

# Article

# Characteristics and Origins of the Difference between the Middle and High Rank Coal in Guizhou and Their Implication for the CBM Exploration and Development Strategy: A Case Study from Dahebian and Dafang Block

Fuping Zhao <sup>1,2,3</sup>, Shuxun Sang <sup>1,4,5,\*</sup>, Sijie Han <sup>4,5,\*</sup>, Zhangli Wu <sup>2,3</sup>, Jinchao Zhang <sup>1</sup>, Wenxin Xiang <sup>1</sup> and Ang Xu <sup>1</sup>

- <sup>1</sup> School of Resources and Geosciences, China University of Mining and Technology, Xuzhou 221116, China; db20010022b4cx@cumt.edu.cn (F.Z.); jinchaozhang@cumt.edu.cn (J.Z.); xiangwx@cumt.edu.cn (W.X.); xuang\_xa@cumt.edu.cn (A.X.)
- <sup>2</sup> Key Laboratory of Unconventional Natural Gas Evaluation and Development in Complex Tectonic Areas, Ministry of Natural Resources, Guiyang 550081, China; lilybrbr@163.com
- <sup>3</sup> Guizhou Engineering Research Institute of Oil & Gas Exploration and Development, Guiyang 550081, China
   <sup>4</sup> Carbon Neutrality Institute, China University of Mining and Technology, Xuzhou 221008, China
- Jiangsu Key Laboratory of Coal-Based Greenhouse Gas Control and Utilization, China University of Mining and Technology, Xuzhou 221008, China
- \* Correspondence: shxsang@cumt.edu.cn (S.S.); hsj\_1991@cumt.edu.cn (S.H.)

Abstract: The coalbed methane (CBM) geology in Guizhou is characterized by a high gas content, pressure and resource abundance, indicating superior CBM resource potential. However, there are also many unfavorable factors, such as complex structure geology, significant regional differences in CBM geology, the widespread development of tectonically deformed coal, and the unclear understanding of the configuration of geological factors for CBM enrichment and high yield, which restrict the increase in CBM production and a large-scale development. Taking the Dahebian Block in Liupanshui coal field and the Dafang Block in Qianbei coal field as examples, this study presented the CBM geological differences between middle- and high-rank coals; their origins were analyzed and the effect of depth on gas content and permeability was discussed. A CBM enrichment and high-yield model was illustrated, and the geologic fitness-related exploration and development methods for Guizhou CBM were finally proposed. The results show that (1) significant differences between the middle- and high-rank coals occur in coal occurrence and distribution, coal qualities, and coal reservoir properties. Compared to Dahebian coal, Dafang coal has a higher coal rank, vitrinite content, and gas content, but a lower number of coal layers and permeability. (2) The sedimentary-tectonic evolution of the Longtan coal-bearing sequence is the fundamental reason for CBM geological differences between the Dadebian Block and Dafang Block, consisting of coal occurrence, qualities, maceral, rank, structure, and their associated reservoir properties. (3) The coordinated variation of gas content and permeability contributes to a greater depth for CBM enrichment and a high yield of the middle-rank coal. It is suggested that the best depths for CBM enrichment and high yield in Guizhou are 600-800 m for the middle-rank coal and 500 m for the high-rank coal, respectively. (4) Considering the bottleneck of inefficient CBM development in Guizhou, we proposed three CBM assessment and development technologies, including the CBM optimization of the classification-hierarchical optimization-analytical hierarchy, multiple coal seams commingling production with the pressure relief of tectonically deformed coal, and surface-underground CBM three-dimensional drainage development. The aim of this study was to provide new insights into the efficient exploration and development of CBM in Guizhou.

**Keywords:** different CBM geology; middle and high rank coal; tectonism and sedimentation; enrichment and high yield model; exploration and development strategy



Citation: Zhao, F.; Sang, S.; Han, S.; Wu, Z.; Zhang, J.; Xiang, W.; Xu, A. Characteristics and Origins of the Difference between the Middle and High Rank Coal in Guizhou and Their Implication for the CBM Exploration and Development Strategy: A Case Study from Dahebian and Dafang Block. *Energies* 2022, *15*, 3181. https://doi.org/ 10.3390/en15093181

Academic Editors: Shu Tao, Dengfeng Zhang, Huazhou Huang, Shuoliang Wang, Yanjun Meng and Manoj Khandelwal

Received: 1 April 2022 Accepted: 25 April 2022 Published: 27 April 2022

**Publisher's Note:** MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



**Copyright:** © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/).

# 1. Introduction

Guizhou Province is rich in coalbed methane (CBM) resources, accounting for 10% of the total CBM geological resources in China. The CBM in Guizhou is characterized by a large reserve, a concentrated distribution, and a high quality, and has high potential for large-scale exploration and development. In the 14th Five-year Plan of Guizhou Province, it has been clearly stated that "accelerating the exploration and development of CBM, promoting the Bijie-Liupanshui-Xingren CBM industrial base and approaching CBM annual output of  $4 \times 10^8$  m<sup>3</sup>" [1]. The government also vowed to support and promote the construction of the Zhijin-Panzhou CBM industrial base. The above policies and advantages reinforce the exploration and development of CBM in Guizhou Province. The coal-bearing sequence in Guizhou was formed during the Late Permian, and the tectonic evolutions of the coal-bearing basin are characterized by the multistage, strong different lifting-subsidence and late shaping. The sedimentary setting of the Longtan coal-bearing sequence showed a strong change between marine and land facies across the surface and at the vertical sequence [2]. There are various coal types, and the Guizhou coals show a wide distribution of coal rank, ranging from high volatile bituminous to anthracite. The genetic types of coal both contain regional magmatic thermal metamorphism and plutonic metamorphism [3,4]. The gas-bearing property of coal is highly related to the structural style and depth, and its control via the coupling of multiple factors is the fundamental reason for the diversity of CBM-rich types in Guizhou [5]. The attributes of CBM, characterized by "small but fat" (a small area but a high abundance of CBM resources), were significantly affected by the sedimentation and tectonic [6]; namely, coal-bearing syncline is the enrichment location of CBM, and there is a positive correlation between depth and gas content. The general characteristics of the coal reservoir in Guizhou consist of low porosity, permeability and high gas saturation, in situ stress, and damage degree; meanwhile, there are significant differences among the coal-bearing tectonic units [7–9]. On the one hand, strong reservoir heterogeneity results in the morphology of pores and fractures, especially nano-pores, and then affects the gas flow and efficient CBM production; on the other hand, various pore structures also contribute to different methane adsorption, which will enlarge the difference between excess and absolute adsorption, and finally affect the accurate evaluation of gas content [10–12]. The extensive occurrence of tectonically deformed coal is an important factor restricting the large-scale development of CBM in Guizhou [13,14]. Significantly, extremely thick coal usually shows a higher deformation and failure degree of the coal body, such as No. 11 coal in Dahebian Block and No. 6 coal in Wenjiaba Block. The CBM geological conditions, associated with its enrichment and accumulation, vary in Guizhou. The lithofacies paleogeography, differential tectonic subsidence and abnormal thermal evolution resulted in the observation that the occurrence and physicochemical properties of coal show a regional and heterogeneous distribution in Guizhou [15–17]. Affected by the sequence stratigraphic framework and hydrogeology, the gas-bearing property, gas-bearing gradient, and pressure coefficient of coal are independently segmented at the vertical sequence without a direct fluid exchange, resulting in the formation of the unattached multiple superposed CBM system [18–20]. Some advances have been made in the exploration and development of the CBM of middle- and high-rank coals in Guizhou in recent years. For example, well Yangmeican 1 (middle-rank coal) and well Wencong 1 (high-rank coal) both show breakthroughs in technology and gas production [21,22]. However, most CBM wells still present a low gas production and short time of stable gas production. The significant geological and regional difference in CBM in different coal-bearing units resulted from their tectonic-sedimentary differentiations, which poses challenges to increasing CBM production and conducting large-scale development in Guizhou.

The representative coal-bearing blocks in Guizhou, the Dahebian Block (middle-rank coal), and Dafang Block (high-rank coal) were used as the cases in this study. The differences in the occurrence, maceral, coal quantity, and reservoir physical properties were analyzed, and their origins of sedimentation and tectonic were interpreted. Then, the effect of depth

on the gas content and permeability of coal was identified, and the geological model of the CBM enrichment and high yield in Guizhou was established. Finally, based on the bottleneck induced by the geological differences in CBM in Guizhou, the exploration and development methods and technologies with geological suitability were put forward. This study aims to provide a geological theory and new insights into the exploration and development of CBM in complex geological settings.

#### 2. Materials and Method

### 2.1. Samples and Data Sources

The samples and data in this study are composed of two parts: one is the coal samples collected from boreholes and underground coal mines, and the other is the logging interpretation data of boreholes in study area. The pulverized coals included Nos. 1, 4, 7, 8, 11, 12, 13, 14, 17, and 30 coals, which are collected from boreholes in the Dahebian Block, and Nos.  $6_1$ ,  $6_2$ ,  $6_3$ , 7, 10, 14, 23, 33, and 34 coals, which were collected from Dafang Block. The pulverized coals were applied for maceral identification, and the determination of the total sulfur, ash and major element contents. The block coals are No. 11 coal from Wangjiazhai mine in the Dahebian Block and No. 6 coal from the Lvtang mine in the Dafang Block. The block coals were made into a cylinder with a size of 2.5 cm  $\times$  2.5 cm  $\times$  5 cm for the porosity and permeability measurement of the core in net confining stress. The wells used for the logging interpretation of gas content, porosity and permeability included Zhong-1, Zhong-1-1, Zhong-1-4, Zhong-1-6, Zhong-1-8, CK2302, CK2402, and CK2602 in the Dahebian Block and Da-201, Da-2, and Da-203 in the Dafang Block.

#### 2.2. Methods

The pulverized coals were crushed and reduced into the required size and qualities for maceral identification and determination of the total sulfur, ash, and major element contents. These experiments were conducted according to Chinese National Standard GB/T 8899-2013 "Determination of maceral group composition and minerals in coal", GB/T 212-2008 "Proximate analysis of coal", GB/T 214-2007 "Determination of total sulfur in coal" and GB/T 14506. 28-2010 "Methods for chemical analysis of silicate rocks".

High-pressure nitrogen was used to provide the confining pressure, and high-purity helium was used as the test gas. The test temperature was the indoor temperature, and its changes were controlled within 1 °C. The test pressure was designed as 3, 6, 9, 12, and 15 MPa, and the equilibrium time for each pressure was 30 min. The test procedures were conducted according to the Chinese oil and gas industry standard "The porosity and permeability measurement of core in net confining stress".

#### 3. Results and Discussion

#### 3.1. Different Characteristics between the Middle and High-Rank Coals

The Dahebian Block in the northwest of the Liupanshui coal field and the Dafang Block in the south of the Qianbei coal field develop the middle- and high-rank coal, respectively. There are obvious differences between them regarding tectonic characteristics. The Dahebian Block is located in the western part of the Yangtze platform with a NNW–SEE direction. There is only one large, wide, and gentle syncline, named Dahebian syncline, with relatively few faults and a simple structure. The Dafang Block is located in the Zhunyi Fault-Arch zone of Qianbei Uplift with a NE–SW direction. The Luojiaohe syncline and Dafang anticline control the structure of the block, and their related faults and sub-folds are widely distributed. There are also great differences in coal occurrence, qualities and properties between these two blocks. Importantly, a stronger tectonic deformation results in Dafang Block having a wider distribution of tectonically deformed coal, accounting for approximately 40% of the total coal distribution. In contrast, this proportion is 10% in the Dahebian Block. The thickness of the coal-bearing sequence in the Dahebian Block ranges from 200.70 m to 257.28 m, with an average of 232.97 m. This sequence contains 14–29 layers of coal, and the thickness of the coal ranges from 14.24 m to 17.54 m, with

an average of 16.08 m. Dahebian low-middle volatile bituminous is mainly composed of semidull and semibright-semidull coal. The ratio of coal maceral is 2:1:1 in Dahebian coal, and vitrinite is the primary maceral. The thickness of the coal-bearing sequence in the Dafang Block ranges from 166.14 m to 261.5 m, with an average of 204.14 m. This sequence contains 23–50 layers of coal, and the thickness of the coal ranges from 3.97 m to 13.75 m, with an average of 9.5 m. Dafang anthracite is mainly composed of bright coal and vitrinite content, which accounts for approximately 80% and inertinite content for approximately 20%. Previous studies have demonstrated that there are significant differences between these two blocks in terms of coal occurrence, coal maceral, coal quality, and reservoir properties [7,23,24]. Therefore, the key geological parameters of the two blocks are summarized here, as shown in Table 1, and the CBM geological conditions are comprehensively compared from the perspectives of the occurrence, composition and physical properties of coal.

**Table 1.** Comparison of the representative CBM geological parameters between Dahebian block and Dafang block.

Geological Parameters		Dahebian Block	Dafang Block
Occurrence	Total thickness of coal/m	14.24-17.54/16.08	3.97-13.75/9.50
	Depth/m	600-1200/800	400-1000/600
	Number of coal layer	14-29/18	23-50/35
	Average coal interval/m	4.79-108.71/25.78	11.64-57.84/34.74
	Total thickness of coal measure/m	200.70-257.28/232.97	166.14-261.50/204.14
Coal properties	Vitrinite reflectance/%	0.73-0.97/0.82	3.03-3.69/3.32
	Vitrinite content/%	38.53-63.95/53.81	79.74-92.84/83.96
	Ash content/%	11.27-39.05/25.16	23.75-28.63/26.05
	Sulfur content/%	0.24-5.91/3.1	1.32-2.76/1.94
Coal reservoir parameters	Gas content/ $m^3 \cdot t^{-1}$	8.39-14.92/11.66	17.84-23.75/20.8
	Permeability/mD	0.03-0.66/0.3	0.016-0.43/0.17
	Gas saturability/%	70.45-102.42/83.34	75.59-84.8/78.33
	Langmuir volume/ $cm^3 \cdot g^{-1}$	10.57-18.72/14.52	28.18-35.14/32.04
	Langmuir pressure/MPa	2.48-3.09/2.71	2.28-2.51/2.38
	Tectonically deformed coal development	Weak	Medium-well developed
	Pressure gradient/MPa 100 m <sup>-1</sup>	0.87-1.32/1	0.82-0.93/0.89

Annotation: Min-Max/Average.

As shown in Table 1, the typical differential CBM geological characteristics between Dahebian and Dafang Blocks include coal layer number; vitrinite reflectance; maceral; coal quality; coal structure; and their highly related reservoir parameters, such as gas content and permeability. First, in terms of coal occurrence, the coals in both blocks have low to medium thickness, but they have a higher thickness and a more concentrated distribution in the Dahebian Block. In the Dafang Block, coals thinner than 0.5 m are more developed, suggesting the differences in the stability of coal environment. Second, in terms of coal properties, there are significant differences in the maceral between the middle- and highrank coals. The vitrinite content of Dafang high-rank coal is dominant, concentrated at approximately 80%, while that of Dahebian middle-rank coal is generally low and varies widely, mainly in the range of 35–65% (Figure 1a). Although the overall average value of the ash and sulfur content of these two blocks is similar, the variation range of Dahebian coal is larger, which also implies the difference in the sedimentary environment. Third, on the one hand, the gas content of Dahebian coal is generally lower than that of Dafang coal, which is related to the coal rank. The scattered distribution of gas content and the occurrence of an abnormally high gas content of Dafang coal suggest the development of tectonically deformed coal (Figure 1b). On the other hand, the porosity of coals in these two blocks is similar, but Dafang coals show more scattered porosity (Figure 2a). The permeability of Dafang coals (<0.1 mD) is generally lower than that of Dahebian coals (0.2–0.3 mD), and the values are more concentrated (Figure 2b). These reservoir characteristics also suggest that Dafang high-rank coals have a larger development of tectonically deformed coal. Tectonic compression promotes the increase in porosity, especially the micropores that affect adsorption capacity; however, the destruction of connectivity of the original pore network finally decreases the permeability.



**Figure 1.** Relationship between vitrinite reflectance with vitrinite content (**a**) and gas content (**b**) of the primary mineable coals.



**Figure 2.** Distribution of porosity (**a**) and permeability (**b**) in various coal seams obtained from the log interpretation.

Significantly, the geological characteristics of typical medium–high-rank CBM in Guizhou are significantly different in most geological parameters, such as the number of coal layer, vitrinite content, coal structure, gas content, and permeability. These key geological characteristics are the results of sedimentation and tectonic. Gas content and permeability, which are the indictors of CBM enrichment and high yield, are not only related to the above key geological characteristics between middle- and high-rank coal were discussed based on their sedimentary, tectonic, and depth dependences.

# 3.2. Origins of Different Geological Characteristics between Middle- and High-Rank Coals 3.2.1. Different Sedimentary Environment

The sedimentary environment, REDOX conditions, terrigenous supply, and seawater activities play important roles in maceral and coal qualities, and the variation of maceral and coal qualities can also indicate the evolution of the sedimentary environment [23,25]. Although the Dahebian and Dafang Blocks are geographically neighbors and have similar

transitional sedimentary facies settings and coal-forming plants, there are obvious differences in sedimentary subfacies, microfacies, and seawater activities intensity. This results in the change in the invasion of exogenous components and gelatinization during the peat accumulation, further contributing to the variation of maceral and coal qualities.

The total sulfur content and ash index (Fe<sub>2</sub>O<sub>3</sub> + CaO + MgO/SiO<sub>2</sub> + Al<sub>2</sub>O<sub>3</sub>) in Dahebian and Dafang Blocks both showed a general increase from bottom to top coal (Figure 3a,b), indicating that the REDOX condition of the sedimentary environment changed from weak oxidation-weak reducibility to strong reducibility, which is consistent with the seawater activities in Guizhou during Late Permian [2]. The difference is that the variation in coal qualities in the Dahebian Block is more significant, suggesting stronger seawater activities during peat accumulation. Significantly, the total sulfur content of No. 12, 13, 14, 17, and 30 coals are lower than 1 %, and the ratio between organic sulfur and total sulfur approach 42.42–68.75%, suggesting that these coals were formed in a terrestrial environment and the organic sulfur mainly came from the absorption of terrestrial plants. The triangular diagram of ash compositions also indicated that the Dafang Block had a relatively stable and weak reducibility environment (Figure 3c). However,  $Fe_2O_3 + SO_3$  gradually increased from bottom to top in Dahebian coals, suggesting that this area evolved from near the provenance to the environment with deep overlying water, weak hydrodynamics, and strong reducibility. Therefore, according to the total sulfur content and ash compositions, it can be inferred that the Dahebian Block experienced the evolution from the upper delta plain fluvial environment to the tidal flat-lagoon environment, while the Dafang Block mainly developed the tidal lower delta plain environment. The sedimentary environment indicated by maceral content showed a similar result with coal qualities. In the Dafang Block, the vitrinite content ranges from 70.84% to 86.36%, with an average of 78.16%, and the inertinite content ranges from 13.64% to 29.16%, with an average of 21.19%. In the Dahebian Block, the vitrinite varies, with the content ranging from 35.37% to 72.4%, and the inertinite content ranges from 11.07% to 52.41%, with an average approximately 25%. However, coals above No. 12 coal have a significantly higher vitrinite content, and the inertinite content is opposite. The results of maceral also suggested that the sedimentary environment in the Dafang Block was relatively stable with a weak hydrodynamic condition and weak to strong reduction environment, but the Dahebian Block underwent a significant change from a weak oxidation to a strong reduction environment.



**Figure 3.** Sedimentary environment indication using different coal qualities parameters. (**a**) Total sulfur; (**b**) Ash index; and (**c**) Triangular diagram of ash compositions.

#### 3.2.2. Tectonic Effects on Coal Rank and Structure

Tectonic and its associated magmatic activities have important effects on the coal rank and structure. The coal rank is the product of the coupling effects of temperature, pressure, and time, and the coal structure indicates the process of in situ stress transformation. Plutonic thermal metamorphism in different geothermal environments during tectonic subsidence and high-temperature thermal anomalies caused by regional magmatic activities are the fundamental driving forces of coalification.

It is well known that the thermal evolution of Longtan coals in Guizhou suffered plutonic thermal metamorphism superimposed by high-temperature metamorphism during the age of the Yanshan period [26]. Therefore, the uneven tectonic subsidence and plutonic magmatic intrusion during the Yanshan period caused the uneven distribution of temperature gradient and further resulted in a significant difference in coal rank. The coal rank in Guizhou presents an X-type distribution with a low coal rank in the east and west, but a high coal rank in the middle north and south of Guizhou [27,28]. The plane distribution of coal rank shows a high relationship with deep faults in Guizhou. Affected by the NW-oriented Ziyun-Shuicheng, NE-oriented Zongshi-Guiyang, and NNE-oriented Zunyi–Huishui faults, anthracites are distributed in the north and south blocks, while bituminous coals often occur in the east and west blocks (Figure 4). Meanwhile, the coal rank of bituminous coals showed a decrease from these deep faults. The middle-rank coals in the Liupanshui coal field are the results of plutonic thermal metamorphism, and they are controlled by the depth, with increasing magmatic thermal effects from west to east [29]. The uneven tectonic subsidence during the evolution of the Ziyun–Shuicheng and Zongshi-Guiyang faults resulted in the Qianzhong Uplift in the northern Zhina coal field. The formation of the Qianzhong Uplift indicated the thinning of the lithosphere and, therefore, the heating induced by the latent magmatic intrusion was most obvious in this area [3]. In fact, the coal rank had a high affinity with the distance of the Qianzhong Uplift. A previous study on the inclusions demonstrated that the highest temperature in the Zhijin area approached 244 °C, but the highest temperature in Panxian only reached 150 °C [4], which verified that the different tectonic thermal events are the governing control on the various coal ranks in Guizhou.



Figure 4. Relationship between deep faults and coal rank in Guizhou. Adapted from [27].

The effect of tectonic activities on coal is also indicated by the deformation and damage of the coal structure, and the development of tectonically deformed coal is its typical feature. Subsequent to the formation of the Longtan coal-bearing sequence in Guizhou, coals suffered a long-term compression during the Yanshan and Himalayan periods, resulting in serious damage to the coal structure and the wide development of tectonically deformed coal. Meanwhile, the effect of structure on tectonically deformed coals is reflected in their distribution and damage degree [30]. The development of tectonically deformed coal is often accompanied by large compressional faults, and the distribution of tectonically deformed coal has a high affinity with Late Permian synsedimentary faults. During the Yanshan period, the squeeze thrust and interlayer slip of these faults reinforced the deformation and damage to the coal structure and, therefore, the closer to the faults, the more broken the coal structure was [31]. A previous study indicated that the Ziyun– Shuicheng, Shizong-Guiyang, and Zunyi-Huishui faults were not only the main areas for tectonically deformed coal, but also the boundary of the high gas content area, suggesting the tectonic effect on gas content and coal structure [32]. In addition to the obvious structural control, thick coal is also the key to searching for tectonically deformed coal in Guizhou. This is because thick coals have a lower mechanical strength compared with their surrounding rocks and, therefore, they are more prone to crumpling and interlayer slipping under the influence of squeezing and shear stress, resulting in greater damage to thick coals. For example, No. 6 coal in the Dafang Block is composed of granulated coal and mylonitized coal, whereas No. 16 and 27 coals, located below No. 6 coal, are composed of primary and cataclastic coal with a minor granulated coal. In addition, the hierarchical structure of thick coal will also produce a stress concentration area in some soft layers, contributing to a typical sandwich-like structure. The classical case is No.11 coal in the Dahebian Block, which has a thickness of 6–8 m; such thick coal is extremely rare in Guizhou and even in southwest China. Primary coal, schistose coal (Figure 5a) or mylonitized coal, granulated coal (Figure 5b), and cataclastic coal/lenticular coal (Figure 5c) occur at their ascend sequence. The small crumpled and sliding surface are often discerned in the middle tectonically deformed coal zone (Figure 5d).



**Figure 5.** Main tectonically deformed coal types of thick coal (11#) in Dahebian Block. (**a**) Schistose coal (2 m below the roof); (**b**) Granulated coal (2.5 m below the roof); (**c**) Cataclastic coal/lenticular coal (0.5 m above the floor); and (**d**) Schistose coal with a small fold (1.5 m above the floor).

3.2.3. Effect of Depth on Gas Content and Permeability between the Middle- and High-Rank Coal

Gas content and permeability, which show high affinities with CBM enrichment and high yield, have different dependences of depth. They show an opposite change against

depth at a low depth; namely, as depth increases, gas content linearly increases, but permeability shows a significant decrease. However, with the increase in depth, both gas content and permeability decrease, but their decrease in amplitude is significantly different. Due to the completely different control effects of depth on gas content and permeability, there is a balance depth that enables these two key factors to meet the requirements of CBM enrichment and high yield [33]. It should be noted that there is a difference in the balance depth between middle- and high-rank coal. This is because (1) the high-rank coal has a higher gas content due to its high Langmuir volume at the same depth; and (2) the permeability of high-rank coal has a stronger stress sensitivity. On the one hand, a previous study showed that the methane adsorption capacity has a maximum value of depth profile, and this value is closely related to temperature and pressure [34]. The gas content of Guizhou coal also follows the above law, but the difference is that the gas content of middle-rank coal is smaller than that of high-rank coal at the same depth, and the critical depth of the maximum gas content of high-rank coal is deeper than that of middle-rank coal (Figure 6a,b), which is related to the control effect of coal rank on gas adsorption capacity [35]. On the other hand, in fact, the control effect of depth on permeability is the modification of effective stress on the gas migration channel. The increase in depth indicates an increase in overburden pressure, as well as effective stress. The stronger effective stress on coal results in the compression or even closure of efficient gas migration channels, such as cleat and fracture, which eventually contributes to the decrease in permeability. The results of the change in the porosity and permeability of Guizhou medium- and high-rank coals under the loading of effective stress show that the porosity and permeability of highrank coal are lower than those of middle-rank coal under the same effective stress, and the permeability attenuation of high-rank coal is more obvious at a high pressure (Figure 7). This demonstrates that the negative effect of the porosity and permeability of the high-rank coal is stronger than that of the middle-rank coal. The permeability of high-rank coal is lower than that of middle-rank coal due to the extinction of macropores and the decrease in cleat density. The dependence of fracture on the permeability of high-rank coal results in its stress sensitivity being stronger than middle-rank coal [36,37].



**Figure 6.** Relationship between gas content obtained from log interpretation and depth of the middle and high rank coals. (**a**) Dahebian Block; (**b**) Dafang Block.



Figure 7. Relationship between effective stress with porosity (a) and permeability (b).

In general, the depths of coal with a high gas content and permeability are different for middle- and high-rank coals. At the same depth, middle-rank coal has a lower gas content than high-rank coal, but its permeability is higher than that of high-rank coal. The increase in depth has a negative effect on the permeability of high-rank coal, but has a positive effect on the gas content of middle-rank coal before its transition depth. Therefore, the depth of high-rank coal with a high gas content and permeability is shallower than that of middle-rank coal, which is consistent with the results of the CBM exploration and development in Guizhou.

#### 3.3. Model of Enrichment and High Yield of CBM in Guizhou

By 2020, more than 300 CBM wells had been constructed in Guizhou, with a production capacity of  $1 \times 10^8$  m<sup>3</sup> per year and an output of  $0.24 \times 10^8$  m<sup>3</sup> per year. However, the vast majority of wells have common problems, such as low single well output and short stable production time. The characteristic of gas-rich coal in Guizhou is significantly superior to that in north and northwest China. The high CBM resource abundance and gas saturation are the original driving forces behind CBM exploration and development in Guizhou. In fact, the key reasons for the low production of CBM wells are the low permeability, development of tectonically deformed coal and weak water content in coals. As a result, the hydrophobic depressed CBM development model has been blocked from widespread application in Guizhou. Therefore, in the current era of low-permeability coal, in which especially tectonically deformed coals have not been broken through, it is an inevitable choice to find high-permeability primary or weakly deformed coals controlled by the configuration of key geological factors.

The enrichment and high yield of CBM is the result of the coupling controlling of gas content and permeability via key geological factors [33]. Guizhou has complex geological conditions, and the coal-bearing basins are divided into uneven tectonic units. The sealed syncline is a potential position for CBM enrichment. On the one hand, the overlying Feixianguan Formation is developed with waterproof mud shale with low porosity and permeability, which provides a good lithologic seal for the CBM reservoir. In addition, the hydrodynamic condition of the Longtan Formation coal-bearing sequence is weak, and the weak runoff area is only developed near the outcrop layer of the wing. Underground water bedding supply plays a hydrodynamic sealing role in deep CBM, and gas content is positively correlated with depth, contributing to gas enrichment in the deep syncline. On the other hand, the synclinal axial is under a compressive stress environment, and the permeability of coal here decreases significantly under the joint action of depth and tectonic stress, which is not conducive to CBM production. Therefore, under the combined control of structure, hydrodynamic sealing, and depth, primary coals in the monocline near the syncline axis can easily form coalbed methane enrichment areas (Figure 8). However, it should be noted that due to the stronger adsorption capacity and higher permeability stress sensitivity of high-rank coals, their depth for CBM enrichment and high yield is

usually lower than that of middle-rank coal. The high-yield CBM development project in Guizhou also shows that the main producing coals in well Zhong 1 in the Dahebian Block is at the depth of 700–800 m, with a gas content of 11.5–17.66 cm<sup>3</sup>/g and permeability of 0.05–0.53 mD, while in the Wenjiaba Block, the producing high-rank coals in well Wen 1 are at the depth of 300–500 m with a gas content of 12.72–13.34 cm<sup>3</sup>/g and permeability of 0.18–0.92 mD. This indicated that the coals of different coal ranks in these two blocks have a similar gas content and permeability. Therefore, it can be speculated that the depth of middle-rank coal for CBM enrichment and high yield is less than 500 m, while the depth of middle-rank coal is expected to be 600–800 m. The key geological factors of CBM enrichment and high yield of different coal ranks in Guizhou have the common characteristics of structure–hydrodynamic coupling control. However, the effect of synergistic depth control on gas-bearing and permeability properties is considerably more important.



Figure 8. High rank coal CBM enrichment and high-yield model in Guizhou.

#### 3.4. Geological Suitable CBM Exploration and Development Strategies in Guizhou

Various sedimentations and tectonics constitute an essential reason for the different geological characteristics of CBM in Guizhou, and they are also the key geological factors controlling gas content and permeability. Such complex geological conditions also pose challenges to the exploration and development of CBM, so it is necessary to propose specific technical methods according to the different coal reservoirs and the coupling law between gas content and permeability.

3.4.1. Optimization of Block and Coal Seam for CBM Exploration and Development Based on Coal Rank Classification

The geological characteristics of CBM vary greatly under complex geological conditions and, therefore, coal reservoirs have strong heterogeneity. There are differences in the collaborative configuration of key geological factors for CBM enrichment and high yield under the coupling effects of gas content and permeability between different coal ranks. As a result, the influence of some parameters on the evaluation results is exaggerated under the same standards. For example, although the gas content of low-rank coal is low, the macropore and microfracture for gas seepage are more developed. In contrast, the high-rank coal has a high gas content, but low permeability, and the attenuation of permeability is more obvious under the action of increased stress. Accordingly, China's energy industry standards NB/T 10013-2014 "CBM Geological Selection Evaluation" stated that there are different quantitative classification indexes of key geological parameters for the CBM geological selection evaluation of different coal ranks. For example, the best gas content and permeability are  $\geq 6 \text{ m}^3/\text{t}$  and  $\geq 3 \text{ mD}$  for the low rank coal and  $\geq 15 \text{ m}^3/\text{t}$ and  $\geq 1 \text{ mD}$  for the middle–high-rank coal. Therefore, in view of the differences in CBM geological characteristics in a complex geological setting, a classification of coal rank is suggested before the original optimization for CBM geological selection evaluation. The main coal-bearing areas in Guizhou, such as Liupanshui, Qianbei, and Zhina coal fields, have a wide distribution of coal rank, ranging from high volatile bituminous coal to anthracite. The coals of different ranks have significantly different gas contents and permeabilities. However, under the same evaluation standard, it is easy to omit middle-rank coals with a low gas content or high-rank coals with a low permeability during optimization for CBM geological selection evaluation. In fact, the CBM exploration and development in China have shown that there are high-yield CBM wells in both middle- and high-rank coal areas [38,39]. At present, there are few high-yielding CBM wells, and there is also no commercialized CBM blocks. However, the high-yielding performance of well Zhong 1 in the Dahebian Block, Liupanshui coal field, and well group Wencong 1 in the Wenjiaba Block, Zhina coal field, both indicate that CBM blocks of different coal ranks in Guizhou both have high production potential under the reasonable configuration of geological factors. Therefore, CBM geological selection evaluation based on the classification of key geological parameter is especially suitable for the geological optimization of CBM blocks and coal seams in a complex geological setting. According to the previous CBM geological optimization used in eastern Yunnan and western Guizhou [40,41], we proposed a modified method for the optimization of block and coal seam for CBM exploration and development in Guizhou, as shown in Figure 9. First, the blocks are classified into two groups according to the coal rank (middle- and high-rank coals). Second, the analytic hierarchy process (AHP) is used to establish the evaluation system. By comparing the importance of geological parameters, the discriminant matrix is established, and then the weight of the geological parameters is calculated for the system. Third, the membership function of each geological parameter is established according to the fuzzy mathematics principle. The actual weight of each geological parameter is calculated, and then the order of the blocks is obtained through the accumulation of the actual weights. The evaluation of the sweet point areas and sections have the same evaluation process as that of blocks. The aim of this process is to obtain the potential block and coal seam for CBM exploration and development.



Figure 9. Flow diagram of optimization of block and coal seam for CBM exploration and development.

3.4.2. Multiple Coal Seams Commingling Production with Pressure Relief of Tectonically Deformed Coal

Tectonically deformed coal is characterized by a high gas content, low permeability, and soft structure. Reservoir reconstruction technology based on hydraulic fracturing has little effect on the permeability improvement of these coals, and even easily leads to hole collapse and blocking. Therefore, the CBM development system based on hydrophobic depressurization and desorption theory of primary coal or weakly deformed coal is not suitable for the efficient development of tectonically deformed coal. Surprisingly, the coalbearing basins in Guizhou were strongly deformed and underwent multi-stage tectonic deformations, resulting in the modification of the coal-bearing sequence. As a result, tectonically deformed coals were widely distributed in Guizhou coal-bearing basins, especially in some complex tectonic areas, such as Zhaozihe syncline, Tudiya syncline, and other tectonic transition zones. How to enhance the CBM recovery of tectonically deformed coal is the key to increasing CBM reserves and yields. According to the positive results of the surface gas drainage technology in the coal mine goaf and open hole cave completion technology in a straight well [42,43], Sang et al. [44] innovatively proposed a CBM development model of tectonically deformed coal stress relief. Based on the volume expansion, increase in permeability and decrease in pressure induced by stress relief of tectonically deformed coal, a large-range efficient desorption-seepage area was formed, resulting from the formation of the horizontal well cavern and significantly enhanced CBM recovery. More importantly, due to the deformation and fracture of the overlying strata, longitudinal and stratified fractures of different sizes were produced, which provides favorable conditions for the development of the overlying multi-coal seam group (Figure 10). The multi-coal seam groups widely occur in Guizhou and southwest China, and the commingling production of CBM has been successfully applied to these areas. According to the permeability improvement of the overlying coals via tectonically deformed coal development, the synthesis of a CBM development technique combined with the stress relief of tectonically deformed coal and the commingling production of multiple coal seams are recommended. A combined implementation of tectonically deformed coal in situ CBM recovery via horizontal well cavern completion and stress relief and hydraulic fracturing in overlying primary coal can further improve the drainage efficiency in multiple coal seam commingling production. This technology transforms the development of tectonically deformed coal CBM into a high-yield advantage, and promotes the efficient exploration and development of CBM under the complex geological condition in Guizhou Province.



**Figure 10.** The multiple coal seams commingling production with tectonically deformed coal in-situ CBM recovery by horizontal well cavern completion and stress relief.

3.4.3. Surface–Underground CBM Three-Dimensional Drainage Development in Coal Mine Area

Due to the imperfect policies and regulations in China's energy industry, the mining rights affiliation of coal and CBM are often different, resulting in a conflict of mining rights between coal and CBM development. As a result, it is difficult for CBM enterprises to enter coal mining areas for CBM exploration and development. However, the CBM projects indicated that the depth of CBM enrichment and high-yield is lower than 800 m, and even 500 m, for high-rank coal. These depths basically overlap with the coal mining depth, which greatly restricts the development of the CBM industry in Guizhou. Significantly, most of the coal mines in Guizhou belong to high gas mines, and the high concentration of gas seriously threatens the safety production of coal mines, which creates an opportunity for CBM extraction in coal mine areas. Surface–underground gas pre-drainage can effectively reduce gas outbursts whilst making full use of CBM, which has great development potential. The driving forces of surface–underground CBM three-dimensional drainage are gas control and coal safety mining. Therefore, this technology needs to be combined with coal production in time and space and make full use of the mining effect on the pressure relief and permeability of coal. The three-dimensional highly efficient migration channel network of CBM was produced via surface vertical well fracturing and downhole long borehole and eventually realized the efficient development of CBM in coal mining areas (Figure 11) [45–47]. Surfaceunderground CBM three-dimensional drainage development has multiple advantages, such as ensuring coal production safety, effectively utilizing CBM resources and reducing methane emissions, which is expected to be an important and suitable technology for CBM exploration and development in Guizhou. In recent years, scholars and engineers have begun to explore the surface-underground CBM three-dimensional drainage in coal mine areas, and the first demonstration project was launched in the Xintian coal mine in 2020. Other similar demonstration projects are also being advanced in Qianbei and Zhina coal fields.



**Figure 11.** Integrated development model of the surface–underground CBM three-dimensional drainage in coal mine area.

#### 4. Conclusions

The middle-rank coal-rich area—Dahebian Block—and the high-rank coal-rich area—Dafang Block—were taken as examples to compare coal occurrence, coal maceral, and properties. The effects of sedimentation, tectonic, and depth on the CBM geological differences between the Dahebian and Dafang Blocks were interpreted. The Guizhou CBM

enrichment and high-yield model and its different depths for the middle- and high-rank coals were shown. Geologically suitable CBM exploration and development technologies were proposed for geological selection, development technology, and modeling in Guizhou. The main conclusions are summarized as follows:

- (1) The geological differences in the middle- and high-rank coal CBM in Guizhou are mainly reflected in the number of coal layers, maceral, coal structure, and their influence on gas-bearing capacity and permeability. Compared to the middle-rank coal in the Dahebian Block, the Dafang high-rank coal shows more coal layers (30–66), and a higher vitrinite (2.94–3.42%) and gas content (17.84–23.75 m<sup>3</sup>/t), but a lower thickness (9.5 m), a lower permeability (0.02–0.64 mD), and a wider tectonically deformed coal distribution;
- (2) Although the sedimentary environment was the transitional sedimentary facies system in most of Guizhou during the Late Permian, the frequent transgression– regression and terrigenous source input resulted in a significant difference in coal occurrence, maceral, and qualities. The distribution of coal rank shows a high affinity with deep faults, and the uneven tectonic subsidence and its related thermal anomaly result in an X-type distribution of coal rank. The distribution and damage degree of the tectonically deformed coal are also related to these faults;
- (3) The favorable configuration of structure, hydrology, and depth promotes enrichment and high CBM yield in Guizhou. However, there are differences in depth for CBM enrichment and high yield between middle-rank coal (<500 m) and high-rank coal (600–800 m). The coupling relationship between permeability and gas content controlled by depth is the fundamental reason for the difference in depth for CBM enrichment and high yield between the middle- and high-rank coal;</p>
- (4) We provided three new concepts for the efficient exploration and development of CBM in Guizhou; namely, (a) the optimization of block and coal seam for CBM exploration and development (classification–successive optimization–analytical hierarchy process), (b) the multi-layer CBM development with the pressure relief of tectonically deformed coal, and (c) surface–underground CBM three-dimensional drainage development in coal mines.

**Author Contributions:** Conceptualization, F.Z., S.H. and S.S.; methodology, F.Z.; validation, S.S. and S.H.; formal analysis, J.Z., A.X. and W.X.; investigation, F.Z., S.H. and J.Z.; resources, F.Z. and Z.W.; data curation, F.Z. and Z.W.; writing—original draft preparation, F.Z.; writing—review and editing, F.Z., S.H. and S.S.; visualization, J.Z., A.X. and W.X.; supervision, S.H. and S.S.; project administration, F.Z. and Z.W.; funding acquisition, F.Z., S.H. and S.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by [National Natural Science Foundation of China] grant number [No. 42030810, 41727801, 42102207] and [Geological Exploration Foundation of Guizhou Province] grant number [No. 208-9912-JBNUTS0, 52000021MGQSE7S7K6PRP]. And The APC was funded by [Geological Exploration Foundation of Guizhou Province].

Acknowledgments: The authors would like to acknowledge Guizhou Natural Gas Energy Investment Co., Ltd. and Guizhou Shuicheng Coal Mining & Orion Clean Energy LLC for assisting in logging data collection.

Conflicts of Interest: The authors declare no conflict of interest.

#### References

- 1. Guizhou Daily. Available online: http://szb.gzrbs.com.cn/pc/cont/202102/27/content\_6542.html (accessed on 27 February 2021).
- Shao, L.; Hua, F.; Yi, T.; Guo, L.; Wang, X. Sequence-paleogeography and coal accumulation of Lopingian in Guizhou Province. *Coal Geol. Explor.* 2021, 49, 45–56.
- 3. Chen, Y.; Qin, Y.; Li, Z.; Chang, H.; Luo, Z. Magma thermal metamorphism of the Longtan formation coals in Zhijin Guizhou. *J. China Univ. Min. Technol.* **2012**, *41*, 406–414.

- 4. Tang, S.; Tang, D.; Xu, H.; Tao, S.; Li, S.; Geng, Y. Geological mechanisms of the accumulation of coalbed methane induced by hydrothermal fluids in the western Guizhou and eastern Yunnan regions. *J. Nat. Gas Sci. Eng.* **2016**, *33*, 644–656. [CrossRef]
- Li, M.; Jiang, B.; Lin, S.; Lan, F.; Wang, J. Structural controls on CBM reservoirs in Faer coal mine, Southwest China. J. Earth Sci. 2013, 24, 437–448. [CrossRef]
- Zhang, Z.; Qin, Y.; You, Z.; Yang, Z. Distribution characteristics of in situ stress field and vertical development unit division of CBM in Western Guizhou, China. *Nat. Resour. Res.* 2021, *30*, 3659–3671. [CrossRef]
- Song, L.; Tang, D.; Xu, H.; Yang, Z. The pore-fracture system properties of CBM reservoirs in the Panguan Syncline, Guizhou, China. *Geosci. Front.* 2012, 3, 853–862.
- 8. Li, S.; Tang, D.; Pan, Z.; Xu, H.; Guo, L. Evaluation of CBM potential of different reservoirs in western Guizhou and eastern Yunnan, China. *Fuel* **2015**, *139*, 257–267. [CrossRef]
- Chen, S.; Tang, D.; Tao, S.; Chen, Z.; Xu, H.; Li, S. Coal Reservoir Heterogeneity in Multicoal Seams of the Panguan Syncline, Western Guizhou, China: Implication for the Development of Superposed CBM-Bearing Systems. *Energy Fuels* 2018, 32, 8241–8253. [CrossRef]
- Tan, Y.; Pan, Z.; Liu, J.; Zhou, F.; Connell, L.D.; Sun, W.; Haque, A. Experimental study of impact of anisotropy and heterogeneity on gas flow in coal. Part II: Permeability. *Fuel* 2018, 230, 397–409. [CrossRef]
- 11. Jia, B.; Xian, C. Permeability measurement of the fracture-matrix system with 3D embedded discrete fracture model. *Pet. Sci.* 2022. [CrossRef]
- 12. Jia, B.; Chen, Z.; Xian, C. Investigations of CO<sub>2</sub> storage capacity and flow behavior in shale formation. *J. Pet. Sci. Eng.* **2022**, 208, 109659. [CrossRef]
- 13. Li, M.; Jiang, B.; Lin, S.; Wang, J.; Ji, M.; Qiu, Z. Tectonically deformed coal types and pore structures in Puhe and Shanchahe coal mines in western Guizhou. *Min. Sci. Technol.* **2011**, *21*, 353–357. [CrossRef]
- 14. Ju, W.; Yang, Z.; Qin, Y.; Yi, T.; Zhang, Z. Characteristics of in-situ stress state and prediction of the permeability in the Upper Permian CBM reservoir, western Guizhou region, SW China. *J. Pet. Sci. Eng.* **2018**, *165*, 199–211. [CrossRef]
- 15. Shen, Y.; Qin, Y.; Guo, Y.; Yi, T.; Yuan, X.; Shao, Y. Characteristics and sedimentary control of a CBM-bearing system in lopingian (late permian) coal-bearing strata of western Guizhou Province. *J. Nat. Gas Sci. Eng.* **2016**, *33*, 8–17. [CrossRef]
- 16. Ren, P.; Xu, H.; Tang, D.; Li, Y.; Chen, Z. Pore structure and fractal characterization of main coal-bearing synclines in western Guizhou, China. *J. Nat. Gas Sci. Eng.* **2019**, *63*, 58–59. [CrossRef]
- 17. Ju, W.; Yang, Z.; Shen, Y.; Yang, H.; Wang, G.; Zhang, X.; Wang, S. Mechanism of pore pressure variation in multiple coal reservoirs, western Guizhou region, South China. *Front. Earth Sci.* **2021**, *15*, 770–789. [CrossRef]
- 18. Qin, Y.; Xiong, M.; Yi, T.; Yang, Z.; Wu, C. On unattached multiple superposed coalbed-methane system: In a case of the Shuigonghe Syncline, Zhijin-Nayong coalfield, Guizhou. *Geol. Rev.* **2008**, *54*, 65–70.
- 19. Shen, Y.; Qin, Y.; Guo, Y.; Yi, T.; Shao, Y.; Jin, H. Sedimentary controlling factor of unattached multiple superimposed coalbedmethane system formation. *Earth Sci.-J. China Univ. Geosci.* **2012**, *37*, 573–579.
- Zhou, P.; Jin, J.; Luo, K.; Gao, W.; Chen, J. Unattached multiple layer superimposed coalbed methane system in Songhe mine, west Guizhou. *Coal Geol. Explor.* 2017, 45, 66–69.
- Shan, Y.; Bi, C.; Chi, H.; Wang, F.; Li, H. Geological characteristics of CBM and optimization for favorable productive intervals of Yangmeishu syncline in Liupanshui area. *Nat. Gas Geosci.* 2018, 29, 122–129.
- 22. Wang, S.; Gao, W.; Guo, T.; Bao, S.; Jin, J.; Xu, Q. The discovery of shale gas, coalbed gas and tight sandstone gas in Permian Longtan Formation, northern Guizhou Province. *Geol. China* **2020**, *47*, 249–250.
- Cheng, W.; Yang, R.; Cui, Y.; Fu, H.; Zhang, T. Characteristic of Late Permian coal quality from Bijie, Guizhou Province, SW China, and its significance for paleoenvironment. *Acta Geol. Sin.* 2013, 87, 1763–1777.
- 24. Fang, X.; Wu, C.; Jiang, X.; Liu, N.; Zhou, D.; Ju, Y. Characteristics of in situ stress and its influence on coal seam permeability in the Liupanshui Coalfield, Western Guizhou. *Energy Sci. Eng.* **2021**, *9*, 1773–1786. [CrossRef]
- 25. Teichmüller, M. The genesis of coal from the viewpoint of coal petrology. Int. J. Coal Geol. 1989, 12, 1–87. [CrossRef]
- 26. Yang, Q.; Ren, D.; Pan, Z. Preliminary investigation on the metamorphism of Chinese Coals. *Int. J. Coal Geol.* **1982**, *2*, 31–48. [CrossRef]
- 27. Chen, X. Distribution law and genesis of Permian coal in Guizhou. Coal Geol. Explor. 1995, 23, 21–24.
- 28. Xiong, M.; Qin, Y.; Yi, T. Sedimentary patterns and structural controls of late permian coal-bearing strata in Guizhou, China. J. *China Univ. Min. Technol.* **2006**, *35*, 778–782.
- 29. Zeng, R.; Zhao, J.; Zhuang, X. Quality of Late Permian coal and its controlling factors in Shuicheng mining district of Liupanshui area, Guizhou. *Acta Petrol. Sin.* **1998**, *14*, 549–558.
- Li, M.; Jiang, B.; Liu, J.; Zhu, P.; Cheng, G. Geological models and structural controls of tectonically deformed coal in Tucheng syncline, western Guizhou Province. J. China Coal Soc. 2018, 43, 1565–1571.
- Zhou, P.; Gao, W.; Deng, L.; Fu, W. Regional distribution and geotectonic control of Late Permian tectonically deformed coal in Zhina coalfield. *Coal Geol. Explor.* 2020, 48, 29–34.
- 32. Jia, T.; Wang, W.; Yan, J.; Tang, C. The rule of tectonic control and the zoning division of coal mine gas occurrence in Guizhou Province. *Earth Sci. Front.* **2014**, *21*, 281–288.
- 33. Song, Y.; Liu, S.; Ma, X.; Ju, Y.; Hong, F.; Jiang, L. Accumulation models for CBM in medium- to high-rank coals: Examples from the southern Qinshui Basin and southeastern Ordos Basin. *Aust. J. Earth Sci.* **2018**, *65*, 575–590. [CrossRef]

- Hildenbrand, A.; Krooss, B.-M.; Busch, A.; Gaschnitz, R. Evolution of methane sorption capacity of coal seams as a function of burial history-a case study from the Campine Basin, NE Belgium. *Int. J. Coal Geol.* 2006, 66, 179–203. [CrossRef]
- Han, S.; Sang, S.; Zhou, P.; Liang, J. The evolutionary history of methane adsorption capacity with reference to deep Carboniferous-Permian coal seams in the Jiyang Sub-basin: Combined implementation of basin modeling and adsorption isotherm experiments. J. Pet. Sci. Eng. 2017, 158, 634–646. [CrossRef]
- Liu, D.; Yao, Y.; Cai, Y.; Zhang, B.; Zhang, K.; Li, J. Characteristics of porosity and permeability and their geological control of Permo-Carboniferous coals in the north China. *Geoscience* 2010, 24, 1198–1203.
- 37. Fan, Q.; Cai, Y.; Bei, J.; Wang, W.; Zhang, X. Pore and Fracture Structure of Coal Reservoir Constrained by Coal Metamorphism. *Geoscience* **2020**, *34*, 273–280.
- 38. Sun, F.; Li, W.; Sun, Q.; Sun, B.; Tian, W.; Chen, Y.; Chen, Z. Low-rank CBM exploration in Jiergalangtu sag, Erlian basin. *Acta Pet. Sin.* 2017, *38*, 485–492.
- Wang, B.; Yao, H.; Wang, H.; Zhao, Y.; Li, M.; Hu, Q.; Fan, M.; Yang, C. Favorable and major geological controlling factors for CBM accumulation and high production in the Chengzhuang Block, Qinshui Baisn. *Oil Gas Geol.* 2018, 39, 366–372.
- 40. Wu, C.; Liu, X.; Zhang, S. Construction of index system of "Hierarchical progressive" geological selection of CBM in multiple seam area of eastern Yunnan and western Guizhou. *J. China Coal Soc.* **2018**, *43*, 1647–1653.
- 41. Shao, L.; Wang, X.; Zhang, J.; Hou, H.; Tang, Y.; Wang, J.; Lin, Y. CBM accumulation characteristics and exploration target selection in northeastern Yunnan, China. *Nat. Gas Ind.* **2018**, *38*, 17–27.
- 42. Shi, J.; Durucan, S.; Sinka, I.C. Key parameters controlling CBM cavity well performance. *Int. J. Coal Geol.* **2002**, *49*, 19–31. [CrossRef]
- 43. Meng, Z.; Li, G.; Yang, Y.; Li, C.; Qiao, Y. Study on key technology for surface extraction of CBM in coal mine goaf from Sihe Wells Area, Jincheng. *Coal Sci. Technol.* **2021**, *49*, 240–247.
- 44. Sang, S.; Zhou, X.; Liu, S.; Wang, H.; Cao, L.; Liu, H.; Li, Z.; Zhu, S.; Liu, C.; Huang, H.; et al. Research advances in theory and technology of the stress release applied extraction of CBM from tectonically deformed coals. J. China Coal Soc. 2020, 45, 2531–2543.
- 45. Wu, H. Study and practice on technology of three-zones linkage 3D CBM drainage in coal mining area. *J. China Coal Soc.* **2011**, *36*, 1312–1316.
- 46. Li, G.; He, H.; Liu, G.; Jiao, H.; Liu, X. Three region linkage three-dimensional gas drainage theory and mode of coal bed methane in coal mining area. *Coal Sci. Technol.* **2012**, *40*, 7–11.
- He, T.; Wang, B.; Tian, Y. Development and issues with coal and coal-bed methane simultaneous exploitation in Jincheng mining area. J. China Coal Soc. 2014, 39, 1779–1785.