Variable gas content, saturation, and accumulation characteristics of Weibei coalbed methane pilot-production field in the southeastern Ordos Basin, China

Yanbin Yao, Dameng Liu, and Yongkai Qiu

ABSTRACT

Using diverse geologic and geophysical data from recent exploration and development, and experimental results of analysis of gas content, gas capacity, and gas composition, this article discusses how geologic, structural, and hydrological factors determine the heterogeneous distribution of gas in the Weibei coalbed methane (CBM) field.

The coal rank of the Pennsylvanian no. 5 coal seam is mainly low-volatile bituminous and semianthracite. The total gas content is 2.69 to 16.15 m³/t (95.00–570.33 scf/t), and gas saturation is 26.0% to 93.2%. Burial coalification followed by tectonically driven hydrothermal activity controls not only thermal maturity, but also the quality and quantity of thermogenic gas generated from the coal.

Gas composition indicates that the CBM is dry and of dominantly thermogenic origin. The thermogenic gases have been altered by fractionation that may be related to subsurface water movement in the southern part of the study area.

Three gas accumulation models are identified: (1) gas diffusion and long-distance migration of thermogenic gases to no-flow boundaries for sorption and minor conventional trapping, (2) hydrodynamic trapping of gas in structural lows, and (3) gas loss by hydrodynamic flushing. The first two models are applicable for the formation of two CBM enrichment areas in blocks B3 and B4, whereas the last model explains extremely...
low gas content and gas saturation in block B5. The variable
gas content, saturation, and accumulation characteristics are
mainly controlled by these gas accumulation models.

INTRODUCTION

Lateral variations in the gas content and gas saturation of coal-
bed methane (CBM) reservoirs are common and important
for the exploration and production of CBM. Coalbed methane
reservoir heterogeneities are affected by sedimentologic,
structural, petrologic, geothermal, and hydrogeologic variables
from the molecular to the regional scale, for example, in the
Black Warrior Basin (Pashin, 1998, 2007, 2010; Pashin and
Groshong, 1998), the San Juan Basin, the Powder River Basin
(Ayers, 2002; Ambrose and Ayers, 2007), and the Illinois Basin
(Strapoć et al., 2008) in the United States; the upper Silesian
Basin in Poland (Kedzior, 2009); the Bowen Basin in Australia
(Kinnon et al., 2010); the Donets Basin in Russia (Sachsenhofer
et al., 2012); and the Qinshui Basin in north China (Cai et al.,
2011; Tao et al., 2012). Scott (2002) reviewed the many hy-
drogeologic factors affecting gas content distribution in several
key CBM basins in the United States. However, investigations
of the lateral variation of gas content and gas saturation and
its geologic controls have not been previously reported for the
southeastern Ordos Basin.

The Ordos Basin is one of the oldest and the most impor-
tant fossil-fuel energy provinces in west-central China and con-
tains large reserves of coal, oil, and natural gas, including CBM.
Coalbed methane gas-in-place resources in this basin are ap-
proximately 9.62 to 10.7 trillion m$^3$ (339.73–377.87 trillion ft$^3$),
accounting for approximately one-fourth to one-third of the
known CBM resources in China. Many studies have been con-
ducted on the tectonic and sedimentary evolution, source rock
distribution, gas origin, reservoir-caprock relationships, and trap
formation in the Ordos Basin (e.g., Ren et al., 1994; Xiao et al.,
2005; Yang et al., 2005; Hanson et al., 2007; Yuan et al., 2007).
Wang (1996) investigated the coal accumulation and resource
characteristics of the Ordos Basin. No interest has been ob-
served in the activity related to CBM in the eastern margin of
the Ordos Basin until the past decade (e.g., Jenkins et al., 1999;
Su et al., 2003). Recent CBM exploration and exploitation by
PetroChina Coalbed Methane Company, Ltd. (PetroChina
CBM) has proven that gas content and other reservoir char-
acteristics are highly variable at the regional and local scales and
that this variability has a strong effect on gas production. The
determination of the origin of the gas and the understanding of the geologic, structural, and hydrogeological factors that control gas content and gas saturation are, therefore, critical in developing an effective exploration program as well as in choosing a successful exploration strategy.

Until now, only a few reports have existed on the geology of CBM reservoirs in the southeastern Ordos Basin. Tang et al. (2012) investigated the composition of microbial communities from a Hancheng coal but did not discuss the origin of CBM. Yao et al. (2009) performed a preliminary evaluation of CBM production potential and its geologic controls at the coalfield scale and forecasted a prospective CBM target area, that is, the Weibei CBM pilot-production field (Weibei CBM field). To the authors' knowledge, no systematic research has been reported so far concerning gas

**Figure 1.** Map of the study area, showing the exploration wells and the geophysical seismic lines. CBM = coalbed methane.
origin, gas properties, and the reservoir characteristics of the Weibei CBM field.

The Weibei CBM field lies in the northeastern part of the Weibei coalfield in the southeastern Ordos Basin (Yao et al., 2009) and covers an area of approximately 1530 km² (590.7 mi²) (Figure 1). The exploration and development of CBM in this area has grown significantly for the past 5 yr. By October 30, 2012, a total of 1045 wells had been drilled, and a CBM production field had been established. The commercial CBM production capacity is approximately 0.7 billion m³ (24.7 billion ft³) per yr. The Weibei CBM field has become the second most productive CBM area in China, behind the southeastern Qinshui Basin.

This article begins with an analysis of structural domains in CBM reservoirs in the Weibei CBM field and continues with a discussion of how geologic, structural, and hydrological factors affect gas generation, gas content, and gas saturation. This article concludes with a discussion of three gas accumulation models and their implications for CBM exploration and production.

**GEOLOGIC SETTING**

The Ordos Basin is situated in the western part of the North China block. It can be subdivided into six tectonic domains, including the western thrust-fault zone, the Tianhuan depression, the Shaanbei slope, the Jinxí fault-fold zone, and the Yimeng and Weibei uplifts (Wang, 1996; Xiao et al., 2005; Yuan et al., 2007). The Weibei CBM field is located in the northeastern part of the Weibei uplift.

The evolution of the Ordos Basin can be subdivided into four major stages: (1) early Paleozoic marine platform, (2) late Paleozoic marine and terrestrial alternation, (3) Mesozoic foreland basin, and (4) Cenozoic basin-margin faulting and subsidence (Xiao et al., 2005). In the lower Paleozoic section, a significant regional unconformity overlies the Ordovician section, and no Silurian or Devonian strata have been preserved (Hanson et al., 2007). Carboniferous strata consist mainly of thin, shallow-marine limestone beds and thick, fluvial-deltaic siliciclastic deposits that are overlain by fluvial Permian strata (Hanson et al., 2007). The Upper Permian–Middle Triassic strata consist mainly of fluvial, deltaic, and shallow-lacustrine clastic red beds that were deposited in an arid climate (Yang et al., 2005). At the end of the Middle Triassic, the collision between the North China and South China blocks resulted in the widespread deposition of continental strata (Yuan et al., 2007). The Upper Triassic–Middle Jurassic formations are made up of fluvial-lacustrine siliciclastic deposits. Lower Cretaceous siliciclastic red beds constitute the youngest sedimentary sequence preserved in the Ordos Basin (Yuan et al., 2007).

In the Weibei CBM field, Carboniferous–Permain coal-bearing strata consist of, in ascending order, the Pennsylvanian Benxi and Taiyuan Formations and the Lower Permian Shanxi and lower Shihezi Formations (Yao et al., 2009). The overlying strata include the Middle–Upper Permian and Lower–Middle Triassic strata. As a result of basin uplift and erosion, in some places, only the Middle Permian strata have been preserved. All strata from the Upper Triassic to Neogene were apparently eroded from the uplift. The principal coal seam for targeting CBM production is the no. 5 coal seam in the bottom of the Taiyuan Formation.

**MATERIALS AND METHODS**

Conventional two-dimensional seismic reflection data, and wellbore and wireline log data were compiled, interpreted, and integrated to predict coal seam thickness and depth, as well as the distribution and orientation of minor structures affecting the geometry and continuity of coal seams. The method used is similar to that used by Marroquín and Hart (2004), except that their method is based on three-dimensional seismic data. Our seismic database consists of six northeast–southwest and six northwest–southeast seismic lines in the northern part of the study area, as well as one west–east and five north–south seismic lines in the southern part of the study area (Figure 1). Well logs from 30 exploration wells were used. Various combinations of natural spontaneous potential (SP), natural gamma-ray (GR), caliper (CAL), density
Table 1. Results of Adsorption Isotherms, Proximate Analysis, and the Determination of Other Coal Properties of the No. 5 Coal*

<table>
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<tr>
<th>Well ID</th>
<th>Depth (m)</th>
<th>Cnt*</th>
<th>$V_L^{**}$ (m$^3$/t)</th>
<th>$P_L^{**}$ (MPa)</th>
<th>$T^{**}$ (°C)</th>
<th>$G_I^{**}$ (m$^3$/t)</th>
<th>$P_R^{**}$ (MPa)</th>
<th>$G_E^{**}$ (%)</th>
<th>$G_I / G_E^{**}$ (%)</th>
<th>$M^1$ (%)</th>
<th>Ash$^1$ (%)</th>
<th>VM$^1$ (%)</th>
<th>$R_o^{**}$ (%)</th>
<th>$X^{**}$ (m)</th>
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*Apart from coal thickness, other data were obtained by averaging all core sections from a single well. The “Cnt” column gives the count of core sections for each well.

**$V_L$, $P_L$, and $T$ are Langmuir volume (in air dry basis), Langmuir pressure, and analytical temperature for methane isothermal adsorption test, respectively. $G_I$ = total gas content in air dry basis; $P_R$ = reservoir pressure; $G_E = V_L / (P_R + P_L)$; $G_I / G_E$ = gas saturation; $R_o$ = mean maximum vitrinite reflectance; $X$ = coal thickness.

1$M$, Ash, and VM are, respectively, moisture, ash, and volatile matter contents obtained from coal proximate analysis in air dry basis.
(DEN), acoustic (AC), neutron (CN), and deep and shallow induction logs (LLD and LLS, respectively) were available for these wells. Using the above well data and combining previous investigations (e.g., Wang, 1996; Yang et al., 2005), we performed a primary analysis of the depositional environment of the coal-bearing strata in the Weibei CBM field. Moreover, we also performed a primary simulation analysis of the burial and thermal history of the study area. The H17, W4, H4, and S3 wells were selected for thermal modeling using Basin-Mod 1D software (Platte River Associates Inc., U.S.A.). The input data used for this modeling were from the investigations on the thickness of the eroded Upper Cretaceous strata (Ren et al., 1994) and the measured vitrinite reflectances of coals.

Seven gas samples were collected from the wells in the CBM production field. These wellhead gases were analyzed for methane and carbon dioxide carbon isotopic compositions.

Core samples provided by PetroChina CBM were sampled from the no. 5 coal seam at multiple locations. In each well, the full thickness of the seam was recovered using a sealed coring process and was placed into desorption canisters. Fresh coal cores were split into approximately 30-cm (11.8-in.) segments, immediately sealed in desorption canisters, and subsequently tested for total gas content with the US Bureau of Mines direct method.
(Diamond and Schatzel, 1998). Desorbed gases from the canisters were quantified volumetrically and analyzed for gas composition (CH₄, CO₂, N₂, C₂H₆, and longer-chain hydrocarbons) and methane carbon isotope composition. Gas composition was analyzed by the Chinese Technical Standard GB/T 13610-2003 (Standardization Administration of the People’s Republic of China [SAC], 2003). The gas composition data provided were corrected for the bulk compositional analyses of oxygen.

After the desorption tests, some coal segments were ground and split then measured for the determination of equilibrium moisture, adsorption isotherms, proximate analysis, and vitrinite reflectance analysis in accordance with the standards GB/T 19560-2008 (SAC, 2008a), GB/T 212-2008 (SAC, 2008b), and GB/T 6948-2008 (SAC, 2008c), respectively. Methane adsorption isotherms were determined at approximate reservoir temperatures of 21°C to 36°C, as given in Table 1.

In this study, the gas saturation of the CBM reservoir is defined by the percentage of total gas content relative to the maximum methane adsorption capacity. This value can be determined for a coal sample at a given reservoir pressure and temperature by comparing desorption data with an adsorption isotherm derived from that sample (Yao et al., 2009; Pashin, 2010). Gas saturation is expressed as S, such that

\[ S = \frac{G_I}{G_E} = \frac{G_I (P_R + P_L)}{(P_R \times V_L)} \]  
(1)

where \( G_I \) is the total gas content from the desorption test, \( G_E \) is the theoretical maximum methane adsorption quantity for in-situ reservoir pressure (\( P_R \)), and \( V_L \) and \( P_L \) are Langmuir volume (in air dry basis) and Langmuir pressure, respectively.

**RESULTS**

**Structural Domains**

The structural contour map of the top of the no. 5 coal seam is shown in Figure 2. Many overthrust faults (dip typically <45°) cut across the Weibei CBM field. Three major overthrust faults exist, named from north to south, the Xuefeng-Bei (F1), Xuefeng-Nan (F2), and Qiangao (F3) faults. Detailed descriptions of these faults are given in Table 2. For the purpose of assessment, the Weibei CBM field is subdivided into five structural domains (i.e., blocks B1–B5) by the three major faults.

Block B1 is the area to the north of fault F1, where a homoclinc dips gently toward the northwest at an angle of 1° to 3° (Figure 2). The depth of the Pennsylvanian no. 5 coal seam increases northwestward from 500 to 1500 m (1640.4–4921.3 ft). Many minor thrust faults inducing intense deformation of the strata exist, and the structural deformation decreases toward the west. These faults commonly have a vertical separation of less than 50 m (164 ft). Also, a small-scale fold exists in the eastern part of the block.

Block B2 is the area between faults F1 and F2. Convergent motion of faults F1 and F2 resulted in the folding of an upthrown fault block (Figure 2). In the eastern part of the block, minor folds are developed, whereas in the western part of the block, the strata form a simple monocline with a dip of approximately 3° to 6°.

Block B3 is the area between faults F2 and F3 and is shallow in the east and deep in the west. A series of minor northwest-striking folds formed during the Indosinian orogeny in the east. These minor folds were reactivated within a major Yan- shanian anticline with a northeast strike. Affected
by the two stages of folding, the strata in the east form an anticlinal structure with two distinct culminations (Figure 2). In the central part of block B3, many southeast-striking faults with a trace length of 0.7 to 5 km (0.4–3 mi) and a vertical separation of less than 50 m (164 ft) are present. In the west, the coal is deeply buried. The present CBM production wells are completed in the eastern part of the block and are generally at a depth of 500 to 900 m (1640.4–2952.8 ft).

Block B4 is southwest of F3. The strata dip gently northwestward at approximately 3° to 4°. The anticlinal structure also develops in the east of the block. Structural deformation increases toward the west, where two minor thrust faults and related folds are developed (Figure 2).

Block B5 belongs to the Heyang district and is different from blocks B1 to B4, which belong to the Hancheng district (Figure 2). This block has a monoclinal geometry and contains a north-dipping monocline with abundant small-scale northwest–southwest-striking faults. The small-scale faults include the normal faults in the southern part and the thrust faults in the northern part of block B5.

Pennsylvanian coal seams underwent three stages of tectonic movement (Tan, 1997). The first compressional deformation during the Late Permian and Triassic is the result of the Indosinian orogeny. At that time, the principal compressive stress was in the north-south direction. The Indosinian orogeny resulted in the formation of the east-west to west-northwest-striking folds and faults (Figure 2). The second more intense compressional deformation occurred during the Jurassic and Early Cretaceous as the result of the Yanshanian orogeny. At that time, the principal stress was southeast to
northwest. The Yanshanian orogeny caused a major reorientation of the regional stress field, causing the formation of northeast-striking folds and thrust faults (Figure 2). Finally, the Himalayan orogeny caused the formation of some minor detachment normal faults in the southern part of block B5 because, at that time, the regional stress field has been adjusted to be extensional.

**Coal Seams and Depositional Environments**

Figure 3 is a typical stratigraphic column that shows the coal seams and depositional environments in the study area (Figure 3). During the deposition of the Pennsylvanian Benxi Formation, an extensive tidal flat developed in the Weibei CBM field (Wang, 1996; Yang et al., 2005). The depositional environments of the Pennsylvanian Taiyuan Formation were characterized by extensive tidal-flat and shallow-marine facies, with three sedimentary cycles (Wang, 1996; Yang et al., 2005). This formation consists primarily of fine-grained rocks such as black shale, limestone, mudstone, and fine sandstone, as well as the no. 5 coal seam at the top and the no. 11 coal seam at the bottom. During the Early Permian, extensive deltaic and lacustrine environments developed in the field (Wang, 1996; Yang et al., 2005). The Lower Permian Shanxi Formation consists of fluvial-deltaic sandstone, shallow lacustrine mudstone, and swamp deposit coal.

Coal seam no. 5 and, locally, seams no. 3 and no. 11 are the principal targets of CBM exploration and development. Among the three coal seams, the no. 5 coal seam is commonly 3 to 8 m (9.8–26.2 ft) thick in blocks B3, B4, and B5 and 1 to 6 m (3.3–19.7 ft) thick in blocks B1 and B2. A maximum thickness of approximately 8 m (26.2 ft) is in the middle of block B3 and in the eastern part of block B5 (Figure 4).
Thermal Maturity of the Coals

The mean maximum vitrinite reflectance ($R_o$), moisture, volatile content, and ash yield of 43 drill cores are given in Table 1. The rank of the no. 5 coal seam ranges from low-volatile bituminous to semianthracite with 1.65% to 2.32% $R_o$ (Table 1).

The semianthracite is mainly in the eastern parts of blocks B3 to B5, whereas most low-volatile bituminous coals are in blocks B1 and B2 and in the eastern part of block B5 (Figure 5).

Gas Composition

The molecular composition of the gas desorbed from the cores of the no. 5 coal seam was analyzed. Analytical results from 22 wells are given in Table 3.

The molecular composition of desorbed gases is predominantly $\text{CH}_4$, with some $\text{N}_2$, $\text{CO}_2$, and traces of $\text{C}_2^+$ (Table 3). As for the major gas component, methane concentration is commonly greater than 85%, and the percentage of $\text{C}_2^+$ is low (0%–3%). The concentration of $\text{N}_2$ is commonly greater than 5%. In block B5, the concentration of $\text{N}_2$ is relatively high, and most of the values are greater than 15%.

The gas compositions are slightly different among the gas samples from blocks B1 to B4, where the concentration of $\text{CH}_4$, $\text{C}_2^+$, $\text{CO}_2$, and $\text{N}_2$ is 79.05% to 96.71%, 0% to 2.85%, 0.57% to 2.65%, and 0.9% to 17.27%, respectively (Table 3). In contrast, gas composition is highly variable for the gas samples from block B5. At the same time, the concentration of $\text{C}_2^+$, $\text{CO}_2$, and $\text{N}_2$ in this block is significantly higher than that in blocks B1 to B4.

Isotopic Composition

The isotopic composition of the gas desorbed from the cores of the no. 5 coal seam was analyzed.
Analysis results are averaged for 15 wells and are given in Table 3. The vertical variation of $\delta^{13}$C isotopic ratios from the 32 samples analyzed during this study is shown in Figure 6A.

The $\delta^{13}$C isotopic ratios span a wide range from $-53.0$ to $-32.8\%_o$ and exhibit a high degree of lateral variation within the five blocks investigated (Table 3). The lowest $\delta^{13}$C values are

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Table 3: Averaging Results of Gas Composition and Carbon Isotopic of Coalbed Gases Desorbed from Cores from the No. 5 Coal Seam

<table>
<thead>
<tr>
<th>Well</th>
<th>Cnt*</th>
<th>Sample Depth (m)</th>
<th>Gas Composition (%)</th>
<th>$\delta^{13}$CCH$_4$ (%o)</th>
<th>Structural Domains</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cnt*</td>
<td>Top</td>
<td>Bottom</td>
<td>CH$_4$</td>
<td>C$_2$+**</td>
<td>CO$_2$</td>
</tr>
<tr>
<td>H14</td>
<td>1</td>
<td>901.30</td>
<td>901.60</td>
<td>79.05</td>
<td>1.03</td>
</tr>
<tr>
<td>H17</td>
<td>1</td>
<td>466.13</td>
<td>466.43</td>
<td>93.59</td>
<td>0.16</td>
</tr>
<tr>
<td>W10</td>
<td>7</td>
<td>531.20</td>
<td>532.90</td>
<td>91.83</td>
<td>1.67</td>
</tr>
<tr>
<td>H12</td>
<td>4</td>
<td>534.14</td>
<td>535.94</td>
<td>96.36</td>
<td>0.23</td>
</tr>
<tr>
<td>W1</td>
<td>7</td>
<td>636.97</td>
<td>640.72</td>
<td>85.40</td>
<td>0.1</td>
</tr>
<tr>
<td>W2</td>
<td>4</td>
<td>1213.95</td>
<td>1215.28</td>
<td>96.71</td>
<td>2.39</td>
</tr>
<tr>
<td>WL1</td>
<td>5</td>
<td>371.20</td>
<td>374.10</td>
<td>94.63</td>
<td>1.52</td>
</tr>
<tr>
<td>H3</td>
<td>4</td>
<td>1213.55</td>
<td>1215.35</td>
<td>94.21</td>
<td>0.85</td>
</tr>
<tr>
<td>H5</td>
<td>1</td>
<td>587.00</td>
<td>587.30</td>
<td>88.58</td>
<td>0.76</td>
</tr>
<tr>
<td>H7</td>
<td>2</td>
<td>867.03</td>
<td>868.83</td>
<td>86.81</td>
<td>0.89</td>
</tr>
<tr>
<td>H10</td>
<td>3</td>
<td>715.74</td>
<td>718.00</td>
<td>90.65</td>
<td>1.07</td>
</tr>
<tr>
<td>H11</td>
<td>2</td>
<td>1049.04</td>
<td>1052.84</td>
<td>95.71</td>
<td>0.65</td>
</tr>
<tr>
<td>W3</td>
<td>5</td>
<td>884.32</td>
<td>886.88</td>
<td>93.60</td>
<td>1.33</td>
</tr>
<tr>
<td>W4</td>
<td>6</td>
<td>997.51</td>
<td>1000.90</td>
<td>91.24</td>
<td>1.56</td>
</tr>
<tr>
<td>W8</td>
<td>10</td>
<td>924.60</td>
<td>932.90</td>
<td>90.41</td>
<td>1.79</td>
</tr>
<tr>
<td>H4</td>
<td>1</td>
<td>1105.02</td>
<td>1105.32</td>
<td>82.67</td>
<td>0.47</td>
</tr>
<tr>
<td>H6</td>
<td>5</td>
<td>1066.44</td>
<td>1069.12</td>
<td>90.27</td>
<td>2.85</td>
</tr>
<tr>
<td>S4</td>
<td>1</td>
<td>882.21</td>
<td>882.51</td>
<td>93.77</td>
<td>2.64</td>
</tr>
<tr>
<td>S5</td>
<td>1</td>
<td>965.27</td>
<td>965.57</td>
<td>66.05</td>
<td>0.73</td>
</tr>
<tr>
<td>S6</td>
<td>7</td>
<td>784.10</td>
<td>789.95</td>
<td>82.89</td>
<td>0.13</td>
</tr>
<tr>
<td>S7</td>
<td>2</td>
<td>747.00</td>
<td>747.94</td>
<td>80.56</td>
<td>1.38</td>
</tr>
<tr>
<td>S13</td>
<td>6</td>
<td>1052.90</td>
<td>1059.80</td>
<td>90.58</td>
<td>1.67</td>
</tr>
</tbody>
</table>

*The data in the table were obtained by averaging all samples taken from a single well.

**C$_2$+ refers to the longer-chain hydrocarbons.

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*Figure 6.* Vertical variation of coalbed methane properties of (A) methane carbon isotopic data, (B) ratio of methane to the sum of gases, (C) total gas content, and (D) gas saturation, defined as the percentage of total gas content to the maximum methane adsorption capacity. The vertical dot lines in the plots illustrate the difference in gas properties between the B5 and other blocks.
from block B5. In this block, $\delta^{13}$C values are commonly less than –42.0‰, with an exception of the samples from the S5 well. The $\delta^{13}$C values range from –41.6‰ to –34.9‰ in blocks B1 to B3. The $\delta^{13}$C values range from –35.0‰ to –33.1‰ in block B4, and they are relatively enriched when compared with the values in other blocks.

Moreover, the isotopic composition results of gas from wellheads show that the $\delta^{13}$C values for methane range from –41.0‰ to –36.8‰, whereas the $\delta^{13}$C values for carbon dioxide range from –16.6‰ to –2.2‰ (Table 4). The $\delta$D values for methane are from –237‰ to –179‰.

### Table 4. Geochemical Analysis Results of the Wellhead Gases

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\delta^{13}$CO$_2$ (%)</th>
<th>$\delta^{13}$CH$_4$ (%)</th>
<th>$\delta$D (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>–10.8</td>
<td>–41.0</td>
<td>–203</td>
</tr>
<tr>
<td>2</td>
<td>–16.5</td>
<td>–38.9</td>
<td>–235</td>
</tr>
<tr>
<td>3</td>
<td>–14.0</td>
<td>–38.3</td>
<td>–231</td>
</tr>
<tr>
<td>4</td>
<td>–12.2</td>
<td>–36.9</td>
<td>–207</td>
</tr>
<tr>
<td>5</td>
<td>–16.6</td>
<td>–40.2</td>
<td>–232</td>
</tr>
<tr>
<td>6</td>
<td>–16.2</td>
<td>–39.8</td>
<td>–237</td>
</tr>
<tr>
<td>7</td>
<td>–13.6</td>
<td>–36.8</td>
<td>–179</td>
</tr>
</tbody>
</table>

# Gas Content and Gas Saturation

The results of gas content, reservoir pressure, Langmuir adsorption volume, and Langmuir adsorption pressure analysis are given in Table 1.

Desorption tests of coal cores from the no. 5 coal seam show that total gas content ranges from 2.69 to 16.15 m$^3$/t (95.00–570.33 scf/t), with a median value of 10.10 m$^3$/t (356.68 scf/t) (Table 1). The distribution of the values is highly variable across the study area (Figure 7). Gas content of greater than 8 m$^3$/t (282.5 scf/t) is concentrated...
in blocks B1, B3, and B4, as well as in the western part of block B2. Gas content of 4 to 8 m³/t (141.3–282.5 scf/t) is in the eastern part of block B5. The lowest gas content of less than 4 m³/t (141.3 scf/t) is in the western part of block B5.

Adsorption isotherms derived at approximate reservoir temperatures indicate that the methane adsorption capacity (i.e., Langmuir volume) of coal commonly ranges from 12 to 32 m³/t (423.8–1130.1 scf/t) on an air dry basis (Table 1). Methane adsorption capacity is consistent with the distribution of gas content (Figures 7, 8). Langmuir volume is high in blocks B1, B2, and B3, and in the northern part of block B4, whereas it is low in block B5 and in the southern part of block B4 (Figure 8).

Gas saturation data from 23 wells in the Weibei CBM field (Table 1) were obtained by equation 1. The results show that gas saturation ranges from 26.0% to 93.2% (median value of 60.4%), indicating that all coals are undersaturated with respect to methane. The map of gas saturation is consistent with that of gas content (Figures 7, 9).

**DISCUSSION**

**Coalification and Thermal History**

We found that coal rank does not increase with depth on a regional or local scale in the study area (Table 1), whereas it does increase when approaching the axis of the major anticline and the upthrown side of fault F3 (Figure 5). Tan (1997) suggested that the thermal maturity of the coals was only the result of normal geothermal coalification. However, we believe that a variety of tectonic and hydrothermal factors are responsible for the lack of correlation between coal rank and depth. Based on our primary simulation study, the
burial and thermal history is divided into four stages (I–IV stages in Table 5). Normal geothermal coalification apparently prevailed during the Pennsylvanian–Late Triassic (stage I), whereas tectonic-hydrothermal coalification, during the Late Jurassic–Early Cretaceous (stage III). The geothermal coalification resulted in the formation of coal of mainly high-volatile bituminous (Ro < 1.0%) throughout the study area. In contrast, tectonic-hydrothermal activity induced anomalously a high paleo–heat flow and thus resulted in the formation of low-volatile bituminous coal and semianthracite (Figure 5). Moreover, other than depth, thermal influences, such as the migration of hydrothermal fluid along faults and fracturing in the axes of folds, seem to have increased thermal maturity by more than 40%. According to previous researches on the Ordos Basin (e.g., Wang, 1996; Zhao et al., 1996; Xiao et al., 2005; Yuan et al., 2007) and the reconstruction of burial and thermal history in this study, the time of maximum heating was during the Late Jurassic as the result of the Yanshanian orogeny.

Regardless of the origin of coal rank, thermal maturity patterns indicate that all CBM reservoirs in the Weibei CBM field are mature enough to have generated thermogenic gas.

**Characteristics of the Gas Composition**

As shown in Table 3, N2 has a relatively high concentration, especially in block B5. To explain the enrichment of N2 in natural gas, Krooss et al. (1995) proposed two hypotheses: (1) migration-related fractionation resulting in a chromatographic separation of CH4 and N2, and (2) the generation of N2 and CH4 at different stages of sedimentary diagenesis, catagenesis, or metamorphism. The first hypothesis is applicable to explaining N2 enrichment in block B5. We suggest that hydrologic...
flushing and preferential solution of gases in formation water facilitated migration-related fraction process. First, CH₄ is more soluble than N₂ in formation water. For the mixed gases of N₂-CH₄, free-state CH₄ was more easily subject to being reduced by hydrologic flushing than free-state N₂, thereby resulting in high N₂ concentration in free-state mixed gases. Then, free-state N₂ can diffuse into coal pores and displace some adsorption-state CH₄ because the previous adsorption equilibrium was broken by the preferential solution of free-state CH₄. Finally, continuous exchange between N₂ and CH₄ increased N₂ concentration in the CBM reservoir.

Moreover, the concentration of CO₂ (commonly <2.5%) is relatively low. The reason is also related to the fractionation effect of CO₂-CH₄ during sedimentary diagenesis, catagenesis, or metamorphism because CO₂ is much more soluble than CH₄ in formation water.

As for the isotopic composition of the methane, it appears that a slight correlation exists between the δ¹³C values and present-day burial in blocks B1 to B4, but not block B5 (Figure 6A). It is evident that methane gases are depleted in ¹³C in block B5, suggesting a difference in the origin of the gas.

It was also found that δ¹³C values are scattered when plotted against the Rₒ of associated coals. This means that the gas samples do not become enriched in ¹³C with increasing thermal maturation as would normally be the case. These factors suggest a complex origin of the gases in the Weibei CBM field.

### Origin of the Coalbed Methane

Thermogenic methane has δ¹³C values higher than −55‰ and biogenic methane has values lower than −60‰ because of preferential δ¹²C consumption by methanogens (e.g., Whiticar, 1999). Intermediate compositions may be produced by mixing biogenic and thermogenic gases or secondary processes, such as water-flushing and thermal cracking of bitumen (e.g., Rice, 1993; Kinnon et al., 2010; Papendick et al., 2011). According to the geochemical classification of Bernard et al. (1978)

<table>
<thead>
<tr>
<th>Geologic Time</th>
<th>Maximum Depth (m)</th>
<th>Pale-heat gradient (°C/100 m)</th>
<th>Tectonic Orogeny</th>
<th>Tectonic Evolution</th>
<th>Thermal Evolution (Metamorphism)</th>
</tr>
</thead>
<tbody>
<tr>
<td>From</td>
<td>To</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>(306.5 Ma)</td>
<td>Late Triassic</td>
<td>Late Hercynian and Indosinian</td>
<td>Significant geothermal</td>
<td>Significantly geothermal</td>
</tr>
<tr>
<td>Early Jurassic</td>
<td>(206.5 Ma)</td>
<td>Middle Jurassic</td>
<td>Early Yanshanian</td>
<td>Negligibly geothermal</td>
<td>Significantly tectonohydrothermal</td>
</tr>
<tr>
<td>Early Cretaceous</td>
<td>(99.6 Ma)</td>
<td>Late Cretaceous</td>
<td>Late Yanshanian</td>
<td>End of metamorphism</td>
<td>Continuous uplift</td>
</tr>
<tr>
<td>Late Cretaceous</td>
<td>(99.6 Ma)</td>
<td>Quaternary</td>
<td>Late Himalayan and Indosinian</td>
<td>Continuous uplift</td>
<td>Continuous uplift</td>
</tr>
</tbody>
</table>

*The data were obtained from our primary research of wells H17, W4, W5, and S1.*
and Whiticar (1999), gas origin in the study area is most possibly thermogenic, and the gas is relatively dry (as illustrated in Figure 10).

When comparing δ

13C values with those from other low-volatile bituminous coals or semianthracites in China (Qin et al., 2000), we found that δ

13C values in the study area tend to be depleted in 13C, especially in block B5. This means that some secondary process resulted in that depleted in 13C (Figure 10).

One possibility is that the intermediate compositions of the gases in block B5 result from the mechanism of bacterial CO2 reduction (Tables 3 and 4). Another plausible explanation for the depleted 13C values and the low concentration of methane in block B5 is hydrodynamic isotopic fractionation (Qin et al., 2006). The methane becomes depleted in 13C because of hydraulic flushing: the more intensive the hydrodynamics, the more negative the carbon isotopic value becomes. Using experimental results and a mathematical simulation, Qin et al. (2006) concluded that the hydrologic flushing can fractionate carbon in CBM and remove the 13C isotope by solution. The fractionation effect results in the increase of 12C in adsorption gas, and the continuous exchange between 12C and 13C increases the 12C content in coal matrix. The previous study by Yao et al. (2009) indicated that the present stress field in the Hancheng district (i.e., blocks B1–B4) is more intense than that in the Chenghe district (i.e., block B5). Thus, the hydrodynamic activity in block B5 is relatively stronger than that in other blocks. This provides good conditions for hydrodynamic isotope fractionation in block B5.

Moreover, thermogenic gas was likely generated from the no. 5 coal seam at an early stage or, alternatively, that the CBM in the no. 5 coal seam mixed with thermogenic gases migrated from the no. 11 coal seam. Because 12C is desorbed from the coal earlier than 13C, cooling, as a result of basin uplift, causes the preferential desorption of 12C (Scott et al., 1994; Bustin and Bustin, 2008). The desorbed 12C may have diffused upward from a deep area with high reservoir pressure to a shallow area with low reservoir pressure, that is, from a low spot to a high spot within the no. 5 coal seam or, alternatively, from the no. 11 coal seam to the no. 5 coal seam.

Finally, note that sampling time may influence the results of isotopic and molecular compositions. For a coal sample, the methane desorbed earlier is commonly isotopically lighter than that desorbed late because of the preferential consumption of 12C. However, it is impossible to accurately choose the sampling time to make sure...
that the same quantity of methane is desorbed from the coal before carbon isotopic analysis because the quantity of lost gas escaped from the sample during its collection and retrieval before being sealed into an airtight desorption canister cannot be determined. Therefore, evaluating the influence of sampling time on the carbon isotopic results is difficult.

Factors Influencing Gas Properties

Both gas content and gas saturation are highly variable in the Weibei CBM field, reflecting geologic heterogeneity. These geologic factors include the thickness, depth, composition, and rank of the coal; reservoir pressure; reservoir temperature; structural characteristics; sedimentary characteristics; and the migration and trapping of gas.

Gas content does not correlate well with coal seam thickness (Table 1). Moreover, no statistical correlation exists between gas properties and the depth of the no. 5 coal seam. As shown in Figure 6, gas content and gas saturation typically do not increase with depth, which is different from the situation in other coal basins, such as the US Black Warrior Basin (Pashin, 2010) and the Polish upper Silesian Basin (Kedzior, 2009). Moreover, Figures 7 and 9 also show that the regional distribution of gas content and gas saturation does not follow the distribution of depth in blocks B1 to B4 (Figure 2).

In contrast, both the distribution of gas content and gas saturation do follow the map of coal rank (Figures 5, 7, 9). As shown in blocks B1, B3, and B4, gas content and gas saturation are commonly greater than 10 m$^3$/t (353.1 scf/t) and greater than 60% in the semianthracite area, whereas they are 5 to 11 m$^3$/t (176.6–388.5 scf/t) and 40% to 60% in the low-volatile bituminous coal area. Similarly, in block B5, gas content and gas saturation in semianthracite are higher than those in low-volatile bituminous coal.

A possible explanation for these phenomena is that the two stages of coalification control not only coal thermal maturity, but also the types and quantity of thermogenic gases generated from the coal. The tectonic-hydrothermal metamorphism in the Middle Yanshanian orogeny (Table 5) has resulted in the local enrichment of secondary thermogenic gases in the northern B2, northern B4, and north-central B3 blocks (Figure 7). Because of increased coalification, thermal cracking of organic compounds causes not only the generation of thermogenic methane, but also the increase in methane adsorption and storage capacity. More and more methane is generated, and the coal structure is modified to accept additional thermogenic methane, resulting in a higher gas content (Scott, 2002). Therefore, coal rank controls the primary distribution of gas content in the study area.

Nevertheless, gas content and gas saturation are also influenced by secondary processes, such as gas migration and changes of sorption capacity related to regional tectonic uplift and cooling. The gas migration results from the uplift that occurred after the significant tectonic-hydrothermal metamorphism in the Middle Yanshanian episode (Table 5). During the early Middle Yanshanian episode, the intense compressional deformation facilitated intensive tectonic-hydrothermal coalification. The tectonic-hydrothermal coalification resulted in the generation of a large volume of secondary thermogenic methane. Thus, at that time, the coal was gas saturated and had a high gas content. After that, prolonged uplift changed the pressure and temperature of the reservoir and thus reduced gas saturation. Note that, in the uplift stage, the coal ceased generating thermal gases.

The uplift also changed the gas saturation. It is well known that the gas adsorption capacity increases with the pressure and decreases with the temperature, although the uplift can decrease both the temperature and pressure of the reservoir. It is generally accepted that coal can become undersaturated with methane because of cooling during basin uplift (e.g., Ayers, 2002; Scott, 2002). The reason is that cooling causes an increase in adsorption capacity with no additional gas generated (Ayers, 2002; Scott, 2002). Moreover, based on quantitative data about the effect of temperature and pressure on the adsorption capacity of the coal with different ranks and depth, Bustin and Bustin (2008) indicated that the adsorption capacity of a middle-rank coal ($R_o$ of 1.68%) may become undersaturated during uplift for large pressure and
temperature gradients. We suggest that the widespread undersaturation may result from the increased adsorption capacity by uplift or by other reasons, such as the loss of adsorbed gas caused by stripping by aquifers (as considered in Cui et al., 2004).

**Gas Accumulation and Implication for Coalbed Methane Production**

The high lateral variations of gas content and gas saturation (Figures 7, 9) suggest that CBM reservoirs are compartmentalized by subtle structures as in other coal basins, such as the Black Warrior Basin (Pashin and Groshong, 1998) and the upper Silesian Basin (Kedzior, 2009).

Many geologic and hydrological factors exist that affect the CBM distribution in the subsurface, and these factors can be classified into four categories: gas generation, reservoir pressure, reservoir temperature, and trap development (Scott, 2002). The CBM in the study area is primary and secondary thermogenic gas, with the latter one as the main contributor to gas content. According to our primary analysis of the burial and thermal history of wells H17, W4, H4, and S3, the geothermal gradient during the Middle Yanshanian orogeny was as much as 4.0°C to 6.1°C/100 m (11.95°F–13.11°F/100 ft) (Table 5), which facilitated the generation of thermogenic gases. The quality of gases generated is variably distributed across the study area, depending on the degree of local thermal maturity of the coal. This explains the general correlation between gas content and coal rank, as illustrated in Figures 5 and 7. However, the present gas content is also a consequence of gas migration. These processes include (1) gas diffusion and long-distance migration of thermogenic gases to no-flow boundaries for eventual resorption and conventional trapping, (2) hydrodynamic trapping of gases in deep structures, and (3) gas loss by hydrodynamic flushing. Figures 11 and 12 illustrate three typical gas accumulation models (A, B, and C) of blocks B3 to B5 in the Weibei CBM field. In the figures, the gas migration directions were primarily estimated by comparing the methane carbon isotopic data from limited exploration wells.

The first accumulation model applies to the block B3 (model A in Figures 11, 12), where gas...
content increases northwestward from the axis of the anticlinal nose to the downthrown side of fault F2. The quantity of thermogenic gases generated from the coal is related to coal thermal maturity, and thus, the distribution of gas content is commonly consistent with the distribution of coal rank. However, in the eastern area of block B3, high gas content is distributed in the northern part (Figures 7, 11), where the coal rank (≈2.0%) is lower than that in the south (2.2%–2.3%) (Figure 5). All of these demonstrate that the present distribution of gas is mainly a result of both gas generation and gas migration.

Two factors apparently facilitated gas migration. First, the coal seam is oriented to permit recharge along an uplifted margin in the anticline...
axis, and groundwater moving slowly through higher-rank coal transports gas northwestward in solution for trapping at a permeability barrier (Figure 12A). Discussion of how the CBM is trapped by faults can be found in Scott (2002) and Karacan et al. (2008). The distribution of gas content and gas saturation in Figures 7 and 9 shows that the migration of the gases ends when approaching an impermeable fault, in this case, F2. The impermeable fault acts as a no-flow boundary for eventual resorption and conventional trapping of gases in the reservoir (Figure 12A). In the northern part of block B3, high gas content may result from the combined effects of hydrodynamic trapping in the south and structural trapping in the north. Second, regional uplift and erosion during the Yanshanian period reduced the gas content, resulting in the coal being undersaturated. The coal seam in the northern area was apparently influenced less by regional uplift, and so, the gas saturation has not been affected as strongly.

The trapping of gas by no-flow boundaries resulted in high gas content and gas saturation in the north of block B3, controlling gas production in the area. Another key control of gas production is related to the shallow burial (400–700 m [1312.3–2296.6 ft]) in the area because the permeability significantly decreases with depth. The high gas content and permeability facilitated a commercial CBM production field in the east of block B3 (Figure 1).

The second accumulation model is represented by block B4 (model B in Figures 11, 12B), where the gases migrated basinward from the low reservoir pressure area in the shallow part to the high reservoir pressure area. Meanwhile, the gases were hydrodynamically trapped in the deep part. In the block, methane carbon isotopic data of the gas-enriched area indicate a weak hydrodynamic activity (δ13C of −36.2‰ to −33.1‰). The weak hydrodynamic condition is favorable for the retention of gases in the reservoir. Moreover, the slow basinward migration of groundwater reduced the quantity of diffusion and migration of gases from the deep area to the shallow area (Figures 11, 12B). Finally, groundwater recharge can potentially increase gas content by increasing reservoir pressure and allowing more gas to be adsorbed in the coal. The increase of reservoir pressure causes the early-generated and/or migrating thermogenic gases to be adsorbed into the coal. In block B4, the enrichment of the CBM results from both the increase of reservoir pressure and migration of gas.

The distribution of gas content and gas saturation in Figures 7 and 9 demonstrates that CBM is enriched in coal seams at a depth of approximately 1100 m (3609 ft) in block B4. In the block, several exploration wells were drilled; however, none of the wells were completed. The reason is that the permeability of the CBM reservoir is uncertain. The block is one of the important CBM production target areas for PetroChina CBM in the next 5 yr.

The third accumulation model applies to block B5 (model C in Figures 11, 12C) where the intensive movement of groundwater through permeable coal has potentially reduced gas content in the south and carried the gas toward a minor fault in the north, where it has been trapped. The CBM accumulation in block B5 underwent intensive secondary destructive processes, driving diffusion and degassing the coal seam. This destruction process can be surmised based on at least four facts. (1) Both gas content and gas saturation are significantly lower than in other blocks (Figures 6, 7, 9). (2) The migration of gas within the coal seam significantly altered the composition of the gas. (3) The δ13C values (commonly of −53‰ to −42‰) are relatively lower than normal thermogenic gases from semianthracite and low-volatile bituminous coal in other areas (as given in Qin et al., 2000). (4) The δ13C values do not correlate with the Ro and depth of the coal seam (Figure 6).

The gas accumulation is uncommercial for two possible reasons. The first reason is related to basin uplift and cooling, as discussed above. Another most important reason is meteoric flushing of gases near the recharge region (Figure 12C). In a static hydrologic system, an equilibrium exists between the amount of gas adsorbed in the coal and that dissolved in the cleat system (“cleat” means the opening-mode fractures in coal; Laubach et al., 1998). However, when these equilibrium conditions are disrupted in an active groundwater system,
the gas in the coal matrix may diffuse into the cleat system, thus reducing gas content. In the active groundwater area, the gas content and gas saturation are low unless a recharge of secondary biogenic gases exists.

In block B5, the gas composition is depth dependent. In the area of shallow active dynamic groundwater flow (the gas weathering or N2-CO2 region), the CH4 is commonly absent, and N2 and CO2 are dominated by the groundwater flushing. The N2-CO2 region is commonly approximately 300 to 400 m (984.3–1312.3 ft) deep and locally may reach depths of 700 m (2296.6 ft) under the influence of faults (Figure 11). Below this region, a transition region exists (~700–900 m [2296.6–2952.8 ft]) with methane concentration increasing downward from 0% to 70% (N2-CH4 region) and a CH4 region (>900 m [2952.8 ft]) with more than 70% CH4.

For coal at depths of less than 700 m (2296.6 ft) in block B5, no mechanism for entrapment exists, and the gas content is relatively low because of water flushing and diffusion. Only in local areas, such as near the S4 well, is a minor structural trap observed, which increases gas content to as much as 10.6 m³/t (374.3 scf/t). In general, meteoric flushing of gases near the recharge region may result in an uncommonly low gas content and gas saturation in block B5, and the presence or absence of seals will ultimately determine whether the gases are trapped in the areas.

CONCLUSIONS

1. In the Weibei CBM field, three major overthrust faults divide the study area into five smaller blocks. The Pennsylvanian no. 5 coal seam is the main CBM target seam at a depth of 500 to 1300 m (1640.4–4265.1 ft) and with a thickness of 1.3 to 8.4 m (4.3–27.6 ft). The coal rank ranges from low-volatile bituminous to semianthracite, which is mainly controlled by tectonic-hydrothermal coalification.

2. Results from molecular and isotopic compositions of CBM and the rank of the associated coal indicate that the CBM is thermogenic in terms of origin. The gases generated early in the basin history have been altered by diffuse fractionation effects resulting from the movement of subsurface water in block B5. The total gas content ranges from 2.69 to 16.15 m³/t (95.00–570.33 scf/t). Almost all gases are unsaturated with respect to methane (gas saturation ranging from 26% to 93.2%) because of cooling during basin uplift.

3. The gas content of coal is enhanced locally by the trapping of gas by no-flow boundaries in block B3. Moreover, a minor hydrodynamic gas trapping in structural lows is found in regions with depths of approximately 1100 m (3608.9 ft) in block B4. In block B5, the gas accumulation has been destroyed by meteoric flushing of gases near the recharge region. The future work should be undertaken to analysis the isotopic and geochemical compositions of produced water samples, and to demonstrate the relationships between the fluid flow pathways and gas accumulations.

REFERENCES CITED


