizable in coals of the SQB (Table 1). The main lithotypes are semi-bright and bright coals. The coal ranks range from low volatile bituminous coal to anthracite. Proximate analysis indicates that the coals from the SQB contain 0.59–3.54% moisture, 3.5–15.54% ash yield, 73.62–88.92% carbon, and 2.14–4.04% hydrogen. The C/H ratio is in range of 19.96–36.25 (Table 2). Coal composition has a marked effect on gas adsorption capacity. However, because the moisture content varies with coal rank and composition, and methane adsorption capacity also changes with these variables, it is difficult to isolate the effects of moisture content (Bustin and Clarkson, 1998). Minerals in coals have different origin and behavior during coalification and metamorphism. Their presence is mainly controlled by the depositional environments of coal deposits (Vassilev et al., 1997).

Previous studies indicate that the optimum coal rank for CBM production is 1.2 to 2.5% Ro,m (Creedy, 1988; Flores, 1998), because less mature coals (<1.2% Ro,m) generally have lower GPs and more mature coals (>2.5% Ro,m) have lower permeability. Coals from the SQB are mainly low volatile bituminous and anthracite with Ro,m ranging from 1.95 to 3.49%. The coals are composed of 18.5–97.4% vitrinite, 2.4–81.4% inertinite (Table 1) and some minerals. Based on the experimental data, the permeability correlates with the macerals and ash yield. In general, the permeability of coals in the SQB is low (normally <0.5 mD) due to the high coal rank, but for some slightly improved reservoirs, the permeability can reach up to 1 mD. The permeability has a decreasing trend until inertinite contents of 60%, but it has an uncertain trend after 60% of inertinite, possibly due to insufficient data (Figs. 8 and 9).

4.1.4.2. Coal thickness and CBM preservation. In the SQB, the target seams for CBM exploration and development are No. 3 and No. 15 coal seams. The coal thickness of No. 3 coal seam is usually between 4 and 7 m and stable (Fig. 4). The CBM gas-in-place (GIP) resources show a positive correlation with coal thickness. Furthermore, to investigate the preservation of coal seams, the burial depth of No. 3 coal seam was evaluated using the contour map as it is relatively thick and continuous across the SQB. The coal burial depth is within 400–1200 m at the mining areas (Fig. 10) and increases toward northwest. The GC increases with increasing burial depth (Fig. 11). In the northwest deep zone, stable and thick coal seams are still un-tapped, which is favorable for CBM preservation. Coal ranks in the SQB generally reach anthracite due to the magma intrusion.

4.1.4.3. Pore-fracture system and production potential. In contrast to oil reservoirs, the helium porosity (including cleat/fracture and matrix porosity) is not very important for the air permeability of CBM reservoirs. The cleat/fracture porosity has greater effect on permeability due to the cleat/fracture variation (aperture or spacing changes). The cleat/fracture porosity (generally lower than 1% for high rank coal) has certain relationship with permeability, which was verified by previous research (Palmer and Mansoori, 1998; Palmer et al., 2007). However, the structure of pore-fracture system is essential for CBM adsorption. For selected coal samples, factors influencing the porosity include the micro-fractures, mineralization-precipitation process and paleoenvironment. The pore-fracture system is the path for

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Sampling location</th>
<th>Coal mine</th>
<th>Coal district</th>
<th>Coal seam</th>
<th>Coal lithotype</th>
<th>Coal composition (%)</th>
<th>Ro,m (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZLS3-1</td>
<td>Zhulingshan</td>
<td>Yangcheng</td>
<td>3</td>
<td>Bright</td>
<td>83.5</td>
<td>14.5</td>
<td>2.10</td>
</tr>
<tr>
<td>ZLS3-2</td>
<td>Zhaozhuang</td>
<td>Gaoping</td>
<td>3</td>
<td>Semi-bright</td>
<td>74.4</td>
<td>24.7</td>
<td>1.92</td>
</tr>
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<td>Gaoping</td>
<td>3</td>
<td>Bright</td>
<td>89.5</td>
<td>6.2</td>
<td>4.3</td>
</tr>
<tr>
<td>ZZ3-2</td>
<td>Zhaohuzhan</td>
<td>Gaoping</td>
<td>3</td>
<td>Semi-bright</td>
<td>89.5</td>
<td>6.9</td>
<td>3.36</td>
</tr>
<tr>
<td>YC4-1</td>
<td>Yicheng</td>
<td>Yangcheng</td>
<td>4</td>
<td>Bright</td>
<td>81.4</td>
<td>8.1</td>
<td>2.2</td>
</tr>
<tr>
<td>YC4-3</td>
<td>Yicheng</td>
<td>Yangcheng</td>
<td>4</td>
<td>Semi-bright</td>
<td>49.1</td>
<td>50.8</td>
<td>0.2</td>
</tr>
<tr>
<td>ZLS3-1</td>
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<td>Yangcheng</td>
<td>3</td>
<td>Semi-bright</td>
<td>89.5</td>
<td>6.2</td>
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<td>Bright</td>
<td>89.5</td>
<td>6.2</td>
<td>4.3</td>
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<tr>
<td>ZZ3-2</td>
<td>Zhaohuzhan</td>
<td>Gaoping</td>
<td>3</td>
<td>Semi-bright</td>
<td>89.5</td>
<td>6.9</td>
<td>3.36</td>
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<td>Gaoping</td>
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<td>Semi-bright</td>
<td>89.5</td>
<td>6.9</td>
<td>3.36</td>
</tr>
</tbody>
</table>

Abbreviations: V = vitrinite; I = inertinite; M = minerals; Ro,m = mean vitrinite reflectance.
CBM migration, and the development of fractures will affect the permeability of CBM reservoir that is important for CBM production potential during CBM exploitation. The porosity and permeability can be acquired from log data (Karacan, 2009).

In the SQB, the helium porosity (including cleat/fracture and matrix porosity) of the coal seams is 1.5%–9.3%, normally less than 5%, which is low in general (Fig. 12). Micro-pores dominate the porosity, followed by large-pores and meso-pores (Fig. 13). Based on previous research (Yao et al., 2008b), the structure of pores is bedding parallel and plane-like in coals of SQB, which has medium to low connectivity in terms of N₂ adsorption and mercury porosimetry. This structure has both positive and negative effects on CBM production potential. For anthracite, large quantity (>75%) of micropores (0–100 nm; Fig. 13) prevents the development of macropores. On the one hand, high content of micro-pores is favorable for CBM adsorption in the reservoir (Yao et al., 2008b). On the other hand, the lack of macropores (diameter >100 nm) may lead to the permeability bottleneck of coal reservoirs. Fractures are the path for CBM gas flow, and are the main factors for controlling reservoir permeability. The permeability of the SQB is generally lower than 1 mD due to the burial depth and tectonic stress. Minerals filling in high-rank coals appear as crystalline forms (Ward, 1989) in fractures, which affect the permeability (Solano-Acosta et al., 2007), porosity and adsorption capability of coals (Bustin and Clarkson, 1998) (Figs. 14 and 15). In the research area, micro-fractures are well developed, and have high density (Table 2). They are characterized by isolated, orthogonal, or Y-shaped structures, with relatively good connectivity and infrequent mineralization (Table 2). Fractures with worse connectivity are anisotropically developed and locally mineralized by diagenetic minerals. The moderately developed fractures in the normal- or cataclastic-structured coals are favorable for gas permeability, whereas the ultra-developed exo-microfractures in sheared coals are unfavorable for gas permeability and production (Li et al., 2010; Yao and Liu, 2009).

### Table 2
Proximate analysis and fractures of coal in the SQB, North China.

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Type A + B</th>
<th>Type C</th>
<th>Type D</th>
<th>Total</th>
<th>Connectivity</th>
<th>Cad(%)</th>
<th>Had(%)</th>
<th>Mad(%)</th>
<th>Aad(%)</th>
<th>C/H</th>
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<td>22</td>
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<td>82.12</td>
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<td>0.59</td>
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<td>81</td>
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<td>3.54</td>
<td>9.75</td>
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</tr>
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<td>7</td>
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<td>2.55</td>
<td>1.89</td>
<td>6.37</td>
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<td>2.24</td>
<td>3.5</td>
<td>32.93</td>
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<tr>
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<td>60</td>
<td>75</td>
<td>Very good</td>
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<td>3.23</td>
<td>1.04</td>
<td>10.84</td>
<td>23.98</td>
</tr>
<tr>
<td>SJ9-2</td>
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<td>15</td>
<td>36</td>
<td>Very good</td>
<td>78.96</td>
<td>3.42</td>
<td>0.66</td>
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<td>23.09</td>
</tr>
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<td>1.92</td>
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<td>1.74</td>
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<td>14</td>
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<td>26.53</td>
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<td>11</td>
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<td>2.76</td>
<td>2.04</td>
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<td>24</td>
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<td>2.87</td>
<td>1.86</td>
<td>11.38</td>
<td>27.60</td>
</tr>
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</table>

Note: ① Microfracture frequency means the numbers of microfractures at the scale of 3×3 cm². Type of microfractures includes Type A, with width (W) ≥ 5 μm and length (L) ≤ 10 mm; Type B, with W ≥ 5 μm and L ≤ 10 mm; Type C, with W ≤ 5 μm and L ≥ 300 μm, and Type D, with W ≤ 5 μm and L ≤ 300 μm. ② Cad (%) = carbon content (as received basis), Had(%) = hydrogen content (as received basis), Mad(%) = moisture content (as received basis), Aad(%) = ash yield (as received basis).

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Fig. 8. Permeability and vitrinite of coal in the SQB (y₀, xc, W, and A are the parameters of the equation).

Fig. 9. Permeability and inertinite of coal in the SQB.
4.2. Evaluation of CBM resources

4.2.1. Evaluation parameters of CBM targets

Based on the above discussions, the influence of geological factors on the CBM potential includes coal thickness, GC, burial depth, \( R_o,m \) and others (e.g., the evaluation parameters in first level of the AHP model: Fig. 16) (Yao et al., 2009b). In evaluating the CBM favorable targets, these geological factors should be first chosen as the evaluation parameters in the AHP model and then the quantification method for these parameters should be determined. The choice of quantification method for each parameter is based on the data from experimental analysis, field work and well tests (Yao et al., 2008a). The first-level parameters consist of sedimentary characterization, coal thickness, vitrinite reflectance, structural setting, roof sealing capability, GC, reservoir condition and burial depth. The second level parameters contain CBM generation (including sedimentary features, coal thickness and coal metamorphism), CBM preservation (including structures, roof sealing and GC) and CBM exploitation (including CBM reservoir condition and coal burial depth). Evaluation result of each block was obtained by fuzzy mathematics and vector stacking calculations in the GIS. Integrated results are used to predict the favorable CBM targets.

4.2.2. Evaluation results

4.2.2.1. CBM resources and its concentrations. CBM gas-in-place (GIP) resources are calculated based on the common volumetric method (Boyer

![Fig. 10. Modern burial depth of No. 3 coal seam in the SQB.](image)

![Fig. 11. Gas content and burial depth in the SQB.](image)

![Fig. 12. Coal porosity in the SQB, North China.](image)
This method can briefly be summarized as in Eq. (2):

\[ Q = A \times H \times D \times C \]  

(2)

where \( A \) is the distribution of coal seams \((\text{km}^2)\); \( H \) represents net accumulative coal thickness \((\text{m})\); \( D \) is coal density \((\text{g/cm}^3)\), here is set at 1.6 \(\text{g/cm}^3\) based on the density test; \( C \) is the GC from experimental test in the field \((\text{m}^3/\text{t})\); and \( Q \) is the GIP by volumetric resource estimation method \((\text{m}^3)\). Based on this volumetric method, the GIP resources >400 m depth are obtained from the overlap calculation system in "MapInfo professional". Total CBM resource preserved in No. 3 coal seam of the SQB is estimated to be 3.62 × 10^{11} \(\text{m}^3\) in burial depth greater than 400 m. The CBM resource concentration \((\text{GIP per square kilometer, } \times 10^8 \text{ m}^3/\text{km}^2)\); 0.01 is the adjustment coefficient for GIP unit. Gas resource concentration decreases from Zhengzhuang coal district to Shitou fault and from Hudi coal district to the basin margins, which is generally about 1.21 × 10^8 \(\text{m}^3/\text{km}^2\), favorable for CBM development.

4.2.2. CBM targets for No. 3 coal seam in the SQB. CBM targets for No. 3 coal seam in the study area were shown in Fig. 17. The evaluation area is divided into 5 levels of subareas, level V to level I with increasing evaluation scores (Fig. 17). The comprehensive index is in the range of 0.39–0.98. Level I subareas with highest comprehensive index (>0.8) are distributed in the southwest and northwest of Zhengzhuang and central Hudi coal districts. Level II subareas with 0.7–0.8 comprehensive index occur in the central part of Zhengzhuang and western part of Fanzhuang coal districts. Level III subareas with 0.6–0.7 comprehensive index are present along the Shitou fault and the deep burial zone of the SQB. Level IV subareas with 0.5–0.6 comprehensive index are distributed along the margins of the SQB. Level V subareas with lowest comprehensive index (<0.5) are in the southeast margins of the SQB.
5. Conclusions

No. 3 coal seam in the SQB has great potential for CBM production. Coal rank across the SQB ranges from low volatile bituminous to anthracite. Coal macerals are dominated by vitrinite and inertinente. GCs are in the range of 10–37 m$^3$/t in the No. 3 coal seam and show structurally controlled pattern: syncline > slope of syncline > slope of anticline > anticline > central of normal fault > surrounding normal fault. There is a positive relationship between CBM content and basin hydrodynamics. The CBM easily concentrates in the groundwater stagnant zone because of the water pressure.

The GIP estimate of the No. 3 coal seam in the SQB is $3.62 \times 10^{11}$ m$^3$. The permeability is generally lower than 1 mD, which is mainly related to the strong tectonic stress, low porosity and mineralization in coals. The best prospective targets for CBM production are evaluated to be the southwest and northwest of Zhengzhuang and central Hudi coal districts.

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References


