Genetic mechanisms of coalbed methane in typical districts from Huaibei Coalfield, Eastern China

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ABSTRACT
Taking insight into genetic mechanisms of coalbed methane (CBM) can provide an effective approach for evaluating the value of CBM resources. In this study, the geo-temperature and the thermal subsidence history were used to investigate the effect of the present geothermal field characteristic on the genetic mechanisms of CBM at the Huaibei Coalfield. The results showed that the Permian coal strata in the study areas had a relatively low geo-temperature (<50°C), high vitrinite reflectance (R_{omax} 0.75%-1.2%) and a coal rank typical of intermediate-high metamorphic bituminous. Comprehensive analyses of the characteristics of the present geothermal field indicate that the CBM at the Huaibei Coalfield are dominated by secondary biogenic gases. Furthermore, the genetic mechanism towards CBM was further proposed based on the tectonic evolution history: (1) Tectonic thrusting contributed to R_{omax} values ranging from 0.5% to 3.0%, with maximum geo-temperatures of 140–180°C, which resulted in the generation of thermogenic CBM. (2) An extensional regime contributed to gradual uplift of the Permian coal-bearing strata, with the gradual escape of CBM at burial depths greater than 700m. (3) A large number of faults and hydrodynamic environments greatly promoted the microbial degradation of the early thermogenic gases, resulting in generation of secondary biogenic gases.

KEYWORDS
Genetic mechanism; coalbed methane; geothermal field; tectonic evolution; Huaibei Coalfield

1. Introduction
As an unconventional energy source, coalbed methane (CBM) is clean and efficient. With the increasing energy demands around the world, the resource effect has gradually gained attention. According to the different generation mechanisms (Flores, 1998; Glasby, 2006; Song et al., 2012; Thielemann, Cramer, & Schippers, 2004), coalbed methane can be divided into biogenic gas, thermogenic gas or a mixture of both. The biogenic gases can further be classified into two types: primary biogenic gases and secondary biogenic gases. CBM reserves are closely related to their genetic types, which are affected by factors such as parent material characteristics, formation environment and basin evolution (Liu, Fokker, & Spiers, 2017). Therefore, it’s significantly meaningful to study the origins of CBM for CBM resource evaluation, to improve the utilization rate of coal and the effective exploration and site selection of CBM (Xia et al., 2017).

It has been shown that the isotopic characteristics of CBM gas composition can be used as an indicator of the type of coalbed methane (Huang et al., 2017). However, due to large differences in the type of organic matter and maturity in the CBM formation environment, the application of this method is limited to a certain extent. The evolution of organic matter and the formation conditions of the coal rock accompany CBM generation and thus can more effectively reflect the formation mechanism of CBM (Golding et al., 2000). For example, Flores, Rice, Stricker, Warden, and Ellis (2008) combined CBM experimental data and underground water samples with an analysis of the tectonic history, geothermal field and microorganisms, concluding that the CBM in the Powder River Basin is biogenic gas. Liu et al. (2010) (Liu et al., 2010) analyzed the factors controlling CBM accumulation such as geology, tectonics, coal accumulation process, coal measure characteristics, formation and preservation of gas. This study preliminarily confirmed that the CBM type in Turpan-Hami basin is biogenic gas. Faramawy, Zaki, and Sakr (2016) (Faramawy et al., 2016) discussed the mechanism of CBM origin from the aspects of the thermal maturity and the hydrodynamic conditions of the basin, found that the shallow portion of the eastern margin is a mixture of secondary biogenic gases and thermogenic gas, while the middle-deep area consists of thermogenic gas.

Huaibei Coalfield is located on the southeastern margin of the North China plate, which is an important coal
resource area in Eastern China, and therefore can be regarded as an important area of reserves. Because Huaibei Coalfield has undergone tectonic-thermal evolution and CBM generation in different geological periods, it is important to discern the origin of CBM to accurately estimate existing CBM resources in the area (Li et al., 2015). Previous researchers have paid more attention to the geochemical characteristics (Chen et al., 2015; Jiang, Cheng, Wang, Li, & Wang, 2011), tectonic deformation (Jiang, Qu, Wang, & Li, 2010; Li, Jiang, & Qu, 2014; Li, Ju, Hou, & Fan, 2013; Li, Ju, Hou, & Lin, 2012), thermal evolution and regional ge-temperature distribution (Tan, Ju, Hou, Zhang, & Tan, 2009; Tan, Ju, Zhang, Hou, & Tan, 2010; Wang, Cheng, et al., 2014; Wu et al., 2011; Yao & Liu, 2012) in Huaibei Coalfield but not paid much attention to the its formation history or origin.

This study focuses on the relationship between the evolution of organic matter components, the characteristics of the present geothermal field and the genesis of coalbed methane. Based on the local tectonic evolution, the formation history of coalbed methane in Huaibei Coalfield is proposed. The improved understanding of the research will help to provide insight into the development and application of Carboniferous and Permian coalbed methane in the Huaibei and Huainan Coalfields and the entirety of Eastern China.

2. Geological setting and sampling

The samples were selected from the Suntuan and Zhaoji exploration areas in the southern part of Huaibei Coalfield. As shown in Figure 1, the Sun Tuan Coal Mine is located in Suixi County, Huaibei City of Anhui Province. It is located in the eastern wing of Tongting anticline and lies within the fault blocks of Subei Fault, Guangwu-Guzhen Fault, Feng county-Kouzi Fault and Gu Town-Changfeng Fault. The Sun Tuan exploration area is a monocline, striking north-south and dipping eastward. On the contrast, the Zhaoji exploration area is located in Mengcheng County, south of Tongting anticline, the middle part of which lies across the shaft of Wangdazhuang anticline. Shaoyuuzhuang syncline also extends into the Zhaoji exploration area. The anticline and syncline are cut by both the Xutuan and DF faults.

The basement rock in this area is of Archeozoic age but Proterozoic, Lower Paleozoic, Upper Paleozoic, Mesozoic

Figure 1. Geological setting of the research area (Jin et al., 2015).
and Cenozoic strata also exist. There are few outcrops of bedrock in the area, and most of them are covered with Quaternary deposits. The Permian is the main recoverable coal seam. The vast majority of coal samples in this study were taken from the Middle Permian and Lower Permian (Figure 2).

3. Methods

3.1. Present geo-temperature measurements

Rock samples were collected from ten boreholes in the Zhaoji exploration area and twenty-four boreholes in the Suntuan exploration area. All of the geo-temperature data could be typically classified into two categories: approximate steady-state temperature data and simple borehole temperature data, the methodology of which is described in detail by Rimi (2000). While steady-state temperature data is relatively accurate, few boreholes were measured using this technique because of the cost limitations and the long time recovery of borehole temperature. For this reason, the simple borehole temperature data were adopted after revision in accordance with the heat recovery law of the local steady-state conditions. Based on these revised increment temperatures of the bottom rock function as cycle time of completion fluid, the revised simple borehole temperature data were generated. The simple borehole temperature data of the bottom rock are usually amended according to the following linear form:

\[ T_0 = T_a (1 + \delta) \]

where \( T_a \) is the field test temperature (°C) and \( \delta \) is the revised coefficient (%).

Subsequently, the geothermal gradients of the rock strata were obtained by using the three-point method (Corrado, Invernizzi, & Mazzoli, 2002). Then, the rock strata temperatures were determined using the arithmetic mean of the geothermal gradients for each borehole. In the present study, four approximate steady-state temperature data as well as thirty simple borehole temperature data were used to calculate the geothermal gradient of each district. The geothermal gradient

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**Figure 2.** Generalized stratigraphic column of the Permian Strata in Huaibei coalfield, modified after (Wang, Ju, et al., 2014).
measurements below the constant temperature strata are derived using the following formula:

\[ G = \frac{T - 16.9}{Z - 30} \]  

where \( T \) is rock strata temperature (°C), \( Z \) is the rock strata depth (m), and 16.9°C and 30m are the temperature and depth of the zone of constant temperature, respectively.

### 3.2. Vitrinite reflectance measurements

The measurements of the reflectivity were based on the national standard (GB/T 6948-2008), using the experimental microscope model Zeiss Axioskop 40 A. Prior to measurement, the sample was air-dried, ground and sieved through a 1 mm square hole sieve, ensuring that no more than 10% of the sample was less than 0.1 mm in diameter. Subsequently, the sample was mixed with mosaic powder with a mass ratio of 2:1. After stirring evenly, the sample was put into the mosaic device used to inlay the sample, according to the equipment operation procedures. The mosaic sample of coal rock was then cooled, ground and polished before measurement.

### 4. Results and discussion

#### 4.1. Effect of the present geothermal field characteristic on the genetic mechanism of coalbed methane

**4.1.1. Present geo-temperature analyses**

Figure 3 illustrates the approximate steady-state temperature data of the ST25-12 borehole in Suntuan district (Figure 3(a)) and the ZJ06-7 borehole in Zhaoji district (Figure 3(b)), which is amended to local simple borehole temperature data. Accordingly, the geothermal gradients of both districts are obtained, summarized in Table 1.

As previously demonstrated (Chen et al., 2017), temperature is an important factor dominating the genetic mechanism of coalbed methane. Therefore, the geothermal gradients were calculated according to eq. 1 to acquire the terrane temperature. The Suntuan district covers a narrow range of geothermal gradients from 2.00°C/hm up to a limit of < 3.16°C/hm. The geothermal gradients from Zhaoji district are of similar range, which varies from 2.20°C/hm to 3.18°C/hm. The results indicated that there was no obvious difference in geothermal gradients between the two districts. Using the approximate steady-state temperature data and the simple borehole temperature data, the average geothermal gradient of the Suntuan and Zhaoji districts were 2.74°C/hm and 2.62°C/hm, respectively, as listed in Table 2. Based on the relationship between coal strata temperature and geothermal gradient, the average temperature of the Permian coal strata lower boundary were calculated to be 45.9°C and 42.4°C for the Suntuan and Zhaoji districts, respectively.

Previous studies have indicated that both primary biogenic and secondary biogenic methane usually occur in areas where the surrounding temperature is relatively low (i.e. below 50°C). With a gradual increase in the temperature to 50°C, thermogenic coalbed gas formation begins. Therefore, the geo-temperatures of the Suntuan and Zhaoji districts imply a generation gas mechanism of biogenic methane gas.

**4.1.2. Vitrinite reflectance**

Coal strata at different thermal evolutionary stages exhibit distinct gas-generating pathways. Continuously increasing the strata temperature results in the thermal evolution of coal rock, which continues to escalate slowly even if under constant high strata temperatures. Nevertheless, the basin elevation would result in an interruption in the thermal hydrocarbon-generating process of coal rock. Therefore, the effect of the thermal evolution on the genetic mechanism of coalbed methane was investigated by determining the \( R_{o,\max} \) of coal rock.

![Figure 3](image_url). Approximate steady-state temperature data of (a) ST25-12 borehole in Suntuan district, and (b) ZJ06-7 borehole in Zhaoji district.
Table 1. Characteristics of the present geothermal field for the Suntuan and Zhaoji districts.

| Borehole ID | T_s (°C) | T_o (°C) | G (°C/hm) | Depth (m) |
|-------------|----------|----------|-----------|-----------|
| ST25-12     | 2.81     |          |           |           |
| ST21-22     | 3.41     |          | 2.32      |           |
| ST26-13     |          |          |           |           |
| ST16-3      | 28.3     | 30.3     | 3.01      | 475       |
| ST16-4      | 29.6     | 31.0     | 2.48      | 598       |
| ST16-5      | 28.5     | 31.2     | 2.51      | 595       |
| ST16-7      | 32.5     | 33.8     | 2.28      | 775       |
| ST16-8      | 31.3     | 32.3     | 2.71      | 598       |
| ST18-19-2   | 25.1     | 26.7     | 2.75      | 383       |
| ST18-19-5   | 27.5     | 29.3     | 2.58      | 515       |
| ST20-3      | 28.2     | 28.9     | 2.24      | 575       |
| ST21-10     | 38.2     | 39.8     | 2.86      | 830       |
| ST21-7      | 29.6     | 31.3     | 2.40      | 625       |
| ST21-8      | 34.6     | 36.3     | 2.72      | 700       |
| ST21-9      | 39.7     | 41.4     | 3.55      | 725       |
| ST21-11     | 24.1     | 25.7     | 2.00      | 476       |
| ST26-27-5   | 33.3     | 33.6     | 3.33      | 545       |
| ST27-3      | 27.5     | 29.0     | 2.69      | 480       |
| ST27-6      | 33.5     | 35.3     | 3.61      | 540       |
| ST27-8      | 33.5     | 35.6     | 2.63      | 749       |
| ST27-9      | 33.5     | 35.4     | 2.47      | 775       |
| ST30-31-2   | 28.8     | 30.7     | 2.93      | 535       |
| ST30-31-3   | 28.5     | 30.5     | 2.93      | 498       |
| ST31-3      | 24.8     | 26.4     | 2.43      | 425       |

Table 2. Permian coal strata parameters of the Suntuan and Zhaoji districts.

| Parameters | Suntuan | Zhaoji |
|------------|---------|--------|
| Avg. Permian top boundary burial depth (m) | 221 | 236 |
| Permian coal strata thickness (m) | 877 | 767 |
| Avg. Permian bottom boundary burial depth (m) | 1098 | 1003 |
| Avg. geo-temperature gradient (°C/hm) | 2.74 | 2.62 |
| Avg. Permian bottom boundary temperature (°C) | 45.9 | 42.4 |

The vitrinite reflectance results of coal samples from the Suntuan and Zhaoji districts are presented in Table 3. A clear variation in $R_o$ max was observed between the two districts. $R_o$ max values of samples from Suntuan district fell into the categories of gas coal, fat gas coal and fat coal according to ISO11760 (Classification of coals). However, the $R_o$ max values of Zhaoji district samples ranged from 0.84%-1.2%, which are mainly fat gas coal and fat coal (according to ISO11760). In general, the coal rock in both districts showed a similar level of thermal evolution, which dramatically differed from Huainan field (Li & Peng, 2009), suggesting different gas-generating mechanisms.

Table 3. Vitrinite reflectance of coal samples from the Suntuan and Zhaoji districts.

| Borehole ID | Coal Strata | Depth (m) | $R_o$ max (%) |
|-------------|-------------|-----------|---------------|
| Suntuan     |             |           |               |
| ST5-16      | 1           | 565.8     | 0.80          |
| ST5-19      | 2           | 640.66    | 0.96          |
| ST5-19      | 3           | 761.29    | 0.79          |
| ST5-19      | 4           | 764.39    | 0.75          |
| ST5-19      | 5           | 1029.40   | 0.96          |
| ST5-19      | 6           | 776.20    | 0.88          |
| ST5-19      | 7           | 788.00    | 0.93          |
| ST5-19      | 8           | 880.75    | 0.95          |
| ST5-19      | 9           | 1092.40   | 0.95          |
| ST16-5      | 10          | 1262.78   | 0.92          |
| ST16-5      | 11          | 1382.20   | 0.98          |
| ST16-5      | 12          | 1036.83   | 0.80          |
| ST16-5      | 13          | 1215.00   | 0.81          |
| ST16-5      | 14          | 1360.25   | 0.9           |
| ST16-5      | 15          | 1451.00   | 0.88          |
| ST16-5      | 16          | 716.84    | 0.83          |
| ST16-5      | 17          | 718.29    | 0.89          |
| ST16-5      | 18          | 876.89    | 0.89          |
| ST16-5      | 19          | 951.78    | 0.92          |
| ST16-5      | 20          | 960.40    | 0.97          |
| ST16-5      | 21          | 973.45    | 0.95          |
| ST16-5      | 22          | 1053.21   | 0.89          |

| Borehole ID | Coal Strata | Depth (m) | $R_o$ max (%) |
|-------------|-------------|-----------|---------------|
| Zhaoji      |             |           |               |
| ZJ1-8       | 3           | 536.58    | 0.97          |
| ZJ1-9       | 4           | 600.56    | 1.20          |
| ZJ1-10      | 5           | 611.2     | 1.01          |
| ZJ1-11      | 6           | 615.95    | 1.03          |
| ZJ1-12      | 7           | 630.02    | 1.06          |
| ZJ1-13      | 8           | 717.13    | 1.07          |
| ZJ1-14      | 9           | 720.15    | 1.05          |
| ZJ1-15      | 10          | 539.25    | 0.88          |
| ZJ1-16      | 11          | 1060.18   | 0.85          |
| ZJ1-17      | 12          | 1211.3    | 1.01          |
| ZJ1-18      | 13          | 1360.44   | 0.88          |
| ZJ1-19      | 14          | 1432.27   | 1.01          |
| ZJ1-20      | 15          | 1319.72   | 0.84          |
| ZJ1-21      | 16          | 1478.46   | 0.86          |
| ZJ1-22      | 17          | 746.37    | 0.97          |
| ZJ1-23      | 18          | 912.57    | 0.95          |
| ZJ1-24      | 19          | 973.66    | 0.99          |
| ZJ1-25      | 20          | 986.40    | 1.04          |

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The wider range of Suntuan district $R_{o,max}$ values compared with that of Zhaoji district is attributed to the differences in geologic age and maturity.

Although peats possess large surface areas, the active surfaces tend to be occupied by water molecules that co-exist in the sedimentary environment. Moreover, the $R_{o,max}$ of primary biogenic methane is typically below 0.3%. However, the $R_{o,max}$ of secondary biogenic methane varies from 0.30%-1.50%. As a result, secondary biogenic methane likely contributed to the methane generation at Huaibei Coalfield.

4.2. Proposed genetic mechanisms of coalbed methane in Huaibei area

From the above results, it can be concluded that the genetic mechanism of coalbed methane was dominated by a combination of the geo-temperature, thermal and tectonic subsidence history of the area. On the basis of the geological construction characteristic (Wu & Wu, 2014), we propose that the generation towards coalbed methane from Huaibei Coalfield occurred through the following three stages (Figure 4):

1. Thermogenic gas generation stage: From the Triassic to the Middle Jurassic, a series of thrust nappe structures formed in Huaibei area and the burial depth of Permian coal-bearing strata increased to approximately 3000 m (Jiang et al., 2010; Ju, Wei, & Xue, 2011; Wei et al., 2017). The coal-bearing strata were typically of fat coal rank, the local coal-bearing strata of which was coking coal rank, corresponding to an $R_{o,max}$ of 0.5%-3.0%. The strong tectonic action contributed to a ge-temperature of Permian coal-bearing strata up to 140–180°C, resulting in the generation of a large number of thermogenic gases (Li et al., 2015).

2. Thermogenic gas escape stage: From the Late Jurassic to the Cretaceous, due to a switch to an extensional system in the Huaibei area, the Permian coal-bearing strata was subjected to high-intensity erosion and gradually began to uplift, resulting strata exposed at the surface. Despite the existence of the intrusion of Mesozoic rocks, the invasive effect was limited, because the depth of fault was deeper and it was able to reach the Moho interface and the dyke was often deflect into a sill because of the stress barrier or stiff strata (Wang et al., 2017; Xu, Cheng, Wang, & Zhou, 2014). Previous studies (Zhang, Cui, Tao, Peng, & Jin, 2005) have shown that CBM buried at depths shallower than 700 m will gradually escape after undergoing uplift, leading to a decrease in CBM content.

3. Secondary biogenic gas generation and preservation stage: From the early Tertiary onward, tectonic activity weakened, subsistence in the basin resulted in a period of deposition and ge-temperatures were low (27–50°C) (Guo, Cheng, Jin, & Liu, 2014; Li et al., 2014). These conditions correspond to $R_{o,max}$ values of 0.3%-1.5%. When the deep-seated CBM was uplifted again to

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**Figure 4.** Proposed genetic mechanism toward coalbed methane in the Huaibei area.
the surface and temperatures fell below 50°C, microorganisms degraded early thermogenic gases and generated secondary biogenic gases. When the coal seam temperature fell below 50°C, a large number of faults in study area created hydrodynamic environmental conditions suitable for the propagation of methane-producing bacteria. The lower temperature of the study area, higher vitrinite reflectance, uplift during the early Mesozoic and the Cenozoic extensional system created favorable conditions for the generation of secondary biogenic gas. In this stage, a large number of secondary biogenic gases were generated and reserved with the stabilization of tectonic activity.

5. Conclusion

On the basis of the results of borehole temperature measurements and vitrinite reflectance testing in typical districts, the effect of the present geothermal field characteristics and the burial history of Permian coal strata on the generation mechanisms of CBM were investigated. In addition, the generation pathways towards coalbed methane were also discussed. The main conclusions are as follows:

1) From the results of the low geo-temperature (< 50°C) and the relatively high vitrinite reflectance (0.75%-1.2%), it is confirmed that the geological environment of the Huaiabei Coalfield favored the genetic mechanism of secondary biogenic gases.

2) The genetic mechanisms toward coalbed gas can be classified into three stages:

1) Thermogenic gas generation stage: Permian coal-bearing strata experienced ge-temperatures of 140–180°C, maximum \( R_o_{max} \) values of 3.0% and thermogenic gas generation increased with the heightened degree of metamorphism.

2) Thermogenic gas escape stage: From the Late Jurassic to the Cretaceous, as the Permian coal-bearing strata was subjected to high-intensity erosion, a large amount of thermogenic CBM (generated during the first stage) gradually escaped due to presence of an extensional system, in particular for the thermogenic CBM that formed in the coal seams with the burial depths shallower than 700 m.

3) Secondary biogenic gas generation and preservation stage: From the early Tertiary onward, as tectonic activity weakened, the ge-temperature of coal-bearing strata was stable at 27–50°C, \( R_o_{max} \) ranged from 0.3%-1.5%, and a large number of faults formed. These faults provided ideal conditions for mass reproduction of methane-producing bacteria. The mass reproduction of methane-producing bacteria degraded the early residual thermogenic gas and secondary biogenic gas generated, which was preserved following a stabilization of tectonic activity.

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Disclosure statement

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