Geological factors on gas entrapment mechanism and prediction of coalbed methane of the no. 6 coal seam in the Jungar coalfield, northeast Ordos Basin, China

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Abstract: Low rank coal reservoirs of the no. 6 coal seam in the Jungar coalfield are characterised by low gas content but favourable porosity and permeability for recovery. The accumulation and enrichment of CBM is favoured by the presence of multiple (five seams) and thick (12.7–40.4 m) seams, adequate permeability (3.6–26 mD) and significant abundance of coal resource (5.44×10^{10} tonnes), but hindered by low observed gas content (0.01–1.5 m^3/t), which is shown to result from both shallow burial depth and high permeability of the seams. However, the sheer magnitude of the no. 6 coal resource offsets this shortcoming of low gas content and makes this a good prospect for exploration and exploitation. Conditions are most favourable in the southwest coalfield where a monoclinal structure and favourable hydrodynamic conditions have prevented gas escape. Areas of the no. 6 coal seam buried under the CH_4 weathering line (> 860 m), with larger coal thickness (> 10 m), and higher gas content (> 1.2 m^3/t) have the greatest potential for CBM enrichment. [Received: January 21, 2014; Accepted: July 27, 2014]

Keywords: low rank coal; coalbed methane; CBM; geological factors, entrapment mechanism; northeast Ordos Basin; China.

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1 Introduction

Low rank coals are coals for which maximum vitrinite reflectance ($R_{o,max}$) < 0.65 and include lignite and subbituminous coals. They have undergone early period coalification during which significant gas will have been generated. Coal reservoirs of low rank are usually characterised as low gas content, large gas resources and with perfect petrophysics (e.g., adequate porosity and permeability) (Li et al., 2008; Wang et al., 2009). Recent research conducted on several low rank coal reservoirs in China confirms the significant content of free and soluble gases (Cui et al., 2005). Half of the total coal reserves in China are identified as low rank coals (Tang and Lin, 2000; Zhao and Tian, 2008). These low rank coal reservoirs contain ~47% of the total coalbed methane (CBM) resource (Fu et al., 2006), which represents an important reserve of unconventional natural gas that can be recovered. The recovered CBM is virtually identical in quality to conventional natural gas for which exploration continues worldwide. The economic success of CBM exploitation in the USA, Canada, and Australia has prompted other countries to examine their own CBM potential. CBM from a low rank reservoir is typified by the Powder River Basin in the USA (Scott, 1993a) which has been successfully developed. This identifies the potential for such low rank reservoirs but points to the need for policy priorities in making this feasible. As high and medium rank plays are successively developed in China (Cai et al., 2011), attention has now switched to the feasibility of developing low rank coals.

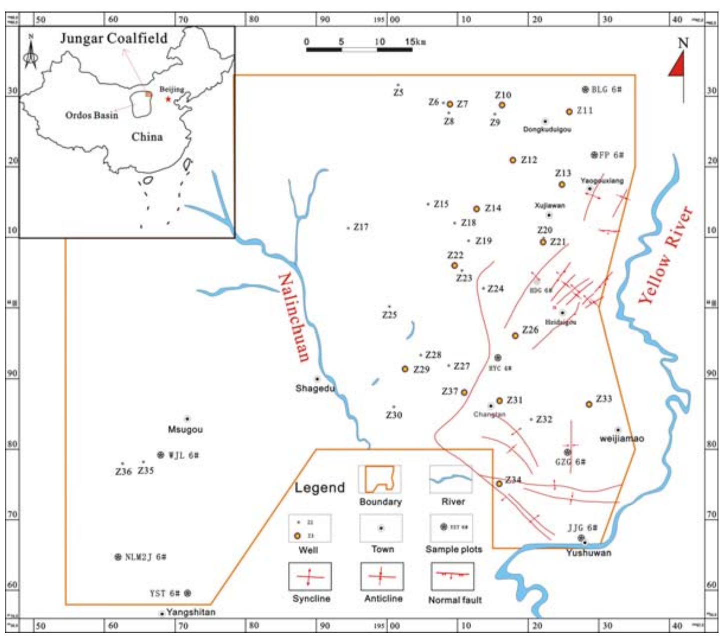
The Jungar coalfield in the northeast Ordos Basin is one such low rank resource – rich in Carboniferous-Permian subbituminous coals, especially no. 6 coal seam. The stratigraphy and structure of the basin is now known in some detail, both from surface and subsurface exploration (Dai et al., 2007). To date, however, no analytical investigation has been undertaken on the potential of exploiting CBM from this coalfield. Some details of the geological background and preliminary evaluations of the CBM reserves of the Ordos Basin have been conducted (Xu et al., 2012; Yao et al., 2009a). However, these data are insufficient to evaluate the CBM production potential and in selecting target areas for initial development. In this paper, we report data of the no. 6 coal seam from field and laboratory studies and integrate this to evaluate the potential as a CBM reservoir.

2 Geological setting

2.1 Tectonics

The Jungar coalfield is located at the northeast margin of the Ordos platform, north China (Dai et al., 2007). The general structure is uniclinal with undulations striking S-N and inclined to the west. The inclination angle of these strata is usually less than 10°. Strata in the northern part of the coalfield strike to the northwest and are inclined to the southwest, which is different from the southern part of the coalfield where the strike to the southwest and then west, inclining to the northwest or north (Duan, 1995). The entire structural outline is in the shape of an 'ear'. The structural patterns in the research area are simple and mainly formed in uplift and subsidence areas in the earth's crust, such as in folds and around normal faults (Figure 1). In the eastern margin of the coalfield, where the inclination of the strata is steeper, anticlines and synclines have developed with short axes and with few normal tensile faults in uniclinal structures. In the inner coalfield, the inclination of the strata is again shallower than that in the eastern margin of the basin where faults have seldom developed.

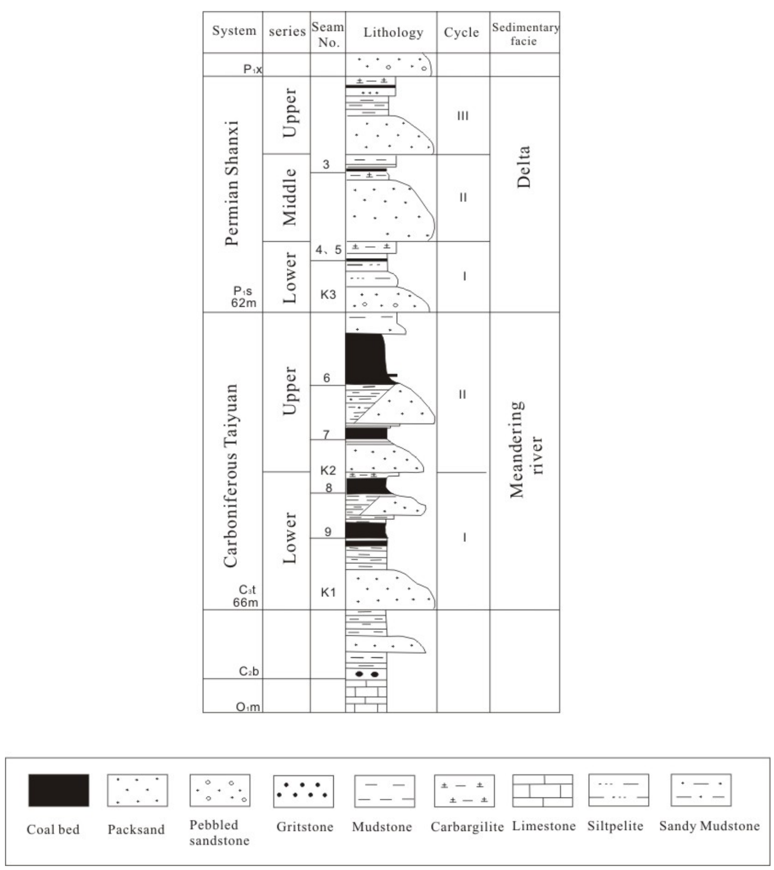
Figure 1 The geographical position and geologic structures in the Jungar coalfield (see online version for colours)



2.2 Sedimentary and coal-bearing strata

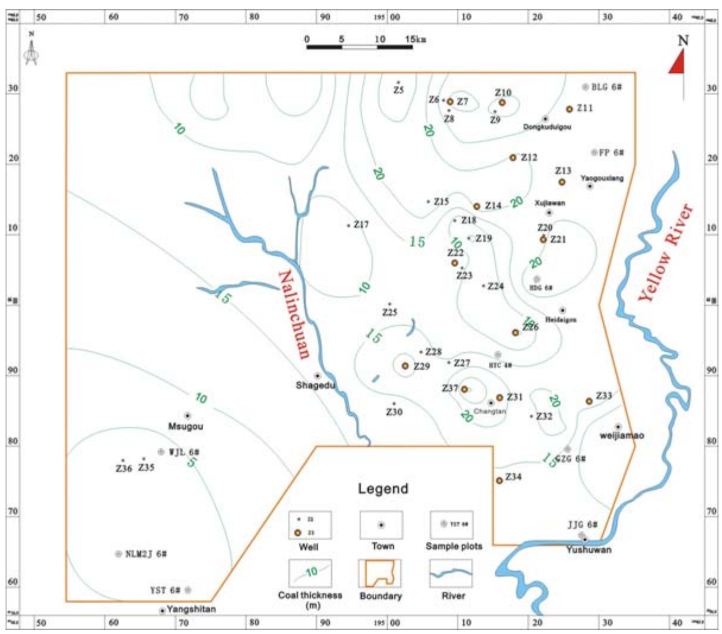
Sediments in the same sedimentary environment have similar lithologic characteristics – these characteristics change as the environment changes. The Taiyuan and Shanxi Formations have sediments of different periods and genetic types and are therefore lithologically different. The Taiyuan Formation deposited as a transitional facies between marine and terrestrial facies, while the Shanxi formation deposited as a terrestrial facies (Liu et al., 1991; Dai et al., 2006, 2008). The Taiyuan formation mainly deposited in three cycles as meandering river facies, while the Shanxi formation mainly deposited in two cycles as a deltaic facies (Figure 2). The sedimentary sequence in the Jungar is similar to that in Carboniferous-Permian areas in North China. Strata deposited in the Jungar include Cambrian and Ordovician Formations, Carboniferous Pennsylvanian Benxi (C_2b) and Taiyuan (C_3t) Formations, Permian Shanxi (P_1s), Xiashihezi (P_1x), Shangshihezi (P_2s) and Shiqianfeng (P_2sh) Formations, Triassic and Cretaceous Formations, and Neogene deposits. The sequence-contact relationship between the Ordovician and Carboniferous is a parallel unconformity with the Benxi formation laying on the limestone of the Ordovician Majiagou (O_1m) formation.

Figure 2 Lithology combinations and depositional cycles in the Jungar coalfield



The C_2b formation is mainly composed of mudstone with some sandstone, with the thickness of 5–50 m (with an average of 25 m). Above the C_2b formation the C_3t and P_1s formations were deposited continuously – this is the host for the coal seams of the Jungar coalfield (Figure 2). The most significant coal-bearing stratum in the Jungar coalfield is the C_3t formation, in which the nos. 6–10 coal seams are present with a total thickness of 12.7–40.4 m. The C_3t formation, with the thickness ranging from 44.9 to 101.6 m (65.9 m on average), is mainly composed of gritstone, sandy mudstone and coal seams. The K1 sandstone at the bottom of the lower C_3t is the roof layer of the no. 9 coal seam. The K2 sandstone is usually present between the nos. 6 and 9 coal seams. The no. 6 coal seam, located at the uppermost C_3t formation, has a thickness between 2.7 and 50 m (30 m on average) (Dai et al., 2006) (Figure 3), and represents the main mining and research target. The nos. 3, 4 and 5 coal seams, with a total thickness of 0–7.6 m, exist in the P_1s formation that is composed of gritstone, mudstone and coal seams, which thickness ranges from 29.5 to 118.7 m (62 m on average). The K3 sandstone is the roof of the no. 6 coal seam. The contact relationship between P_1s and P_1x is a parallel unconformity.

Figure 3 Thickness contour map of the no. 6 coal reservoir in the Jungar coalfield (see online version for colours)



3 Samples and methods

A total of 13 fresh block coal samples (25 × 25 × 25 cm^3) were obtained from nine mines in the no. 6 coal seam of the Jungar coalfield (see Figure 1 for sampling locations). These samples were collected following the Chinese Standard Method GB/T 19222-2003 and were carefully packed and directly delivered to the laboratories for experiments.

Helium (true) porosity and air permeability were determined using routine core analysis methods (Chinese Oil and Gas Industry Standard SY/T 5336-1996). For each block sample, a horizontal cylindrical core of 2.5 cm in diameter (length > 2.5 cm) was drilled parallel to the bedding plane. Porosity was measured using the helium expansion method and the absolute permeability was determined using a bubble flowmeter by flowing air through the core sample until the flow-rate became steady (Cai et al., 2011). The permeability to gas is commonly calculated with the following equation,

$$k_g = \frac{2 p_o q_g \mu_g L}{A\left(p_1^2 - p_2^2\right)} \tag{1}$$

where k_g is the coal permeability to gas; p_o is the standard atmospheric pressure; q_g is the gas flow rate at standard atmospheric pressure; p_1 and p_2 are the upstream and downstream gas pressures, respectively; μ_g is the coefficient of kinetic viscosity for the gas at the mean pressure $((p_1 + p_2) / 2)$ at the experimental temperature; L is length of the sample; and A is the cross-sectional area of the core.

Vitrinite reflectance ($R_{o,m}$), coal composition and micro-fracture analyses were carried out on moderate-size blocks (~10 × 10 × 10 cm^3). Before these analyses, all the blocks were sectioned and polished to be a surface 3 × 3 cm^2 based on the Chinese standard GB/T 6948-1998. These analyses were performed on a Laborlxe 12 POL microscope with an MPS 60 photo system (Leitz, Germany). Proximate analysis of the coals and methane adsorption isotherm experiments were conducted following the Chinese standards GB/T 212-2001 and GB/T 19560-2004. Based on the data from these experiments the CBM reservoir characteristics including pore-fracture system, coal petrology and adsorption capacity will be discussed.

Thickness, burial depth and gas content of no. 6 coal reservoir were analysed and drawn in contour maps (Figures 3, 6, 8), based on the data from more than 30 wells through the whole coalfield. CBM gas-in-pace (GIP) resources were calculated from GIS representations of the coalfield (MapInfo Professional 8.5), based on the usual volumetric method (Boyer and Bai, 1998; Drobniak et al., 2004; Langenberg et al., 2006; Liu et al., 2009; Cai et al., 2011).

4 Results and discussions

4.1 Reservoir characteristics

Coal metamorphism in the Jungar coalfield is low and comprises mostly high volatile bituminous coal. Former studies indicate that the optimum coal rank for CBM production is 1.2 to 2.5% $R_{o,m}$ (Creedy, 1988; Flores, 1998), because less mature coals (< 1.2% $R_{o,m}$) generally have lower gas contents and the more mature coals (> 2.5% $R_{o,m}$) have lower permeability. The maximum vitrinite reflectance ($R_{o,max}$) of the coals from the Jungar coalfield ranges from 0.44% to 0.66% (Table 1), with an average of 0.57%. Based on the experimental data, the permeability has a certain relationship with the macerals and ash yield (Cai et al., 2011). In general, the permeability of the coals in the Jungar coalfield is high (normally higher than 5 mD) due to the low coal rank. But for some slightly compressed reservoirs, the permeability can be as low as 1 mD. Permeability is one of key parameters that affect gas production and preservation. High permeability is favourable for gas production but unfavourable for gas preservation. However, several other parameters, such as reservoir pressure and temperature, need to be considered for estimating gas production and preservation.

Table 1 Coal petrographic analysis results in the Jungar Coalfield, NOB, China

Sample no.	*Coal mine*	*Coal seam*	*Coal lithotype*	*Maceral composition (%)*				$R_{o,m}$ *(%)*
				V	*I*	*L*	*M*	
BLG6-1	Buliangou	6	Semi-bright	69.9	18.3	11.6	0.2	0.61
FP6-1	Fupin	6	Semi-bright	63.4	28.8	7.5	0.3	0.59
HDG6-1	Heidaigou	6	Bright	12.4	78.8	8.8	-	0.59
HDG6-2	Heidaigou	6	Semi-bright	72.3	11	16.2	0.5	0.61
HDG6-3	Heidaigou	6	Bright	11	75.8	13.2	-	0.63
GZG6-1	Guanzigou	6	Bright	57.4	25.5	16.4	0.7	0.61
GZG6-2	Guanzigou	6	Semi-bright	60.3	20.3	18.2	1.2	0.6
JJG6-1	Jiaojiugou	6	Semi-bright	77.6	15	5	2.4	0.66
WJL6-1	Wujialiang	6	Bright	65.7	29.6	2.2	2.5	0.46
WJL6-2	Wujialiang	6	Semi-bright	19.4	74.9	5.5	0.2	0.44
WJL6-3	Wujialiang	6	Bright	64.7	30.5	4.5	0.3	0.45
NLM2J	Nalinmiao	6	Bright	36.4	58.8	3.5	1.3	0.58
YST6-1	Yangshita	6	Semi-bright	45.2	49.9	4.6	0.3	0.56

Notes: V = vitrinite; I = inertinite; L=liptinite; M = minerals;
$R_{o,m}$ = mean vitrinite reflectance.

Macerals of no. 6 coal in the Jungar coalfield are made up of vitrinite, inertinite, liptinite and minerals, but are generally dominated by more than 50% vitrinite and less than 40% inertinite and followed by less than 10% liptinite and less than 1% minerals (Table 1). In comparison with other late Paleozoic coalfields in the Ordos Basin, the no. 6 coal in the Jungar coalfield has the highest inertinite and liptinite content, and the lowest vitrinite (Dai et al., 2006). Coal composition has a marked effect on gas adsorption capacity. Thermal simulation and adsorption tests of coals indicate that: liptinite has the highest hydrocarbon generation capacity (Crosdale et al., 2008; Pone et al., 2009), but makes little contribution to CBM content due to its low (~10%) content. Vitrinite is the dominant composition and its hydrocarbon generation capacity and adsorption capacity are both higher than that of inertinite. Although the porosity of inertinite is clearly higher than that of vitrinite, the moisture content varies with coal rank and composition, and methane adsorption capacity also changes with these variables – correspondingly it is difficult to isolate the effects of moisture content on gas content (Bustin and Clarkson, 1998; Cai et al., 2013a). The minerals and other compositions in the coal have various types of genesis and behaviour during coalification and metamorphic progression. Their occurrence is related to differences in the regional, depositional and paleoenvironmental conditions of coal deposits (Vassilev et al., 1997).

Based on the pore classification of Hodot (1966), the pore system of coals in the Jungar coalfield is dominated by micropores (< 10 nm) and transitional pores (10–100 nm) and secondary mesopores (100–1,000 nm) but with few macropores

(> 1,000 nm) (Figure 4). The percentages of micropores and transitional pores are in the range of 47.7%–87.6%, with an average of 69.9%. Research on coal adsorption (Liu et al., 2009) indicates that micropores form the adsorption space; transitional pores form the capillary condensation and diffusion space; mesopores and macropores form the seepage and laminar flow space. Micropores may affect the gas-storage capacity of coals and transitional pores may affect the gas-diffusion capacity through the pore structure system, therefore they could play an important role in gas recovery from coal seams (Yao et al., 2009b). The relationship between adsorption capacity and micropore content shows that a large number of micropores may be favourable for gas adsorption in the coal reservoir (Crosdale et al., 1998). For coals with high macroporosity, they generally have a positive effect on flow capability (Cai et al., 2013b). Coal microfractures were divided into four types by performance (Yao et al., 2006): type A (width (W) > 5 μm, length (L) > 10 mm) is the largest with long reach and good continuity. Type B (W ≥ 5 μm, 10 mm ≥ L > 1 mm) and C (W < 5 μm, 1 mm ≥ L > 300 μm) are intermediate, usually appearing as branch. Type D (W < 5 μm, L < 300 μm) is the smallest, usually connecting with the other three types as branch (Li et al., 2011) and has the poorest directivity and connectivity. Fabric analysis indicates that types C and D comprise the majority of microfractures. Fracture density for type B is relatively low, and type A is barely developed (Table 2), which means that the permeability should be favourable for gas migration.

Table 2 Proximate analysis and fractures of coal in the Jungar coalfield, NOB, China

Sample no.	*Type A*	*Type B*	*Type C*	*Type D*	*Total*	*Connectivity*	*Cad (%)*	*Had (%)*	*Mad (%)*	*Aad (%)*	*C/H*
BLG6-1	2	4	18	44	68	Poor	68.06	4.10	8.63	5.38	16.60
FP6-1	2	5	24	36	67	Poor	66.24	3.84	8.88	7.95	17.25
HDG6-1	1	3	28	24	56	Very good	67.30	3.50	6.38	11.30	19.23
HDG6-2	1	4	22	25	52	Very good	61.75	3.94	8.42	13.63	15.67
HDG6-3	1	5	24	24	54	Very good	71.78	3.60	5.52	7.94	19.94
GZG6-1	0	3	15	22	40	Good	66.36	3.60	4.35	12.56	18.43
GZG6-2	0	1	9	23	33	Good	65.80	3.83	5.18	13.25	17.18
JJG6-1	0	0	21	48	69	Good	58.53	3.98	4.78	21.96	14.71
WJL6-1	0	3	23	124	150	Good	63.26	3.79	12.10	7.90	16.69
WJL6-2	0	3	31	115	149	Good	67.87	3.00	11.88	4.78	22.62
WJL6-3	0	4	46	169	219	Good	67.38	3.57	11.39	3.77	18.87
NLM2J	0	2	14	45	61	Good	70.40	3.93	8.84	4.15	17.91
YST6-1	1	3	32	55	91	Poor	72.24	4.38	8.70	3.33	16.49

Notes: Microfracture frequency means the numbers of microfractures at the scale of 3 × 3 cm^2.

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.

Cad (%) = carbon content (as received basis), Had (%) = hydrogen content (as received basis), Mad(%) = moisture content (as received basis), Aad(%) = ash yield (as received basis).

Figure 4 Pore size distribution of the no. 6 coal samples in the Jungar coalfield (see online version for colours)

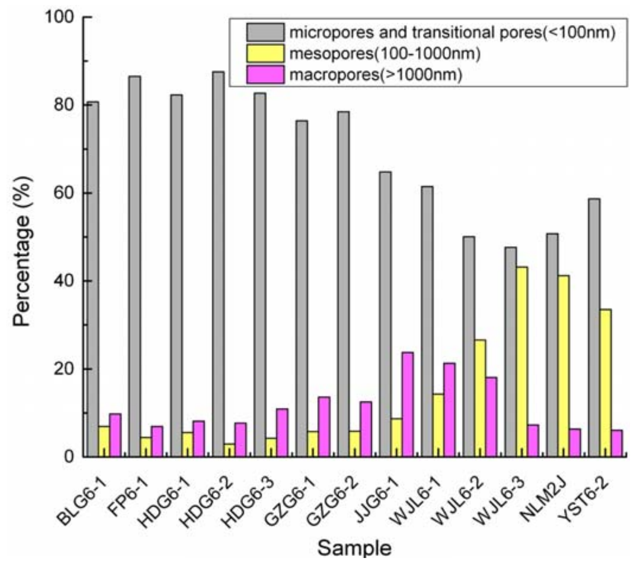
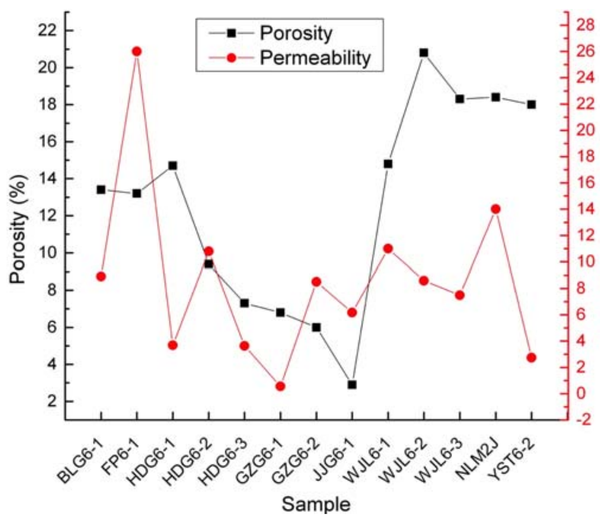


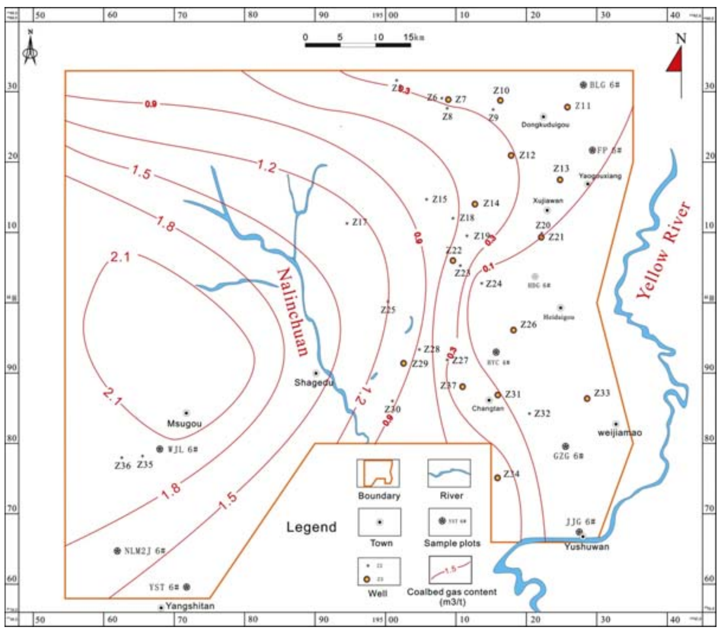
Figure 5 Porosity and permeability of the no. 6 coal samples in the Jungar coalfield (see online version for colours)



The effective porosity of the coal reservoir ranges from 2.9%–20.8% (Figure 5), with an average of 16.2%. Coals have a specific surface area in range of 2.6–50.8 m^2/g, with an average of 21.9 m^2/g, indicating a significant capacity for CBM adsorption if the other reservoir conditions are suitable. The permeability of the coal reservoir ranges from

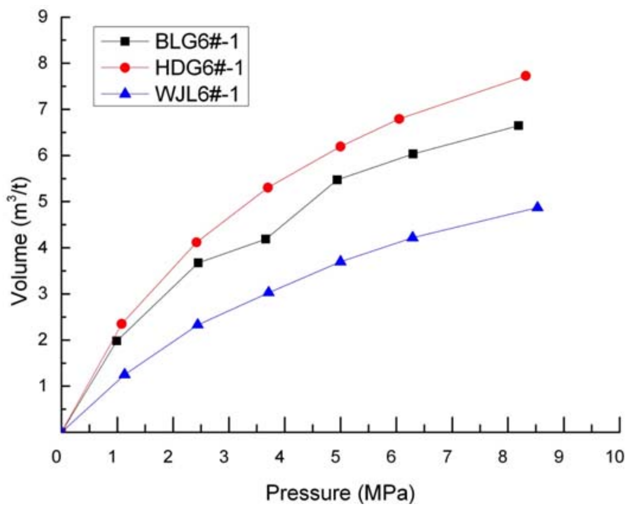
3.6–26 mD (Figure 5), with an average of 8.5 mD. There is a positive correlation between the effective porosity and the permeability. These experimental results indicate that the porosity and permeability of the coal reservoir in the Jungar coalfield could be favourable for gas adsorption and recovery, but may be unfavourable for CBM preservation. Although there is enough pore volume for CBM adsorption, the gas contents are relatively low due to the high permeability of the coals (Figure 6). In addition, the matrix shrinkage effect induced by desorption would result in high permeability during the exploitation of low rank CBM reservoirs, which is favourable for CBM recovery.

Figure 6 Gas content contour map of the no. 6 coal reservoir in the Jungar coalfield (see online version for colours)



Adsorption isotherms derived at 30°C indicate that the CH_4 adsorption capacity (i.e., Langmuir volume) of coals in the Jungar coalfield ranges from 8.74 to 11.82 cm^3/g (Figure 7), with an average of 10.24 cm^3/g (air dried basis). Factors, such as mineral matter, moisture, and maceral content are all subordinate controls on adsorption capacity (Carroll and Pashin, 2003; Pashin et al., 2009). The correlation between volatile matter content and Langmuir volume is emphasised herein, and even stronger correlations can be derived by plotting adsorption capacity at specific pressures against rank parameters (e.g., Carroll and Pashin, 2003; Pashin et al., 2009). Rank has long been recognised to correlate strongly with adsorption capacity (Kim, 1977; Carroll and Pashin, 2003). In the Jungar coalfields the Langmuir pressure averages 4.41 to 6.81 MPa, with an average of 5.23 MPa, indicating that the shape of the isotherm curves cannot vary significantly.

Figure 7 Isotherm adsorption capacity of the no. 6 coal samples (air dried basis) in the Jungar coalfield (see online version for colours)

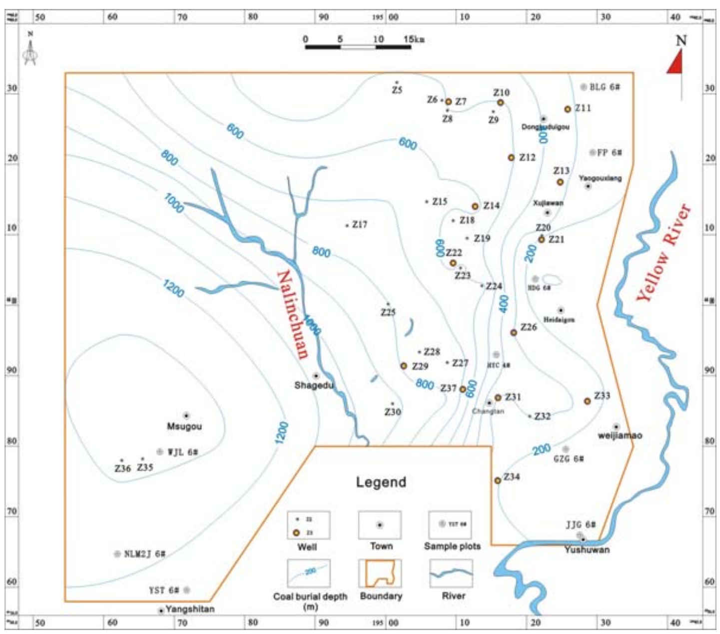


Gas adsorption capacity is chiefly determined by coal composition, coal metamorphism and reservoir physical properties (Mastalerz et al., 2004; Yao et al., 2008). The gas content and gas composition in the no. 6 coal seam were measured throughout the eastern Jungar coalfield. Measurements show that the gas composition is dominated by N_2, with secondary CO_2 and some CH_4. Only a few sample plots locate in N_2-CH_4 space with most embedded within CO_2-N_2 space. The gas content on a dry basis is usually lower than 1 m^3/t. Based on sample analysis from the eastern Jungar coalfield, where the coal seams were buried shallow and open faults developed well that gas would easily escape, it indicates that the gas content is relatively low, and the permeability is high throughout the eastern Jungar coalfield. Thus neither gas content nor permeability has a good correlation with depth, even though the burial depth varies from 180–450 m. Although the gas content in the western area is also low it increases as the coal seam burial depth increases. Gas content could potentially reach 1.5–2.5 m^3/t as burial depth increases in the west, with the even deeper burial depth in the western area offering even better prospectives for CBM preservation and recovery (Figure 6).

4.2 Geological factors on gas entrapment mechanism

Due to complex geological conditions in this area, we have to consider several factors to evaluate the condition for gas entrapment and then estimate CBM resources. Geological factors of shallow burial depth and poor roof sealing have restrained the potential for CBM development in the shallow eastern Jungar coalfield. As in the main mining area, burial depth of the coal seam in the eastern coalfield is commonly shallow, in the range of 180–450 m (Figure 8) – some mines outcrop to the ground surface, forming strip mines. Shallow burial depth results in low reservoir pressure and easy release from the surface of the coal micropores or of free gas from the macropores/fractures. Thus, shallow burial depth results in the escape of CBM and is considered as one of the main factors influencing the low CBM content. As discussed above, no. 6 coal seam is buried progressively deeper from east to west in the coalfield, reaching as deep as 1,200 m. Laboratory pyrolysis of lignite suggests that significant generation of gas (9.4 cm^3/g) occurs at thermal maturity levels of 1.0% R_o (Tang et al., 1991). Therefore, it is possible that coal seams in the deeply-buried western extent are rich in CBM. Based on a requirement for 70% CH_4 and 1.0–1.5 m^3/t gas content, a burial depth of 860 m is calculated as the bottom border line of CH_4 weathering zone, respecting the local conditions (Liu et al., 2007). Therefore, areas of the coal seam buried under the CH_4 weathering line should have a potential for CBM enrichment (Figure 9).

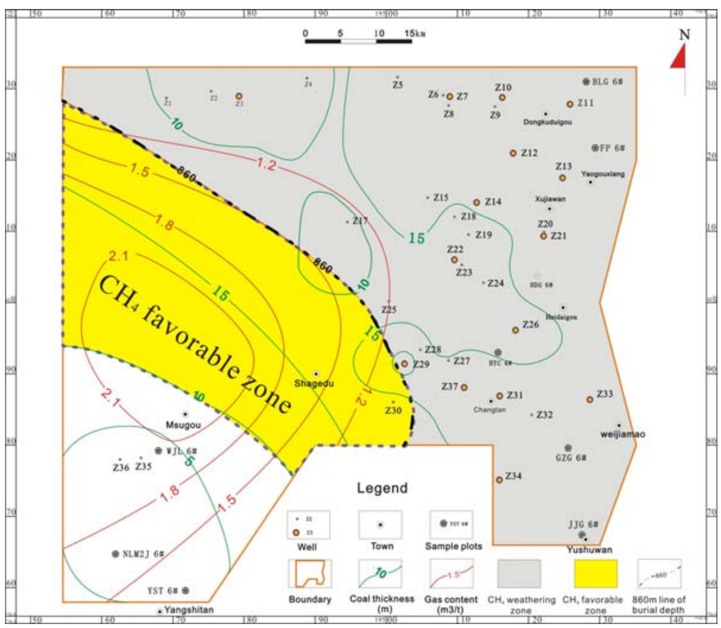
Figure 8 Burial depth contour map of the no. 6 coal reservoir in the Jungar coalfield (see online version for colours)



The lithologic characteristic of the cap rock determines the sealing capability for CBM. The Taiyuan Formation deposited as a transitional facies between marine and terrestrial facies, which is composed of dark gray mudstone, fine- to medium-grained sandstone, and gray-white coarse-grained sandstone. This has a large pore-fracture system and high permeability that is unable to seal the coal seam and to trap CBM. However, mudstone roofs exist in this research area could locally improve sealing capability. These local areas may be good spot targets for CBM recovery (Song et al., 2007).

Hydrodynamic conditions are usually considered to be a key factor in the formation of CBM reservoirs, especially in low rank coals. Meteoric water flows downward along major fractures and migrates westward, down gradient, in highly fractured sandstones and coals of the no. 6 coal seam. The Jungar coalfield is located in an arid region, with little precipitation. The recharge area of the aquifer within the coal bed is too small to fill the coal seam and to therefore trap the CBM – due principally to the undulation of the bed. However, the westward-flowing hydrodynamic system still affects the gas content in two ways. First, as water from meteoric recharge flows through the permeable coals in the northeastern area, the advancing front flushes gas ahead of the advancing ground water flow to the surface (Scott, 1993b; Scott et al., 1991, 1994). Since the coals are exposed at the surface, the reservoir pressure has been reduced and gas has desorbed from the coals and has been swept out and lost to the atmosphere. This mechanism may also explain the very low gas content in the northeastern portion of the trend. However, hydrodynamics also has an impact on the gas content in the deep southeastern part of the Jungar coalfield. Moreover, the general uniclinal structure should be favourable for the gas accumulation and storage in stagnant areas due to the water pressure and also as a result of occlusion of pores.

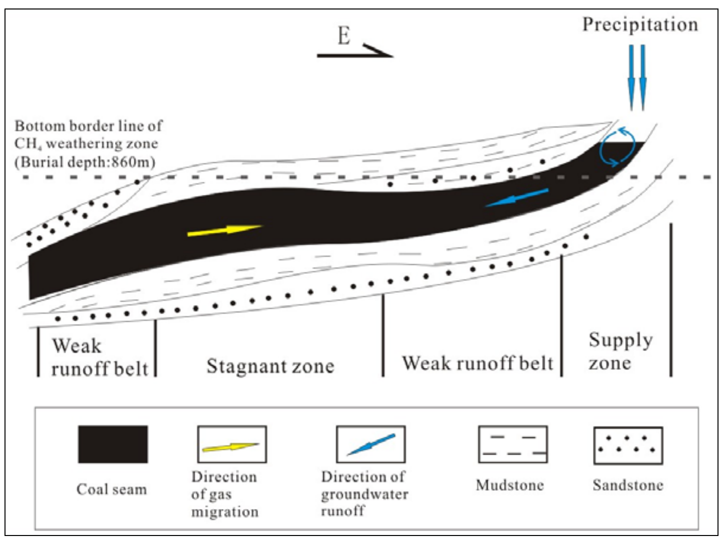
Figure 9 CBM weathering zone and favourable zone of the no. 6 coal reservoir in the Jungar coalfield (see online version for colours)



In addition, due to the small fraction of the original gas generation in the low rank coals a significant process for gas enrichment of the CBM reservoir is the secondary biogenic gas generation. In favourable low rank CBM reservoir, water supply usually from precipitation may transport methanogens into the coal seams that may then convert native coals into methane (Liu et al., 2006; Papendick et al., 2011). From the previous results, it is estimated that about 40 scf and 60 scf, of methane annually could be generated per ton of bituminous coal, and lignite, respectively, using no nutrient amendments. With addition of a 50% nutrient solution, potential methane generation could be increased to about 26,700 scf and 14,670 scf per ton of the tested bituminous coal and lignite, respectively (Opara et al., 2012). Therefore significant quantities of biogenic gas could be generated by methanogens in the low salinity formation waters as presented in the Jungar coalfield.

The structures in this area are simple with only a few folds and faults developing at small scale and stretching in a short distance. These faults are usually normal faults formed in extension and with ready transmission of gas to the surface and out of the reservoir (Cai et al., 2011). In addition, large open structures rarely develop in this area, without which CBM cannot be trapped into structural gas pools. The preservation process for CBM of these low rank coals has usually undergone one episode of subsidence and an adjustment (Li et al., 2006). Therefore, tectonic condition generated during this process may be slightly unfavourable for the preservation of CBM. At the northeast margin of the Ordos Basin, the coal-bearing strata of the Jungar coalfield have not been buried at great depth nor have been subject to coalification at high temperature and high pressure. Thus, these coals have not metamorphosed at high temperature/pressure and have generated little thermogenic gas during their limited thermal process. Thus the only possible significant source of gas to make a productive field, therefore, is from biogenic gas. However, more evidence is required to support this contention, although the uniclinal structure should be favourable for the accumulation and storage of the gas, if generated. Similarly, the favourable hydrodynamic setting should prevent gases from dissipating from the coal seam as the strata began to be uplifted during the tectonic evolution of the basin, which is named uniclinal water-pressured CBM reservoir (Figure 10).

Figure 10 Uniclinal water-pressured CBM reservoir in the Jungar coalfield (see online version for colours)



4.3 *CBM favourable zone optimisation and resource evaluation*

As discussed above, shallow burial depth and poor roof sealing have restrained the potential for CBM development in the shallow eastern Jungar coalfield. However, no. 6 coal seam is buried progressively deeper from east to west in the coalfield, reaching as deep as 1,200 m. Although there was no evidence from CBM wells in the west, the coal seams were deeply buried, and may have good gas preservation conditions. Further data especially from well test are needed to investigate the potential for gas production in the west. Based on the acquired data, the no. 6 coal seam in the Jungar coalfield buried under the CH_4 weathering line (> 860 m), with larger coal thickness (> 10m), and higher gas content (> 1.2 m^3/t), should have a potential for CBM enrichment (Figure 9). Considering the large area and thickness of the coal seam, CBM GIP resources are calculated based on the usual volumetric method (Boyer and Bai, 1998; Drobniak et al., 2004; Langenberg et al., 2006; Liu et al., 2009; Cai et al., 2011). This method can briefly be summarised as

$$Q = A \times H \times D \times C \tag{2}$$

where A is surface area of the favourable zone (km^2); H represents net accumulative coal thickness (m); D is coal density (g/cm^3) and here is set at a measured magnitude of 1.14 g/cm^3; C is the gas content recovered from well tests (m^3/t); and Q is the GIP by the volumetric resource estimation method (m^3).

According to equation (2), the GIP in the Jungar coalfield is calculated from GIS representations of the coalfield (MapInfo Professional 8.5). The total CBM resource preserved in the no. 6 coal seam of the Jungar coalfield is estimated to be 3.49×10^{10} m^3 with burial depth deeper than the baseline of CH4 weathering. The CBM resource concentration (GIP per square kilometre) is 0.26×10^8 m^3/km^2. Gas resource concentration decreases from the deep southwestern coal district to the shallow outcrops of the coals in the Jungar coalfield. Thus, this resource is locally favourable for CBM development with enhanced CBM technologies including biotechnology (Opara et al., 2012) and heat treatment (Cai et al., 2013a).

5 Conclusions

Based on the data acquired from laboratory and coalfields, this study finished a preliminary evaluation of gas content distribution and predicted the potential CBM enrichment area. The no. 6 coal seam in the Jungar coalfield has the potential to be economically viable for CBM production. The maximum vitrinite reflectance ($R_{o,max}$) of the coals ranges from 0.44% to 0.66%, with an average of 0.57%. Based on experimental data, the permeability correlates with macerals and ash yield. In general, the permeability of the coals is high (normally higher than 5 mD) due to the low coal rank. Petrophysical results of the CBM reservoir in the Jungar coalfield are systematically presented and indicate that the porosity and permeability could be favourable for gas generation and adsorption but may be unfavourable for CBM preservation and hence recovery – except in identifiable sweet-spots. Although there is low gas content overall, it still has vast CBM resource potential due to its large coal thickness and significant areal extent. For such a marginal field, widespread development may be possible through enhanced CBM recovery through use of biotechnology and heat treatment. In addition, the presence of uniclinal structures may be favourable for CBM preservation in the deep southwestern coal district due to the effects of water pressure and the occlusion of pore escape conduits.

The GIP estimate of the total CBM resource preserved in the no. 6 coal seam deeper than 860 m is 3.49×10^{10} m^3 with a CBM resource concentration of 0.26×10^8 m^3/km^2. Gas resource concentration decreases from the deep southwestern coal district to the shallow outcrops of the coals on the periphery of the coalfield. Areas of the coal seam buried under the CH_4 weathering line (> 860 m), with larger coal thickness (> 10 m), and higher gas content (> 1.2 m^3/t), should have a potential for CBM enrichment.

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