Coalbed methane geology and exploration potential in large, thick, low-rank seams in the Bayanhua Sag of the Erlian Basin, northern China

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Abstract
The Erlian Basin may be one of the most promising areas for low-rank coalbed methane (CBM) in China. The Cretaceous coal-bearing strata in the Bayanhua sag contain abundant low-rank CBM resources with suitable depths and large coal thicknesses (1.00–78.85 m, avg.22.53 m). However, the research on CBM geology and exploration potential is still lacking, which severely hinders its exploration and development. This paper presents an integrated study of CBM geology in terms of gas reservoir properties, gas-bearing characteristics and controlling factors. The results of the analysis show that lignite and subbituminous coals are the main coal types present in the study area, with medium porosity (7.3–27.8%, avg.20.77%) and low permeability (0.05–21.8 mD, avg.5.54 mD) being dominant. The pores are dominantly transition pores with inkpot shapes, which is beneficial to the adsorption of CBM. The gas content of the coal seams is 1.66–4.45 m³/t and most coal reservoirs are oversaturated. The CBM is primarily of secondary microbial origin, mostly carbon dioxide reduction. The accumulation of CBM is mainly influenced by the structure type, roof lithology and hydrogeology in the study area. According to the integrated analysis of the vertical changes in the physical properties and gas-bearing characteristics, the dominant horizon tends to be the No. 6-7 coal seam, followed

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by the No. 6-4 coal seam. Based upon the CBM geology and the factors controlling enrichment, the prospecting potential in the Bayanhua sag was appraised, and two favorable areas are proposed for CBM exploitation.

Keywords
Erlian basin, low rank, CBM, accumulation characteristics, exploration potential, Bayanhua sag

Introduction
Industrial exploitation of high to medium-rank coalbed methane (CBM) has been realized in China. However, the annual production of CBM is far below the set targets (Chen BY et al., 2019; Liu et al., 2014; Tao S et al., 2014 Zhao et al., 2017). Recently, low-rank CBM has been successfully developed in the Powder River Basin, Uinta Basin, Alberta Basin and Surat Basin (Ayers, 2002; Hamilton et al., 2014; Tang et al., 2018), indicating that new blocks with high resource potential may exist to be discovered and researched in China (Lau et al., 2017; Sun et al., 2008; Yun et al., 2012). The Erlian Basin is considered a new block for CBM exploitation in China. The CBM resources of the Erlian Basin account for 8.5% of the nation (approximately 1.25 trillion cubic meters) according to the fourth round of oil and gas resource evaluation (Liu et al., 2005; Sun et al., 2017). Nevertheless, due to a lack of systematic study of gas geological characteristics and controls, the degree of CBM research and exploration is still in its infancy.

It is necessary to evaluate the CBM exploitation potential through synthetic research on CBM geology and its enrichment controlling factors. The factors affecting CBM accumulation include the sedimentary environment, structural characteristics, coal seam distribution, coal rank, reservoir properties, gas bearing properties, roof and floor lithology, hydrodynamics, etc. (Kaiser et al., 1994; Li H et al., 2018 Li ZT et al., 2018 Wang et al., 2020; Yao et al., 2014). Among them, reservoir physical properties have proven to be critical to CBM adsorption, diffusion, seepage and production (Levine, 1992; Xin et al., 2020; Xu et al., 2014). Moreover, the gas content tends to directly affect the economy of CBM exploitation. Reservoirs of low-rank coal have a lower gas content than medium to high-rank coal. However, the characteristics of a large thickness, moderate burial depth, and high permeability mostly compensate for these shortcomings (Esen et al., 2020; Scott, 2002). Additionally, the dynamic process of hydrocarbon generation history determines the CBM generation types, leading to a diversity of CBM origins (Chen et al., 2016; Wang et al., 2020). Hence, understanding CBM geology requires a comprehensive analysis of reservoir properties, gas-bearings characteristics and their controls.

Previous research in the Erlian Basin has primarily focused on the structural and sedimentary geological characteristics of coal-bearing strata (Bonnetti et al., 2014; Ding et al., 2015) and on the CBM genetic types, biogas generation influencing factors, nanopore structure characteristics and feasibility studies of biogas recovery in the Jiergalangtu sag (Chen H et al., 2019; Sun B et al., 2018; Sun F et al., 2017; Sun QP et al., 2018; Tao JJ et al., 2019; Zhao et al., 2021). The Bayanhua sag is the key sag with low-rank CBM exploration potential in the Erlian Basin. However, only a few studies related to CBM, mainly focusing on the key geologic factors affecting coal reservoirs, have been performed, and the classification of coal seams may be relatively simple (Yao et al., 2020). To date, no commercial CBM production wells have been developed in the Bayanhua sag, although several companies are conducting exploration in
this area. Recently, six CBM production wells have been completed, which contain a cluster well of three, and a quantity of gas-bearing layers have been discovered in this area. Hydraulic fracturing work has just been carried out, and the wells are ready for drainage and gas production. Even so, the geological characteristics and exploration potential of CBM still need to be further systematically studied.

In this paper, CBM geology, coal reservoir properties and gas-bearing characteristics are analyzed in detail based on synthetic research of collected and experimental data. Geological controls on CBM accumulation in the Bayanhua sag are comprehensively studied in the Bayanhua sag. In view of the CBM geology and controlling factors, the CBM exploitation potential is evaluated to provide the basis for further industrial development of CBM in the Bayanhua sag.

**Geological setting**

**Tectonic setting**

The Erlian Basin is a Mesozoic continental rifted basin situated in Inner Mongolia, northeastern China, and covers a surface area of approximately 117,685 km² (Charles et al., 2013; Lin et al., 2001). Additionally, the Erlian Basin is one of the main areas containing lignite and subbituminous coal in China, with abundant coal resources (<2,000 m) that mostly formed in the Cretaceous. The coal reserves are 142.5 Gt, and the predicted coal resources are approximately 85.7 Gt (Li et al., 2016). The Erlian Basin consists of five depressions and one uplift and is further subdivided into 21 ranges and 56 sags, with graben-shaped and residual lacustrine subbasins (Ding et al., 2015; Dou and Chang, 2003).

The Bayanhua sag is a half-graben-shaped syncline structure with a dip of 10°–15° and an orientation of NE-NNE, and it is located at the northeastern end of the Wunite Depression. Small-scale folds also formed in the area, all trending in the NE direction. In addition, the faults in the area mostly trend in the NE-SW direction and developed during the large-scale rifting period (Figure 1(b)).

**Coal-bearing strata in the Bayanhua sag**

The majority of Erlian subbasins were subjected to erosion in the Triassic and entered the rifting period from the early Middle Jurassic to the Late Cretaceous, during which they experienced a sedimentary process characterized by rapid filling with terrigenous clasts and lacustrine expansion. This process deposited the Lower Cretaceous Aershan Formation (K1a), the Tengger Formation (K1t), the Neogene (N2) and the Quaternary strata (Q). The Tengger Formation (K1t) is the predominant coal measure in the Bayanhua sag.

The Tengger Formation is composed of six coal groups in the Bayanhua sag, which are 4Sun F et al., 2017; Sun QP et al., 2018; divided into 23 coal seams. There are five principal coal seams, including the No. 6-7, No. 6-4, No. 6-1, No. 5-2, and No. 5-1 coal seams, in ascending order (Figure 1(c)). The main coal seams have a cumulative thickness of 1.00-78.85 m (avg.22.53 m) with an occurrence area of 565 km² (Figure 2), which is representative of the large, thick coal seams in the Erlian Basin. The coals have an average burial depth of 300–1,200 m, and the burial depth ranges from 600 to 1,200 m in the northeastern region, which is beneficial to the formation and preservation of CBM and is also a suitable exploration depth range for CBM in this region (Ruppert et al., 2010).
At the beginning of the Early Cretaceous, due to the differential movement of the basement in the Erlian Basin, the Bayanhua sag began to extend and rift along the NE direction. In the middle of the Early Cretaceous, it continued to subside and experience deposition, forming a series of braided river deltas, fan deltas and shore-shallow lacustrine deposits, i.e., the Tengger Formation. Peat swamps widely developed in delta plains and lacustrine bogs, forming the main coal seams, namely, the No. 5 and No. 6 coal groups. During the deposition of the upper member of the Tengger Formation, sediments overlapped the margin of the sag, and the lacustrine regime expanded, which was disadvantageous to peat swamp growth. During this period, the No. 2, No. 3 and No. 4 coal groups were deposited discontinuously. Additionally, gray siltstone, pelitic siltstone, and large thick mudstone were deposited, which was conducive to CBM sealing. After the Late Cretaceous, the crust began to uplift, the lake silted up, the climate gradually became drier, the fluvial and alluvial fan facies developed widely, and coal accumulation ceased (Figure 3).

Coal seams are mostly present in the middle of the Tengger Formation in the Bayanhua sag. The thickness of the No. 6-7 coal seam is 1.50–12.46 m (avg. 5.09 m) and shows three coal accumulation centers in the sag (Figure 4(a)). The thickness of the No. 6-4 coal seam is 1.52–44.37 m (avg. 16.98 m), which is greater than that of other coal seams (Figure 4(b)). The No. 5-2 coal seam (1.51–18.07 m, avg. 5.74 m) and No. 5-1 coal seam (1.55–13.50 m, avg. 3.62 m) are thicker than the No. 6-1 coal seam (1.51–21.78 m, avg. 4.25 m), but they have similar distributions, i.e., a saddle pattern (Figure 4(c)–(e)).
Samples and experiments

Data and sample sources

In this paper, CBM geological setting data were collected from 200 coal exploration holes and CBM exploration wells. These coal exploration holes and CBM wells were carried out by the
Coalfield Geology Bureau of Inner Mongolia. The CBM geological characteristics in the Bayanhua sag were analyzed with these data.

The coal samples used in these experiments, such as maceral composition, proximate analysis, vitrinite reflectance, mercury intrusion, and low-temperature nitrogen were taken from 6 large fresh samples collected from open-pit mines and 20 core samples freshly recovered from CBM exploration wells. Additionally, the gas samples used in experiments of gas content, gas composition, carbon and hydrogen isotopic compositions came from in situ desorption gas. All samples were numbered, classified, carefully sealed and packaged and delivered to the laboratory immediately.

**Experiments**

Vitrinite reflectance (% R_0) and maceral measurements were carried out on the same section of the coal samples with a Leitz MPV-3 photometer microscope, according to China National Standards GB/T 6948-2008 and GB/T 8899-2013, respectively. Proximate analysis and elemental analysis were performed based on Chinese standards GB/T 212-2008 and GB/T 31391-2015.

Low-field nuclear magnetic resonance (NMR) tests were implemented by a RecCore-5000 instrument to obtain pore structure, porosity and other reservoir data (Table 1) in light of Chinese standard SY/T 6490-2014. A low-temperature nitrogen adsorption trial was then conducted to acquire pore morphology data following Chinese standard GB/T21650.2-2008 with an ASAP 2460 instrument. The microtopography of pores was observed using an FESEM JSM-7500F scanning electron microscope based on the Chinese standard GB/T 12334-2001. The porosity and permeability of coal reservoirs were measured at a confining pressure of 400 psi (average formation pressure) with an HKY-300 automatic porosity and permeability tester based on the Chinese standard GB/T 29172-2012.

Gas content data were measured through desorption experiments of field cores based on the Chinese standard NB/T 10018-2015. After the gas content was measured, some gas samples were gathered to detect gas components and carbon and hydrogen isotopes to analyze the gas origin. A 7820A gas chromatograph and MAT-253 isotope mass spectrometers were used to

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**Figure 3.** Cretaceous burial history diagram of CBM in well B-C1 in the Bayanhua sag.
Figure 4. Thickness of each main coal seam in the Bayanhua sag: The No. 6-7 coal seam (a), No. 6-4 coal seam (b), No. 6-1 coal seam (c), No. 5-2 coal seam (d), and No. 5-1 coal seam (e).
analyze gas conditions based on the Chinese standards GB/T 13610-2014 and SY/T 5238–2008, respectively. The adsorption isotherm experiment was conducted by the Chinese standard GB/T 19560-2008 using the adsorption isotherm YRD-2 apparatus.

**Results and discussion**

**Physical properties of CBM reservoirs**

**Coal maceral composition and quality.** The macrolithotypes of coals in the Bayanhua sag are mostly xylitic coal and minor amounts of detritic coal with black and asphaltic lusters and light brown streaks. The experimental results indicate that the maceral composition is dominated by organic matter, ranging from 58.4% to 99.6% (avg. 82.32%) (Table 2). The huminite content accounts for the highest proportion (91.14%–99.86%, avg. 98.56%), followed by inertinite (0.14–8.10%, avg. 1.05%) and liptinite (0–2.5%, avg. 0.39%). The coal seams feature low sulfur contents (0.32–1.84%, avg. 0.76%), which indicates a nonmarine sedimentary environment (Tang et al., 2015). Vertically, there is no obvious change in the maceral composition of the main coal seams. However, comparing the No. 5-1 coal and No.5-2 coal with the No. 6-1 coal, No. 6-4 coal and No. 6-7 coal, the huminite content and sulfur content of the former are slightly lower than those of the latter, and this difference is mainly related to the sedimentary environment and coal accumulation (Tang et al., 2015). Combined with the maceral composition, it could be concluded that the coal-forming plants are mainly woody, and the coal seams formed in moist and deeply covered swamps (Diessel, 1982).

The proximate analysis tests show that the moisture, ash content and volatile matter content are 2.82–13.24% (avg. 7.00%), 1.78–23.63% (avg. 12.55%), and 16.9–38.66% (avg. 28.99%), respectively (Table 2). The coal quality of the main coal seams has no evident vertical changes. However, comparing the No. 5-1 coal and No.5-2 coal with the No. 6-1 coal, No. 6-4 coal and No. 6-7 coal,
Table 2. Results of maceral composition test and proximate analysis.

| Well number | Coal seam | Burial depth (m) | Total organic content (%) | Maceral composition (%) | Proximate analysis (%) | St,d (%) | R_o, max (%) |
|-------------|-----------|------------------|---------------------------|-------------------------|------------------------|----------|-------------|
|             |           |                  |                           | Macrolithotype          |                        | Mad      | Aad         | Vad         |
| B2-7        | 5-1       | 498.55           | 82.60                     | xylitic                 | 97.34                  | 7.96     | 23.63       | 33.63       | 0.34       | 0.311       |
|             | 5-2       | 506.40           | 81.80                     | xylitic                 | 97.56                  | 11.56    | 10.07       | 20.07       | 0.36       | 0.415       |
|             | 6-1       | 561.70           | 78.80                     | xylitic                 | 98.98                  | 8.34     | 18.06       | 18.06       | 0.82       | 0.410       |
|             | 6-4       | 582.50           | 70.10                     | detritic                | 99.43                  | 6.27     | 16.34       | 26.34       | 0.53       | 0.427       |
|             | 6-7       | 632.05           | 69.00                     | detritic                | 99.86                  | 5.64     | 21.89       | 31.89       | 1.05       | 0.425       |
| B6-13       | 5-1       | 577.65           | 83.50                     | xylitic                 | 99.76                  | 2.85     | 3.33        | 22.33       | 0.45       | 0.371       |
|             | 5-2       | 588.15           | 84.40                     | xylitic                 | 98.82                  | 3.11     | 18.88       | 28.88       | 0.91       | 0.411       |
|             | 6-1       | 637.80           | 68.90                     | xylitic                 | 99.13                  | 5.95     | 19.49       | 29.49       | 0.55       | 0.424       |
|             | 6-4       | 679.85           | 83.10                     | xylitic                 | 99.94                  | 3.06     | 13.89       | 23.89       | 0.54       | 0.421       |
|             | 6-7       | 721.60           | 78.00                     | detritic                | 99.74                  | 3.63     | 17.08       | 27.08       | 0.76       | 0.429       |
| B8-5        | 5-1       | 544.25           | 78.30                     | xylitic                 | 99.11                  | 5.32     | 10.03       | 20.03       | 0.42       | 0.424       |
|             | 5-2       | 547.50           | 79.50                     | xylitic                 | 98.99                  | 5.15     | 6.9         | 16.9        | 0.35       | 0.432       |
|             | 6-1       | 632.10           | 84.40                     | detritic                | 99.29                  | 2.82     | 22.6        | 32.6        | 0.46       | 0.434       |
|             | 6-4       | 652.30           | 82.40                     | xylitic                 | 99.76                  | 7.72     | 22.55       | 32.55       | 0.82       | 0.431       |
|             | 6-7       | 725.50           | 81.30                     | xylitic                 | 99.51                  | 3.32     | 17.55       | 27.55       | 0.96       | 0.425       |
| B-C1        | 5-1       | 906.85           | 99.60                     | detritic                | 98.11                  | 13.24    | 6.66        | 34.17       | 0.32       | 0.451       |
|             | 5-2       | 922.71           | 84.90                     | xylitic                 | 98.59                  | 7.86     | 3.47        | 38.4        | 0.61       | 0.462       |
|             | 6-1       | 1,001.78         | 89.25                     | xylitic                 | 91.14                  | 12.83    | 14.41       | 25.95       | 0.9        | 0.513       |
|             | 6-4       | 1,038.27         | 77.88                     | xylitic                 | 99.07                  | 7.42     | 13.4        | 31.08       | 1.1        | 0.462       |
|             | 6-7       | 1,107.81         | 99.47                     | xylitic                 | 97.23                  | 7.92     | 5.83        | 33.29       | 0.51       | 0.513       |

Mad, moisture (air-dried basis); Aad, ash (air-dried basis); Vad, volatile (air-dried basis); St,d, total sulfur (dry, ash free).
the ash and volatile contents of the former are lower than those of the latter, while the moisture content is higher than that of the latter (Table 2). Based on the Chinese standard GB/T15224.1-2004, the coals in the study area exhibit low-medium ash and moisture levels and medium-high volatile contents, which can be conducive to CBM accumulation (Fu et al., 2016).

Coal rank usually has a positive correlation with gas content. Coals from the Bayanhuag sag are mainly lignite and subbituminous according to ASTM D388-2015. The maximum reflectance of vitrinite ($R_o,_{\text{max}}$) is 0.311–0.592% (avg. 0.449%). The reflectance is largely proportional to the burial depth, indicating that coals are dominated by plutonic metamorphism (Figure 5(a)). Based on the contour map of vitrinite reflectance ($R_o$), $R_o$ increases from southwest to northeast, with the highest $R_o$ in the northeastern area (Figure 6).

**Reservoir porosity and permeability.** The seepage of the CBM reservoir is generally evaluated by the permeability parameter (Li et al., 2014). The laboratory outcomes demonstrate that the permeability

![Figure 5](image-url). Scatter plots showing the correlations between depth and $R_o,_{\text{max}}$ (a), permeability (b), gas content (c) and CBM $\delta^{13}C(CH_4)$ (d) modified from Yao et al. (2020).
and porosity of coal reservoirs are 0.05–21.8 mD (avg. 5.54 mD) and 7.3–27.8% (avg. 20.77%), respectively (Table 1). As a result, the reservoir can be classified as low permeability and medium porosity, and it is higher than high and middle-rank coal (Fu et al., 2006). The relationship between permeability and burial depth is notably poor (Figure 5(b)). Furthermore, the porosity and

Figure 6. Vitrinite reflectance contours of the tengger formation No. 6-7 coal seam in the Bayanhua sag.
permeability changes in the main coal seams are vertically inconsistent. The sequence of coal seams in terms of porosity from high to low are No. 6-7 coal, No. 6-4 coal, No. 5-1 coal, No. 5-2 coal, and No. 6-1 coal. The sequences of coal seams in terms of permeability from high to low are No. 6-4 coal, No. 6-7 coal, No. 6-1 coal, No. 5-1 coal, and No. 5-2 coal. Overall, the porosity and permeability of the No. 6 coal group are better than those of the No.5 coal group, which may be caused by the formation of more microfissures during the process of pressolution.

**Pore structure.** Pores of coal reservoirs can be systematically classified as micropores (<10 nm), transition pores (10–100 nm), mesopores (100–1,000 nm) and macropores (>1,000 nm), which mainly determine the adsorption, diffusion and seepage of natural gas in coal reservoirs (Liu et al., 2009; Xu et al., 2012).

Low-field NMR is a nondestructive inspection method for coal reservoirs. The pore structure with a full aperture can be effectively studied based on the characteristics of the NMR T2 spectrum (Yao et al., 2010). The results indicate that transition pores dominate the porosity, followed by mesopores, micropores and macropores, which account for only a small proportion. Changes in the pore volume ratio of the main coal seams in the vertical direction are not obvious. However, the proportions of micropores and transition pores in the No. 6-4 coal, No. 6-7 coal and No. 5-2 coal are slightly higher than those in the No. 6-1 coal and No. 5-1 coal (Figure 7). The data show a poor-medium degree of pore connectivity (Liu et al., 2009). In addition, plant tissue pores, residual plant tissue pores, and intergranular pores mainly present in the huminite and intergranular pores present in the inertinite contribute to the transition pores and mesopores (Figure 8).

The morphology of micropores and transition pores can be well detected by the N2 adsorption method (Liu et al., 2009). The structure of transition pores and micropores is dominated by inkpot, open cylindrical or flat shapes, yielding low-medium connectivity according to N2 adsorption (Figure 9). The N2 adsorption volume of the No. 6 coal group is larger than that of the No. 5

![Figure 7. Proportion of pore volume of the main coal seams in the Bayanhua sag.](image-url)
coal group as a whole, indicating that the No. 6 coal group has a strong adsorption capacity. This structure has both negative and positive influences on CBM exploitation. Pores with inkpot shapes can be conducive to CBM adsorption, although they may increase the difficulty of CBM desorption and diffusion. Pores with open cylindrical or flat shapes can be beneficial to CBM adsorption, desorption and diffusion.

**Microfractures.** Fractures in coal reservoirs have an important impact on CBM adsorption, diffusion and migration (Yuan et al., 2022). In this study, the development of microfractures in the coal reservoirs was observed by photon microscopy and scanning electron microscopy (SEM). The results indicate that microfractures are mainly developed in huminite, such as corpohuminite, gelinite and attrinite, and are mostly distributed in a parallel and interleaved manner. Most microfractures are not filled by secondary minerals and have widths of 1–30 μm (Figure 10). Huminite is the primary form of organic matter in the coals in the study area, and the macrolithotype of coal is dominated by xylitic coal. Xylitic coal tends to develop abundant natural fractures, which tend to improve the permeability of CBM reservoirs (Lyu et al., 2020; Yuan et al., 2022). Therefore, hydraulic fracturing technology should be applied to connect different sizes of pore-fracture systems to improve CBM productivity.

Through comprehensive analysis of the vertical changes in the physical properties of the main coal seams, it is found that the reservoir porosity and permeability and pore structure of the No. 6-7

![Figure 8](image_url). The main types of pores developed in coal reservoirs of the Bayanhua sag (SEM). (a): Pores in the textinite, 1–10 μm; (b): Pores in the textinite, 2–20 μm; (c): Pores in the fusinite, 0.5–3 μm; (d): Pores in the fusinite, 1–4 μm.
Figure 9. N\textsubscript{2} gas adsorption/desorption curves of coal seams from the Bayanhua sag.

Figure 10. Microfractures developed in the coal reservoirs of the Bayanhua sag (photon microscopy and SEM). (a): Microfractures in corpohuminite; (b): Microfractures in gelinite; (c): Microfractures in gelinite; (d): Microfractures in attrinite.
coal, No. 6-4 coal and No. 6-1 coal are better than those of the No. 5-1 coal and No. 5-2 coal. The dominant horizon tends to be the No. 6-7 coal and No. 6-4 coal seams.

**Coal seam gas-bearing properties**

*Origin of coalbed methane.* Many researchers have proposed a number of identification indicators for the origin of biogas, among which the major characteristics of biogas involve two aspects: (1) methane is the main component of biogas, and it has a quite high drying coefficient; (2) the carbon isotopic value of methane is comparatively light (Ju et al., 2014; Tao MX et al., 2014). The CBM composition in the Bayanhua sag varies little, and methane is the dominant component (Table 3), ranging from 70.87% to 97.18% (avg. 81.54%), followed by a small amount of ethane, ranging from 0.23% to 0.42% (avg. 0.34%). Additionally, the drying coefficient is much higher than 198. These features suggest that the CBM in the study area is a typical dry gas. The nonhydrocarbon gases are mainly N2, CO2 and CO, accounting for 1.76–27.84%, 0.32–1.05% and 0–0.15%, respectively. Additionally, the coal seam burial depth is relatively shallow, and N2 primarily comes from the atmosphere and enters the coal seam through groundwater. Consequently, the high content of methane, the low content of heavy hydrocarbons and CO2 in the CBM, and the low degree of coalification (0.371%-0.592% Ro) indicate that the CBM in the Bayanhua sag is mainly of secondary biological origin.

The carbon isotopic value of methane in the Bayanhua sag ranges from $-62.3$‰ to $-54.1$‰ according to the CBM isotopic test results. The test data are plotted on the Whiticar template, and the data indicate that the CBM originated mainly from microbes and certain mixed gases

**Table 3.** Gas content test and methane isothermal adsorption results.

| Coal seam | Burial depth (m) | Gas content (m3/t) | Gas composition (%) | V_L (m3/t) | P_L (MPa) | Reservoir (MPa) | Gas saturation (%) |
|-----------|------------------|--------------------|---------------------|-----------|-----|-----------|-----------------|
| 5-1       | 902.27           | 2.37               | 97.18 0.23 1.76 0.79 0.05 | 4.68 8.31 | 10.11 | 92.22     |
| 5-2       | 921.27           | 3.43               | 81.78 0.36 16.75 1.05 0.06 | 7.88 6.28 | 10.32 | 70.00     |
| 5-3       | 928.58           | 3.34               | 76.64 0.35 22.04 0.82 0.15 | 4.24 7.24 | 10.4  | 133.60    |
| 5-4       | 952.00           | 3.66               | 75.55 0.3 23.81 0.32 0.03 | 4.98 7.02 | 10.66 | 122.00    |
| 5-5       | 955.50           | 2.28               | 93.59 0.42 5.02 0.92 0.04 | 2.78 4.88 | 10.7  | 119.37    |
| 5-6       | 959.84           | 3.47               | 70.87 0.33 27.84 0.88 0.08 | 4.71 6.9  | 10.75 | 120.91    |
| 6-1       | 1,001.00         | 3.31               | 80.47 0.39 18.08 1.03 0.03 | 5.28 7.09 | 11.21 | 102.48    |
| 6-2       | 1,008.00         | 3.53               | 83.02 0.4 15.57 0.96 0.04 | 7.32 6.76 | 11.29 | 77.07     |
| 6-3       | 1,013.00         | 3.02               | 77.89 0.35 20.91 0.84 0.01 | 6.9 13.87 | 11.35 | 97.42     |
| 6-4       | 1,038.95         | 3.72               | 78.61 0.36 20.23 0.8 0 | 8.11 11.89 | 11.41 | 93.70     |
| 6-5       | 1,023.00         | 4.25               | 77.85 0.35 21.08 0.7 0.02 | 6.14 8.49 | 11.46 | 120.40    |
| 6-6       | 1,027.68         | 3.97               | 78.48 0.36 20.26 0.89 0.02 | 6.47 7.33 | 11.51 | 100.51    |
| 6-7       | 1,035.00         | 3.08               | 80.37 0.37 18.48 0.88 0.02 | 3.85 6.02 | 11.59 | 121.74    |
| 6-8       | 1,049.00         | 3.16               | 71.5 0.36 27.2 0.93 0.01 | 6.38 6.49 | 11.75 | 76.89     |
| 6-9       | 1,071.00         | 3.14               | 81.32 0.38 17.51 0.77 0.02 | 5.22 7.29 | 12  | 96.62     |
| 6-10      | 1,095.00         | 2.25               | 88.41 0.27 9.95 0.57 0.04 | 5.28 8.66 | 12.26 | 72.82     |
| 6-11      | 1,101.80         | 3.47               | 91.39 0.28 7.45 0.84 0.04 | 6.79 7.74 | 12.34 | 83.21     |
| 6-12      | 1,108.00         | 3.99               | 82.94 0.32 16.33 0.39 0.01 | 2.78 8.78 | 12.41 | 244.79    |
(Whiticar, 1999), and carbon dioxide reduction was the major process of methane generation (Figure 11). As the burial depth increases, a small amount of thermogenic gas was generated and mixed with the biogenic gas and was preserved during coal metamorphism. Further research has revealed that the $\delta^{13}$C(CH$_4$) value of the CBM is positively correlated with burial depth (Figure 5(d)). The linear fitting analysis reveals that an important conversion is present at a burial depth of approximately 1,200 m, roughly corresponding to a $\delta^{13}$C(CH$_4$) value of $-55\%$ (Figure 5(d)). A small amount of mixed gas appears at depths deeper than 1,200 m, which is consistent with the origin suggested by the Whiticar template.

**Gas-bearing characteristics.** The gas content of the coal seams is 1.66–4.45 m$^3$/t (avg. 3.34 m$^3$/t) (ad), and shows a poor relationship with the burial depth (Figure 5(c)). This means that gas content is likely to be affected by other factors, such as hydrodynamics, roof lithology, and coal quality.

The gas content of the No. 6-7 coal seam is 0–3.58 m$^3$/t (avg. 2.12 m$^3$/t), with the maximum in the middle of the Bayanhua sag (Figure 12(a)). Moreover, the gas contents of the No. 6-4, No. 6-1, No. 5-2, and No. 5-1 coal seams are 0–3.29 m$^3$/t (avg. 1.59 m$^3$/t), 0–3.27 m$^3$/t (avg. 1.54 m$^3$/t), 0–3.23 m$^3$/t (avg. 1.35 m$^3$/t), and 0–3.09 m$^3$/t (avg. 1.13 m$^3$/t), respectively (Figure 12(b)–(e)). The distribution of the gas content is mainly similar and generally increases near the syncline axis, especially in the northeastern and central areas, which is primarily caused by hydrodynamic, structural and preservation conditions.

Vertically, coal No. 6-7 and coal No. 6-4 have the highest gas contents in most regions of the Bayanhua sag, followed by coal No. 6-1, No. 5-2, and No. 5-1, which is mainly due to the factors of reservoir properties and preservation conditions. Coal seams No. 5-1 and No. 5-2 formed when the shore-shallow lacustrine regime transitioned to fan delta and braided river delta.
Figure 12. Gas content distributions in the main coal seams in the Bayanhua sag: The gas content of the No. 6-7 coal seam (a), No. 6-4 coal seam (b), No. 6-1 coal seam (c), No. 5-2 coal seam (d), and No. 5-1 coal seam (e).
systems, and the supply of continental debris was sufficient. As a result, relatively poor-quality coal seams formed in the low-steady peat swamps, which is one of the prime reasons leading to the differences in gas content. The preservation conditions of the coal seams are detailed in CBM accumulation and its controlling factors.

The gas content of low-rank coals cannot well reflect the degree of CBM enrichment. Gas saturation, as a major factor affecting CBM production (Moore, 2012), could reflect the CBM distribution vertically in the same or different areas. Based on statistics, when per-well production exceeds 1,000 m$^3$/d (Li et al., 2010), adsorption saturation of the coal seams is mostly more than 60%; as a result, high gas saturation is an important factor for the high yield of CBM wells. The analysis data show that the gas saturation of the Bayanhua sag ranges from 70% to 244.79% (avg. 108.1%), especially for the No. 5-3, No. 5-4, No. 5-5, No. 6-3 and No. 6-4 coal seams (Table 3), which indicates that the CBM wells in the Bayanhua sag have the potential for high production during the exploitation process.

**CBM accumulation and its controlling factors**

**Structural types.** Tectonics directly affect the formation and evolution of coal-bearing strata, as well as CBM generation, migration, enrichment and preservation. In the process of tectonic evolution, structural deformation and stress field changes also affect CBM migration and occurrence, restricting CBM accumulation (Bai et al., 2014; Hamilton et al., 2012). The Bayanhua syncline is the primary structure in the research area. The syncline axis regions tend to deposit comparatively thick coal-bearing strata, accumulate tectonic stress and maintain relatively stagnant hydrodynamic conditions, which are generally beneficial to CBM accumulation (Li et al., 2005; Yao et al., 2009, 2013; Zhu et al., 2004). In addition, the gas content distributed in the axis regions is much higher, especially in the middle of the Bayanhua syncline (Figure 12). The small-scale synclines and anticlines in the central regions may also have a positive influence on the gas content.

In addition, faults are also an important structural factor that affects CBM accumulation. On the basis of the influence on gas content, faults can be classified as open faults and closed faults. Open faults can be regarded as gas migration and diffusion channels (Chen XJ et al., 2019; Losh et al., 2002), while closed faults can be considered barriers to gathering and trapping migratory gas (Bense and Person, 2006; Jolley et al., 2007). The faults in the Bayanhua sag are all normal faults, which are generally considered gas escape channels (Kedzior et al., 2013; Liu et al., 2009). However, most of the normal faults developed in the Bayanhua sag are closed on account of the dense lithologies present on both sides of the faults. However, the normal faults adjacent to the sag boundary in the southeast are open faults. As a result, it is better to avoid faults during the initial CBM exploration stage.

**Roof lithology.** Previous studies have shown that roof lithology directly affects CBM preservation and accumulation. Dense, fine-grained and thick roofs possess better sealing capabilities than high-porosity, coarse-grained roofs (Buttinelli et al.,2011; Drobniaek et al.,2004; Jin et al.,2015; Ouyang et al.,2017). Three sealing models are divided by different roof lithologies. Models A and B are conducive to CBM preservation. In contrast, model C is adverse to CBM accumulation (Figure 13).

Different sedimentary environments deposit different types of roof lithologies. The studied coals were primarily deposited in peat swamps associated with braided rivers, fan delta plains and lacustrine areas, which mainly resulted in roofs composed of siltstone, mudstone, pelitic siltstone, and fine sandstone. The roofs of the No. 6-7, No. 6-4, No. 5-2 and No. 5-1 coal are mainly composed of fine-grained mudstone in most of the study area (model A). The roof lithologies of the No. 6-7, No. 6-4, No. 6-1 and No. 5-1 coal are made up of siltstone and pelitic siltstone in the northeastern part of the
study area (model B). The fine sandstone on the margin of the Bayanhua sag is partly developed in the roof of the No. 6-1 and No. 5-2 coal (model C) (Figure 14). The gas contents of coal seams No. 6-7 and No. 6-4 are higher than those of coal seams No. 6-1, No. 5-2 and No. 5-1.

**Hydrogeological condition.** Hydrogeology tends to affect CBM generation, migration and accumulation, especially for the enrichment of low-rank CBM (Ayers, 2002; Flores et al., 2008; Yao et al., 2014). For low-rank CBM, weak runoff hydrodynamics could not only be conducive to CBM preservation but also favorable for biogas generation (Beaton et al., 2006; Chen H et al., 2019; Fu et al., 2016). The sandstone pore-confined aquifers interbedded with the main coal seams directly influence CBM enrichment. The unit water inflow rate and permeability coefficient are 0.0091–0.017 L/(s·m) and 0.0098–0.016 m/d, respectively, indicating weak aqueous aquifers (Table 4). Aquicludes interbedded with coal-bearing strata are thick and continuous between the layers. Therefore, groundwater can only be recharged laterally, CBM is sealed in the weak runoff-stagnant zone.

The aquifers of coal strata are in direct contact with the exposed formations on the eastern and western margins of the study area and can be replenished by meteoric precipitation and lateral runoff. From the edge of the study area to the syncline axis regions, the hydrochemical type changes from Ca•Mg-HCO₃ to Na-HCO₃ and Na-Cl, with salinities of 791–1,849 mg/L, indicating that most of the axis regions are in a weak runoff and stagnant state. The active groundwater in the shallow strata mostly flows to the axis regions in the downward-dipping direction, forming hydraulic sealing of CBM. Additionally, groundwater can transport methane bacteria that can degrade coal seams and generate secondary biogenic gas, which accumulates in coal reservoirs.

![Figure 13](image)

**Figure 13.** The sealing models of roof lithology of coal seams in Bayanhua sag.
Figure 14. Roof lithology distribution of the main coal seams in the Bayanhua sag: The roof lithology distribution of the No. 6-7 coal seam(a), No. 6-4 coal seam(b), No. 6-1 coal seam(c), No. 5-2 coal seam(d), and No. 5-1 coal seam(e).
Integrated analysis of groundwater flux and CBM enrichment implies that the hydrological units of the study area are separated into two zones: runoff zones and weak runoff-stagnant zones. Influenced by the flux of groundwater, CBM accumulates from the shallow to the deep areas of the syncline. Consequently, the gas content is lower in the runoff zone and higher in the weak runoff-stagnant zone (Figure 15).

According to the integrated analysis of the vertical changes in the physical and gas-bearing characteristics of the main coal seams and the controlling factors, the dominant horizon tends to be the No. 6-7 coal seam, followed by the No. 6-4 coal seam.

**CBM exploration potential and favorable area appraisal**

Influenced by the elements of structure, hydrodynamics, coal mining activities and preservation conditions, it is difficult to accumulate CBM where coal seams are shallower than 300 m. Based on a comprehensive analysis of CBM reservoir properties, gas-bearing characteristics, structural complexity, hydrodynamics and preservation conditions, this paper divided the study area into three zones horizontally A, B, and C, and each of them was evaluated (Figure 16 and Table 5).

### Table 4. Hydrogeological parameters of coal measure strata in the Bayanhua Sag.

| Aquifer     | Hydrochemical type | Salinity (mg/L) | Unit water inflow (L/(s·m)) | Permeability coefficient (m/d) |
|-------------|--------------------|-----------------|-----------------------------|-------------------------------|
| No. 5 coal  | Na-Cl Na-HCO3      | 791~1,823       | 0.0091~0.017                | 0.0098~0.012                  |
| group       |                    |                 |                             |                               |
| No. 6 coal  | Ca·Mg-HCO3 Na-HCO3 | 836~1,849       | 0.001~0.015                 | 0.0011~0.016                  |
| group       | Na-Cl              |                 |                             |                               |

**Figure 15.** Comprehensive profile of hydrodynamic gas controls in the Bayanhua sag (see Figure 1 for the location).
Zone A is mostly located along the southwestern, southeastern and northwestern edges of the study area, with a main coal seam burial depth of 20.65–425.32 m. Affected by coal mining activities and weathered zones, the CBM preservation conditions in this zone are generally poor. The main coal seams are 0–95.59 m thick, and the faults barely develop, resulting in a relatively simple structure. In addition, the coal seams are generally located in the replenishment and runoff zone, leading to low gas content of 0–2.2 m³/t. Therefore, the abundance of CBM resources is only $0.43 \times 10^8$ m³/km², which is unfavorable for CBM exploration. Furthermore, all open-pit

![Figure 16. Schematic diagram of zone division in the Bayanhu sag.](image-url)
mines in the study area are located in this zone. As a consequence, Zone A might not be conducive to CBM exploitation.

Zone B is distributed in the middle of the Bayanhua sag. The main coal seams have burial depths of 140.48–974.57 m. In contrast with other zones, this zone has the thickest accumulated thickness of coal seams (1.36–131.75 m). The coal-bearing strata are mostly distributed in the weak runoff-stagnant zone, and the thickness of mudstone in the roof is 0.6–89.03 m. Therefore, the gas content (0.5–3.18 m³/t) of the coal seams is comparatively higher. The abundance of CBM resources is approximately 1.66×10⁸ m³/km² and has good exploitation potential from the perspective of resources. According to the structural development, zone B is subdivided into two subzones B1 and B2.

Subzone B1, where the faults are barely developed, is conducive to CBM exploration and development. Subzone B2, where 11 normal faults are distributed, exhibits a complex structure. Although the gas content and resource abundance in this subzone are relatively high, CBM development may be technically difficult in the initial stage; as a result, it could be regarded as a candidate area.

Zone C is located in the northeastern Bayanhua sag and is mainly in the syncline axis region. The burial depth is 90.95–1,300 m and mostly deeper than 600 m. Although the cumulative thickness of the coal seams is 1.23–57.38 m, most of them are distributed in the stagnant zone with respect to hydrodynamic conditions. Coupled with the thick mudstone in the roof (0.7–101.4 m), the coal seams chiefly possess the highest gas contents (0.6–3.53 m³/t). Only small-scale normal faults are developed on the western side of this zone, creating relatively simple tectonic conditions. Therefore, the CBM resource abundance is 1.91×10⁸ m³/km², which is beneficial to CBM exploration. According to the burial depth, zone C is partitioned into two subzones. Subzone C2 is located at the edge of the sag, with burial depth shallower than 300 m, which is not conducive to CBM development. Subzone C1 is located in the syncline axis region. All CBM wells have good gas indications during drilling, and are advantageous to CBM exploration on the basis of the comprehensive analysis of coal seam thickness, burial depth, hydrodynamics, roof lithology and gas-bearing conditions.

Conclusions

1. The Bayanhua sag features large, thick coal seams in most regions, with an accumulated thickness of the main coal seams of 1.00–78.85 m (avg. 22.53 m). The low-rank coal is mainly lignite and subbituminous coal, with Ro values ranging from 0.311% to 0.592%, and is primarily affected by

| Evaluation parameters                  | A               | B               | C               |
|----------------------------------------|-----------------|-----------------|-----------------|
| **Main coal seam thickness (m)**       | 0–95.59         | 1.36–131.75     | 1.23–57.38      |
| **Burial depth (m)**                   | 20.65–325.32    | 140.48–974.57   | 90.95–1,300     |
| **Roof mudstone thickness (m)**        | 1.4–11.45       | 0.6–89.03       | 0.7–101.4       |
| **Gas content (m³/t)**                 | 0–2.2           | 0.5–3.18        | 0.6–3.53        |
| **Structural complexity**              | Simple          | Medium          | Simple          |
| **Hydrodynamics**                      | Recharge and runoff zone | Weak runoff and stagnant zone | Stagnant zone |
| **Resource abundance (×10⁸ m³/km²)**   | 0.43            | 1.66            | 1.91            |

Table 5. CBM geological characteristics in each zone of the Bayanhua sag.
plutonic metamorphism. Coals in the Bayanhua sag tend to be characterized by a relatively high content of organic components (avg. 82.32%) and low levels of ash and moisture, high volatile contents and moderate burial depths, which are beneficial to CBM accumulation and preservation.

2. The coal reservoirs in the Bayanhua sag are characterized by mainly medium porosity (7.3–27.8%, avg. 20.77%) and low permeability (0.05–21.8 mD, avg. 5.54 mD). Pore morphology is represented by transition pores with inkpot, open cylindrical or flat shapes, leading to low-medium connectivity. To improve the permeability of coal reservoirs and penetrate through pores and fracture systems of different sizes, hydraulic fracturing should be used to enhance CBM production.

3. The gas content of the Bayanhua sag is affected by various factors such as hydrodynamics, roof lithology, and structure. The gas content of coals is 1.66–4.45 m³/t (avg. 3.34 m³/t). Gas saturation ranges from 70% to 244.79% (avg. 108.1%). Horizontally, the gas content generally increases toward the syncline axis regions, with the highest in the central and northeastern regions. Vertically, the No. 6-7 and No. 6-4 coal seams have higher gas contents than the No. 6-1, No. 5-2, and No. 5-1 coal seams. The CBM in the Bayanhua sag is mainly of secondary biological origin.

4. The Bayanhua syncline is the main structure, and most of the faults are closed. The roof lithology mainly consists of mudstone and sandy mudstone, which are dense, fine grained and thick. The syncline axis region, with relatively thick coal-bearing strata, accumulated tectonic stress and weak runoff-stagnant hydrodynamic conditions, is favorable to CBM enrichment and preservation. According to the integrated analysis of the vertical changes in the physical properties and gas-bearing characteristics, the dominant horizon tends to be the No. 6-7 coal seam, followed by the No. 6-4 coal seam.

5. Based on the coal seam distribution, gas-bearing characteristics, structure, roof lithology, and hydrodynamic conditions of the Bayanhua sag, the main coal seams in zone B and zone C exhibit thick and moderate burial depths, weak runoff-stagnant hydrodynamic conditions, and comparatively better gas-bearing conditions. The abundances of CBM resources in these zones are $1.66 \times 10^8$ m³/km² and $1.91 \times 10^8$ m³/km², respectively. Based on these conditions, subzone B1 and subzone C1 possess opportune geological conditions for CBM exploration, while the structure of subzone B2 is fairly complex and can be considered a candidate area for CBM exploitation.

**Highlights**

1. The Lower Cretaceous Tengger Formation coal and the geological characteristics of large, thick and low-rank CBM in the representative graben-shaped sag (Bayanhua sag) are analyzed in detail.
2. Gas-bearing analysis makes clear that almost half of coal reservoirs are supersaturated, and microbial carbon dioxide reduction is the dominant methane genetic type in situ.
3. The CBM prospecting potential in the Bayanhua sag was appraised, and two favorable zones are predicted for CBM development.

**Acknowledgements**

This work was subsidized by the National Science and Technology Major Project of China (2016ZX05041-003), Geological Exploration Fund Project of Inner Mongolia (20-1-NY02), Key Technology Research Project of Inner Mongolia, and the Major Science and Technology Project of China National Petroleum Corporation (2021DJ2303). The authors appreciate the anonymous reviews for their elaborative reviews and detailed comments.
Declaration of conflicting interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the the Major Science and Technology Project of China National Petroleum Corporation, the National Science and Technology Major Project of China, Key Technology Research Project of Inner Mongolia, Geological Exploration Fund Project of Inner Mongolia, (grant number 2021DJ2303, 2016ZX05041-003, 20-1-NY02).

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