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Investigation on coal seam gas formation of multi-coalbed reservoir in Bide-Santang Basin Southwest China

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Abstract This paper presents a comprehensive study on the geological characteristics of a multi-coalbed reservoir using coal cores collected from well drilling tests in Bide-Santang Basin, China. The study focuses on the investigation of the coalbed methane (CBM)-bearing property, porosity and permeability, sealability of capping rocks, and groundwater characteristics in coal seams, providing the experimental information on the control function of sequence strata for the coalbed methane. This reservoir is comprised of a large number of coalbeds and exhibits many distinctive geological characteristics of a CBM reservoir, such as high CBM content, complex vertical volatility of CBM content, vertical discontinuous distribution of porosity and permeability, strong sealing capping property and many vertical water-bearing systems, etc. The investigation shows that the unattached multiple superposed CBM-bearing system (UMSCS), which formed the unique multi-coalbed CBM reservoir, can be identified in the study area. Depending on the development scale of vertically unattached CBM-bearing coal seams, the CBM reservoir in the study area can be classified as simple UMSCS and complex UMSCS. The former, typically appearing in Zhuzang syncline and Agong syncline, exhibits the continuity of geological reservoir-forming characteristics in terms of less coal seams, much weaker sealability of capping rocks, higher CBM content, and many vertical water-bearing systems. The latter, typically represented by Shuigonghe syncline and Santang syncline, shows the continuity of geological reservoir-forming characteristics with a large number of coal seams, strong sealing capping property, and reasonably high CBM content. For simple UMSCS reservoirs, a sublevel exploitation method should be adopted for CBM exploitation in order to minimize the effect caused by larger variation of the reservoir energy in different systems. For complex UMSCS reservoirs, one effective way for CBM exploitation is to fracture virtual reservoir (mainly key sandstone member) to depressurize it uniformly and thus achieve large-scale discharging and mining in several adjacent CBM-bearing subsystems.

Keywords Coal · Coal seam group · Coalbed methane (CBM) · Coal reservoir · Reservoir characterization · Reservoir formation

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Introduction

Coal seam gas (CSG) or coalbed methane (CBM) has been recognized as an important nonconventional natural gas and clean energy source and has been receiving growing attention. For example, the CBM production in China had increased to 2.6 billion cubic meters (bm^3) in 2012 from 0.17 bm^3 in 2005 and is expected to be 16 bm^3 by 2015. By the end of 2012, there were 12,547 CBM wells in this country (Ye 2013). To meet the growing demand for clean energy supply, there are increasing investments for exploration and development of CBM around the world, particularly in China. Understanding the geological characteristic of CBM reservoirs is essential to minimize the risk of investments for CBM exploration and exploitation and improve the performance of commercial CBM development (Cai et al. 2011; Pashin 1998, 2010; Xu et al. 2012; Hamiltion et al. 2012;

Kędzior 2011; Tim 2012; Lamarre 2003; Kędzior 2009). This will be more important for CBM development from the coal reservoirs with multiple coal seams.

The geological characteristics of CBM reservoirs, such as CBM-bearing potential, porosity and permeability, and the sealing ability of the capping rocks, determine the commercial potential of CBM exploration. Liu et al. investigated pore structure of coal reservoir characteristics of Huainan and Huaibei coalfields by means of mercury porosimetry and low-temperature N_2 adsorption/desorption and found that pores of the coal in the reservoirs mainly comprised of well-developed micro- and mesopores (pore diameter <100 nm) and less developed macropores (pore diameter >100 nm). This type of pore characteristic was thought as favorable for gas adsorption but unfavorable for gas permeability. So far, most active areas for CBM exploration and exploitation in China are in the southern part of Qinshui Basin, North China (Liu et al. 2009). Su et al. investigated the coal distribution, coal rank, CBM content, and permeability of the coal seams no. 3 and no. 15 of Qinshui Basin to correlate the CBM content with basin hydrology and found that deep stagnant zones with abnormally high and normal reservoir pressures were favorable for the accumulation of coalbed methane (Su et al. 2005). Cai et al. investigated gas content and permeability of the coal seam no. 3 of Qinshui Basin and discovered that the coal seam has great potential for CBM production due to the higher CBM content and relatively favorable permeability (Cai et al. 2011). Liu et al. investigated the synergetic gas enrichment and higher permeability properties of the coal seam no. 3 of Qinshui Basin by statistical analysis of different geological factors and confirmed the coal seam being a favorable synergetic gas enrichment and higher permeability region (Liu et al. 2012). Xu et al. studied CBM accumulation characteristics of the coal seam no. 4 in the Binchang area of southwestern Ordos Basin to predict the best prospective target zone for CBM production, including its roof and floor properties, gas content, permeability, and pore structure (Xu et al. 2012). However, all of these studies were conducted mainly focusing on single-coalbed reservoirs.

In fact, most CBM reservoirs consist of multiple coal seams, i.e., the so-called multi-coalbed reservoirs defined in this study. Currently, CBM industry in China is still immature and CBM production is mainly based on single coal seam via surface development. Recently, exploration and development of CBM in the southwest of China, such as the Zhina coalfield in Guizhou Province, have been receiving increasing attentions (Gao et al. 2009; Lei et al. 2012). Bide-Santang Basin in the Zhina coalfield has been identified to be another attractive area for CBM development in China. However, the coalfield is deposited in a typical multi-coalbed reservoir with complicated reservoir formations featured by many unique CBM geological characteristics. Those particular reservoir properties are of vital significance for CBM development and have not yet been fully understood. So far, evaluation of geological characteristics of multi-coalbed reservoirs is still limited while there are many researches on single-coalbed reservoirs (Cai et al. 2011; Xu et al. 2012; Liu et al. 2009; Mares et al. 2009).

This paper presents a study on the geological characteristics of a multi-coalbed reservoir through the comprehensive analyses of coal cores collected from a large number of CBM well tests. The study focuses on the investigation of the CBM-bearing property, permeability, water abundance in coal seams, and sealability of capping rocks. It provides the experimental information on the control function of sequence strata for the coalbed methane. As a result, two types of reservoir formation are discussed, providing useful benchmark models for exploration and production in the multi-coalbed reservoir.

Geological setting

This study was carried out in Zhina coalfield, China's largest anthracite coal occurrence area located in western Guizhou of China. The coalfield includes the Bide-Santang Basin which takes up the main part of the Zhina coalfield, with a total area of 1692 km^2. The coal-bearing area is estimated at about 1000 km^2. The Bide-Santang Basin is a composite syncline residual basin. It is constituted by several synclines, including Bide syncline, Shuigonghe syncline, Bainijing syncline, Santang syncline, Agong syncline, and Zhuzang syncline, referring to Fig. 1.

Longtan and Changxing formations of Upper Permian are coal-bearing strata in the basin with formation thicknesses of 300~450 m. The depth of the coal-bearing strata is about 1300–2000 m. In this area, Longtan formation is coal-bearing deposition of classic interbedded carbonate with a paralic facies and a cycle structure. In reference to the preceding researches (Wang 2000; Yang 2000), the coal-bearing strata can be divided by five third-order sequences (Fig. 1). The thickness of coal-bearing strata gradually becomes thinner from southwest to northeast. Besides, the coal-bearing strata represents disconformable contacts with overlain Feixianguan formation of Lower Trassic, underlying Emeishan basalt in western Guizhou or Maokou formation in southeastern Guizhou (Xu and He 2002).

In geotectonic framework, the basin is located in the southwest of Zunyi fault arc of northern Guizhou uplift on upper Yangtze landmass. This develops two groups of structure lines in NW direction and NE direction. The former is represented by Bide syncline and Shuigonghe anticline, generally in the form of ejective folds while the latter, mainly in the form of brachy folds, is represented by Santang syncline, Agong syncline, and Zhuzang syncline. Furthermore, the structure lines in NW direction are cut off by the faults of NE direction. Therefore, the formation period of structure in NW direction is much earlier than that of structure in NE direction (Xu and He

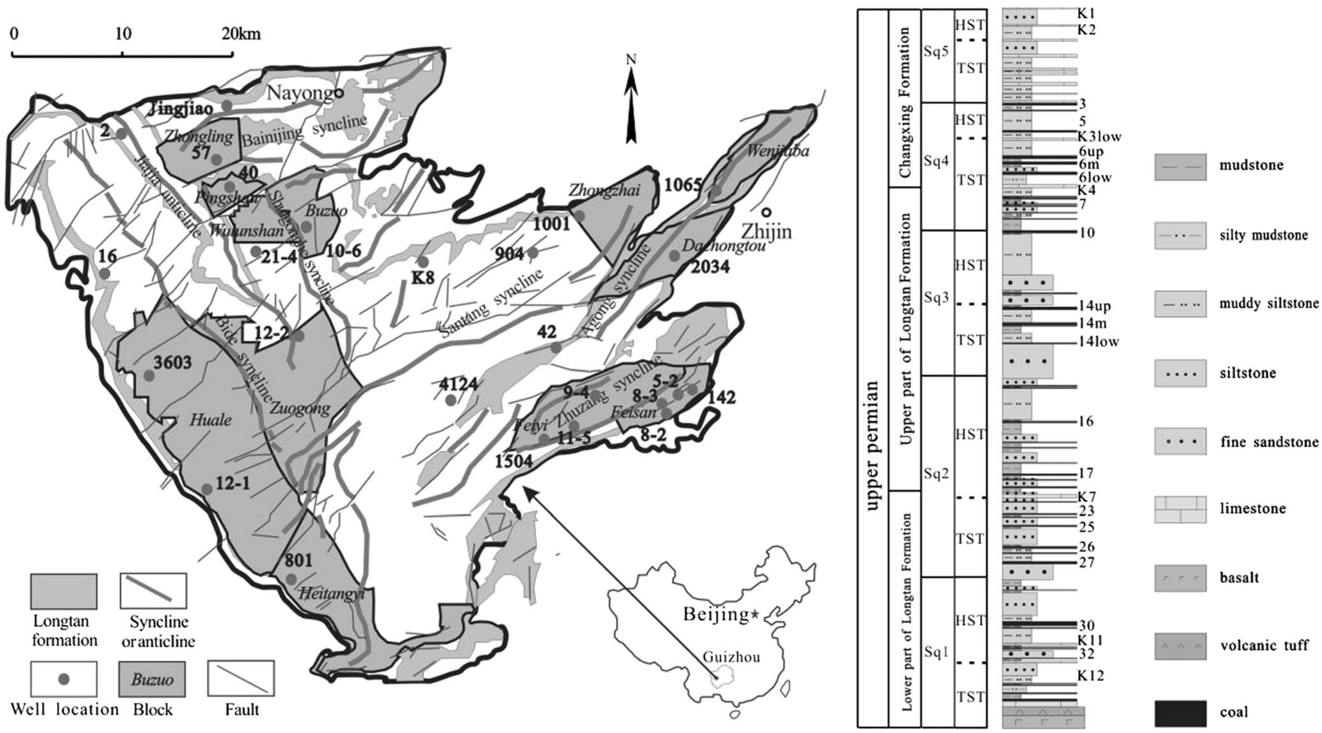

Fig. 1 Study area location and schematic histogram of coal-bearing stratum: borehole 1001. *Kn* key coal-bearing strata (mainly limestone), *TST* transgressive systems tract, *HST* high stand systems tract

2002; Gui 2001; Zhu et al. 2008; Jin and Tang 2010). In this basin, strike-slip faults development in NE direction often leads to wrong shift of coal-bearing strata and tectonic fault lines.

In the current study area, coal seams are mainly comprised of semi-bright coals in the Upper Permain. The vitrinite is the major microscopic maceral component with the content varying from 73.74 to 81.45 % and the maximum reflectance ranging from 1.56 to 3.60 %. In the western margin of the basin, there is a stripped distribution of lean coals and meagre coals. Ash content in the coal varies from 17.22 to 26.14 %, and total sulfur content is about 1.61~3.67 %. The latter gradually increases from west to east.

Date resources, samples, and experimental methods

Date resources

Date of coal seam numbers in this article comes from coalmines and CBM wells in the Bide-Santang Basin. Date of groundwater level of wells comes from pumping test in the study area.

The coal seam gas content was estimated based on a direct measurement method (Wang et al. 2011). It includes three procedures: lost gas (V_{gl}) analysis, desorbed gas (V_{gd}) collection and analysis, and residual gas (V_{gr}) measurement. As a result, the total in situ coalbed gas content (V_{gt}) can be estimated as follows:

$$V_{gt} = V_{gl} + V_{gd} + V_{gr}$$

The combined drilling tests in the field and desorption experiments in laboratory were performed on each exploration well by the above procedures.

Samples and main test methods

A total of seven coal samples and ten rock samples were obtained from Zhongzhai no. 1001 borehole in the Bide-Santang Basin. Figure 1 shows the no. 1001 borehole location.

Helium porosity and air permeability

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 and rock block, a cylindrical core with 2.5 cm diameter (length >2.5 cm) was cut. 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.

NMR measurements

The nuclear magnetic resonance (NMR) measurement was conducted using a Rec Core 2500 instrument. After porosity and air permeability of samples were measured, the samples were analyzed using the NMR instrument. Firstly, the samples were put into a drying oven until dried to a constant mass. The dry mass of each coal sample was then recorded. Secondly, we measured saturated water contents and porosities of each coal-rock sample. The samples were held in vacuo for over 12 h, and saturated standard salt water was also pressurized to 5 MPa to form a flow into each sample. Next, the wet mass was measured and the porosity was calculated. Thirdly, a test of transverse relaxation time (T_2) for each coal sample was undertaken with water as the permeant. The saturated samples were then placed into the probe of the core analyzer of the low-field NMR so as to evaluate T_2. Meanwhile, T_2 spectra were obtained by inverse calculation. Fourthly, T_2 testing of the coal-rock samples with irreducible water was undertaken. The water-saturated rock samples were placed into a centrifuge to dewater them under a pressure of 200 psia (1.37 MPa). Finally, tests involving seven coal samples were completed.

The testing parameters included the following: resonant frequency (2 MHz), echo time (0.13 ms), recovery time (6000 ms), echo number (1024), signal/noise ratio (controlled at above 30 dB), and T_2 spectrum fitting points (64).

SEM analysis

The rock samples were analyzed by scanning electron microscope S-3000N. The main technology index of this operator is that the point resolution is 6 nm and the maximum magnification is 200,000 times.

Characterization of multi-coalbed reservoir

Coal seam numbers

Coal seam is statistically determined by means of the thickness of monolayer coal seam through drilling tests, accounting for the coal seams with a thickness greater than 0.3 or 0.70 m. The coal reservoir of Black Warrior Basin in the USA was assessed by taking the minimum thickness of coal seams at 0.3 m (Pashin 2010). From the viewpoint of CBM resources, it is reasonable to set the minimum thickness of coal seam at 0.3 m in statistics. Therefore, this study treated 0.3 m as the minimum thickness of a single coal seam for characterization of multi-coalbed reservoir, which will be discussed as follows.

To investigate the coal seam groups in the multi-coalbed reservoir, a series of drilling tests were carried out in the given exploration area and the cored coal samples were measured. The results provide geological information about deposit of the coal seams for characterization of the multi-coalbed reservoir, such as thicknesses, spacing, and numbers of coal seams in the reservoir. According to the drilling tests (see Table 1), the maximum thickness of coal seam in the study area is 33.56 m, appearing in no. 12-1 borehole in Huale exploration area of Bide syncline. The minimum thickness is 13.26 m detected from no. 1065 borehole in Wenjiaba of Agong syncline. Total seam thickness gradually increases from southeast, such as Agong syncline and Zhuzang syncline, to northwest, including Shuigonghe syncline and Bide syncline (referring to Fig. 1). The average thickness of coal seams is 23.03 m. The spacing between coal seams is 12.37 m on average in the exploration area. The maximum spacing among coal seams is 28.37 m found in no. 1504 borehole in Zhuzang syncline located in Feiyi. The minimum spacing between coal seams is 8.06 m, appearing in Zuogong no. 12-2 borehole. The results further show that the number of coal seams varies from 14 to 42. No. 1504 borehole in Feiyi has the least coal seams, while no. 12-2 borehole of Jiajia anticline in Zuogong has the most. Similar to the total thickness of coal seams, the number of coal seams increases from southeast to northwest. On the contrary, the seam spacing is generally decreasing from southeast to northwest.

Table 1 Total thicknesses, numbers, and spacing of coal seams in Bide-Santang Basin

Borehole number	Coal seam total thickness (m)	Coal seam numbers	Coal seam spacing (m)
3603	24.95	31	10.14
801	28.59	29	11.47
12-2	30.41	42	8.06
12-1	33.56	36	10.28
21-4	32.11	35	10.12
16	29.53	31	9.36
K8	23.68	36	8.79
10-6	25.44	32	9.3
42	18.06	22	13.44
11-5	21.13	26	11.41
5-2	18.72	18	13.99
2034	13.26	18	14.76
9-4	18.48	21	15.63
1001	20.2	27	9.31
Jingjiao	22.84	32	9.39
2	23.53	27	10.84
57	26.22	31	9.08
904	23.33	22	12.96
4124	17.27	21	18.01
1065	17.56	21	14.96
1504	14.66	14	28.37

Coal seam gas

The results are summarized in Fig. 2, which show that higher methane content appears in Shuigonghe syncline and Agong syncline, lower content in Zhuzang syncline, and intermediate in Bide syncline and Santang syncline. It can further be seen that the CBM content of coal seams in Wulunshan, Zhongling, Buzuo, and Zuogong is generally higher than 12 m^3/t on average with the highest of 16.52 m^3/t. Another CBM-rich region is located in Wenjiaba and Dachongtou blocks in Agong syncline where the CBM content is about 12 m^3/t on average and total methane and ethane contents could reach about 14 m^3/t. The CBM content in Feiyi and Feisan blocks of Zhuzang is the lowest (about 10 m^3/t). In Huale and Heitang blocks of Bide syncline and Zhongzhai block of Santang syncline, the CBM content is about 10–12 m^3/t. These distribution characteristics of CBM content are closely related to the gas preservation conditions, which will be discussed in details later.

The coal reservoir pressure usually increases with burial depth of coal seams, and CBM content in coal seams progressively increases or successively decreases as the burial depth increases under the critical saturated depth, depending on the gas preservation conditions of coal reservoirs (Mavor et al. 1990; Qin et al. 2005; Scott 2002; Scott et al. 2007). Figure 3 shows the mean CBM content of the corresponding coal seams in representative exploration blocks. According to Fig. 3, the relationship between the CBM content and burial depth of coal seams in the study area can be approximately divided into three types. The first refers to Wenjiaba and Dachongtou in eastern Bide-Santang Basin where burial depth vs. CBM content volatility curve is relatively simple. Their CBM content is the highest at the same burial depth. This would be resulted from characteristics of well preservation and strong fluid energy. The second refers to Heitangyi and Pingshan blocks where burial depth vs. CBM content volatility curve is also relatively simple with the lowest CBM gradient. Under the same burial depth, the CBM content is the lowest, which implied that the preservation condition might be ordinary. The third refers to the Buzuo and Wulunshan blocks where the volatility curve is relatively complex, which suggests that there were multiple sets of CBM-bearing systems.

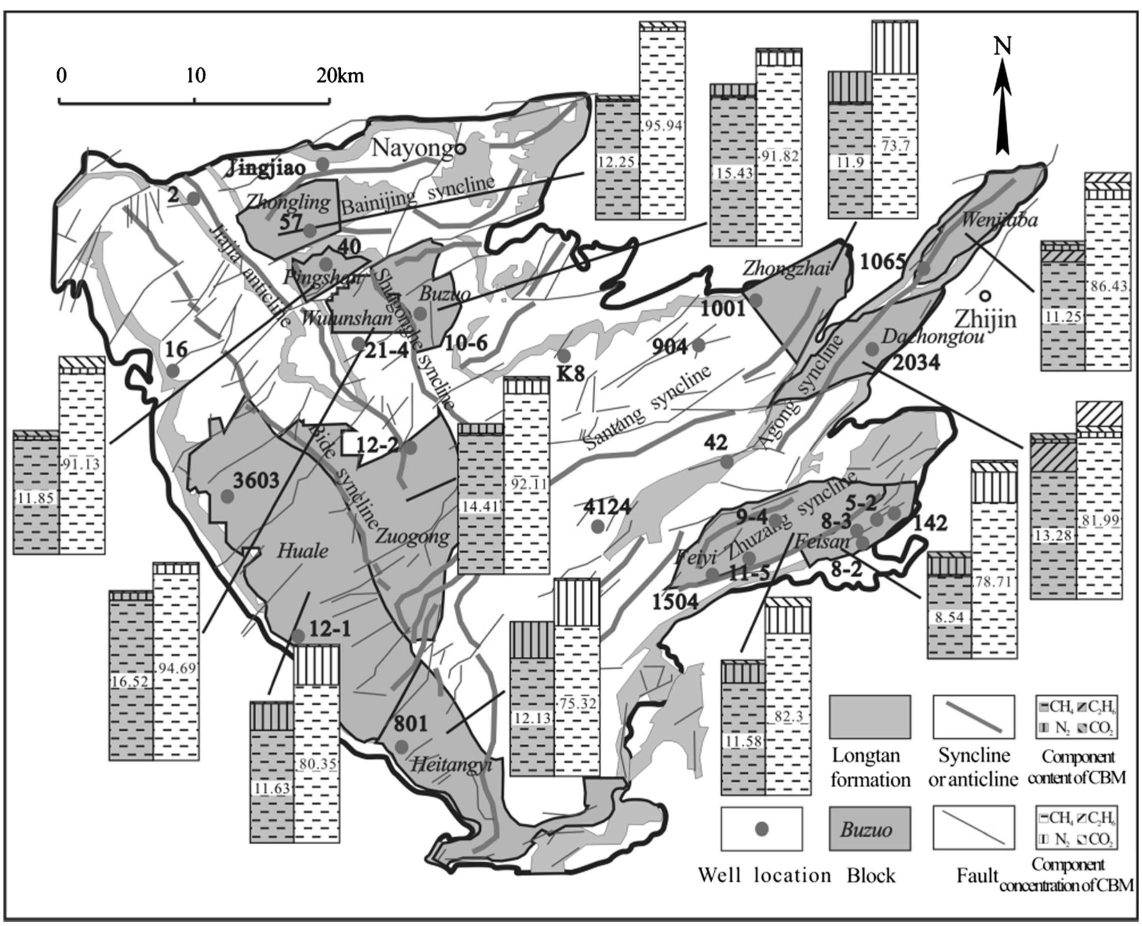

Fig. 2 Distribution of gas content and associated component concentration in Bide-Santang Basin

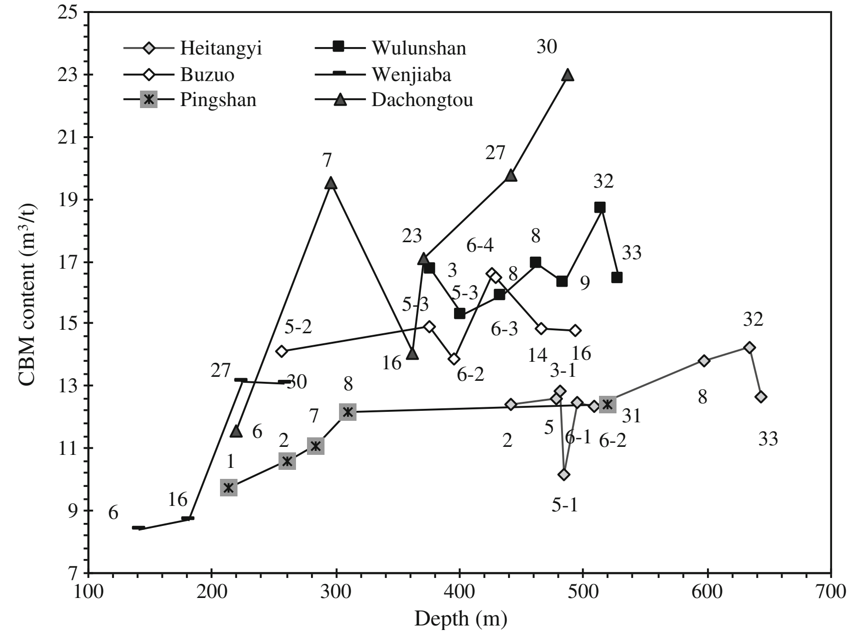

Fig. 3 Mean CBM content of coal seams in representative exploration blocks (*digits* beside the data points denotes numbers of coal seams)

Porosity and permeability in coals

Coal samples collected from no. 1001 borehole were further measured using nuclear magnetic resonance (NMR) spectroscopy in order to investigate the porosity and permeability of coal seams. Figure 4 shows several NMR properties measured with coal samples from the same drilling hole used for porosity analysis as discussed above. These properties are irreducible water saturation, relaxation time threshold or cutoff value (T_{2c}), mobile fluid porosity (free water porosity), and permeability of methane. Here, T_{2c} is a time threshold that divides the T_2 spectrum into two parts of irreducible water and free water in NMR spectroscopy (Yao et al. 2010). As can be seen, the irreducible water saturation and T_{2c} increase as burial depth increases and, thus, worsen the overall porosity and permeability. Meanwhile, the results apparently exhibit the cyclicity with burial depth in line with the third-order sequence (Sq), as indicated by the dot lines in Fig. 4. The irreducible water saturation and T_{2c} of Sq 3 and Sq 4 are overall relatively small, and the corresponding porosity of mobile fluid is large. Accordingly, the coal seams of these sequences exhibit the relatively higher porosity and permeability. This characteristic was also observed more clearly in coal seams nos. 17, 23, and 26 of Sq 2, the three main coal seams that are currently mining. Among these coal seams, the irreducible water saturation and T_{2c} of coal seam no. 23 are

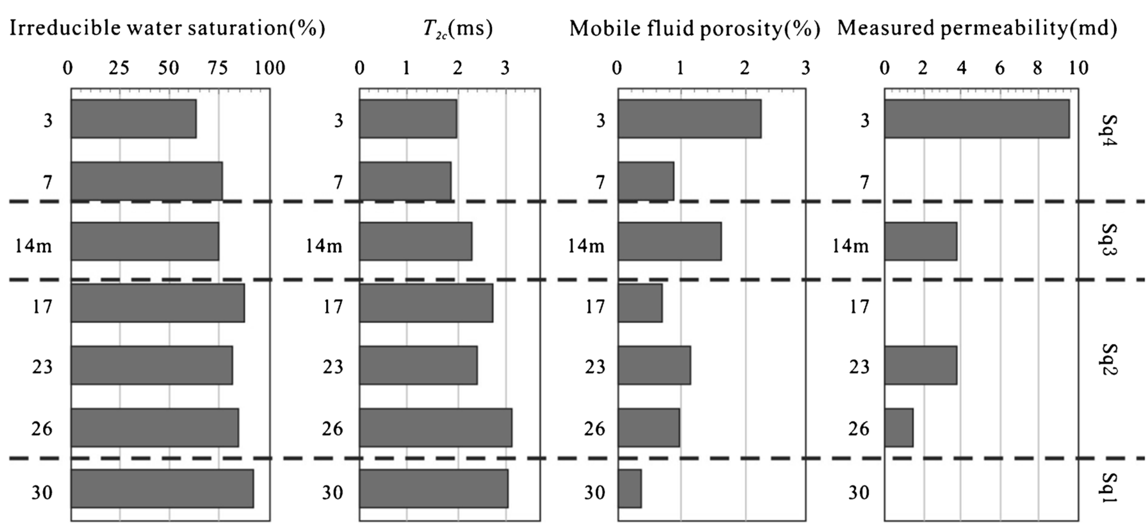

Fig. 4 Vertical variation of NMR properties of coal seam groups from Zhongzhai no. 1001 borehole (*digits* beside the vertical axis denotes numbers of coal seams)

smaller, but water porosity is relatively larger and the corresponding air permeability is favorable and better than other seams inside this sequence. Note that coal seam no. 23 is located under maximum flooding surface (MFS).

In summary, the porosity and permeability of multi-coalbed reservoir presented a trend that porosity and permeability deteriorated with horizon reduction. However, within each third-order sequence, the coal seam surrounded by MFS has relatively good porosity and permeability. The reason is that accommodation space of peat swamp developed near MFS increased to maximum. More importantly, the change rate of the accommodation space might reach stabilization but is smaller. Thus, the peat production rate and accommodation space can achieve a balance or accommodation space is slightly bigger. As a result, it is not only suitable for the peat accumulation but also more beneficial to the gelation of coal seams in reduction environment and, hence, promotes the formation of vitrinite-rich coal seams. By virtue of post-coalification, the endogenous fissure of coal seam was quite well developed. Coal rock types were mainly light and semi-light. This may be the main reason why the porosity and permeability of the coal seams are relatively favorable.

Sealability of capping rocks

Drilling tests revealed that the strata in exploration area mainly consist of fine-grained classic rocks. The coarse sandstone was founded in some boreholes. A large proportion of the coarsest lithology was fine sandstone, implying the excellent sealability of the capping rocks in the multi-coalbed reservoir.

Generally speaking, the stratum permeability is directly related to the diagenesis of coal-bearing strata environment in the formation of coal seam gas. In early diagenetic stage, coal-bearing strata usually lack carbonate cements due to the formation of acidic aqueous medium and, hence, formed a strong mechanical compaction. In late diagenesis, coal-bearing strata generated vast organic acid that further promoted quartz overgrowths and wide development of metakaolinite. As a result, the pores in strata might be further closed, resulting in poor reservoir properties such as the lower reservoir permeability (Zheng and Ying 1997). This is the most prominent feature of coal-bearing strata that differs from other ordinary formations due to the frequent, lasting, and stable acid coal-bearing strata environment, particularly in multi-coalbed reservoirs.

Figure 5 shows typical microscopic structure of capping rocks observed from the scanning electronic microscopy (SEM) using parts of the rock samples in no. 1001 borehole located in Zhongzhai of China (referring to Fig. 1). It can be seen that the mudstone and muddy siltstone contain the pores filled with fresh and intact crystal face quartz (Fig. 5a, b). These capping rocks are estimated to be formed at the late diagenesis corresponding to its B and C stages. At stage B of the late diagenesis, the organic matter in rock was maturely developed, usually the reflectance of vitrinite (R_o) value varying from 1.3 to 2.0 %, and the capping rocks were formed by autogenous and interconnected quartz crystals. In the C stage,

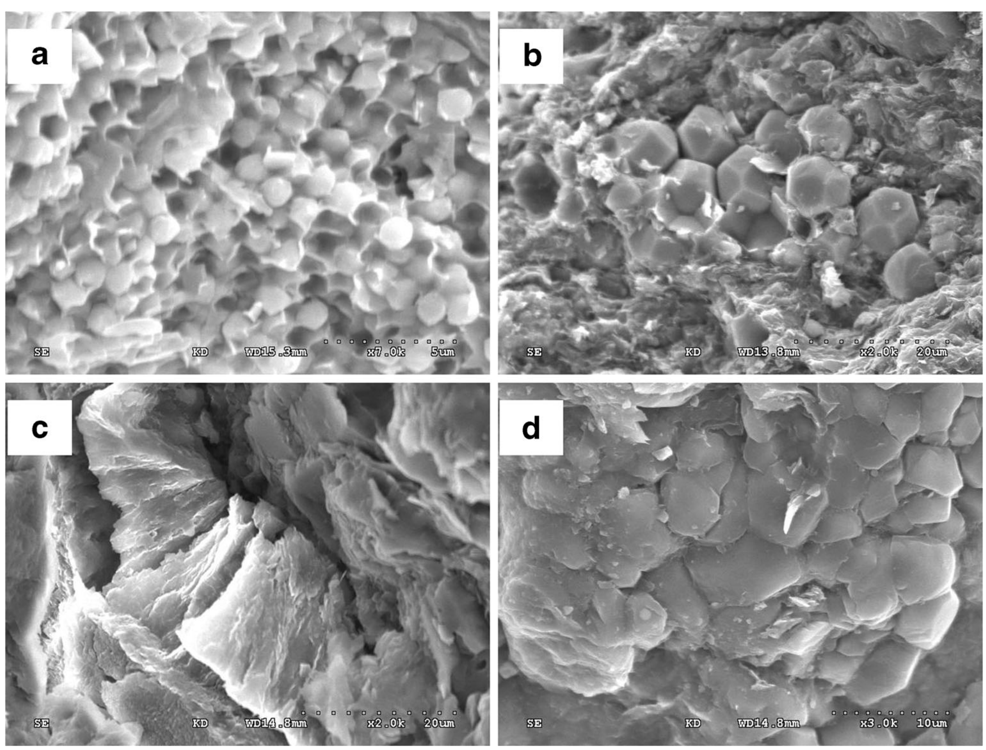

Fig. 5 SEM images of capping rock samples from Zhongzhai no. 1001 borehole at different burial depths of **a** 125.21 m: muddy siltstone, growth quartz in pores; **b** 348.53 m: growth quartz in mudstone pores; **c** 345.5 m: fine sandstone, pore filled with metakaolinite; and **d** 345.5 m: fine sandstone, metakaolinite

the organic matter was overdeveloped in which R_o value is from 2.1 to 4.0 % and rocks are very compact compared with the B stage (Chen and Jiang 1994). As observed, sandstone pores were very fine and filled with book-like or hexagon-sliced metakaolinite (Fig. 5c, d). Under compaction, due to diagenesis of coal-bearing strata, overgrowth of quartz and wide development of metakaolinite in the capping rocks led to poor porosity and permeability of the coal-bearing strata.

Table 2 summarizes the porosity and permeability measured with the typical lithology from no. 1001 borehole in Santang syncline. It can be seen that helium porosity of the capping rocks is lower than 5 %, and the air permeability through most of these rocks is below 0.1 md. The results show that the capping rocks are the lower permeability and good water- and gas-resistant layers.

Groundwater characteristics

There are rich hydrology dates in the Zhuzang syncline of the study area. By analyzing the pumping test date, fluid connectivity in the coal-bearing strata can be understood. In the tests, as shown in Fig. 6, water level elevation of four sets of coal seams (nos. 2~6, 7~16, 17~30, and beyond 30) in three boreholes were measured severally. Each set of the coal seams was maintaining a unified water level elevation during the multi-coalbed measurement. The results show that four sets of the coal apparently exhibited different water level elevations, implying different pressure systems. If all the seams were exploited in such a multi-coalbed drainage pattern, the fluid in coal seam set with the higher water level elevation would flow to that with the lower water level elevation. In other words, desorption and seepage would start earlier in coal seam set with higher water elevation than that with lower water level elevation. Since their energy systems in the multi-coalbed exploitation are different, coal seam set with higher water elevation would restrain desorption in the coal seam set with lower water level elevation. Therefore, a sublevel exploitation method by which the coal seams with higher water elevation is first exploited is suggested to be adopted in multi-coalbed CBM exploitation in order to minimize the effect caused by large variation of the reservoir energy in different systems. This is because, in multi-coalbed CBM exploitation, coal seam set with lower energy usually fails to conduct normal desorption of coalbed methane due to suppression.

Models of reservoir formation

Variations of the physical properties of coal seam groups and the adjoining rocks in vertical direction determined the differentiation of the CBM reservoir-forming characteristics (Yang et al. 2013). Thus, there is one unique kind of reservoir-forming model, the unattached multiple superposed CBM-bearing system (UMSCS) featured by a vertically superposed CBM-bearing system (Qin et al. 2008).

Bide syncline, Agong syncline, and Zhuzang syncline in the study area are simple typical UMSCSs. In Bide syncline, the average permeability in test well is 0.28 md and permeability of the three coal seams is all above 0.1 md, showing a good coal reservoir property. The analyses of the whole coal-bearing formation and sequence show that the Bide syncline in the west of the study area is dominated by fine-grained sandstones and Agong syncline in the east is dominated by limestones. Both of the synclines exhibit a favorable permeability compared with Shuigonghe syncline which is dominated by argillaceous rocks (Yang et al. 2011). The results from hydrological condition of Zhuzang syncline analysis also show that there were four CBM-bearing systems. This simple UMSCS is superposed vertically by multiple coal seams in a large scale, forming a simple UMSCS corresponding to a sedimentary cycle or a third-order sequence. In this system, the transgressive systems tract (TST) formation is fining upward, being a relatively confining bed.

Table 2 Porosity and permeability of representative lithology rocks from Santang syncline no. 1001 borehole

Rock sample	Test orientation	Lithology	Burial depth (m)	He porosity (%)	Air permeability (md)
3	–	K3 (limestone)	132.35	0.3	0.0055
4	–	Siderite	136.71	0.3	0.0069
5	–	Sandy mudstone	149.41	5.3	0.0350
9	–	Mudstone	214.00	0.1	0.0060
12	–	K7 (limestone)	293.01	0.1	0.0040
13	–	Siltstone	299.01	2.3	0.0140
14	–	Mudstone	315.01	1.8	0.2220
15	–	Muddy siltstone	322.43	3.6	0.2230
16	–	Fine sandstone	345.50	1.3	0.0110
18	–	K12 (mudstone with siderite)	367.71	0.2	0.0057

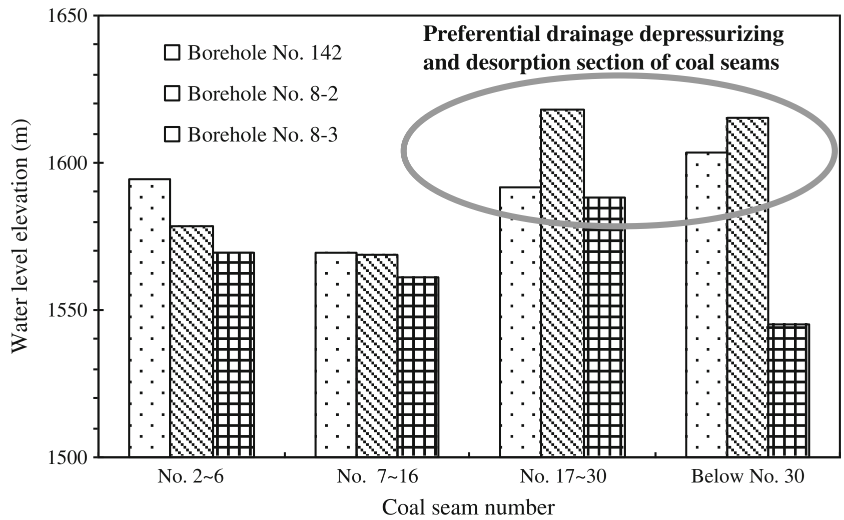

Fig. 6 Distribution of water level elevation in coal-bearing series from a single well in Zhuzang syncline

For this simple UMSCS, each different CBM-bearing system possesses different reservoir energy. The CBM exploitation is generally operated at a unified drilling pressure if this situation is not taken into consideration. Thus, CBM would not be effectively recovered because the exploitation pressure may be insufficient in some of the CBM-bearing systems. In other words, since each CBM-bearing system has different reservoir energy, desorption of methane will occur in a certain order and hence affects the CBM exploitation.

The complex UMSCS was developed in Shuigonghe syncline and Santang syncline confirmed by its CBM-bearing property, porosity, and permeability of coal rocks. As can be observed in Fig. 3, the CBM content in this system complicatedly changes with burial depth of coal seams. The sealability of capping rocks is favorable because they mainly consisted of the argillaceous rocks. In this area, each single coal seam may form a sub-CBM-bearing system that is small and superposed by each other. Meanwhile, the overlying and underlying rocks have the good sealability. The main characteristic in this kind of system is its higher CBM content with superpressure.

Adjacent CBM-bearing systems can be exploited alone or together. In this case, adjacent systems are close and they could be linked together by fracturing virtual reservoir (mainly key sandstone member) between them, making it possible for pressure-conducting and depressurizing uniformly. Compared with simple UMSCS, it needs more reservoir reconstructions to achieve large-scale discharging and mining in several adjacent systems because of large numbers of CBM-bearing subsystems formed from each coal seam. One effective way for CBM exploitation is to fracture the virtual reservoir instead of whole coal reservoir to depressurize uniformly. The so-called virtual reservoir is the critical layer mingled in the middle of adjacent coal seams. For example, the critical layer can be sandstone. By fracturing the virtual reservoir, two or multiple coal seams are enabled to reach an effective link. As for a simple UMSCS, a system corresponding to a third-order sequence includes many coal seams. Therefore, integral pressure conduction and uniform depressurization could be achieved easily by fracturing one of those seams.

Conclusions

This paper presents a comprehensive study on the geological characteristics of coal seam groups located in Zhina coalfield of Bide-Santang Basin in China for exploration and development of coalbed methane (CBM). A series of well tests have been conducted in given areas in Bide-Santang Basin, focusing on the investigation of the CBM-bearing property, porosity and permeability, and sealability of capping rocks and groundwater in coal seam. The results show that Bide-Santang Basin is typically a multi-coalbed CBM-rich reservoir with a good prospect for CBM exploration. It has particular geological features and a reservoir-forming model associated with CBM formation.

According to the drilling tests, the study areas consist of 14–42 coal seems within a burial depth of 1000 m. The thicknesses of those coal seams vary from 0.3 to 5.13 m estimated to be 23.03 m in total. Both the number and total thickness of coal seams increase from southeast to northwest. Due to the good sealability of capping rocks, those coal seams contain relatively higher CBM contents, varying from 12 m^3/t and up to 16.52 m^3/t on average. Changes in the mean CBM content and burial depth of the coal seams in the multi-coalbed reservoir are complicated with reduction of their horizons, forming different CBM-bearing systems under the given reservoir formation conditions. It has been identified that the reservoir formation for the multi-coalbed reservoir in this study is unique, which can be described by the unattached multiple superposed CBM-bearing system (UMSCS). The simple UMSCS consists of multiple coal seams, approximately associated with the third-order sequence, while the complex UMSCS usually includes multiple CBM-bearing subsystems formed by individual coal seams. It is suggested that, for simple UMSCS reservoirs, a sublevel exploitation method should be adopted in multi-coalbed CBM exploitation in order to minimize the effect caused by larger variation of the reservoir energy in different systems. For complex UMSCS reservoirs, one effective way for CBM exploitation is to fracture virtual reservoir to depressurize it uniformly and thus achieves large-scale discharging and mining in several adjacent CBM-bearing subsystems.

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