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Research Article

Study on Reservoir Properties and Critical Depth in Deep Coal Seams in Qinshui Basin, China

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Coalbed methane (CBM) reservoir properties and relationship of properties with burial depth were studied based on the data derived from 204 deep CBM production wells in Qinshui Basin, China. Through the study, it is found that permeability and porosity decrease with the increase of burial depth and the decreasing trend shows step-change characteristics at a critical burial depth. They also show divisional characteristics at certain burial depth. Gas content, geostress, and geotemperature increase with the increase of burial depth, and the increasing trend shows step-change characteristics and also have divisional characteristics at certain burial depth. Based on the previous study on the reservoir property changes with burial depth, three series of critical depth using different parameters are obtained through simulating the critical depth using the BP neural network method. It is found that the critical depth is different when using different parameters. Combined the previous study with the normalization of three different parameter types, the critical depth in Qinshui Basin was defined as shallow coal seam is lower than 650 m and transition band is 650–1000 m, while deep coal seam is deeper than 1000 m. In deep coal seams, the geological conditions and recovery becomes poor, so it can be defined as unfavorable zones. Therefore, other development means, for example, CO_2 injection, need to be used to accelerate the deep coal methane development.

1. Introduction

Reserve of coalbed methane (CBM) resource and its production potential is huge in deep coal seams in China [1–4]. Furthermore, the exploration target is impelling gradually forward to deep coal seams in recent years. Compared to the CBM in shallow coal seams, coalbed methane in deep coal seams are usually poor in gas production [5, 6]. Moreover, there has been a long lack of studies on reservoir properties and corresponding changing rules in deep coal seams.

The critical depth of reservoir property change in coal seams has important guidance to geological study, drilling, fracturing, and other engineering processes. However, the critical depth of the deep coal seam is not well studied. Previous studies about critical depth of deep coal seams either focus on single parameter, for example, gas content, or are based on the data derived from shallow wells [7–11]. Thus, the study about how properties change with burial depth and confirming the critical depth in deep coal seams is urgent and necessary to speed up the exploration and development of deep coalbed methane.

In order to study reservoir properties and development conditions for the CBM production wells in deep coal seams, so as to better guide the CBM exploration activities, it is necessary to collect and analyze the present data in deep wells and summarize the relationship between reservoir properties and geological conditions. This study about reservoir property and critical depth is aimed at providing important guidance to the CBM exploration and development in deep coal seams in China.

2. Data Collection

In this study, two kinds of data are collected to analyze the relationship of reservoir properties and burial depth. One kind of data is collected from internal files of CUCBM Corporation in China, and the other kind of data is derived from the literatures. The figures are drawn mainly based on the internal data in China. The studied areas in this research focus on Qinshui Basin in China [5, 12, 13]. In total, data derived from 204 CBM production wells were collected and only 43 wells' data are listed in Table 1 to avoid the paper becoming lengthy. The following analyses of reservoir properties with burial depth are mainly based on the data collected in Table 1. Moreover, some well's parameters, for example, permeability, gas content, geostress, and geotemperature, were measured in situ and the relationship with burial depth is also analyzed in this study.

It can be seen from Table 1 that burial depth value ranges mainly from 428 m to 1135 m, gas content ranges from 2.11 m^3/t to 20.72 m^3/t, coal seam permeability ranges from 0.015 md to 18.9 md except for the abnormal value 81.3 md, and geostress value ranges from 5.57 MPa to 24.33 MPa.

3. Relationship between Main Properties and Depth

Reservoir properties and conditions, such as permeability, geostress, and temperature, are sensitive to burial depth. Some researchers have studied the behavior of reservoir property changing with burial depth in shallow coal seams [14–16], but these rules and relationships may not be suitable for deep coal seams and cannot be used directly. Therefore, a further study aiming at deep coal seam is required.

3.1. Relationship between Permeability and Burial Depth. Some researchers [17–20] have studied the relationship between permeability and burial in depth of less than 1000 m. Studies [21–24] also show that coal seam permeability which is affected by strata stress gas pressure and temperature progressively decreases with the effective vertical stress which deepens with burial depth.

However, because of the different study purposes, the relationship between permeability and burial depth has not systematically been studied in deep coal seams. In this study, the relational diagram of permeability and burial depth is drawn in Figures 1 and 2.

Figure 1 is a box plot of permeability and with burial depth, and Figure 2 is a scatter diagram of permeability with burial depth. The reason of using the two types of figures is to analyze the different aspects of relationship of reservoir property. It can be seen from Figure 1 that permeability decreases with the increasing of burial depth. Moreover, the decreasing trend shows step-change characteristics at certain burial depth. For example, permeability presents big difference before and after burial depth 600 m.

It can be seen from Figure 2 that the relationship of permeability and burial depth shows obvious divisional characteristics. When the burial depth is deeper than 600 m, almost all of the permeability values are smaller than 0.45 md, while when the burial depth is shallower than 600 m, most of the permeability values are larger than 0.45 md.

3.2. Relationship between Porosity and Burial Depth. In order to study the relationship between porosity and burial depth, the box plot and relationship graph of porosity and burial depth are drawn in Figures 3 and 4.

It can be seen from Figures 3 and 4 that porosity decreases with the increasing of burial depth and the decreasing trend shows step-change characteristics at a burial depth of 800 m. Because the stress including horizontal and vertical stresses increases with the increasing of burial depth [25], the relationship of stress with porosity and permeability is both negative correlation. When the burial depth is deeper than 800 m, almost all of the porosity is smaller than 6.5%, while when the burial depth is shallower than 800 m, the distribution of porosity value spreads widely, from 0 to 13%.

3.3. Relationship between Gas Content and Burial Depth. Figure 5 is the box plot of gas content and burial depth in Qinshui Basin, and Figure 6 is the relational graph of gas content and burial depth.

Like the above relationship of permeability and burial depth, it can be seen from Figures 5 and 6 that gas content increases with the increasing of burial depth and the decreasing trend shows step-change characteristics at a burial depth of 600 m. Moreover, the relationship of gas content and burial depth also shows obvious divisional characteristics.

3.4. Relationship between Geostress and Burial Depth. According to the statistical data, the geostress in the deep coal seam in China is generally beyond 25 MPa, with some wells understressed at 15 MPa and some wells overstressed at 30 MPa. In order to further study the rules of geostress changing with burial depth, the relationship diagram of geostress and burial depth is drawn in Figure 7 on the basis of analyzing the mass data derived from main deep coal seam producing wells.

Through analyzing the graph of horizontal geostress and burial depth, it can be seen from Figure 7 that horizontal geostress increases gradually with the increasing of burial depth. Another relationship is that horizontal geostress presents step-increasing characteristics at a burial depth of 600~900 m.

3.5. Relationship between Geotemperature and Burial Depth. Another important reservoir characteristic for the coal seam is geotemperature. In order to study the relationship of temperature and burial depth, 10 wells' data of temperature in Qinshui Basin were studied in this study. The relational graph of temperature and burial depth is drawn in Figure 8.

It can be seen from Figure 8 that geotemperature increases linearly with the increasing of burial depth. However, the slope of the line at the burial depth of 820 m is quite different. The slope shallower than 820 m is about 90, while it

Table 1: Statistics table of depth and productivity in main CBM producing wells.

Basin	Number	Depth (m)	Gas content (m^3/t)	Permeability (md)	Geostress (MPa)	T (°C)
Qinshui Basin	001	778	11.89	0.015	11.67	26.1
	002	513.5	18.4	0.0289	7.70	18.4
	003	475	19.66	0.95	8.08	22.8
	004	588.33	13.51	0.06	9.30	25.4
	005	470		0.11	7.52	15.6
	006	570.25	16.07	0.87	7.93	23.25
	007	428.3	20.11	2	5.57	24.16
	008	531	16.4	0.088	9.56	20.44
	009	584	18.63	0.26	10.10	26.7
	010	688.73	12.76	0.026	10.12	28.8
	011	772.4	8.79	0.494		25.26
	012	746.18	20.49	4.6		25.6
	013	868.4	19.31	0.46	11.20	29.3
	013	840.4		0.9442	13.37	36.69
	014	895.29		0.034	18.44	37.5
	015	977.8	20.72	1.2	22.76	
	016	1128.2	16.65	18.9	23.75	
	017	1011.2	14.82	0.49	23.41	
	018	967	18.84	0.19	20.67	
	019	1134.9	11.76	81.3	24.33	
	020	712.1	10.465	0.06	14.67	30.1
	021	733.05	5.01	0.016	12.97	28
	022	568.55	5.04	0.16	13.59	28.6
	023	871.8	5.14	1.39	19.79	35.1
	024	871.8	2.72	0.11	18.83	30.2
	025	723.7	13.03	0.11	15.99	30.06
	026	489.4	11.24	0.0285	11.07	24.572
	027	1001.45	1.15	0.18	20.73	37.9
	028	965.3	8.17	0.07	18.05	35.9
	029	577.45	7.31	0.28	12.47	28
	030	731.8	5.01	0.016	13.03	28
	031	739.5	2.11	0.02	13.31	28.2
	032	578.6	4.15	0.06	13.71	28.4
	033	883.15	3.9	0.138	20.84	35.5
	034	883.15	3.41	0.18	18.19	30.5
	035	735.2	4.9	0.06	16.84	30.71
	036	496.6	9.93	0.0374	9.34	24.717
	037	1010	3.28	0.03	19.29	37.9
	038	624.7	9.35	0.42	12.81	27.5
	039	973.3	11.58	0.21	17.13	36.8
	040	587.75	5.79	0.04	10.76	28.2
	041	738.4	2.11	0.045	13.73	28.2
	042	887.35	5.23	1.7	13.77	27.76
	043	495.1	7.9	1.43	7.08	25.35

is 24.3 when the burial depth is deeper than 820. Namely, temperature has inflection point at burial depth of 820 m in Qinshui Basin.

3.6. Summary of Changing Rules of Main Reservoir Characteristics with Burial Depth. To summarize, the changing rules of main reservoir characteristics with burial depth can be drawn as follows.

Permeability and porosity decrease with the increasing of burial depth, and the decreasing trend shows step-change characteristics at certain burial depth. Moreover, the relationship of permeability and porosity with burial depth also shows obvious divisional characteristics. Gas content, geostress, and geotemperature increase with the increasing of burial depth, and the decreasing trend shows step-change characteristics at certain burial depth. Moreover, the relationship of gas content and burial depth shows divisional characteristics, and geotemperature has inflection point at certain burial depth.

Therefore, according to the study above, it is proposed in this study that reservoir properties and geological conditions present step-changing rules in the deep coal seam with the increasing of burial depth, and the reservoir properties have divisional characteristics at certain burial depth in deep coal seams. Combined with the study of earth science and astronomical geology, the reason that the corresponding law changing with burial depth probably because of the changing of physical property, such as density and pressure.

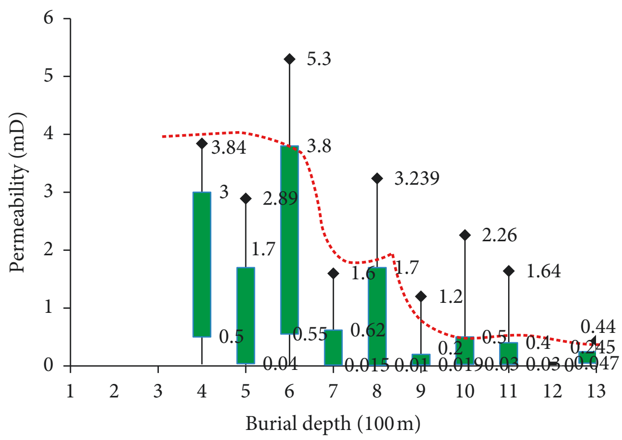

FIGURE 1: Box plot of permeability and burial depth in Qinshui Basin.

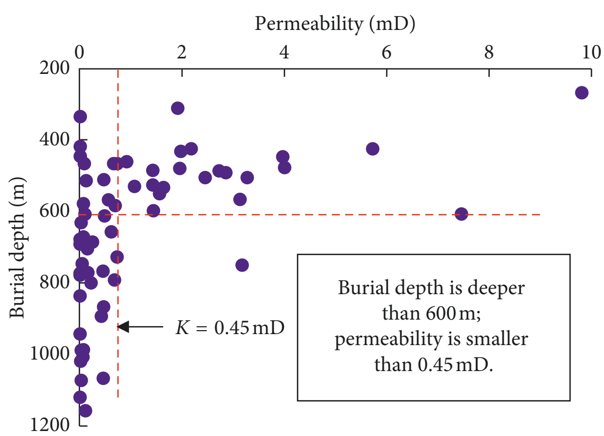

FIGURE 2: Relational graph of permeability and burial depth.

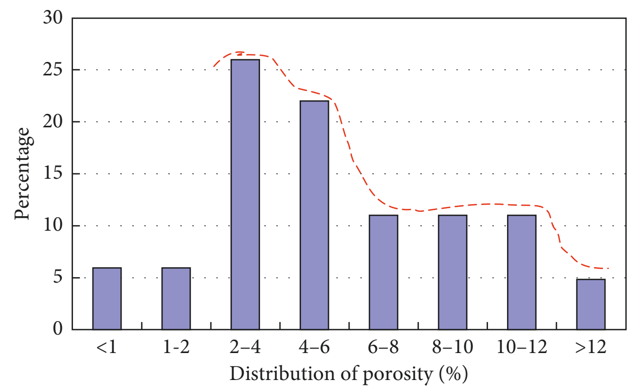

FIGURE 3: Box plot of porosity and burial depth in Qinshui Basin.

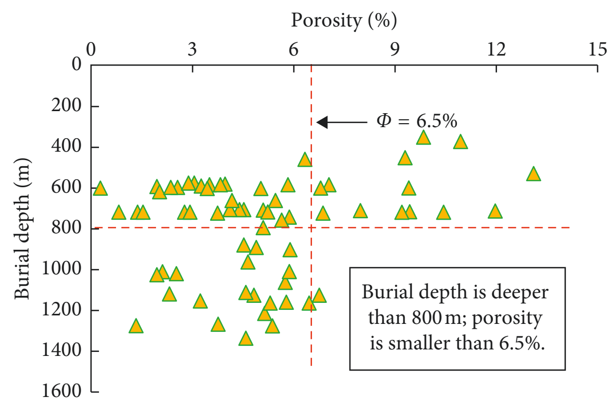

FIGURE 4: Relational graph of porosity and burial depth.

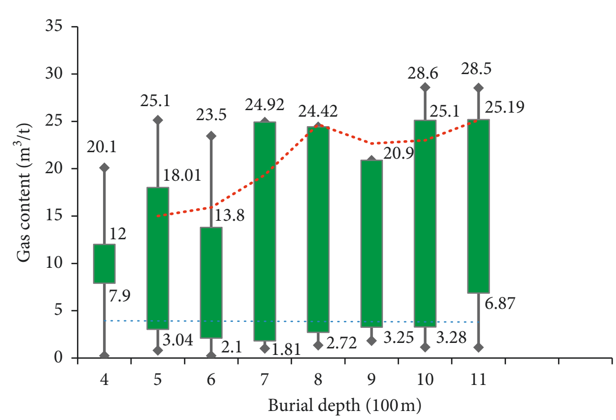

FIGURE 5: Box plot of gas content and burial depth in Qinshui Basin.

From the study above, it can be seen that there exists one or several inflection points for each parameter in deep coal seams. After and before the inflection point, the reservoir property is quite different or changes sharply. We define this inflection point in this study as critical depth.

4. Definition of Critical Depth in Deep Coal Seams

4.1. Simulation Method and Data Processing. In order to study the critical depth in the deep coal seam, the back propagation (BP) neural network numerical simulation method is used. The BP neural network has self-organized learning ability and is now used widely in science forecasting area. The main operation steps of BP neural network method include: selecting the original data, data normalization processing, nonlinear regression using Matlab software, determining the parameters' weight, determining the range of catastrophe point, and determining the critical depth using iteration method. Table 2 is sample data of parameters used in simulation process after being normalized.

4.2. Simulation Results and Analysis. In this study, three main parameter systems including mechanical parameters, reservoir property, and production parameters are selected to simulate the critical depth using the BP neural network method.

The parameters of burial depth, velocity of longitudinal wave, temperature, and fracture pressure are selected when using mechanical parameters to simulate. The coupling

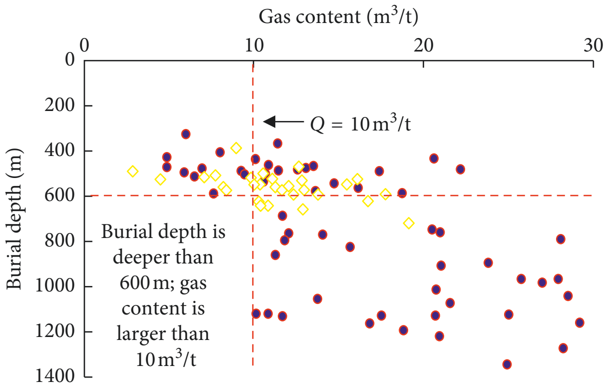

FIGURE 6: Relational graph of gas content and burial depth.

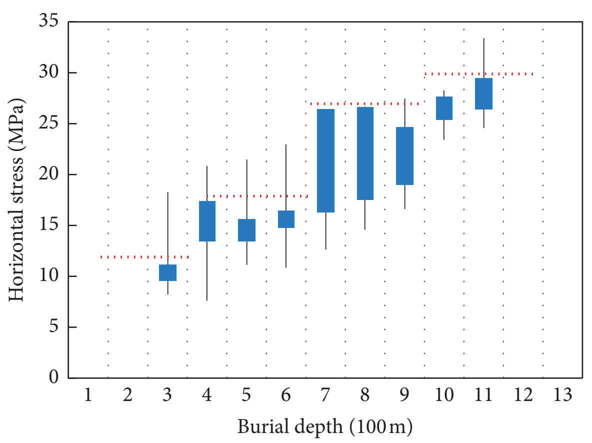

FIGURE 7: Relational graph of horizontal geostress and burial depth.

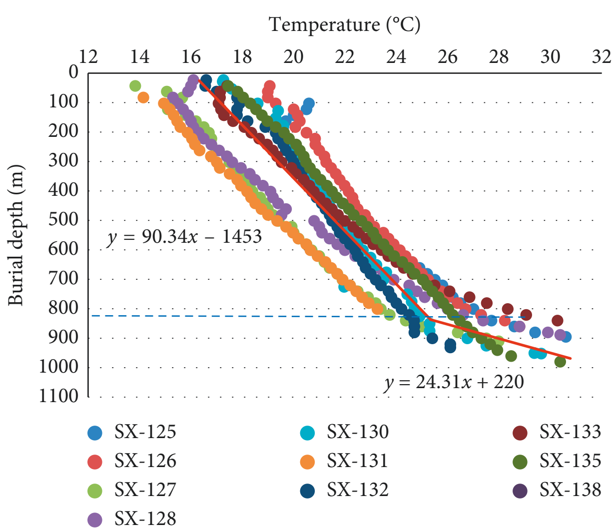

FIGURE 8: Relational graph of temperature and burial depth in Qinshui Basin.

regression equation using mechanical parameters can be obtained through numerical simulation:

$$H = 0.247 - 0.2107P + 0.9394T + 0.0044\text{Pt}, \quad (1)$$

where H is the burial depth (m), P is the velocity of the longitudinal wave (m/ms), T is the temperature in the well (°C), and Pt is the fracture pressure (MPa).

After a series of calculation, the critical depth using mechanical parameters is 1043 m, while the actual inflection point selected is 997 m. The error between the calculated depth and actual depth is 4.6%, which is within the error.

Another series of parameters including permeability, adsorption amount, reservoir pressure, temperature, and vitrinite reflectance are selected to simulate the critical depth. Through the numerical simulation, the regression equation using reservoir property parameters can be obtained as follows:

$$H = 0.0118 - 0.0251K - 0.1570Q + 0.6160\text{Pc} + 0.3968T. \quad (2)$$

The critical depth using reservoir property parameters is confirmed as 614–1077 m.

The production parameters which are reservoir pressure, permeability, gas content, and gas production are selected to simulate. The regression equation is as follows:

$$H = 0.0755 + 0.1636Q - 0.0709k + 0.8886\text{Pc} - 0.0664Q_g. \quad (3)$$

Finally, the critical depth using production parameters is confirmed as 660–980 m.

4.3. Verification of Simulated Results and Definition of Critical Depth. In order to eliminate the affection of different units, the normalized matching curves are drawn in Figure 9 using three differential parameters. From the normalized curves, it can be seen that there are two inflection points in 0.60 and 0.90, which can be converted to 659 and 988 m in actual depth. The critical depth using mechanical parameters, reservoir property parameters, and production parameters are 1043 m, 614–1077 m, and 660–980 m, respectively. They are mainly located in the range of 659–988 m within the margin of error using the normalized matching curve method. This verifies the accuracy of previous simulated results using three different parameter series.

Combined the previous study of reservoir properties with the normalization of three different parameter types, the critical depth in Qinshui Basin was defined as shallow coal seam is lower than 650 m and transition band is 650–1000 m, while deep coal seam is deeper than 1000 m. For the shallow coal seam, the development condition is quite good and is defined as favorable zones; for the transition band, the reservoir properties, temperature, and stress show step-changing characters; for the deep coal seam, the temperature, geostress, permeability, and gas content conditions become worse. In deep coalbed methane zone, the recovery becomes poor and can be determined as the unfavorable zone for the exploration and development of coalbed methane. Therefore, other development means, for example, CO_2 injection, need to be used to accelerate the deep coal methane development.

Table 2: Sample data table of parameters after normalized.

Wells	Depth	Parameters				
		Compressional wave	Transverse wave	Temperature	Pressure	Well depth
SX~001	1318~1321	0.80186	0.68234	0.76755	0.62741	0.90212
	1325~1326	0.85535	0.60741	0.76988	0.82581	0.90691
SX~002	1126~1128	0.81994	0.56756	0.74027	0.88819	0.77070
	1170~1180	0.80311	0.55640	0.76142	1.00000	0.80082
SX~003	1412~1413	0.88674	0.59585	0.97018	0.85733	0.96646
	1452~1456	0.79935	0.54882	0.99831	0.82979	0.99384
	1461~1464	0.85535	0.66481	1.00000	0.87226	1.00000
SX~004	1301~1309	0.88147	0.68035	0.70241	0.41274	0.89049
SX~005	1198~1199	1.00000	0.67756	0.77200	0.93033	0.81999
SX~006	1225~1236	0.92767	0.56955	0.78257	0.79230	0.83847
	869~875	0.79935	0.56955	0.68126	0.64665	0.59480
	960~961	0.96459	1.00000	0.73012	0.59655	0.65708
	977~978	0.96786	0.76046	0.73794	0.64366	0.66872
	993~994	0.90558	0.78717	0.74323	0.53251	0.67967
	997~999	0.83752	0.61259	0.74492	0.71334	0.68241

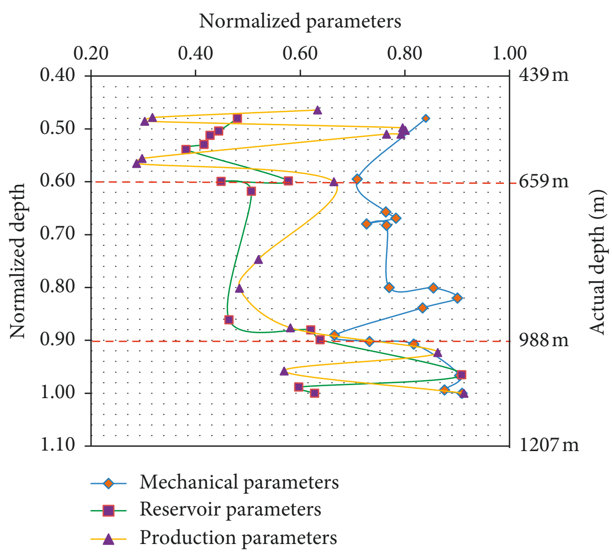

Figure 9: The fitted curve using the normalization method using three different parameter types.

5. Conclusion

In this study, the main reservoir properties are studied and analyzed based on investigating a large number of producing well data in China and the USA. Through this study, it is proposed that reservoir properties and geological conditions present step-changing rules with the increasing of burial depth and have divisional characteristics at certain burial depth in the deep coal seam. Permeability and porosity decrease with the increasing of burial depth, and the decreasing trend shows step-change characteristics at certain burial depth. Gas content, geostress, and geotemperature increase with the increase of burial depth, and the increasing trend shows step-change characteristics at a critical burial depth.

Moreover, through simulating the critical depth using the BP neural network method, three series critical depth when using different parameter systems which are mechanical parameters, reservoir property, and production parameters are obtained, respectively. The critical depth using mechanism parameters is 1043 m, and it is 614–1077 m using reservoir parameters, while it is 660–980 m using production parameters. Combined the previous study with the normalization of three different parameter types, the critical depth in Qinshui Basin was defined as shallow coal seam is lower than 650 m and transition band is 650–1000 m, while deep coal seam is deeper than 1000 m. The shallow coal seam is determined as favorable zones and the deep coal seam is determined as the unfavorable zones for CBM exploration.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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