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Evaluation of Heterogeneity in Tectonically Deformed Coal Reservoirs Based on the Analytic Hierarchy Process-Entropy Weight Method Coupling Model: A Case Study

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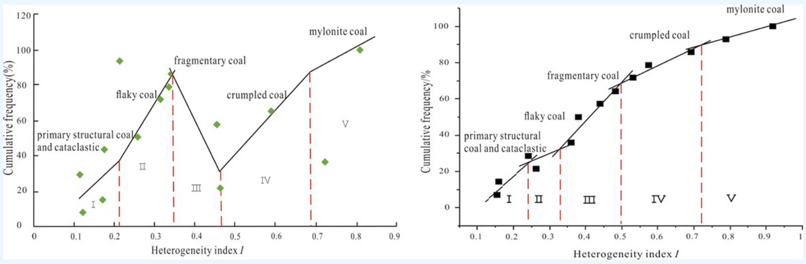
Cite This: ACS Omega 2023, 8, 36700−36709



ABSTRACT: This article presents a comprehensive analysis of the factors influencing the heterogeneity of tectonic coal reservoirs, focusing on the metamorphic degree and pore-fracture parameters of tectonic coal. To ensure a reliable evaluation, the AHP-EWM coupling evaluation model (analytic hierarchy process and entropy weight method), which integrates the strengths of both evaluation models and minimizes the potential errors associated with a single model, was employed to assess the heterogeneity index of coal reservoirs in the Panguan syncline. According to the findings of the AHP-EWM model, it was observed that the comprehensive index of coal heterogeneity consistently increases as the degree of coal deformation increases. Notably, a critical value of $I = 0.48$ was identified as the threshold for the comprehensive index of brittle and ductile deformation coal heterogeneity. Furthermore, the pore-fracture characteristic was determined to have the greatest effect on the heterogeneity of coal reservoirs, followed by the metamorphic degree. This research contributes significantly to the identification of high-quality coalbed methane reservoirs in the Panguan syncline of western Guizhou, serving as a valuable point of reference.

1. INTRODUCTION

In China, the main coal-bearing basins have experienced multiple tectonic movements, resulting in the formation of deformed tectonic coal seams.[1,2] Many researchers have found that tectonic coal has extremely strong heterogeneity, characterized by low strength, low permeability, high adsorption capacity, and high desorption capacity, which also significantly affect the enrichment of coalbed methane (CBM).[3−8] As a typical "self-generated and self-stored" reservoir, the heterogeneity of coal seams has always been an important indicator of physical properties and can significantly affect the production of CBM wells.[9−13] Therefore, refined research on the heterogeneity characteristics of tectonic coal reservoirs is of great significance for finding high-yield CBM blocks and achieving large-scale development of CBM.

Previous researchers have used various fractal models to characterize the heterogeneity of tectonic coal, especially in terms of pore heterogeneity, and have achieved fruitful results.[12−15] For example, Li et al.[14] calculated the fractal dimensions of various tectonic coals based on the surface fractal model and found that crumpled coals with higher pore fractal dimensions ($D > 2.9$, Frenkel−Halsey−Hill (FHH) model) have more pore morphology types, while the cataclastic coal and flaky coal with a lower fractal dimension ($2.6 < D < 2.9$) contain more flat pores. Song et al.[15] compared the applicability of Menger, thermodynamics, Sierpinski, and FHH fractal models in structural coal, further revealing the fractal characteristics of pores. In fact, tectonism can significantly affect the pore-fracture structure of coal seams, as well as the metamorphic degree and molecular structure.[2] However, the heterogeneity evaluation of these indicators of tectonic coal is still relatively weak.

In recent years, with the intersection and integration of mathematics and geology, various mathematical evaluation models have enabled quantitative and in-depth research on the resource evaluation and geological hazard assessment.[16−19] Among these mathematics models, the AHP-EWM coupling

Received: April 22, 2023
Accepted: September 15, 2023
Published: September 28, 2023

https://doi.org/10.1021/acsomega.3c02764
ACS Omega 2023, 8, 36700−36709

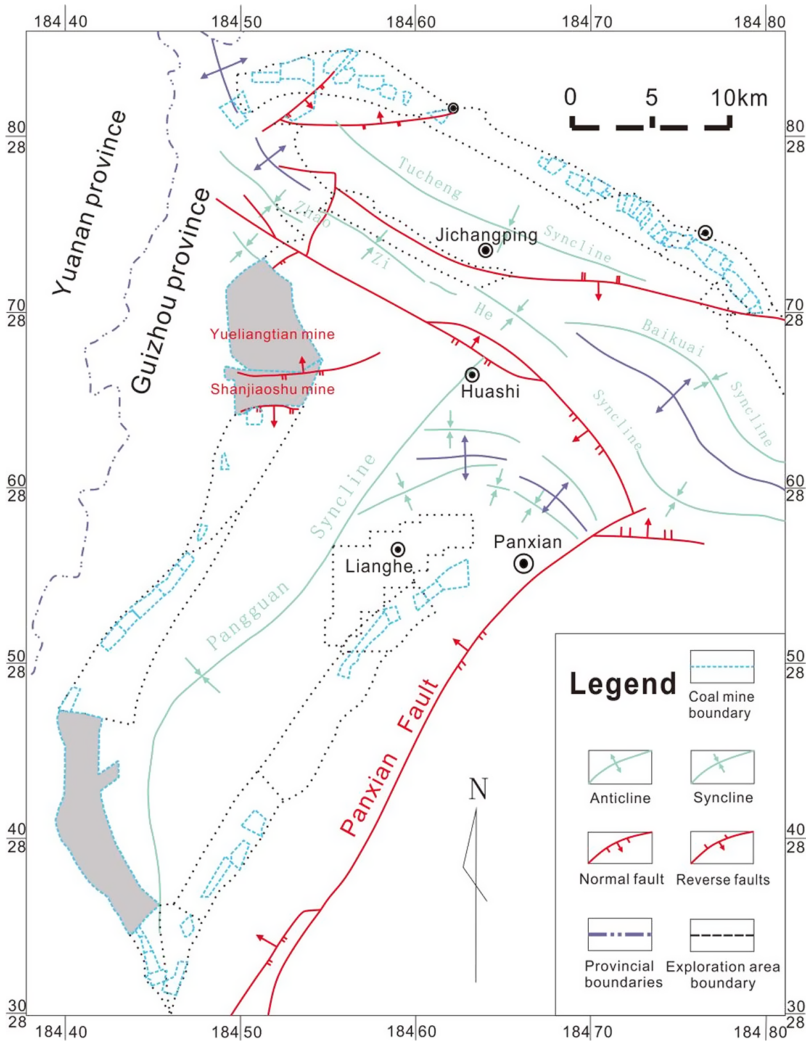


Figure 1. Sampling location of the collieries in the Panguan syncline.

evaluation model has a wide range of applications because the AHP model can get the subjective weight of the evaluation index, and the EWM model can get the objective weight of the evaluation index.[20] The AHP-EWM coupling evaluation model can also be applied to evaluate the heterogeneity of tectonic coal seams, which is of great significance for regional CBM exploration and development.

Panguan syncline in western Guizhou has been proved by many practical exploration and development projects to be a favorable block for CBM accumulation.[21,22] However, the widely developed tectonic coal seams limited the exploration and development of CBM; thus, it is necessary to conduct quantitative evaluation of tectonic coal heterogeneity. This study selected five types of tectonic coal (primary structural coal, cataclastic coal, cataclastic coal, flaky coal, and crumpled coal) in the Panguan syncline and quantitatively analyzed the fracture characteristics, pores, and chemical structure fractal characteristics of coal. Subsequently, the AHP-EWM coupling model was used to quantitatively evaluate the contribution of various indicators to the heterogeneity of the structural coal reservoir. Through the key indicators and weight ranking of tectonic coal heterogeneity, the heterogeneity characteristics of coal with different deformation degrees were quantitatively characterized, and the sensitivity analysis of parameters was carried out. In addition, a division scheme characterizing the heterogeneity types of tectonic coal reservoirs is proposed, which provides a powerful reference for the identification of high-quality CBM reservoirs in the Panguan syncline in western Guizhou.

2. MATERIALS AND METHODS

2.1. Sample Collection. In order to analyze the heterogeneity of the tectonic coal reservoir in the Panguan syncline, we collected 14 coal samples from different structural parts of the Panguan syncline (Figure 1; the two wings and the turning section of the syncline) and ensured that coal samples have different deformation characteristics. In addition, the primary structural coal samples were collected from areas with weak tectonic deformation and magmatic activity.

According to the classification scheme proposed by Jiang et al.,[2] the collected coal samples include 3 pieces of primary tectonic coal, 2 pieces of cataclastic coal, 2 pieces of fragmented coal, 2 pieces of flaky coal, 3 pieces of crumpled coal, and 2 pieces of mylonite coal (Table 1). In addition, the sample collection and the preservation process of coal samples were based on the national standard (GB/T482-2008). In particular, coal samples with strong deformation are prone to damage; thus, it is necessary to pay attention to their original state.

2.2. Sample Test Methods. In order to accurately obtain the pore structure and chemical structure characteristics of the coal samples with different deformation degrees, this study used

https://doi.org/10.1021/acsomega.3c02764
ACS Omega 2023, 8, 36700−36709

Table 1. List of Sampling Points Information in the Study Area

no.	coal seam	location	tectonic deformation coal type
SJS1	middle and lower layers of 12 coal	221210 working face of Shanjiaoshu Mine	primary structural coal
SJS2	15 coal	221159 haulage lane of Shanjiaoshu Mine	primary structural coal
SJS3	18 coal	intersection of the 221188 haulage roadway and No. 18 coal face in Shanjiaoshu Mine	cataclastic coal
YLT1	upper layer of 12 coal	131218 working face of Yueliangtian Mine	flaky coal
YLT2	top layer of 12 coal	131213 haulage lane of Yueliangtian Mine	flaky coal
YLT3	16 coal	131613 haulage lane of Yueliangtian Mine	crumpled coal
YLT4	upper layer of 12 coal	131218 working face of Yueliangtian Mine	crumpled coal
YLT5	middle of 8 coal	131017 working face of Yueliangtian Mine	mylonite coal
HG1	3 coal	Hongguo Coal Mine	crumpled coal
HG2	3 coal	Hongguo Coal Mine	primary structural coal
JJ1	middle of 9 coal	Jinjia Coal Mine	fragmented coal
JJ2	middle of 7 coal	Jinjia Coal Mine	fragmented coal
HP1	top layer of 5 coal	junction of 2351 haulage roadway and working face in Huopu Mine	cataclastic coal
HP2	top layer of 17 coal	21175 working face of Huopu Mine	mylonite coal

the HCl−HF−HCl three-step method to predeash the sample. After pretreatment of the collected coal samples, the maturity and coal petrology characteristics were determined using experiments such as industrial analysis, element analysis, vitrinite reflectance measurement, and maceral analysis. In addition, pore-fracture characteristics of coal samples were characterized by microfracture observation description, high-pressure mercury intrusion method, low-temperature liquid nitrogen, and carbon dioxide adsorption. In addition, the chemical structure of the coal samples was determined using X-ray, Fourier transform infrared spectroscopy, and micro-Raman spectroscopy.

2.3. AHP-EWM Coupling Model. *2.3.1. Analytic Hierarchy Process, AHP.* AHP can solve complex decision-making problems as an orderly hierarchical structure model and give the subjective weight of each parameter through subjective judgment and scientific calculation of each evaluation parameter.[23] In previous studies, metamorphic degree, the pore-fracture structure, and the chemical structure of tectonic coal were considered important factors affecting the heterogeneity of coal reservoirs;[2−5] thus, we used these indicators as secondary evaluation indicators for the hierarchical structure model. The metamorphic degree of coal samples can be reflected by vitrinite reflectance R_o. In addition, pore-fracture parameters of tectonic coal mainly included microfracture density D, adsorption pore fractal dimension D_{ad}, and seepage pore fractal dimension D_{sp}. In addition, the chemical structure parameters of structural coal mainly contained aromaticity f_a, d(G-D1), Raman spectral peak area ratio A_G/A_{D1}, and aromatic ring lamella diameter L_a. Overall, there are eight main parameters that affect the heterogeneity of tectonic coal reservoirs, including the vitrinite reflectance, microfracture density, adsorption pore fractal dimension, seepage pore fractal dimension, aromaticity, Raman spectral peak area ratio, and aromatic ring lamella diameter; hence, these indicators can be used as three-level evaluation indicators for heterogeneity evaluation.

Then, on the basis of the established hierarchical structure model, a judgment matrix was constructed. According to the nine-level scale scoring method proposed by Professor Thomas L. Saaty (Table 2), the indicators were compared in turn, and the corresponding judgment matrix can be established according to the comparison results.[23] The established judgment matrix is shown in formula 1. The elements on the corner of the judgment matrix are all 1, and the elements on both sides of the diagonal are reciprocal to each other; that is, $a_{ji} = 1/a_{ij}$.

Table 2. Nine Scale Scoring Method of the AHP Evaluation Model

score	meaning
1	indicates that the two factors have the same importance
3	indicates that one factor is slightly more important than the other when compared with two factors
5	indicates that one factor is obviously more important than the other when compared with two factors
7	indicates that one factor is strongly more important than the other when compared with two factors
9	indicates that one factor is extremely more important than the other when compared with two factors
2, 4, 6, 8	the median value of the above two adjacent judgments
positive reciprocal matrix	the judgment for comparing factor i with factor j is a_{ij}, and the judgment for comparing factor j with factor i is $a_{ji} = 1/a_{ij}$

$$R = [r_{ij}]_{n\times n} = \begin{bmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{nn} \end{bmatrix}, \quad \left(r_{ij} > 0;\ r_{ij} = \frac{1}{r_{ji}};\ r_{ii} = 1;\ i = 1, 2, ..., n;\ j = 1, 2, ..., n\right) \tag{1}$$

where R is the constructed judgment matrix and the normalized eigenvector of R can be used as the weight vector. According to the nine-level scale scoring method of Saaty, the r_{ij} value in R can be obtained by comparing each evaluation factor in pairs, namely, r_i and r_j.

Second, the maximum eigenvalue of the constructed judgment matrix R is calculated by formula 2 λ_{max} and its corresponding normalized eigenvector W.

$$\mathrm{RW} = \lambda_{max}W,\ \ (W = (w_1, w_2, \cdots, w_n)^{\mathrm{T}}) \tag{2}$$

where λ_{max} is the maximum eigenvalue of the judgment matrix R and W is the corresponding normalized eigenvector.

Then, the weight value of each factor in the AHP evaluation model can be obtained by formulas 3−5.

$$u_j = \frac{1}{n}\sum_{j=1}^{n} c'_{ij},\ \ (i = 1, 2, ..., n) \tag{3}$$

$$c'_{ij} = \frac{c_{ij}}{\sum_{i=1}^{n} c_{ij}},\ (i = 1, 2, \cdots, n) \tag{4}$$

$$W = [w_1, w_2, ..., w_n]^{\mathrm{T}} = \left[\frac{1}{n}\sum_{k=1}^{n} c'_{1n},\ \frac{1}{n}\sum_{k=2}^{n} c'_{2n},\ ...,\ \frac{1}{n}\sum_{k=n}^{n} c'_{nn}\right]^{\mathrm{T}} \tag{5}$$

https://doi.org/10.1021/acsomega.3c02764
ACS Omega 2023, 8, 36700−36709

Table 3. Standard Value of the Average Random Consistency Index RI

matrix order	1	2	3	4	5	6	7	8	9	10	11
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

Finally, it is necessary to check the consistency of the judgment matrix R to ensure that it reaches the threshold level. The consistency check is performed according to formula 6. If the consistency check is passed, then the decision could be made according to the calculation results obtained from the combination weight vector. Otherwise, the hierarchical structure model needs to be rebuilt or the pairwise comparison matrix with a large consistency ratio needs to be reconstructed.

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1} \tag{6}$$

where CI is the consistency indicator. The smaller the CI, the greater the consistency. If CI = 0, there is complete consistency. CI is close to 0, with a satisfactory consistency. The larger the CI, the more serious the inconsistency.

The eigenvector corresponding to the maximum eigenvalue is used as the weight vector of the influence degree of the compared factor on a certain factor in the upper layer. The greater the degree of inconsistency, the greater the judgment error caused. To measure the size of CI, the random consistency index RI is introduced, which can be obtained from Table 3. In order to avoid the error of consistency test caused by random reasons, it is also necessary to compare CI and random consistency index RI to obtain the test coefficient CR when checking whether the judgment matrix R has satisfied consistency, as shown in formula 7.

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{7}$$

In formula 7, the random consistency index RI is related to the order of the judgment matrix R. Generally, the greater the order of the matrix, the greater the probability of random deviation of consistency. The corresponding relationship is shown in Table 3.

2.3.2. Entropy Weight Method, EWM. In 1948, Shannon first proposed the concept of "information entropy" on the basis of thermodynamic entropy,[24] which was usually used to characterize the degree of chaos in the information system and was a measure of the uncertainty of random variables, as shown in formula 8. Given this method can comprehensively and objectively evaluate the distribution of various evaluation factors and eliminate the deviation of evaluation results caused by subjective reasons of evaluators, it has been widely applied in energy assessment and geological disaster assessment.[25,26] Subsequently, Rényi further improved its computational flexibility on the basis of information entropy[27] and proposed Rényi entropy, as shown in formula 9.

Actually, the EWM method is very suitable for evaluating the impact of various factors on the heterogeneity of coal seams. The heterogeneity of different types of tectonic coal reservoirs in the Panguan syncline was measured by the parameters of coal quality, pore-fracture characteristics, and chemical structure. If the discrete type of the above parameters is large, the smaller the entropy value, the greater the weight value. On the contrary, the smaller the discrete type of the above parameters, the greater the entropy value and the smaller the weight value. Therefore, the weight of corresponding parameter indexes can be determined by studying the difference degree of coal quality, pore-fracture characteristics, chemical structure, and other parameters of different types of tectonic coal reservoirs.

$$S = -\sum_{i=1}^{n} p_i \log p_i \tag{8}$$

where S is the information entropy, P_i is the probability of the occurrence of certain information, and the information entropy reflects the degree of disorder of the system information. The smaller the information entropy, the smaller the degree of disorder of the system, that is, the more orderly the system is, the greater the information entropy, the greater the degree of disorder of the system.

$$R_\alpha = \frac{1}{1-\alpha}\ln\left(\sum_{i=1}^{n} p(x_i)^\alpha\right),\ \alpha \geq 0,\ \alpha \neq 1 \tag{9}$$

The main steps of using the EWM evaluation model to calculate the heterogeneity of the structural coal reservoir are as follows. First, one needs to determine the evaluation matrix A. If the evaluation target contains n evaluation indicators and m evaluation items, then the original evaluation matrix A can be established. The matrix elements are the heterogeneity attribute parameters of the above reservoirs, as shown in formula 10.

$$A = \begin{array}{c} A_1 \\ A_2 \\ A_3 \\ \cdots \\ A_N \end{array} \begin{bmatrix} a_{11} & a_{12} & & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2m} \\ a_{31} & a_{32} & & a_{3m} \\ & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nm} \end{bmatrix} \tag{10}$$

Second, one needs to classify and normalize the original measurement data of each evaluation index. In view of the difference of the heterogeneity parameters of different structural coal reservoirs, the larger the reservoir heterogeneity value is, the weaker the corresponding reservoir heterogeneity parameter index, one needs to use formula 11 to normalize. On the contrary, the smaller the reservoir heterogeneity value is, the stronger the corresponding reservoir heterogeneity parameter index is normalized using formula 12. The normalized relationship matrix B is shown in formula 13.

$$b_{ij} = \frac{a_{ij} - \min a_{ij}}{\max a_{ij} - \min a_{ij}} \tag{11}$$

$$b_{ij} = \frac{\max a_{ij} - a_{ij}}{\max a_{ij} - \min a_{ij}} \tag{12}$$

$$B = \begin{array}{c} B_1 \\ B_2 \\ B_3 \\ \cdots \\ B_N \end{array} \begin{bmatrix} b_{11} & b_{12} & & b_{1m} \\ b_{21} & b_{22} & \cdots & b_{2m} \\ b_{31} & b_{32} & & b_{3m} \\ & \vdots & \ddots & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{nm} \end{bmatrix} \tag{13}$$

https://doi.org/10.1021/acsomega.3c02764
ACS Omega 2023, 8, 36700−36709

Table 4. List of Heterogeneity Parameters of Different Types of Tectonically Deformed Coals in the Study Area

	evaluating indicators *A*							
	coal metamorphism *B1*	pore and fissure parameters of coal *B2*				chemical structure parameters of coal *B3*		
no.	$R_{o,max}$ *C1*	DC2	D_{ad} *C3*	D_{sp} *C4*	f_a *C5*	d(G−D$_1$) *C6*	A_G/A_{D1} *C7*	L_aC8
SJS1	0.96	18	2.61	2.94	0.78	232	1.57	2.8432
SJS2	0.98	14	2.76	2.98	0.77	241	1.56	2.8397
HG2	0.98	32	2.68	2.98	0.78	229	1.53	2.8843
SJS3	0.98	58	2.72	2.99	0.83	228	1.66	2.7483
HP1	0.95	100	2.79	2.94	0.85	231	1.71	2.7498
JJ1	1.05	99	2.80	2.95	0.85	229	1.7	2.9079
JJ2	0.96	105	2.82	2.97	0.88	234	1.74	2.9126
YLT1	1.02	126	2.72	2.92	0.79	226	1.64	2.7053
YLT2	1.15	109	2.81	2.96	0.77	231	1.67	2.7614
YLT3	1.09	16	2.80	2.80	0.83	232	1.81	3.0125
YLT4	1.23	81	2.90	2.86	0.84	231	1.87	3.0154
HG1	0.98	125	2.91	2.79	0.82	229	1.86	3.0158
YLT5	1.07	66	2.93	2.54	0.89	226	1.88	3.1943
HP2	1.19	226	2.97	2.65	0.91	224	1.91	3.0736

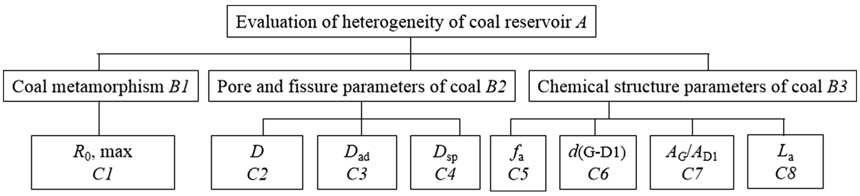


Figure 2. Hierarchical structure evaluation model for coal reservoir heterogeneity in the Panguan syncline.

Then, the entropy weight value and weight value of each parameter are calculated by formula 14. Through the weight values of each parameter index obtained, the corresponding weight vector W is constructed, as shown in formula 15.

$$\begin{cases} p_{ij} = \dfrac{x_{ij}}{\sum_{i=1}^{n} x_{ij}}, \ (i = 1, 2 \cdots n; \ j = 1, 2 \cdots m) \\ e_j = -k \sum_{i=1}^{n} p_{ij} \ln\left(p_{ij}\right), \ k > 0, \ k = \dfrac{1}{\ln(m)}, \ e_j \geq 0 \\ g_j = \dfrac{1 - e_j}{m - E_e}, \ E_e = \sum_{j=1}^{m} e_j, \ 0 \leq g_j \leq 1, \ \sum_{j=1}^{m} g_j = 1 \\ w_j = \dfrac{g_j}{\sum_{j=1}^{m} g_j} (1 \leq j \leq m) \end{cases} \tag{14}$$

where x_{ij} is the i_{th} value of index j; E_j is the entropy value of index j; G_j is the difference coefficient of index j; E_e is the sum of entropy values of each index; W_j is the weight of the j index; and p_{ij} is the weight of the index under the influence of the j factor.

$$W = (W_1, W_2, W_3, ..., W_m) \tag{15}$$

Finally, the comprehensive index I of structural coal reservoir heterogeneity is obtained, as shown in formula 16.

$$I = W \cdot B \tag{16}$$

The value range of I is 0−1. The larger the value of I, the weaker the heterogeneity of the structural coal reservoir. On the contrary, the smaller the I value, the stronger the heterogeneity of the structural coal reservoir. B is the normalized calculation matrix.

2.3.3. AHP-EWM Coupling Model. In order to avoid the calculation deviation caused by the separate calculation of the two weight calculation methods, this paper used the AHP-EWM coupling evaluation model to synthesize the calculation results of the two weighting methods, and the calculation formula is shown in formula 17.

$$W_i = \beta a_i + (1 - \beta) b_i, \ (0 \leq \beta \leq 1) \tag{17}$$

where W_i is the comprehensive weight of the ith evaluation index; A_i is the subjective weight obtained from the AHP model; B_i is the objective weight obtained by the EWM model; and β is a proportional coefficient, with a value range of 0−1. The specific value depends on the decision-maker's preference for the two evaluation methods. This evaluation of the heterogeneity of the coal reservoir in the Panguan syncline structure has the same preference for subjective and objective weights. Therefore, the value of β is 0.5 in this article, which is the arithmetic mean of the weights calculated by the two evaluation models.

3. RESULTS AND DISCUSSION

3.1. Test Results of Comprehensive Evaluation Parameters. Heterogeneity evaluation of tectonic coal reservoir is a systematic work that involves the comprehensive impact of the sedimentary and structural environments of coal reservoirs, including coal quality, metamorphism characteristics, pore-fracture characteristics, chemical structure characteristics, etc.[2,5−7] Given the correlation and typical characteristics of various indicators, this study selected the coal metamorphism index (vitrinite reflectance R_0), pore-fracture characteristic index (fracture density D, adsorption pore fractal dimension D_{ad}, and seepage pore fractal dimension D_{sp}) and chemical structure index (aromaticity f_a, d(G−D1), A_G/A_{D1}, and the diameter of aromatic ring L_a) as the indicators for the comprehensive

Table 5. Subjective Weight of Each Evaluation Parameter

evaluating indicators	R_o, max	D	D_{ad}	D_{sp}	f_a	$d(G-D_1)$	A_G/A_{D1}	L_a
W_i	0.1879	0.0911	0.0711	0.2525	0.1176	0.0793	0.1021	0.0984

evaluation of the heterogeneity of the tectonic coal reservoir, and the test results are shown in Table 4.

3.2. Calculation of the Subjective Weight Based on the AHP Model. Based on the above analysis, the hierarchical structure evaluation model for the evaluation of the heterogeneity of the coal reservoir in the Panguan syncline in western Guizhou was established in this article, as shown in Figure 2.

According to the hierarchy evaluation model, this study further constructed a judgment matrix, as shown in formula 18. In addition, the weight value of AHP was calculated by Matlab programming. The final CR = 0.0966 < 0.1 calculated by Matlab was consistent with the consistency test, and the subjective weight of each evaluation index finally calculated is shown in Table 5. Table 5 also shows the weight order of each index: the fractal dimension of the seepage pore D_{sp} > vitrinite reflectance (R_o) > f_a > A_G/A_{D1} > L_a > fracture density D > d(G−D1) > fractal dimension of the adsorption pore D_{ad}.

$$A = \begin{bmatrix} 1 & 3 & 3 & 1/2 & 2 & 2 & 2 & 3 \\ 1/3 & 1 & 3 & 1/3 & 2 & 1/2 & 1/2 & 1/2 \\ 1/3 & 1/3 & 1 & 1 & 1/2 & 1/2 & 1/2 & 1/2 \\ 2 & 3 & 1 & 1 & 3 & 4 & 3 & 3 \\ 1/2 & 1/2 & 2 & 1/3 & 1 & 2 & 2 & 2 \\ 1/2 & 2 & 2 & 1/4 & 1/2 & 1 & 1/2 & 1/2 \\ 1/2 & 2 & 2 & 1/3 & 1/2 & 2 & 1 & 1 \\ 1/3 & 2 & 2 & 1/3 & 1/2 & 2 & 1 & 1 \end{bmatrix} \quad (18)$$

According to the calculation results of subjective weight, the fractal dimension of seepage pore D_{sp} and vitrinite reflectance (R_0) have the greatest impact on the heterogeneity of the tectonic coal reservoir, while d(G−D1) and adsorption pore fractal dimension D_{ad} have the least impact on the heterogeneity of the tectonic coal reservoir (Figure 3). In addition, there is no significant difference in the impact extent of fa, A_G/A_{D1}, and L_a and fracture density D.

3.3. Calculation of the Subjective Weight Based on the EWM Model. Table 4 lists the original test data of each evaluation index affecting the heterogeneity of the tectonic coal reservoir. Based on formulas 11 and 12, the normalized results of the heterogeneity index affecting different types of tectonic coal can be obtained, as shown in Table 6.

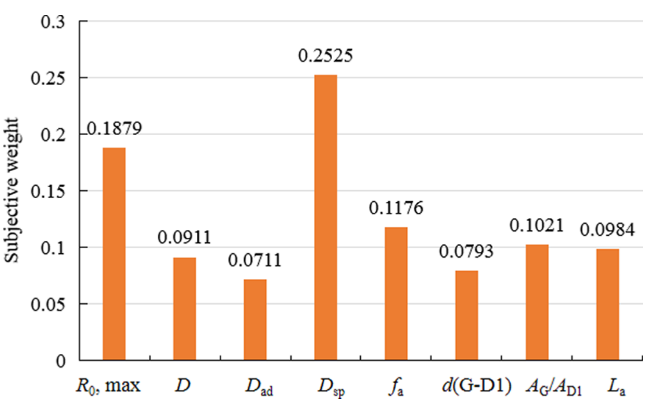


Figure 3. Subjective weight of each evaluation index based on the AHP model.

Table 6. Normalization Results of Heterogeneity Parameters of Different Tectonic Deformed Coals in the Study Area

no.	R_o	D	D_{ad}	D_{sp}	f_a	$d(G-D_1)$	A_G/A_{D1}	L_a
SJS1	0.04	0.02	0.00	0.11	0.07	0.47	0.11	0.28
SJS2	0.11	0.00	0.42	0.02	0.00	1.00	0.08	0.27
HG2	0.11	0.08	0.19	0.02	0.07	0.29	0.00	0.37
SJS3	0.11	0.21	0.31	0.00	0.43	0.24	0.34	0.09
HP1	0.00	0.41	0.50	0.11	0.57	0.41	0.47	0.09
JJ1	0.36	0.40	0.53	0.09	0.57	0.29	0.45	0.41
JJ2	0.04	0.43	0.58	0.04	0.79	0.59	0.55	0.42
YLT1	0.25	0.53	0.31	0.16	0.14	0.12	0.29	0.00
YLT2	0.71	0.45	0.56	0.07	0.00	0.41	0.37	0.11
YLT3	0.50	0.01	0.53	0.42	0.43	0.47	0.74	0.63
YLT4	1.00	0.32	0.81	0.29	0.50	0.41	0.89	0.63
HG1	0.11	0.52	0.83	0.44	0.36	0.29	0.87	0.63
YLT5	0.43	0.25	0.89	1.00	0.86	0.12	0.92	1.00
HP2	0.86	1.00	1.00	0.76	1.00	0.00	1.00	0.75

Through analysis, vitrinite reflectance R_o, fracture density D, fractal dimension of adsorption pore D_{ad}, f_a, d(G−D1), A_G/A_{D1}, L_a are positive indicators, specifically manifested as the larger measured value, the greater the heterogeneity of the tectonic coal reservoir. However, the fractal dimension D_{sp} of the seepage pore is a negative index. With the measured value increase, the heterogeneity of the tectonic coal reservoir decreases. Subsequently, this study also used formulas 11 and 12) to normalize the positive and negative indicators, respectively. In addition, the entropy value and objective weight of each evaluation index were obtained by using formula 14, as shown in Table 7.

Table 7 and Figure 4 show that the entropy value $E(P)$ of each evaluation index is between 0.827 and 1.000, and the entropy value and the weight value exhibit opposite changing patterns. In addition, the order of the objective weight of each index shows fractal dimension D_{sp} of the seepage pore > vitrinite reflectance (R_0) > f_a > fracture density D > L_a > A_G/A_{D1} > d(G−D1) > fractal dimension of the adsorption pore D_{ad}. According to the distribution of objective weights of each evaluation index, fractal dimension D_{sp} of the seepage pore and vitrinite reflectance (R_0) are still the two most important indexes affecting the heterogeneity of tectonic coal reservoir, and fa, fracture density D, L_a, and A_G/A_{D1} are the four indicators with the middle impact degree. In addition, d(G−D1) and the fractal dimension of adsorption pore D_{ad} are still two indicators that have less impact on the heterogeneity of the tectonic coal reservoir.

3.4. Comprehensive Weight Calculation Based on the AHP-EWM Coupling Model. The subjective weight of each evaluation index was calculated by the AHP model, and the results showed that the fractal dimension of seepage pore D_{sp} > vitrinite reflectance (R_0) > f_a > A_G/A_{D1} > L_a > fracture density D > d(G−D1) > fractal dimension of adsorption pore D_{ad}. The objective weight of each evaluation index was obtained through

https://doi.org/10.1021/acsomega.3c02764
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Table 7. Entropy Value and Weight of Each Evaluation Parameter

evaluating indicators	R_0	D	D_{ad}	D_{sp}	f_a	$d(G-D_1)$	A_G/A_{D1}	L_a
$E(P)$	0.881	0.923	1.000	0.827	0.922	0.978	0.966	0.955
W_j	0.152	0.145	0.134	0.162	0.146	0.137	0.139	0.140

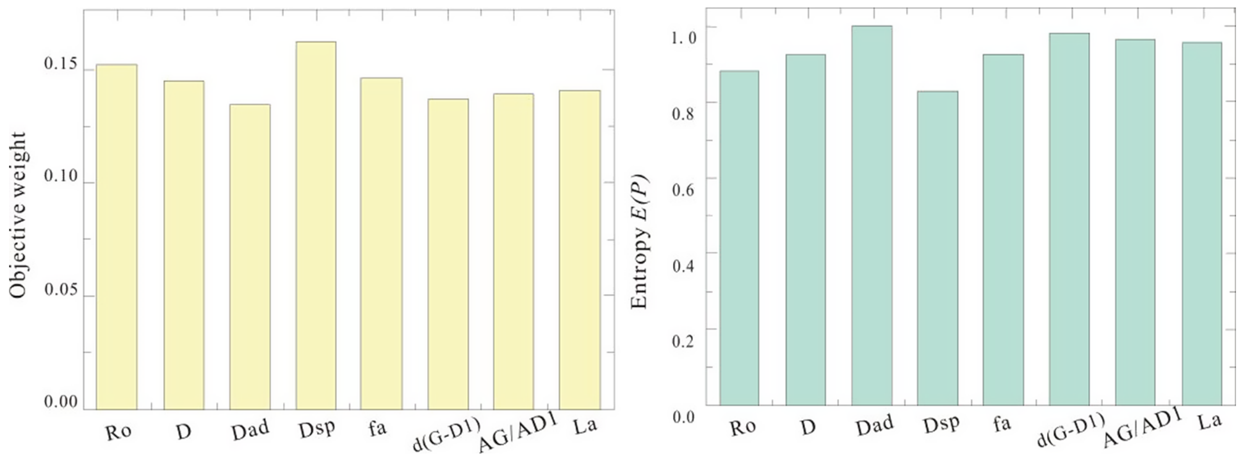

Figure 4. Entropy and objective weight of each evaluation parameter.

Table 8. Comprehensive Weight W Calculated Based on the AHP-EWM Coupling Model

evaluating indicators	R_0, max	D	D_{ad}	D_{sp}	f_a	$D(G-D_1)$	A_G/A_{D1}	L_a
W_i	0.1879	0.0911	0.0711	0.2525	0.1176	0.0793	0.1021	0.0984
W_j	0.152	0.145	0.134	0.162	0.146	0.137	0.139	0.140
W	0.1700	0.1181	0.1026	0.2073	0.1318	0.1082	0.1206	0.1192

the EWM model, and the results showed that the fractal dimension of seepage pore D_{sp} > vitrinite reflectance (R_0) > f_a > fracture density D > L_a > A_G/A_{D1} > d(G−D1) > fractal dimension of adsorption pore D_{ad}. In order to effectively avoid the systematic and artificial errors caused by the single weight calculation model, the comprehensive weight of the impact of each evaluation index on the heterogeneity of the tectonic coal reservoir can be obtained more accurately by superposing the weight values calculated by the two models. Based on formula 17, the comprehensive weight W calculated by the AHP-EWM coupling model is shown in Table 8.

The calculation results of the coupling model based on AHP-EWM showed that the order of comprehensive weight calculation results affecting the heterogeneity of the structural coal reservoir was fractal dimension of seepage pore D_{sp} > vitrinite reflectance (R_0) > f_a > A_G/A_{D1} > L_a > fracture density D > d(G−D1) > fractal dimension of adsorption pore D_{ad}. The results of comprehensive weighting also express the similarity with the results of single weighting calculation; that is, the fractal dimension D_{sp} of seepage pores and vitrinite reflectance (R_0) are the two indicators that have the greatest impact on the degree of heterogeneity of structural coal reservoirs; f_a, A_G/A_{D1}, L_a, and fracture density D are the four indicators with moderate impact and similar weight results. However, d(G−D1) and adsorption pore fractal dimension D_{ad} are still the two indicators that have the lowest impact on the heterogeneity of the structural coal reservoir.

3.5. Comprehensive Evaluation of Tectonically Deformed Coals Heterogeneity. The heterogeneous index method is a widely used characterization method to characterize the heterogeneity of structural coal reservoirs.[2,11,17] And previous studies mostly used a single calculation model to obtain the heterogeneity index of the reservoir.[3,12−15]

In order to reduce the systematic and human error of the single weight calculation method, this study obtained the comprehensive weights of evaluation indicators through the AHP-EWM coupling model and thus calculated the heterogeneity index of the tectonic coal reservoir. Based on formula 16, the heterogeneity index I of different tectonic coal samples can be calculated, and the heterogeneity types of coal samples with different deformation degrees can be divided. The specific calculation results are shown in Table 9 and Figure 5.

Table 9 and Figure 5 show the distribution range of nonuniformity index I of coal samples with different

Table 9. Comprehensive Weight W Calculated Based on the AHP-EWM Coupling Model

no.	I_i	I_j	I
SJS1	0.12	0.15	0.135
SJS2	0.17	0.26	0.215
HG2	0.11	0.16	0.135
YLT1	0.18	0.24	0.210
YLT2	0.26	0.36	0.310
YLT3	0.34	0.44	0.390
YLT4	0.34	0.48	0.410
HG1	0.21	0.26	0.235
SJS3	0.31	0.38	0.345
HP1	0.46	0.53	0.495
JJ1	0.59	0.69	0.640
JJ2	0.45	0.58	0.515
YLT5	0.72	0.79	0.755
HP2	0.81	0.92	0.865

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ACS Omega 2023, 8, 36700−36709

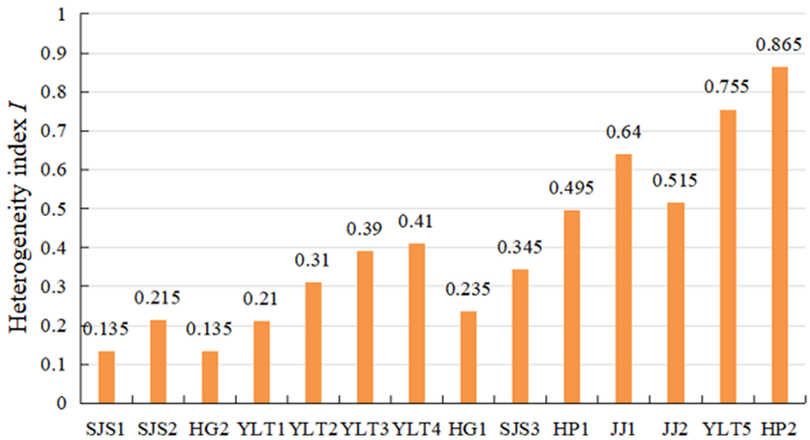

Figure 5. Nonuniform exponential distribution of coal samples with deformation degrees.

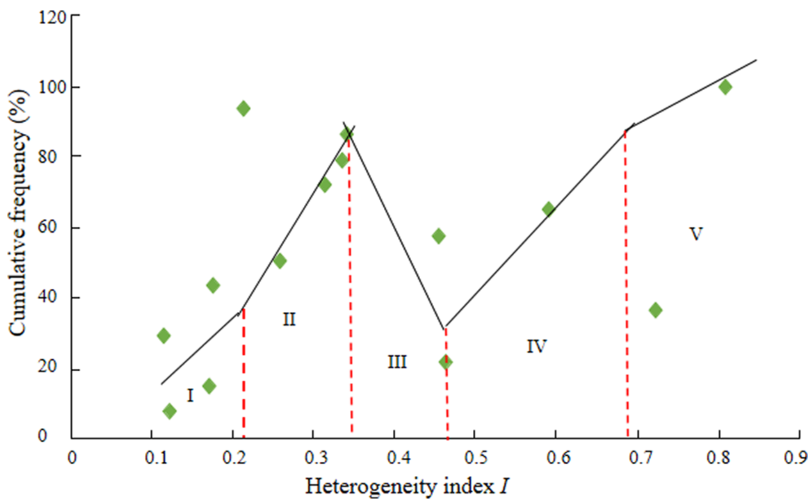

Figure 6. Cumulative probability percentage of the heterogeneous composite index using the AHP model.

deformation degrees between 0.135 and 0.865. The heterogeneity index of HP2 (mylonite coal) is the largest, while the SJS1 (primary tectonic coal) and HG2 (primary tectonic coal) have the lowest heterogeneity index. Overall, as the deformation degree increases, the heterogeneity index gradually increases, specifically manifested as primary structural coal < flaky coal < crumpled coal < cataclastic coal < broken spot coal < mylonite coal.

In order to characterize the comprehensive heterogeneity characteristics of tectonic coal reservoirs, this paper classifies the heterogeneous types of coal reservoirs with different deformation degrees. By conducting cumulative probability feature analysis on the comprehensive index values of heterogeneity of 14 coal samples, the heterogeneity types of coal reservoirs were divided into five categories (I, II, III, IV, V). In addition, Figure 6 also shows that the comprehensive index of heterogeneity of reservoirs with the same heterogeneity was almost on the straight line of the same slope, and the intersection of different straight lines was the threshold for the classification of heterogeneity types of coal reservoirs.

Based on the AHP calculation model, the Class I tectonic coal reservoir ($I \leq 0.21$) corresponds to primary structural coal and cataclastic coal in brittle deformation series; Class II tectonic coal ($0.21 < I \leq 0.35$) corresponds to flaky coal; Class III tectonic coal ($0.35 < I \leq 0.46$) corresponds to fragmentary coal; Class IV tectonic coal ($0.46 < I \leq 0.69$) corresponds to crumpled coal; and Class V tectonic coal ($0.69 < I \leq 0.99$) corresponds to mylonite coal. It is worth mentioning that the critical value of the heterogeneous comprehensive index of brittle and ductile tectonic deformation coal is $I = 0.46$, as shown in Figure 6 and Table 10.

Based on the EWM calculation model, the Class I tectonic coal reservoir ($I \leq 0.24$) corresponds to primary structural coal and cataclastic coal in brittle deformation series; Class II tectonic coal ($0.24 < I \leq 0.32$) corresponds to flaky coal; Class III tectonic coal ($0.32 < I \leq 0.50$) corresponds to fragmentary coal; Class IV tectonic coal ($0.50 < I \leq 0.72$) corresponds to crumpled coal; and Class V tectonic coal ($0.72 < I \leq 0.99$) corresponds to mylonite coal. In addition, the critical value of the comprehensive index of brittle and ductile deformation coal heterogeneity is $I = 0.50$, as shown in Figure 7 and Table 10.

The calculation results obtained by using the AHP-EWM coupling calculation model show that the tectonic coal reservoir ($I \leq 0.225$) of Class I corresponds to the primary structural coal and cataclastic coal in brittle deformation series; Class II tectonic coal ($0.225 < I \leq 0.335$) corresponds to flaky coal; Class III tectonic coal ($0.335 < I \leq 0.48$) corresponds to fragmentary coal; Class IV tectonic coal ($0.48 < I \leq 0.705$) corresponds to crumpled coal; Class V structural coal ($0.705 < I \leq 0.99$) corresponds to mylonite coal. In addition, the critical value of the comprehensive index of the heterogeneity of brittle and ductile deformed coal was $I = 0.48$, as shown in Table 10.

https://doi.org/10.1021/acsomega.3c02764
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Table 10. Classification of Heterogeneous Types of Coal Reservoirs

model	heterogeneous types of structural coal reservoirs	heterogeneous composite index I	distribution range
AHP	I	0.19	(0, 0.21]
	II	0.30	(0.21, 0.35]
	III	0.32	(0.35, 0.46]
	IV	0.46	(0.46, 0.69]
	V	0.60	(0.69, 0.99]
EWM	I	0.19	(0, 0.24]
	II	0.30	(0.24, 0.32]
	III	0.32	(0.32, 0.50]
	IV	0.46	(0.50, 0.72]
	V	0.60	(0.72, 0.99]
AHP-EWM	I	0.19	(0, 0.225]
	II	0.30	(0.225, 0.335]
	III	0.32	(0.335, 0.48]
	IV	0.46	(0.48, 0.705]
	V	0.60	(0.705, 0.99]

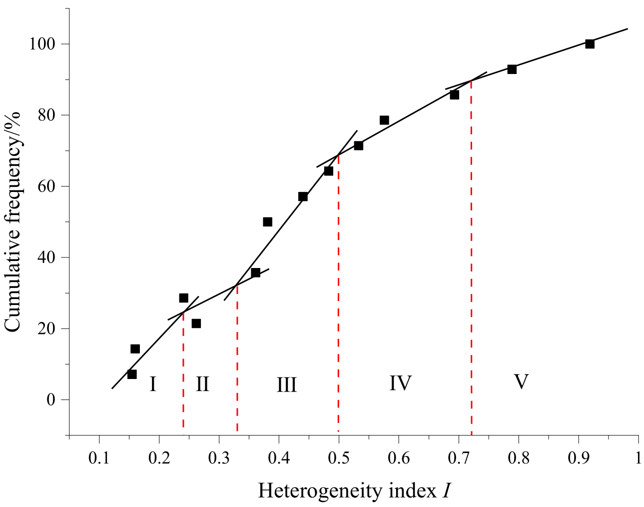

Figure 7. Cumulative probability percentage of the heterogeneous composite index using the EWM model.

4. CONCLUSIONS

The main conclusions are as follows:

(1) Based on the AHP and EWM model, this study obtained the order of subjective and objective weights of each evaluation index that affects the heterogeneity of tectonic coal reservoirs. In addition, the specific order is as follows: the fractal dimension of seepage pore D_{sp} > vitrinite reflectance (R_0) > f_a > A_G/A_{D1} > L_a > fracture density D > d(G−D1) > fractal dimension of adsorption pore D_{ad}, which means that the fractal dimension D_{sp} of seepage pores and the reflectance of vitrinite (R_0) have the greatest impact on heterogeneity, followed by f_a, A_G/A_{D1}, L_a, and fracture density D, and d(G−D1) and adsorption pore fractal dimension D_{ad} have the smallest impact on heterogeneity.

(2) Based on the AHP-EWM coupling evaluation model, combined with the nonuniformity index method, the heterogeneity of the coal reservoir in the Panguan syncline is comprehensively evaluated. Among the heterogeneity evaluation indexes of the tectonic coal reservoir, the pore fracture characteristic has the largest contribution to the heterogeneity of the coal reservoir, followed by the degree of coal metamorphism and coal chemical structure.

(3) Based on the above results, this study further classified the heterogeneous types of coal reservoirs. The specific results show that Class I ($I \leq 0.225$) corresponds to the primary structural coal and cataclastic coal in the brittle deformation series; Class II ($0.225 < I \leq 0.335$) corresponds to flaky coal; Class III ($0.335 < I \leq 0.48$) corresponds to the broken coal; Class IV ($0.48 < I \leq 0.705$) corresponds to crumpled coal; the Class V coal reservoir ($0.705 < I \leq 0.99$) corresponds to mylonite coal. In addition, the critical value of the comprehensive index of brittle and ductile deformation coal heterogeneity is $I = 0.48$.

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Conceptualization, Z.W.; formal analysis, Z.W.; investigation, Z.W.; methodology, Z.W.; project administration, Z.W.; supervision, Z.W. All authors have read and agreed to the published version of the manuscript.

Notes

The author declares no competing financial interest.

ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support from the Major Projects of National Science and Technology (2016ZX05044001-02).

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