Influences of igneous intrusions on coal rank, coal quality and adsorption capacity in Hongyang, Handan and Huaibei coalfields, North China

Yanbin Yao *, Dameng Liu, Wenhui Huang

School of Energy Resources, China University of Geosciences, Beijing 100083, PR China

ARTICLE INFO

Article history:
Received 10 June 2011
Received in revised form 2 September 2011
Accepted 3 September 2011
Available online 10 September 2011

Keywords:
Igneous intrusion
Coal
Coalbed methane
Adsorption capacity
North China

ABSTRACT

Localized igneous intrusions with varying types of intrusion patterns were found in the Pennsylvanian–Permian coals in north China. Five typical patterns, including dike cut-through (pattern-I), dike cut-in (pattern-II), floor intrusion by sill (pattern-III), roof intrusion by sill (pattern-IV) and dual intrusions of roof and floor by sills (pattern-V), were investigated at five different underground profiles. It was found that the influence of localized intrusions on coal rank, petrology and coal quality characteristics are mainly related to the emplacement temperature, the style of heat transfer (convection or conduction), the intrusion forms (dike or sill) and size, the distance from the contact and the thermal properties of the surrounding rocks at the contact of the intrusion. Among the five patterns, only pattern-V was found to have two distinct contact metamorphic aureoles within a distance of 1–2 times the thickness of the intrusion, whereas patterns I through IV show wave-like profiles of vitrinite-relectance, ash and volatile matter. This resulted from the typical characteristics of “multiphasic and superimposed thermal metamorphic evolution” of north China coals. Except for the heat conduction by intrusion contact, the hydrothermal convection and tectonic-heat played important roles in heat transfer away from dike/sill. Intrusion-induced coal changes including coal rank, organic/inorganic composition and pore properties work together to influence the adsorption capacity of coals. The effect of intrusion upon the adsorption capacity of altered coals is related to the values of their altered coal ranks. Adsorption capacity is elevated from the Langmuir volume (VL) of 7.6 (pre-intrusion) to 17.5 m3/t (post-intrusion) for altered bituminous coals and semi-anthracites with VRr<2.1%. In contrast, the adsorption capacity is moderately reduced from background levels of about 27.2 m3/t to about 19.3 m3/t for altered semi-anthracites and anthracites with VRr of 2.1–3.4%. Adsorption capacity is significantly reduced (~5 m3/t) for altered anthracites and meta-anthracites with VRr of >3.4%, because of the accumulation of coal basic structure unit and distinctly decreasing pores. The relationships between altered coal rank and adsorption capacity are different for different coals, which is mainly due to changes of pore characteristics and coal structures resulting from three important coalification jumps during contact and/or other heat metamorphism.

© 2011 Elsevier B.V. All rights reserved.

1. Introduction

Many key coalbed methane (CBM) basins such as the San Juan and Raton basins in the USA, the Gunnedah basin in Australia, and the Qinshui and Puxin basins in China, have undergone contact metamorphism or thermal maturation directly or indirectly related to igneous intrusions (Cooper et al., 2007; Gurba and Weber, 2001). The igneous intrusions may have positive or negative effects on the generation and accumulation of methane gas, the physical properties of in-situ coal reservoirs and even the development of CBM (Johnson and Flores, 1998). However, studies on the influences of localized intrusions on coalbed methane reservoirs are still insufficient.

Igneous intrusions can influence the rank, type, petrographic, geochemical and stable isotopic features of coals and change the style of microstructure development in coal beds (e.g., Barker et al., 1998; Dai and Ren, 2007; Finkelman et al., 1998; Gröcke et al., 2009; Rimmer et al., 2009; Sarana and Kar, 2011; Schimmelmann et al., 2009; Singh et al., 2008; Stewart et al., 2005; Yang et al., 2011). They can also impact the CBM potential in sedimentary basins. For example, Gurba and Weber (2001) indicated that two igneous sills in the Gunnedah Basin had positive effects on the gas content and gas composition of CBM. More recently, Saghaei et al. (2008) indicated that the heating effect of a dike had enhanced not only the adsorption and porosity of metamorphosed coals, but also the gas diffusivity and trap capacities of gas storage. In the Illinois Basin, intrusion dikes changed the coal mesopore and pore properties that may have negative effects on gas migration in coal beds adjacent to the dike due to the decrease of porosity and surface area (Mastalerz et al., 2009). Few studies, however, have focused on the effects of igneous intrusions on coal in the context of different types of intrusion patterns, although these patterns are considered to be important (Murchison, 2005). In addition, as far as we know, no investigation has been conducted on...
the thermal influence of intrusion patterns to the change of adsorption capacity of coals in north China.

Various patterns of igneous intrusions have been documented in the late Palaeozoic coal-bearing strata in north China. The influences of these igneous intrusions on the exploration and exploitation of CBM in coalfields have not been adequately studied. For simplicity purposes, we describe five typical dike/sill patterns in the igneous intrusions at five underground profiles in the Hongyang, Huaiabei and Handan coalfields, north China (Fig. 1). The five coalbed intrusion patterns are: dike cut-through (pattern-I, Fig. 2), dike cut-in (pattern-II, Fig. 3), floor intrusion by sill (pattern-III, Fig. 4), roof intrusion by sill (pattern-IV, Fig. 5) and dual intrusions of roof and floor by sills (pattern-V, Fig. 6). The characteristics of these patterns are given in Table 1. The aim of this study is to investigate the effects of these intrusion patterns on coal metamorphism, coal quality and methane adsorption capacity.

2. Methodology
2.1. Geological settings

The late Palaeozoic coals in north China are very important for both coal and CBM resources. In contrast to most coals in other coal-bearing basins in the world, north China coal is well known for its metamorphic complexity resulting from Meso-Cenozoic igneous intrusions, which has been described as “multiphasic and superimposed thermal metamorphic evolution” (Yang et al., 1988). The north China coals have commonly undergone three metamorphic stages, resulting in high coal ranks. In the first stage, the geothermal metamorphism increased coal rank to high volatile bituminous (HVB) with random vitrinite reflectance (VRr) of 0.8%–1.1%. In the second stage, hydrothermal metamorphism caused the coal rank to increase to low volatile bituminous coal (LVB) through semi-anthracite to meta-anthracite. In this stage, the hydrothermal metamorphism mainly resulted from multiple episodes of magma intrusion during the Jurassic–Cretaceous Yanshanian Orogeny. In the last stage, Tertiary tectonic events created local coal metamorphic zones in north China. Of these tectonic and igneous events, the Cretaceous igneous intrusions had constructive influences on CBM generation, accumulation, and improvement of permeability of CBM reservoirs, which has been confirmed in two commercial CBM basins, i.e. the Qinshui and Fuxin basins.

The Cretaceous igneous intrusions associated with the Yanshanian Orogeny had multiple episodes and orientations (Yang et al., 1988). Taking the Handan coalfield as an example, igneous events, diorite and syenite intrusions were superimposed early and late in the Yanshanian Orogeny, respectively. In addition, igneous intrusions were distributed mainly along six latitudinal tectonic zones. From north to south, the Hongyang coalfield in Liaoning Province, Handan coalfield in Hebei Province, and Huaiabei coalfield in Anhui Province are located in three different latitudinal tectonic zones, i.e. the latitudes 41°–42°30′, latitudes 36°–37° and latitudes 34°–35° tectonic zones, respectively (Fig. 1).
2.2. Samples and experiments

Twenty-four samples (including coal, coke and magmatic rocks) were taken from five different underground geological profiles in the Hongyang, Handan and Huaibei coalfields. All samples are grab samples with an approximate size of 30 cm × 20 cm × 15 cm. Among these samples, HL12-1 and HL12-2 were collected from the unaltered (by intrusion) area, while the other samples were collected from the altered area. The sampling location of the unaltered coals (HL12-1 and HL12-2) was about 2 km away from the location of the heat-affected coals (G1, G2, G3 and G4), in the Hongling mine.

The coal samples were prepared for polished slabs. On each polished slab, petrologic observations (50 points) were taken under white light using a magnification of 500×. Mean maximum (VRmax), minimum (VRmin) and random (VRr) vitrinite reflectances in oil immersion were determined using a Leitz MPV-III photometer system, following the Chinese standard (GB/T) 6948–1998. Based on vitrinite reflectance data, the birefringence coefficient (VRbc) is calculated by VRbc = (VRmax − VRmin)/VRmax. Birefringence, a measure of the reflectance anisotropy of vitrinite, can be explained by coalification in the presence of directed stress and is the main effect of pressure and temperature during coalification (Levine and Davis, 1989). High VRbc means high anisotropy of vitrinites. The results of vitrinite reflectances and VRbc are given in Table 2.

Coal proximate analyses and ultimate analyses were performed on coal samples following the GB/T 212–2008 and GB/T 476–2008 procedures, respectively. Analytical results including ash, volatile matter and moisture content, and carbon and hydrogen contents are given in Table 3.

Moreover, methane isothermal adsorption analyses were conducted for sixteen samples by the GB/T 19560–2004 procedure. Analytical results including the Langmuir volumes (as-received and dry-ash-free basis) and Langmuir pressure are given in Table 3.

3. Results and discussions

3.1. Coal-profiles chosen for detailed study

3.1.1. Pattern-I in Hongling mine

Dike cut-through pattern (pattern-I) was investigated in the Hongling mine, an underground mine in the middle of Hongyang coalfield (Fig. 1 and Table 1). In this mine the igneous intrusion area is 2.71 km².
accounting for 29% of the coal-mining area. The coal beds occur in the Pennsylvanian Taiyuan Formation and Lower Permian Shanxi Formation that gently dip towards southeast at 20°–45°. Three thick coal seams are Nos. 3 and 7 of the Shanxi Formation and the No. 12 of the Taiyuan Formation, with an average thickness of 0.8 m, 1.04 m and 2.72 m, respectively. The No. 12 coal consists of three sub-seams, the Nos. 12-1, 12-2 and 12-3 with average thickness of 0.8 m, 3 m and 0.4 m, respectively. Before the igneous intrusion, the coals were mainly bituminous coals with VRr of 1.7%–2.0%.

The selected geological profile is located at No. 1204 underground working-face in West-2 mining block, where mafic dolerite dikes intrude along a normal fault system (Fig. 2). The dike cut vertically through the No. 12-2 coal seam. The dike has a thickness (width) of about 1.8 m, visible length of about 24 m and a dip angle of 9°. The dike was inferred to have intruded the coal seam during the Himalayan orogenic movement. In the profile the bituminous coals were converted to natural coke by the heat of the intrusion within 2 m distance from the dike.

Along the underground working-face, a suit of four samples (including a coked-coal and three altered coals) were collected at a distance of about 15 m from the coal/coke contact. These samples are adjacent to each other with a distance of about 3 m (Fig. 2).

3.1.2. Pattern-II in Mengzhuang mine

Dike cut-in pattern (pattern-II) was investigated in the Mengzhuang mine, Huaibei coalfield (Table 1). The Mengzhuang mine is located in Xiao County, Huaibei city (Fig. 1). Geologically, it is part of the northern limb of the Zahe syncline in Huaibei Coalfield. In this mine, the No. 3 coal of the lower Shihezi Formation (Permian) and the No. 7 coal of the Shanxi Formation (Permian) are the two major mining seams. The No. 3 coal has an average thickness of about 2.5 m and the unaltered coals are mainly HVB (VRr of about 0.5%–0.8%) in this mine.

The selected geological profile is located at a temporary face at a coal roadway, where a white, massive granite dike intruded into the No. 3 coal seam (Fig. 3). The dike shows large lateral variations from zero to a few meters wide. Concentric weathering and bleaching were observed on the surface of the white granite dike. Three coal samples (B1, B2 and B3) were collected over a broad area at varying distances from the intrusion (Fig. 3).

3.1.3. Pattern-III in Zhuzhuang mine

Floor intrusion by sill (pattern-III) was studied in the Zhuzhuang mine, Huaibei coalfield (Table 1). The Zhuzhuang mine is located north of Huaibei city, Anhui province. Geologically, it is part of the southern limb of the Zahe syncline in Huaibei Coalfield, where Nos. 4, 5 and 6 coal seams of the lower Shihezi Formation (Permian) are the major mining seams. The thickness of Nos. 4, 5 and 6 coal seams are commonly 1.5–2 m, 2.8–3.2 m and 2–3 m, respectively. In this mine, intrusive rocks are mostly sills but with dikes in some places. The sills extend laterally along the roof or floor of the coal seams. Close to the coal seam/sill contact, most high volatile bituminous coals have turned into cokes.

The selected geological profile was located in the No. 25810 working face with the depth of 180 m from surface. Geologically, the site is close to a small syncline. A gray dioritic porphyrite locally intruded
along the floor of the No. 5 coal seam (Fig. 4). In locations without the sill, the No. 5 coal seam is roofed by a light-gray sandstone and overlies sandy shale and mudstone. Six samples were collected across the floor to the roof at a space of approximately 0.5 m, with the first sample taken directly at the sill/coal contact (Fig. 4).

### 3.1.4. Pattern-IV in Guoerzhuang mine

Coalbed roof intrusion by sill (pattern-IV) was investigated in the Guoerzhuang mine, Handan coalfield (Table 1). The Guoerzhuang mine is located between Handan and Wuan city (Fig. 1). The Pennsylvanian–Permian strata are the main coal bearing formations and among them the No. 2 coal seam (2.81 m in average) of the Shanxi Formation and No. 9 (2.96 m in average) coal seam of the Taiyuan Formation are the main mining seams.

In this mine, the No. 9 coal seam was strongly influenced by sheet-like sills and lenticular dikes. The dikes commonly show thickening, thinning-out, or bifurcating in the coal seam. These dikes are compositionally diorite, monzonite and diorite-porphyrite and were thought to have intruded during the Cretaceous Yanshanian Orogeny. The dikes were commonly broken by epigenetic faults.

Pattern-IV was studied in the No. 29102 working-face, the second pit of the Guoerzhuang mine. In this location, the diorite-porphyrite sill was intruded along the roof of the Shanxi Formation No. 9 coal seam (Fig. 5). Four coal samples (E1, E2, E3 and E4) were collected in this locality. In the sampled profile, the No. 9 coal seam was divided into a 1.1-m-thick upper layer and a 1-m-thick lower layer. Between the two layers are interbedded sandy shale and black siltstone. Sample E1 was taken directly from the upper layer, 0.8 m away from the sill, whereas E2, E3 and E4 were taken from the lower seam with distance of 0.85 m, 1.3 m and 1.55 m from the sill, respectively.

### 3.1.5. Pattern-V in Tao-1 mine

Dual intrusions of roof and floor by sills (pattern-V) were studied in the Tao-1 mine (Table 1). The Tao-1 mine is located between Handan and Wuan city (Fig. 1). In the mine, the No. 2 coal seam of the Shanxi Formation (Permian) and Nos. 8 and 9 coal seams of the Taiyuan Formation (Pennsylvanian) are the main minable coal seams. The No. 2 coal has a thickness of 0.79–4.58 m (3.5 m in average) and the unaltered coals are mainly high to medium volatile bituminous coals (VRr of about 0.9%–1.3%) in this mine. Igneous intrusions are widespread in the mine and they intrude into the coal seams along the floor, roof or middle of coal seams. Both coal seams and intrusive bodies are laterally unstable; in some cases the coal seams are completely cut by intrusive rocks. The intrusive rocks were found to be cut through by late-stage fractures and were inferred to have formed during the Late Cretaceous Yanshanian Orogeny.

The sampling location is the No. 12701 working face in the mine (Fig. 6), where two sills intruded the roof and floor of the No. 2 coal seam, respectively. Both sills are composed of dioritic porphyry. Between the two sills, the 2.9-m-thick No. 2 coal seam contains a 0.2-m-thick carbonaceous shale in the middle. Five coal samples (D1–D5) were collected downward from the roof. Among these, D1 and D2 were sampled above

---

**Table 1**

Five different igneous intrusion patterns investigated in this study.

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Mine</th>
<th>Coalfield</th>
<th>Form</th>
<th>Occurrence</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Hongling</td>
<td>Hongyang</td>
<td>Dike</td>
<td>Nervation-like</td>
<td>Cut through coal seam</td>
</tr>
<tr>
<td>II</td>
<td>Mengzhuang</td>
<td>Huaihai</td>
<td>Dike</td>
<td>Lens-like</td>
<td>Cut in coal seam</td>
</tr>
<tr>
<td>III</td>
<td>Zhuzhuang</td>
<td>Huaihai</td>
<td>Sill</td>
<td>Sheet-like</td>
<td>Intrude along floor of coal seam</td>
</tr>
<tr>
<td>IV</td>
<td>Guoerzhuang</td>
<td>Handan</td>
<td>Sill</td>
<td>Sheet-like</td>
<td>Intrude along floor of coal seam</td>
</tr>
<tr>
<td>V</td>
<td>Tao-1</td>
<td>Handan</td>
<td>Sill</td>
<td>Sheet-like</td>
<td>Intrude both roof and floor of coal seam</td>
</tr>
</tbody>
</table>
VRbc, the birefringence coefficient that is equal to \((VR_{max} - VR_{min})/VR_{max}\). *na, not analyzed.*

Samples HL12-1 and HL12-2 were collected from the unaltered (by intrusion) area.

### Table 2

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Mine</th>
<th>Coalfield</th>
<th>Coal seam</th>
<th>Macroscopic description</th>
<th>VRmin (%)</th>
<th>VRmax (%)</th>
<th>VRr (%)</th>
<th>VRbc (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Zhuzhuang</td>
<td>Huabei</td>
<td>No. 5</td>
<td>Gray dense coke</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>A2</td>
<td>Zhuzhuang</td>
<td>Huabei</td>
<td>No. 5</td>
<td>Semi-dull coal</td>
<td>1.47</td>
<td>1.55</td>
<td>1.52</td>
<td>5.16</td>
</tr>
<tr>
<td>A3</td>
<td>Zhuzhuang</td>
<td>Huabei</td>
<td>No. 5</td>
<td>Semi-dull coal</td>
<td>2.00</td>
<td>2.27</td>
<td>2.19</td>
<td>11.89</td>
</tr>
<tr>
<td>A4</td>
<td>Zhuzhuang</td>
<td>Huabei</td>
<td>No. 5</td>
<td>Granular-blocky semi-dull coal</td>
<td>1.44</td>
<td>1.57</td>
<td>1.50</td>
<td>8.28</td>
</tr>
<tr>
<td>A5</td>
<td>Zhuzhuang</td>
<td>Huabei</td>
<td>No. 5</td>
<td>Crumpled semi-dull coal</td>
<td>1.79</td>
<td>1.94</td>
<td>1.85</td>
<td>7.73</td>
</tr>
<tr>
<td>A6</td>
<td>Zhuzhuang</td>
<td>Huabei</td>
<td>No. 5</td>
<td>Semi-bright coal</td>
<td>1.48</td>
<td>1.57</td>
<td>1.53</td>
<td>5.73</td>
</tr>
<tr>
<td>B1</td>
<td>Mengzhuang</td>
<td>Huabei</td>
<td>No. 3</td>
<td>Mylonitic semi-dull coal</td>
<td>3.15</td>
<td>4.45</td>
<td>3.54</td>
<td>25.21</td>
</tr>
<tr>
<td>B2</td>
<td>Mengzhuang</td>
<td>Huabei</td>
<td>No. 3</td>
<td>Tegular semi-bright coal</td>
<td>3.35</td>
<td>4.65</td>
<td>3.93</td>
<td>27.96</td>
</tr>
<tr>
<td>B3</td>
<td>Mengzhuang</td>
<td>Huabei</td>
<td>No. 3</td>
<td>Mylonitic semi-dull coal</td>
<td>3.10</td>
<td>3.43</td>
<td>3.31</td>
<td>9.62</td>
</tr>
<tr>
<td>D1</td>
<td>Tao-1</td>
<td>Handan</td>
<td>No. 2</td>
<td>Bright coal</td>
<td>4.68</td>
<td>6.72</td>
<td>5.68</td>
<td>30.36</td>
</tr>
<tr>
<td>D2</td>
<td>Tao-1</td>
<td>Handan</td>
<td>No. 2</td>
<td>Semi-bright coal</td>
<td>5.57</td>
<td>7.15</td>
<td>6.10</td>
<td>22.10</td>
</tr>
<tr>
<td>D3</td>
<td>Tao-1</td>
<td>Handan</td>
<td>No. 2</td>
<td>Semi-bright coal</td>
<td>1.82</td>
<td>1.94</td>
<td>1.87</td>
<td>6.190</td>
</tr>
<tr>
<td>D4</td>
<td>Tao-1</td>
<td>Handan</td>
<td>No. 2</td>
<td>Semi-bright coal</td>
<td>5.42</td>
<td>6.70</td>
<td>6.17</td>
<td>19.10</td>
</tr>
<tr>
<td>D5</td>
<td>Tao-1</td>
<td>Handan</td>
<td>No. 2</td>
<td>Semi-bright coal</td>
<td>5.23</td>
<td>6.50</td>
<td>5.98</td>
<td>19.54</td>
</tr>
<tr>
<td>E1</td>
<td>Guerzhuang</td>
<td>Handan</td>
<td>No. 9</td>
<td>Clastic semi-dull coal</td>
<td>3.99</td>
<td>4.38</td>
<td>4.20</td>
<td>8.90</td>
</tr>
<tr>
<td>E2</td>
<td>Guerzhuang</td>
<td>Handan</td>
<td>No. 9</td>
<td>Semi-bright coal</td>
<td>4.85</td>
<td>6.63</td>
<td>5.75</td>
<td>26.85</td>
</tr>
<tr>
<td>E3</td>
<td>Guerzhuang</td>
<td>Handan</td>
<td>No. 9</td>
<td>Semi-bright coal</td>
<td>4.67</td>
<td>5.69</td>
<td>5.38</td>
<td>17.93</td>
</tr>
<tr>
<td>E4</td>
<td>Guerzhuang</td>
<td>Handan</td>
<td>No. 9</td>
<td>Semi-bright coal</td>
<td>4.75</td>
<td>5.77</td>
<td>5.48</td>
<td>17.68</td>
</tr>
<tr>
<td>G1</td>
<td>Hongling</td>
<td>Hongyang</td>
<td>No. 12</td>
<td>Coked coal</td>
<td>2.32</td>
<td>2.61</td>
<td>2.49</td>
<td>11.11</td>
</tr>
<tr>
<td>G2</td>
<td>Hongling</td>
<td>Hongyang</td>
<td>No. 12</td>
<td>Semi-dull coal</td>
<td>2.54</td>
<td>2.80</td>
<td>2.70</td>
<td>9.290</td>
</tr>
<tr>
<td>G3</td>
<td>Hongling</td>
<td>Hongyang</td>
<td>No. 12</td>
<td>Semi-dull coal, crumpled, banded semi-bright</td>
<td>2.45</td>
<td>2.90</td>
<td>2.69</td>
<td>15.52</td>
</tr>
<tr>
<td>G4</td>
<td>Hongling</td>
<td>Hongyang</td>
<td>No. 12</td>
<td>Semi-dull coal; crumpled, banded semi-bright</td>
<td>2.45</td>
<td>2.90</td>
<td>2.71</td>
<td>15.52</td>
</tr>
<tr>
<td>D1</td>
<td>Tao-1</td>
<td>Handan</td>
<td>No. 2</td>
<td>Bright coal</td>
<td>1.68</td>
<td>1.80</td>
<td>1.74</td>
<td>6.67</td>
</tr>
<tr>
<td>D2</td>
<td>Tao-1</td>
<td>Handan</td>
<td>No. 2</td>
<td>Semi-bright coal</td>
<td>1.14</td>
<td>1.24</td>
<td>1.14</td>
<td>5.73</td>
</tr>
<tr>
<td>D3</td>
<td>Tao-1</td>
<td>Handan</td>
<td>No. 2</td>
<td>Semi-bright coal</td>
<td>1.14</td>
<td>1.24</td>
<td>1.14</td>
<td>5.73</td>
</tr>
<tr>
<td>D4</td>
<td>Tao-1</td>
<td>Handan</td>
<td>No. 2</td>
<td>Semi-bright coal</td>
<td>1.14</td>
<td>1.24</td>
<td>1.14</td>
<td>5.73</td>
</tr>
<tr>
<td>D5</td>
<td>Tao-1</td>
<td>Handan</td>
<td>No. 2</td>
<td>Semi-bright coal</td>
<td>1.14</td>
<td>1.24</td>
<td>1.14</td>
<td>5.73</td>
</tr>
<tr>
<td>E1</td>
<td>Guerzhuang</td>
<td>Handan</td>
<td>No. 9</td>
<td>Clastic semi-dull coal</td>
<td>3.99</td>
<td>4.38</td>
<td>4.20</td>
<td>8.90</td>
</tr>
<tr>
<td>E2</td>
<td>Guerzhuang</td>
<td>Handan</td>
<td>No. 9</td>
<td>Semi-bright coal</td>
<td>4.85</td>
<td>6.63</td>
<td>5.75</td>
<td>26.85</td>
</tr>
<tr>
<td>E3</td>
<td>Guerzhuang</td>
<td>Handan</td>
<td>No. 9</td>
<td>Semi-bright coal</td>
<td>4.67</td>
<td>5.69</td>
<td>5.38</td>
<td>17.93</td>
</tr>
<tr>
<td>E4</td>
<td>Guerzhuang</td>
<td>Handan</td>
<td>No. 9</td>
<td>Semi-bright coal</td>
<td>4.75</td>
<td>5.77</td>
<td>5.48</td>
<td>17.68</td>
</tr>
<tr>
<td>G1</td>
<td>Hongling</td>
<td>Hongyang</td>
<td>No. 12</td>
<td>Coked coal</td>
<td>2.32</td>
<td>2.61</td>
<td>2.49</td>
<td>11.11</td>
</tr>
<tr>
<td>G2</td>
<td>Hongling</td>
<td>Hongyang</td>
<td>No. 12</td>
<td>Semi-dull coal</td>
<td>2.54</td>
<td>2.80</td>
<td>2.70</td>
<td>9.290</td>
</tr>
<tr>
<td>G3</td>
<td>Hongling</td>
<td>Hongyang</td>
<td>No. 12</td>
<td>Semi-dull coal, crumpled, banded semi-bright</td>
<td>2.45</td>
<td>2.90</td>
<td>2.69</td>
<td>15.52</td>
</tr>
<tr>
<td>G4</td>
<td>Hongling</td>
<td>Hongyang</td>
<td>No. 12</td>
<td>Semi-dull coal; crumpled, banded semi-bright</td>
<td>2.45</td>
<td>2.90</td>
<td>2.71</td>
<td>15.52</td>
</tr>
<tr>
<td>H12-1</td>
<td>Hongling</td>
<td>Handan</td>
<td>No. 12</td>
<td>Semi-bright coal</td>
<td>1.81</td>
<td>1.95</td>
<td>1.88</td>
<td>7.18</td>
</tr>
<tr>
<td>H12-2</td>
<td>Hongling</td>
<td>Handan</td>
<td>No. 12</td>
<td>Semi-bright coal</td>
<td>1.68</td>
<td>1.80</td>
<td>1.74</td>
<td>6.67</td>
</tr>
</tbody>
</table>

The intrusion causes lateral discontinuity of coal seams. In areas with extensive intrusions, coal seams may be partially or completely cut or offset by the intrusive rocks. In some cases, intrusive sills form the roof and floor of the entire coal seam. Thus, intrusive rocks not only make the mining more difficult but also increase the potential of accidents of the outburst of coal and gas (Jiang et al., 2011; Saghaﬁ et al., 2008).

The intrusive dikes and sills behave differently in coal-bearing strata of north China. Intrusive dikes commonly cut through coal seams through passageways along fault zones or macroscopic fracture zones. The Hongling profile is an example of intrusive dikes along the downthrown block of a normal fault (Fig. 2), and the Mengzhuang profile is an example of intrusive dikes along low-strength strata (Fig. 3). Intrusive sills commonly occur parallel to coal seams. The Zhuzhuang, Tao-1 and Mengzhuang mines are typical examples of intrusions along the floor, roof and middle of coal seams, respectively (Figs. 3–5).

Intrusive intrusions cause changes in coal structure or texture. Some coals in the vicinity of dikes/sills are metamorphosed into natural coke or coked coal. The distribution of altered coals or cokes is related to the size and orientation of the intrusion body.

In general, from the unaltered area to the intrusion/coal contact, four metamorphic zones of coals can be recognized: normal coal, coked coal, natural coke and mixed coked rock. The mixed coke-rock zone consists mainly of igneous rocks, with some natural coke. Carbonaceous xenoliths and xenocrysts are common in this zone. The natural-coke zone contains of well-developed pores and fractures. Within this zone, with increasing distance from the intrusion/coal contact, subzones of columnar coke, lumpish coke, and granular-texture coke can be distinguished. The coke–coal zone is composed of a disproportionate mixture of natural coke and coal. In this zone, the coal roughly maintains the original bedding but has an altered coke structure. In contrast, the normal coal zone maintains the stratigraphic bedding and does not have coke structure. In this zone, macroscopic petrological features can be distinguished in the field, although the coal rank and coal quality may have been altered by the intrusion. Overall, coal rank increases towards the intrusions, and anisotropy and reaction rims may be found.
It needs to be noted, however, that not all metamorphic zones are present in each case. In most intrusion-influenced profiles, only two or three metamorphic zones can be distinguished. For example, in the Mengzhuang, Yao-1 and Guoerzhuang mines, the coal seams contact directly with igneous rocks, but the natural coke and mixed coke-rock zones were not found. Only in the Zhuzhuang mine were all of the four metamorphic zones found.

3.3. Effects of igneous intrusion upon coal metamorphism and coal quality

When magma intrudes a coal seam, the coal will be chemically decomposed and its physical and chemical properties changed by the abnormal heat. At the same time, metasomatic reactions may occur between the coal and its surrounding rocks, which may incorporate external minerals/elements into the coal. The heat-induced changes in coal metamorphism and coal quality are different among the five investigated intrusion patterns.

3.3.1. Pattern-I igneous intrusion

The sampling profile and the VRr data of pattern-I intrusion are shown in Fig. 2. In this profile, G1 is a coaled coal with VRr of 2.49%. Three altered coals (G2, G3 and G4) have VRr of 2.70%, 2.69% and 2.71%, respectively (Table 2). The VRr of G2, G3 and G4 are distinctly higher than the background values of the two reference samples (1.88% of HL12-1 and 1.74% of HL12-2), but the VRr values of the three coals do not show significant change with distance from the contact. Vitrinite anisotropy results from G3 and G4 (VRr of 15.5%) are slightly higher than that of G2 (VRr of 9.3%). From the Vitrinite reflectance, typical contact metamorphic aureoles are not found surrounding the intrusion body (about 1.8 m wide) in this profile. This is different from those documented from the other coal basins such as Raton, Illinois and Gunnedah Basins (Barker et al., 1998; Cooper et al., 2007; Gurbu and Weber, 2001; Stewart et al., 2005), but it is similar to that of the Midland Valley of Scotland (Murchison and Raymond, 1989; Raymond and Murchison, 1988). The formation of a contact metamorphic aureole is mainly controlled by the maximum temperature \( T_{\text{max}} \) during contact metamorphism. Barker et al. (1998) proposed four cooling models that could be used to evaluate the \( T_{\text{max}} \). The phenomenon seen in our profile can be explained by the combination of the simple conductive model and the convection cell model in Barker et al. (1998), the latter is indicated by a wavy \( T_{\text{max}} \) profile and relatively high temperatures. Because conductive heat transfer would drop to background values at no more than two intrusion body widths from the contact, the metamorphic zonation formed by purely conductive heat transfer should be identical at an equal distance from the intrusion/coal contact (Barker et al., 1998; Cooper et al., 2007). Schimmelmann et al. (2009) proposal that the hydrologic conditions could influence the thermal maturity of coal near igneous intrusions, can be used to explain the VRr profile in this mine. It is likely that a convection cell with local recharge of hydrothermal fluids has resulted in a VRr profile that does not show a smooth decrease away from the contact. It is uncertain, though, whether the temperature change associated with hydrothermal fluids were related to igneous activity of the intrusion body itself or it is a regional phenomenon.

Coal proximate and ultimate analyses show that the effects of the intrusion upon carbon content and ash yields are distinct (Fig. 2 and Table 3). Carbon contents (wt.%) of G1 and G2 (66.84% and 57.72%) are lower than those of G3 and G4 (85.54% and 85.41%). In contrast, ash yields (wt.%) of G1 and G2 (23.73% and 24.64%) are significantly higher than those of G3 and G4 (5.32% and 5.34%). The reason for the high ash yield near the contact is possibly owing to the formation of carbonates in veins and cell fillings (Finkelman et al., 1998). These carbonates were likely formed hydrothermally from fluids associated with the gradual cooling after the igneous intrusion (Mastalerz et al., 2009; Schimmelmann et al., 2009). It seems that the volatile matter content of the coal does not show a common decrease toward the contact. This indicates that during contact metamorphism, volatiles may either never be released or later be reabsorbed by the seam close to the contact (Creeiling and Dutcher, 1968). According to Dutcher et al. (1966), volatile matter may not be an appropriate parameter for defining changes in coals influenced by contact metamorphism because of the possible interference of inorganic materials (especially carbonates) from adjacent areas.

Comparison of the vitrinite reflectance and coal quality data indicates that 1) G1 and G2 are very similar; 2) G3 and G4 are also similar; 3) data of G3 and G4 are significantly different from those of G1 and G2. Since the distance from G2 to the intrusion/coal contact is about 2 m, the data indicate that the direct influence by the intrusion is at least 2 m distant from the contact. This is approximately the width of the intrusion bed. Within such a short distance, the heat influence should be dominated by simple heat-conduction from the dike. However, comparing with the two referenced background samples indicates that the area indirectly influenced by the dike may be much longer than one intrusion width. The indirect influence was likely from the heat convection cell with local recharge of the hydrothermal fluids (Barker et al., 1998).

3.3.2. Pattern-II igneous intrusion

The pattern-II igneous intrusion was studied in the Mengzhuang mine, where a dike intruded directly into the coal seams (Fig. 3). The heat-induced changes in coal metamorphism and coal quality are presented in Tables 2 and 3.

In this profile, the ranks of three selected coals were elevated to meta-anthracite with a VRr of 3.31%–3.93%. In comparison, the rank of coal with the distance away from the intrusion in this mine is HVB. Moreover, both ash (average vol. of 25.55 wt.%) and moisture (average of 5.13 wt.%) contents of these altered coals are significantly higher than unaltered coals in this mine (Liu et al., 2009). They are also higher than most coals that have been affected by the heat from the other four intrusion profiles. It thus appears that both the duration of heating and the heating rate are high during the intrusion inducing high-grade metamorphism of the coals. More importantly, regionally elevated temperatures probably result from the intrusion-triggered hydrothermal convection, not the conduction. It is because conduction is only significant on a local scale, while the convective heat transfer can occur on a large scale elevating the background rank of coal (Barker et al., 1998). The hydrothermal activity is responsible for the high coal rank, which was proven by underground hydrological investigations in this mine. Another possible alternative explanation is that the heating duration controls vitrinite reflectance in addition to the \( T_{\text{max}} \). Moreover, the hydrothermal product from the acidic granite dike was trapped in the coals, which is a major reason for the high moisture and ash contents in the coals.

For the three coal samples, it seems that VRr generally increases toward the contact following a concave-down profile. Samples B3 (0.9 m from the contact), B2 (0.5 m from the contact) and B1 (0.1 m from the contact) have a VRr of 3.31%, 3.93% and 3.54% respectively. Analogously, the carbon content also increases toward the contact following a similar rule. It should be noted that an abrupt drop-off of reflectance in the immediate vicinity of the contact (sill or dike) was also found in other basins (Barker et al., 1998; Cooper et al., 2007; Singh et al., 2008). This kind of reversal of reflectance trend approaching a sill and dike margins was also reported by Khorosani et al. (1990), who suggested that the reversal phenomenon may be related to more general molecular disordering due to the thermal effects of intrusions. Resulting from the intrusion heat, the vitrinite was transformed to carbonaceous material with a turbostratic or para-crystalline structure or even to fully ordered graphite. Barker et al. (1998) indicated that this kind of profile is induced by a heat convection cell with local recharge of the hydrothermal fluids occurring at
the time of intrusion. Furthermore, underground geological investigation shows the coal was further altered by epigenetic tectonic-heat. At the sample location the coal was found to be intensively deformed by tectonic stress as shown by mylonitic structures in samples B1–B3 (Table 2). The coal metamorphism here resulted from both magma heat by convection cell model and epigenetic tectonic-heat. This is also the reason for the complex profile of coal quality data (e.g., ash and moisture) versus the distances from the contact.

Bireflectance coefficients of the three coal samples are very high and increase toward the contact, which means that the vitrinite anisotropy increases toward the contact.

3.3.4. Pattern-IV igneous intrusion

On the coal seam (Fig. 4), the A1 within 0.5 m of the dike was converted to natural coke by the heat of the intrusion. It seems that for Samples A6–A2, the VRr generally increases toward the igneous sill floor and the increase follows two concave-down profiles. Samples A6 and A2 have lower VRr (1.5%) than the other samples, while A3 has a maximum VRr of 2.19%. This situation is similar to that in pattern-II. The bireflectance coefficient data show a similar tendency to VRr; i.e., an increase followed by a concave-down curve (Fig. 4). Thus, coal rank and the anisotropy of vitrinite were enhanced by the intrusion; however, a typical contact metamorphic aureole was not found in this profile either. This indicates that the convection cell model also fits well for the metamorphism in this profile.

The metamorphic aureole of this intrusion pattern is nonlinear because several factors may affect this signature. Besides the convection cell model which is the main control for the formation of VRr profiles in this mine, other factors including intrusion geometry, rheological behavior of coal, and the thermal properties of the surrounding rocks at the contact of the intrusion. The geometry of intrusion contact appears to play an important role in the style of contact metamorphism. The igneous sill floor is a mixture of dioritic porphyrite and sandy shale, and its lens-like attitude results in heat heterogeneity for the overlying coal samples in the vertical section (Fig. 4). Moreover, carbonaceous shale interbedded in the coal seam may also influence the conduct of heat in the coal seam. Finally, multiple episodes of magma intrusion have induced multiphase heat influences on the coal seam.

3.3.5. Pattern-V igneous intrusion

At the sampling spot of the Tao-1 mine (Fig. 6), the roof and floor of the coal seam were replaced by an intruded dioritic porphyry. A thin carbonaceous shale with a thickness of 0.2 m is interbedded in the middle of the coal seam. This situation resulted in the formation of two symmetrical contact metamorphic aureole profiles around the 0.2 m-thick interlayer, one in the upper interlayer and the other in the lower interlayer (Tables 2 and 3). For the upper contact metamorphic zone, D1–D3, progressively farther from the floor contact, have decreasing VRr, moisture content but increasing volatile content, ash yield and hydrogen content. D1 and D2 have much higher VRr (5.68% and 6.10%) than D3 (1.87%), because D3 was taken at a distance of about 1.5-times the intrusion thickness from the roof, where the carbonaceous shale isolated the heat from the roof contact. For the same reason, in the lower coal metamorphic zone, samples D5–D3, progressively farther from the floor contact, have decreasing VRr, moisture content and ash yield, but increasing volatile content and hydrogen content. D5 and D4 have much higher VRr (5.98% and 6.17%) than D3. For both metamorphic zones, the relationship between the distance and VRr is similar to the relationship between the distance and VRr. The varying profiles of VRr and VRbc in this mine are very similar to the situation in the Gunnedah Basin, Australia, where a coal seam was intruded by both upper and lower sills (Gurba and Weber, 2001). Although a slight decreasing of VRr was found in the upper and lower metamorphic zones, it was suggested that the simple conductive mode proposed by Barker et al. (1998) contributed to the metamorphism in this profile.

3.3.6. Summary of thermal coal metamorphism caused by igneous intrusions

As discussed above, several factors may influence the characteristics of thermal metamorphism of igneous intrusions. These factors include rates and duration of heat transfer, heat conductivity/convection model, intrusion forms (dike or sill) and size, the distance from the contact, and the thermal properties of the surrounding rocks at the contact of the intrusion. Intrusive body types, which may be either igneous dike or sill, are important for thermal influence. For example, without consideration of the size of the intrusion bodies, then 1) the thermal influence of a sill is generally higher than that of a dike, and 2) the grade of coal metamorphism resulting from cut-in coal seam by dike is higher than the cut-through coal seam by dike. It was also found that coal metamorphism significantly increases toward the contact within one or two intrusion widths; however, at the location of coal–cokc contact, coal rank may appear to be very low. The reversal phenomenon of vitrinite reflectance may be induced by a heat convection cell with local recharge by the hydrothermal fluids present at the time of intrusion. Furthermore, the degree of igneous metamorphism is also related to the contact between the intrusion body and the coal. The heat effect may be different for different types of rocks surrounding the coal. According to Barker et al. (1998), the heating duration within the contact zone of an intrusion should be greater for coal or organic shale than sandstone because thermal conductivity is the lowest for coal, lower for shale, and higher for sandstone. In a certain situations, interbedded shale can act as a nonconductor isolating the heat from the intrusion (e.g., pattern-V in Fig. 6).
In the five intrusion patterns (Figs. 2–6), the intrusion altered coals all show increasing ash, vitrinite reflectance and vitrinite anisotropy, and decreasing volatile matter near the intrusion. This pattern agrees well with most studies from other coal basins (e.g., Dai and Ren, 2007; Mastalerz et al., 2009; Rimmer et al., 2009; Saghafi et al., 2008; Singh et al., 2008; Stewart et al., 2005). However, not all patterns display a typical contact metamorphic aureole, in which the VRr progressively decreases to the ambient value within the distance of 1–2 times the thickness of the intrusion. Except for pattern-V with two distinct contact metamorphic aureoles, the other patterns are very complex. Pattern-III is a typical convection cell heating model in which the VRr shows a wave-like form in the vitrinite-reflectance profile and extended zone of high VRr values far from the sill contact. Pattern-I is an integration of a simple conductive model and a convection cell model in which the VRr dramatically decreases away from the contact within one intrusion width but does not return to the reference value until a distance of several intrusion widths. As for pattern-II and pattern-IV, VRr profiles are complex because the coal ranks were elevated not only by the contact metamorphism but also by other thermal metamorphism processes, such as hydrothermal and tectonic-heat metamorphism.

3.4. The effects of intrusion upon methane adsorption capacity

As discussed above, when the coal was altered by igneous intrusion, its structure and chemical composition were changed. These changes can influence its physical characteristics, such as the adsorption capacity for gas. Coal samples from four profiles (patterns) were investigated in terms of the influence of the intrusion on methane adsorption capacity. For gas adsorption capacity, the Langmuir volume (VL) represents the maximum adsorption capacity of coals at a constant temperature. In this study, the data of VL at dry-ash-free (daf) basis were used to evaluate the methane adsorption capacities of the coals (Table 3).

3.4.1. Methane adsorption capacity of analyzed coals

In the Tao-1 mine, the VL of D1, D2, D4 and D5 are very low with the values of 0.76, 0.75, 0.78 and 1.08 m$^3$/t, respectively (Table 3). Yang et al. (1988) indicated that the unaltered coals in this mine have average vitrinite reflectance of about 1.9%, which corresponds to a presumable VL of 18.9 m$^3$/t according to Yao and Liu (2007). Thus, the adsorption capacity of the coals in this profile was found to be reduced by the intrusion.

In the Guoerzhuang mine, the VL data of four altered coal samples show very large differences. E1, E2, E3 and E4 have the values of 5.03, 2.77, 15.96, and 3.76 m$^3$/t respectively (Table 3). It seems that adsorption capacity does not show any correlation with the distance from the contact.

In the Hongling mine, the isothermal adsorption curves of three altered samples and two reference samples show that adsorption capacity was reduced by the intrusion (Fig. 7 (a)). The altered coals of G2–G4 have much lower adsorption capacity than the unaltered coals, HL12-1 and HL12-2. The VL of the altered coals was reduced by about 29% on average. In addition, three altered coals, G2, G3 and G4 have a VL of 18.06, 21.01 and 18.91 m$^3$/t respectively, which means that no linear increase/decrease tendency was found among these coals; however, the coal near the contact seems to have a low adsorption capacity.

In the Zhuzhuang mine, the isothermal adsorption curves of three altered samples show that A3, A4 and A5, progressively farther from the contact, have a VL of 21.87, 17.46 and 13.13 m$^3$/t respectively (Fig. 7(b)). These values are much higher than that of the unaltered coal with an average VL of 7.6 m$^3$/t. Moreover, a clear tendency of adsorption capacity increasing toward the contact was found in the three coals.

Fig. 7. Methane isothermal adsorption curves of thermally metamorphosed and unaffected adjacent coals. (a) three thermally metamorphosed coal samples (G2–G4) sampled near a dike and two unaltered coals (HL12-1 and HL12-2), in Hongling mine; (b) Coals sampled near an igneous sill floor in the Zhuzhuang mine.

3.4.2. Discussions on the influence of the intrusion

Of the investigated mines, only the Hongling mine has the dike intrusion pattern, while the others are of sill intrusion patterns. However, only in the Zhuzhuang profile did we find a positive effect of intrusion on adsorption capacity. The adsorption capacity of altered coals in the Hongling, Tao-1 and Guoerzhuang mines is reduced (even significantly reduced) by the intrusion. Therefore, it seems that the intrusion forms (dike or sill) and their size and morphologic characteristics have no direct correlation with the changes in adsorption capacity. However, intrusion induced changes including degree of coal rank, ash, moisture, volatile matter, coal structure and pore characteristics work together to influence the adsorption capacity of the coal.

It is most likely that the variable degree of coal rank has a crucial effect on the adsorption capacity because of the coal’s physical and chemical structure characteristics are dominated by coal rank. Raymond and Murchison (1989) indicated that for studying the alteration by intrusion, rank at the time of intrusion was also important. The level of organic maturity, sediment compaction and volume of pore water are critical factors influencing the degree of alteration produced by an intrusion. It is very important to note that not only pre-intrusion coal rank but also the altered coal rank need to be taken into consideration.
A typical example is found in the Zhuzhuang profile (Fig. 4), where the intrusion has elevated coal rank from HVB (VRr of 0.83–0.87%, data from Yao and Liu, 2007) to semi-anthracite (VRr of 1.50–2.19%). As a result, the adsorption capacity has been elevated by the intrusion by about 130% (Table 3). This agrees well with the common tendency of VL and VRr in unaltered coals in north China (Yao and Liu, 2007). As shown in Fig. 8, for unaltered coals (normal geothermal metamorphic coals), the VL shows an inverse-U-shaped relationship with the increase in VRr. The relationship comprises three typical phases, i.e. rapid increasing (P1), steady state (P2) and rapid decreasing (P3) phases (Fig. 8). For the investigated coals in this profile, magma intrusion has induced the rank changes corresponding to P1 in Fig. 8 accounting for the increased VL.

In the Hongling profile, the intrusion has elevated coal rank from LVB (VRr of 1.74–1.88%) to anthracite (VRr of 2.69–2.71%). However, the adsorption capacity has been reduced (about 29% on average) by the intrusion (Table 3). As shown in Fig. 8, for unaltered coals with the rank of LVB to anthracite (P2 in Fig. 8), the VL keeps a steady state with the increase in VRr. This cannot explain the decrease of VL in the coals in this profile. In other words, coal rank in the P2 phase does not induce direct negative influences on the adsorption capacity. The factors, including structure and composition of the coals, pore development and other geological characteristics at the sampling spot, should be taken into consideration. On the one hand, contact metamorphism resulted in stronger influences on coal structure and compositions than geothermal metamorphism for an equal degree of coal rank; on the other hand, changes in porosity and pore structure by contact metamorphism are stronger than geothermal metamorphism. Mastalerz et al. (2009) indicated that strongly decreasing mesopore and micropore volumes in the altered zone, together with frequent cleat and fracture filling by calcite, are the main reasons for the deteriorating conditions for coalbed gas adsorption. This explains the situation in this profile. The characteristics of porosity and pore structure development resulting from the intrusion and their implications will be discussed in a future paper.

Finally, in the Guoerzhuang and Tao-1 profiles, intrusions have elevated coal rank from LVB to meta-anthracite with a VRr of >5% (Table 2). Accordingly, the adsorption capacities of the coals were dramatically reduced by an order of magnitude (Table 3). As shown in Fig. 8, as for the unaltered coals with VRr >5% in north China, the adsorption capacity is very low with an approximate VL value of <5 m³/t. For the coals in the two mines, the coal ranks have been elevated to VRr >5%. Thus, their adsorption capacities are very low. Furthermore, the altered coals have very high density, very low porosity and poorly-connected pore structures, also accounting for the low induced adsorption capacities (Mastalerz et al., 2009).

To clearly disclose the relationships between adsorption capacity and coal rank for altered coals, both relationships of VL vs. VRr and VL vs. VRbc are given in Fig. 9. As shown in Fig. 9 (a), the VL shows a negative relationship with VRr. For the coals with VRr of 1.5–2.7%, their adsorption capacities are intermediate (VL of 13.1–17.5 m³/t), and the VL slightly decreases with the increase in VRr. Comparably, for the coals with VRr >4.2%, their adsorption capacities are low (VL of ≤5 m³/t), and at the same time the VL shows a distinct decrease with the increase in VRr. The VL also shows a negative correlation with VRbc for these coals (Fig. 9 (b)). The two unaltered coals have very low VRbc accompanied by very high VL. Except for E1, the coals with VRbc ≤18% have a VL of ≥13.1 m³/t, while the coals with VRbc >18% have a VL of <3.8 m³/t. Thus, for altered coals (VRr >1.5%), the coal with relatively low coal rank and low anisotropy of vitrinite commonly has high adsorption capacity.

3.4.3. Summary of adsorption capacity change caused by igneous intrusions
Coal is a complex polymeric material with complicated porous structures. Pores in coals include micropore (<10 nm), mesopore (10–100 nm) and macropore (>100 nm). The adsorption capacity of...
coals are mainly related to their organic/inorganic compositions and micropore properties such as porosity, surface area, structure and heterogeneity (e.g., Bustin and Clarkson, 1998; Yao and Liu, 2007; Yao et al., 2008).

Coal compositions and pore property change with increasing coal rank. During coal metamorphism, the third important coalification occurs at VRr of 1.3%–2.1% with the third coalification jump point of 2.1% VRr. As shown in Fig. 8, the P1 corresponds to the third important coalification (VRr < 2.1%) when micropores and the inner surface areas of coals begin to increase rapidly (Bustin and Clarkson, 1998; Gurba and Weber, 2001; Gürdal and Yalcın, 2001). This is the main reason for increasing adsorption capacity in the P1 phase for geothermally metamorphosed coals (Fig. 8). For the altered coals whose VRr have been elevated up to 1.50%–2.19%, their pore characteristics are similar to the thermally metamorphosed coals with equal rank. Therefore, the main reason for the 130% increase of adsorption capacity in the Zhuhuang profile is the increase of micropores by the intrusion. This is consistent with previous research in South Africa that documented the initial covariation of VL and coal rank for both methane and carbon dioxide gases, but constant VL values after VRmax of 2% (Saghafi et al., 2008).

The fourth important coalification occurs at VRr of 2.1%–3.4% with the fourth coalification jump point of 3.4% VRr. During this stage, the mesopore and micropore contents have reached the maximum and thus the adsorption capacity does not show a distinct increase/decrease with increasing coal rank (Fig. 8). However, for altered coals whose VRr are ≥ 2.69%–2.71%, pores have a low proportion of micropores but a high proportion of mesopores and macropores when compared with thermally metamorphosed coals with equal rank. This may be the origin of the 25% reduction in adsorption capacity by intrusion in the Hongling profile.

In the Guoerzhuang and Tao-1 profiles, intrusions have increased coal ranks from LVB to meta-anthracite with VRr of > 4.5%. During the coal metamorphism of anthracites and meta-anthracites stages, coal basic structural units accumulate maximum aromatic layers and form so-called crystallites and at the same time the micropore content and pore surface area rapidly decrease. This may be a main reason for the decrease of adsorption capacity of selected coals in the two profiles. More importantly, the meta-anthracites may totally lose the capacity of adsorption for methane when the intrusion influence is severe.

4. Conclusions

The present study has identified five different igneous intrusion patterns that affect the coal rank, coal quality and adsorption capacity.

(1) In five investigated intrusion patterns, altered coals commonly show increasing ash, vitrinite reflectance and its anisotropy and decreasing volatile matter adjacent to the intrusion. The changes of coal metamorphism and coal quality are mainly related to the factors including emplacement temperature and heating model, intrusion forms (dike or sill) and size, the distance from the contact, and the thermal properties of the surrounding rock at the contact of the intrusion.

(2) Only pattern-V was found to have two distinct contact metamorphic aureoles within a distance of 1–2 times of the width of the intrusion body. Patterns-I through pattern-IV show wavy vitrinite-reflectance and variable ash and volatile contents. Pattern-III is a typical convection cell heating model where VRr shows a wave-like form in the vitrinite-reflectance profile and extended zone of high VRr values far from the sill contact. Pattern-I is an integration of a simple conductive model and a convection cell model in which VRr dramatically decreases from the contact within one intrusion width, but it does not return to the reference value until a distance of several intrusion widths. As for pattern-II and pattern-IV, the VRr profiles are complex because the coal ranks were elevated not only by contact metamorphism, but also by other thermal metamorphism processes such as hydrothermal and tectonic-heat metamorphism.

(3) The relationships between altered coal rank and altered adsorption capacity are mainly related to changes of micropores characteristics and coal structures resulted from three important coalification jumps during contact and other heat metamorphism. For altered bituminous coals and semi-anthracites with VRr < 2.1%, adsorption capacity is increased by intrusion. For the altered semi-anthracites and anthracites with VRr of 2.1%–3.4%, adsorption capacity is moderately reduced. For altered anthracites and meta-anthracites with VRr of > 3.4%, adsorption capacity is significantly reduced. This is due to the accumulating of coal basic structure units and decreasing of micropores during the coal metamorphic process.

Acknowledgments

This research was funded by the National Basic Research Program of China (Grant Nos. 2009CB219604), National Natural Science Foundation of China (Nos. 21072099 and 40972107), Fundamental Research Funds for Central Universities (Grant Nos. 2010ZYG04 and 2011YLX030), National Major Research Program for Science and Technology of China (2011ZX05034-001) and Program for Changjiang Scholars and Innovative Research Team in University (Grant No. IRT0864). Professors Gangjing Jiang and Robert F Finkelstein are greatly appreciated for their assistance in checking English of the manuscript.

References


