Experiments on the effects of igneous sills on the physical properties of coal and gas occurrence

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A B S T R A C T
The violent igneous intrusion produced two layers of igneous cover sills and an annular dike and led to several gas dynamic accidents and repeated phenomena of unusual gas emission in the Yangliu Coal Mine in Huabei Coalfield, China. Six coal samples were collected at different distances from the igneous sills for the experiments to study the physical properties of coal and gas adsorption/desorption properties. The results indicate that the vitrinite reflectance and ash and moisture contents increase irregularly while the volatile content decreased irregularly with decreasing distance from the igneous sills. The coal mass being researched was divided into three zones based on the degree of thermal erosion: strong thermal erosion zone, weak thermal erosion zone and no thermal erosion zone. The metamorphism of the coal in two adjacent zones changes gradually rather than suddenly. The thermal erosion caused by the igneous intrusion volatilized the organic matters, left a large number of pyrolysis stomata, greatly increased the volume and surface area of pores, especially micropores, and improved the gas adsorption and preserved abilities of the coal. The thermal erosion, gas trapping and tectonic stress effects of the igneous intrusion on the underlying coal mass increased the outburst risk of coal covered by igneous sills to a greater extent than that of coal without the effect of igneous intrusion. The regions covered by igneous sills are sites where the gas resource is enriched, and the engineering applications show that the gas extraction technology via surface wells can ensure the safe and high-efficiency co-exploitation of coal and gas and be of significant commercial value.

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1. Introduction
Intrusive igneous rocks are commonly associated with coal and are present in many coal mines throughout the world (Jiang et al., 2011b). Igneous intrusion provides a high-temperature and high-pressure environment for coal seams; so the shape, lithologic characteristics and occurrence of the igneous rocks play extremely important roles in coal quality, gas occurrence and outburst control. Many scholars worldwide have studied the physical and chemical properties of coal with the thermal erosion of igneous rocks from the perspective of petrographic and geochemical analyses, pore structures and gas adsorption/desorption properties (Beamish and Crosdale, 1998; Dai and Ren, 2007; Golab and Carr, 2004; Gurba and Weber, 2001; Rimmer et al., 2009; Stewart et al., 2005; Yao et al., 2011). The thermal erosion effects of igneous rocks on coal increase the vitrinite reflectance, decrease the volatile content and promote the metamorphism of coal (Wang et al., 2013a). After the organic matter in coal was volatilized, a large number of pyrolysis stomata remained, promoting the generation of pores, especially micropores, and thus improving the gas adsorption and desorption abilities of coal (Yao and Liu, 2012).

The thermal erosion of igneous rocks increases the rate of the secondary hydrocarbon generation of coal (Dias et al., 2014), and the igneous sills covering the coal seam trap and preserve the gas (Wang et al., 2013c), resulting in a rapid increase in the gas content and pressure of coal within the igneous intrusion regions. In addition, the igneous rocks intruded the coal and rock strata like wedges, transforming the existing geological structure to a certain extent and causing the localized concentration of tectonic stress (Cao et al., 2007). In short, the risk of coal and gas outburst within the igneous intrusion regions is greater than that outside the igneous intrusion regions (Chen et al., 2012; Wang et al., 2013b).
Numerous coal and gas outburst accidents have occurred in coal mines in China, for example, in the Haizi Coal Mine, the Wolonghu Coal Mine and the Yangliu Coal Mine in Huaibei; the Daxing Coal Mine in Tiefa; and the Anlin Coal Mine in Anyang, due to igneous intrusion (Jiang et al., 2011a).

A violent igneous intrusion produced two layers of igneous coversills and an annular dike in Yangliu Coal Mine in Huaibei Coalfield, China. Four gas-dynamic accidents and repeated phenomena of unusual gas emission, which were associated with igneous intrusion, occurred during the tunneling and mining of coal seam #10. By experimenting and analyzing the physical properties of coal samples at different distances from the igneous sills, we discuss the thermal erosion effects of igneous rocks on the physical properties of the coal and on the gas occurrence. The results may provide useful references for coal and gas control and high-efficiency co-exploitation of coal and gas under similar geological conditions.

2. Geological setting

2.1. Mine introduction

Yangliu Coal Mine, located in Suixi County of Anhui Province, China, is outburst-prone with a production of 1.8 Mt/a (Fig. 1). Yangliu Coal Mine contains nine coal seams, of which coal seams #82 and #10 are the most mineable. Coal seam #10, which is located at an intermediate height in the Shanxi Formation, has an average thickness of 3.19 m. Coal seam #82, which is 74 m above coal seam #10, is 1.87 m in average thickness.

2.2. Occurrence of igneous rock

Nearly all of the coal seams in Yangliu Coal Mine have experienced extensive igneous intrusion. Although mining area #107 did not undergo igneous intrusion, three layers of igneous sills intruded mining areas #104 and #106 (Fig. 1). Igneous sill #1, with an average thickness of 33.40 m, is located 58 m above coal seam #51. Igneous sill #2, with an average thickness of 40.24 m, is located 67 m below igneous sill #1, 29 m over coal seam #82 and 102 m above coal seam #10. Igneous sills #1 and #2 are called “cover sills”. Igneous sill #3, which possesses a widely varying thickness from 1.66 m to 66.50 m, intrudes coal seam #10 and the underlying rock mass, annularly surrounds the mining areas #104 and #106, and is called an “annular dike”. In addition, both Daniujia Fault and Dai-miao Fault are closed normal faults. The cover sills, annular dike and closed normal faults comprise a natural “gas-preserving box” to preserve the gas in the coal seams.

3. Sampling and experimental methods

3.1. Sampling

Six coal samples were collected from coal seams #82 and #10 of mining area #104 and coal seam #10 of mining areas #106 and #107 (Fig. 1 and Table 1). Coal samples #1 and #2 were collected from coal seam #82 of mining area #104, which is located closer to igneous sill #2 than the other coal samples. Coal samples #3 and #4 were collected from coal seam #10 of mining areas #104 and #106 with a nearly equivalent distance from igneous sill #2. However,
igneous sill #2, which is located above coal sample #3, is thicker than igneous sill #2, which is located above coal sample #4. Coal samples #5 and #6 were collected from coal seam #10 of mining area #107, where no igneous rock was detected.

3.2. Experimental methods

The vitrinite reflectance of the coal samples was tested using a ZEISS microscope photometer with a particle size of less than 0.20 mm. The industrial analysis was performed using a 5EMAG6600 automatic industrial analyzer with a particle size of 0.074–0.20 mm. The scanning electron microscopy (SEM) experiments were carried out using a HITACHI S-3000N microscope. The firmness coefficient of the coal samples was measured using a drop hammer crusher with a particle size of 1–3 mm. The initial gas release rate was measured using a WT-lister with a particle size of 0.20–0.25 mm. The pore volume and surface area of coal were measured with the 9510 automatic mercury porosimeter. The gas adsorption isotherms were obtained with the high-capacity gas adsorption set with the particle size of 0.20–0.25 mm.

4. Experimental results and discussions

4.1. Effect of igneous intrusion on petrographic and geochemical properties of coal

The experimental results of vitrinite reflectance $R_{\text{m, max}}$, industrial analysis, coal firmness coefficient $f$ and initial gas release rate $\Delta P$ from six coal samples are shown in Table 2 and Fig. 2. The $R_{\text{m, max}}$ values of coal samples #5 and #6 are similar, and both are smaller than the $R_{\text{m, max}}$ values of coal samples #1–#4, which increase from 1.19% to 4.41% with decreasing distance from igneous sill #2, which indicates that coal samples #1 and #2 underwent strong thermal erosion, coal samples #3 and #4 experienced weak thermal erosion and coal samples #5 and #6 had no thermal erosion. Thus, the coal mass can be divided into three zones based on the degree of thermal erosion: strong thermal erosion zone, weak thermal erosion zone and no thermal erosion zone. The thermal erosion of the igneous sill affected the coal metamorphism. Coal seam #82 of mining area #104 and part of coal seam #10 of mining area #106 are composed of anthracite ($2.0% < R_{\text{m, max}} < 6.0%$); coal seam #10 of mining area #104 is composed of coking coal ($1.2% < R_{\text{m, max}} < 1.6%$), and coal seam #10 of mining area #107 is composed of 1/3 coking coal ($0.8% < R_{\text{m, max}} < 1.0%$). It is noted that the metamorphism of the coal in two adjacent zones changes gradually rather than suddenly, which differs from the findings of some scholars (Jiang et al., 2011b).

The ash content ($A_{\text{ad}}$) and moisture content ($M_{\text{ad}}$) increased variably, while the volatile content ($V_{\text{daf}}$) decreased variably from 31.28% to 4.20% with decreasing distance from igneous sill #2. The decreasing of $V_{\text{daf}}$ proves that coal metamorphism increases due to the thermal erosion effect of the igneous sill. The experimental results of $M_{\text{ad}}$ are inconsistent with the results of previous studies for two reasons (Jiang et al., 2011b): the igneous sills prevent moisture from escaping, and experimental errors occur.

Scanning electron microscopy (SEM) experiments were performed (Fig. 3). A substantial amount of large pyrolysis stoma associated with igneous intrusion appeared in coal sample #1, whereas a slightly smaller amount of pyrolysis stoma appeared in coal samples #2 and #3, and no pyrolysis stoma appeared in coal samples #4–#6. The results indicate that the thermal erosion from the igneous intrusion increased the rate of the secondary hydrocarbon generation of coal, which resulted in a larger coal gas content and a large number of pyrolysis stoma, and that with increasing distance from and decreasing thickness of the igneous sills, there is weaker thermal erosion and fewer pyrolysis stoma.

4.2. Effect of igneous intrusion on pore structures of coal

The pore structures of coal largely affect the gas adsorption/desorption properties and transport laws (Cai et al., 2013; Clarkson and Bustin, 1999; Clarkson et al., 2013; Labani et al., 2013; Mastalerz et al., 2009; Wu et al., 2010). The pore volume and surface area of the six coal samples were tested based on the decimal classification of apertures (Yu, 1992) (Table 3, Figs. 4 and 5). For a specified coal sample, the volume and surface area of the pores of different apertures vary with in the following order: micropore (3–10 nm) > minipore (10–100 nm) > macropore (>1000 nm) > mesopore (100–1000 nm). The pore volume of different apertures increases with decreasing distance from igneous sill #2, while the pore volume of the micropores increases from 0.0141 cm$^3$/g to 0.027 cm$^3$/g with a faster rate than those of the minipores, mesopores and macropores, indicating that the thermal erosion of igneous intrusion has a greater influence on the generation and development of micropores. The micropores and minipores tend to increase, but the mesopores and macropores barely change within the pore surface area. The trends for pore volume and surface area of pores, especially micropores, and improved the gas adsorption and preserved abilities of coal.

### Table 1
Sampling locations.

<table>
<thead>
<tr>
<th>No.</th>
<th>Location</th>
<th>Elevation (m)</th>
<th>Thickness of igneous sill #2 (m)</th>
<th>Vertical distance from igneous sill #2 (m)</th>
<th>Horizontal distance from annular dike (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>Coal seam #82 above Workface #1014</td>
<td>-502</td>
<td>43</td>
<td>29</td>
<td>407</td>
</tr>
<tr>
<td>#2</td>
<td>Coal seam #82 above Workface #1016</td>
<td>-499</td>
<td>34</td>
<td>28</td>
<td>957</td>
</tr>
<tr>
<td>#3</td>
<td>Intake roadway #1061</td>
<td>-597</td>
<td>54</td>
<td>128</td>
<td>462</td>
</tr>
<tr>
<td>#4</td>
<td>Return roadway #10141</td>
<td>-583</td>
<td>38</td>
<td>115</td>
<td>618</td>
</tr>
<tr>
<td>#5</td>
<td>Return roadway #1071</td>
<td>-535</td>
<td>0</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>#6</td>
<td>Intake roadway #1071</td>
<td>-566</td>
<td>0</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

### Table 2
Experimental results of physical properties of six coal samples.

<table>
<thead>
<tr>
<th>No.</th>
<th>Vitrinite reflectance $R_{\text{m, max}}$ (%)</th>
<th>Industrial analysis</th>
<th>Coal firmness coefficient $f$</th>
<th>Initial gas release rate $\Delta P$ (mmHg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>4.41</td>
<td>2.57</td>
<td>36.04</td>
<td>4.2</td>
</tr>
<tr>
<td>#2</td>
<td>3.67</td>
<td>1.4</td>
<td>37.74</td>
<td>22.09</td>
</tr>
<tr>
<td>#3</td>
<td>2.26</td>
<td>1.04</td>
<td>39.06</td>
<td>20.67</td>
</tr>
<tr>
<td>#4</td>
<td>1.19</td>
<td>1.46</td>
<td>21.11</td>
<td>23.32</td>
</tr>
<tr>
<td>#5</td>
<td>0.83</td>
<td>0.65</td>
<td>28.26</td>
<td>31.28</td>
</tr>
<tr>
<td>#6</td>
<td>0.86</td>
<td>1.13</td>
<td>14.59</td>
<td>29.63</td>
</tr>
</tbody>
</table>
4.3. Effect of igneous intrusion on gas adsorption properties of coal

The Langmuir adsorption isotherm is the most common formula to describe the gas adsorption properties of coal (Langmuir, 1918; Ruppel et al., 1974). The Langmuir volume $V_L$ is the maximum monolayer adsorption capacity and represents the gas adsorption ability of coal (Dutta et al., 2011; Laxminarayana and Crosdale, 1999). The Langmuir pressure $P_L$ is the pressure at which the gas adsorption capacity is half of $V_L$, representing the gas adsorption difficulty of coal. The gas adsorption isotherm experiments were carried out at a constant temperature of 30 °C (Table 4 and Fig. 6). Except for coal sample #3, the $V_L$ values of the coal samples increase from 19.8736 mL/g to 28.1344 mL/g with the increasing $R_o, max$. The $P_L$ values of the coal samples are 0.5497–1.734 MPa and show the segmented trends with increasing $R_o, max$: when $R_o, max$ is less than 2.26%, $P_L$ decreases with the increasing $R_o, max$; when $R_o, max$ is more than 2.26%, $P_L$ increases with the increasing $R_o, max$. The results prove that the thermal erosion of igneous intrusion volatilized the organic matter, promoted the generation of pores, especially micropores, improved the gas adsorption abilities of coal and reduced the gas adsorption difficulty. The $V_L$ value of coal sample #3 is 45.5513 mL/g, while the $P_L$ value is only 0.5497 MPa because igneous sill #2, which is located over coal sample #3, has the largest thickness and the strongest thermal erosion, resulting in a larger surface area of pores and a stronger gas adsorption ability.

4.4. Effect of igneous intrusion on coal and gas outburst

The coal gas pressure, the initial gas releasing rate ($\Delta P$), the firmness coefficient of coal ($f$) and the destruction type of the coal,
with the critical values of 0.74 MPa, 10 mmHg, 0.5 and class III, respectively, are the four indexes used to determine whether the coal seam is outburst-prone in China (China State Administration of Work Safety, 2009). The coal gas pressure in mining areas #104, #106 and #107 in the Yangliu Coal Mine were measured in the field (Fig. 7). The experimental results of gas pressure are less but still representative in coal seam #8 of mining area #104 and coal seam #10 of mining area #107 because these areas are not yet excavated. The gas pressure is 0.8–1.6 MPa in coal seam #8 of mining area #104, 0.15–2.5 MPa in coal seam #10 of mining area #104, 0.15–1.1 MPa in coal seam #10 of mining area #106 and 0.2–0.89 MPa in coal seam #10 of mining area #107. The gas pressure data are therefore relatively concentrated and larger than the critical value in coal seam #8, while they are relatively discrete in coal seam #10, and the maximum gas pressures in mining areas #104 and #106 are larger than that in mining area #107. The results indicate that the thermal erosion of igneous intrusion increased the rate of the secondary hydrocarbon generation of coal and that the cover sills and the annular dike trapped and preserved the gas, resulting in the larger gas content and pressure.

Affected by the thermal erosion of igneous intrusion, $\Delta P$ increased from 5.8 mmHg to 21.4 mmHg with decreasing distance from igneous sill #2, and this value is larger than the critical value of 10 mmHg (Table 2 and Fig. 8). The trends for $\Delta P$ and $V_t$ of the six coal samples are consistent because they both represent the gas adsorption/desorption abilities. $f$ decreased variably from 0.74 to 0.19 with decreasing distance from igneous sill #2, which is less than the critical value of 0.5. This result proves that the tectonic stress caused by the igneous intrusion resulted in the localized concentration of in situ stress, crushed the coal and reduced $f$. It was observed in the field that the coal mass in mining areas #104 and #106 consists mainly of crushed coal and mylonite coal, while the coal mass in mining areas #107 consists mainly of raw coal and cracked coal.

In summary, the thermal erosion, gas trapping and tectonic stress effects of igneous intrusion on the underlying coal mass increased the outburst risk of coal covered by igneous sills, making it greater than that of coal not affected by igneous intrusions. The regions covered by igneous sills are sites where the coal is mined with greater risk and where gas resources are enriched, so necessary measures must be taken to ensure the safe and efficient co-exploitation of coal and gas (Cheng and Yu, 2003; Wang et al., 2012).

### 5. Engineering applications

Workface #10414 in mining area #104, which is the first mined workface in the Yangliu Coal Mine, is covered by igneous sills and enriches gas resources. After Workface #10414 was mined, coal

<table>
<thead>
<tr>
<th>No.</th>
<th>$V_t$ (mL/g)</th>
<th>$P_t$ (MPa)</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>28.1344</td>
<td>1.0346</td>
<td>0.9932</td>
</tr>
<tr>
<td>#2</td>
<td>27.3192</td>
<td>0.9146</td>
<td>0.9877</td>
</tr>
<tr>
<td>#3</td>
<td>45.5513</td>
<td>0.5497</td>
<td>0.9666</td>
</tr>
<tr>
<td>#4</td>
<td>23.9329</td>
<td>0.6292</td>
<td>0.9732</td>
</tr>
<tr>
<td>#5</td>
<td>21.8391</td>
<td>1.7340</td>
<td>0.9841</td>
</tr>
<tr>
<td>#6</td>
<td>19.8736</td>
<td>1.6651</td>
<td>0.9683</td>
</tr>
</tbody>
</table>

Table 4 Experimental results of gas adsorption properties of six coal samples.
seam #82 was at the bottom of the continuous deformation zone with a lower pressure-relieved effect and a greater amount of horizontal tension fissures. As a result, a substantial amount of pressure-relieved gas could not eject naturally; thus gas extraction technology via surface wells must be applied.

Five surface wells were drilled over Workface #10414. The previous well spaces were 200 m, and the following well spaces were less than 120 m for more efficient gas extraction.

The pure gas extraction rates of all of the wells during the extraction periods of April 19, 2011, to January 10, 2012, and March 3, 2012, to July 1, 2012, are shown in Fig. 9. The initial pure gas extraction rate increased variably with the mining of Workface #10414. The maximum gas extraction rate reached 22.84 m³/min in mid-July, 2011. Then, the pure gas extraction rate decreased variably. The average pure gas extraction rate during the entire process was approximately 4.4 m³/min. It was determined that the gas reserve in the extraction area was approximately 13.36 M m³ and the accumulative volume of the extracted gas in the five surface wells was 8 M m³. Thus, the gas extraction rate was approximately 60%, showing the significant gas extraction effects and commercial benefits of using the gas extraction technology via surface wells in regions covered by igneous sills.

6. Conclusions

Six coal samples were collected at different distances from the igneous sills to study the physical properties of coal and gas adsorption/desorption properties. The vitrinite reflectance, ash and moisture contents increase while the volatile content decreased with decreasing distance from igneous sill #2. The coal mass of interest was divided into three zones based on the degree of thermal erosion: strong thermal erosion zone, weak thermal erosion zone and no thermal erosion zone. The metamorphism of the coal in two adjacent zones changes gradually rather than suddenly.

Except for coal sample #3, the \( V_l \) value increases while the \( P_l \) value shows segmented trends with the increasing vitrinite reflectance: when \( R_{o, max} \) is less than 2.26%, \( P_l \) decreases with increasing \( R_{o, max} \); when \( R_{o, max} \) is more than 2.26%, \( P_l \) increases along with \( R_{o, max} \). The thermal erosion of igneous intrusion volatilized the organic matter, left a large number of pyrolysis stomata, greatly increased the volume and surface area of pores, especially...
micropores, and improved the gas adsorption and preservation abilities of coal.

The thermal erosion caused by the igneous intrusion increased the rate of the secondary hydrocarbon generation of coal. The cover sills and the annular dike trapped and preserved the gas, resulting in a larger gas content and pressure of the coal. The tectonic stress caused by the igneous intrusion resulted in the localized concentration of in situ stress, crushed the coal and reduced f. Several superimposed effects increased the outburst risk of coal covered by igneous sills such that this risk is greater than that of coal without the effect of igneous intrusion.

The regions covered by igneous sills are sites where the gas resource is enriched, and the engineering applications show that the gas extraction technology via surface wells can ensure the safe and highly efficient co-exploitation of coal and gas and be of significant commercial value.

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