IN THE FIELD

Approaches for the evaluation of favorable shale gas areas and applications: Implications for China's exploration strategy

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Abstract
To explore practical approaches for the evaluation of favorable shale gas areas, a structural decomposition analysis with respect to the index system, evaluation criteria, weight determination, and evaluation methods was carried out. Five types of indexes were determined from 25 subindexes that formed the index system, and improved whitenization weight functions are proposed to establish evaluation criteria. The index weights calculated using entropy weight and Euclidean distance methods are consistent, whereas the weights determined by gray relational analysis are significantly affected by the relative number of indexes and evaluation objects, selected mother factor, and resolution coefficient. The significant linear positive correlation between the relative approach degree values calculated using TOPSIS and the scores obtained using fuzzy comprehensive evaluation (FCE) is indicative of a consistent evaluation result, but it should be noted that extreme indicator values can have strong effects on the evaluation using the fuzzy similarity method. Finally, an exploration strategy for China's shale gas is suggested: Areas with weak reformation and relatively low maturity are expected to be favorable for marine shale production in South China, and continental and transitional shale-bearing basins are promising for the prospecting multiple-origin shale gas and coal measure gas, respectively.

KEYWORDS
evaluation approaches, exploration strategy, favorable areas, index system, shale gas, weight determination

1 | INTRODUCTION

With the increasing global population, as well as economic pressure, there is growing demand for energy, especially environmentally friendly, clean energy fuels.1,2 A large number of studies have shown that the utilization of natural gas is important for economic security and environmental protection,3,4 and a recent study hinted that the fossil fuel industry has great potential to mitigate anthropogenic climate change.5 Therefore, unconventional natural gas, which has huge resource potential, will play an important role in future social development. Dark shale or mudstone is a good hydrocarbon source rock,6 and to date, shale, an unconventional natural gas source, has been successfully used to produce gas.7,9 Although China has made a significant breakthrough in commercializing marine shale gas in the southern region,10-13 the
commercialization of continental and transitional shale gas has been comparatively stagnant.12-14 Considering the state of China’s shale gas basic geological survey and local breakthroughs in commercial development, there is an urgent need for the nationwide optimization of shale gas strategic areas.

Numerous studies have focused on the evaluation and key parameters for favorable exploration zones for shale gas. Zhang et al15 reported that the selection of areas favorable for exploration should be based on existing shale gas geological data and meet the requirements and purposes of the current exploration and development stage with reference to tectonic conditions, sedimentary environments, geochemistry, reservoir characteristics, and gas properties, and the most favorable areas should be chosen by means of the assessment indicators in a certain spatial range. Li et al16 proposed that the general requirements for shale gas favorable areas should focus on the location and structural characteristics of the gas-bearing shale, and, on this basis, the other evaluation parameters, including burial depth, total organic carbon (TOC), organic matter maturity (Ro), brittle mineral content, and distribution area, are taken into consideration. The key parameters of North American marine shale gas evaluation include shale thickness, burial depth, TOC, Ro, gas content, mechanical properties, and mineral contents,7,17,18 and these parameters are widely used in other countries and regions.19,20 The current shale gas evaluation in China is principally targeted at the southern marine strata, in which the main target area is the Sichuan Basin and its adjacent area.13 Marine shales in favorable areas tend to be characterized by high values of some key evaluation indicators, such as TOC, porosity, gas content, siliceous content, and hydrocarbon generation intensity.21,22 The preservation conditions might also be a crucial factor for the shale gas evaluation in structurally complex regions,22 and the tight shales that form the direct seals and Lower Middle Triassic gypsum layers and mudstone that form regional seals with low TOC and porosity maintain the high gas content of the first member shale of the Longmaxi Formation, as well as overpressure systems in the Sichuan Basin.23 Integrated evaluation maps prepared by the stacking process were widely used in delineating the distribution of favorable areas in a specific region.24 Furthermore, there are a good number of quantitative approaches, for instance, the fuzzy evaluation method, fuzzy similarity method, and TOPSIS method, which can be used in the field of hydrocarbon evaluation.25-28 Actually, the selection of favorable shale gas areas can be abstracted mathematically as the multi-index decision, and these approaches, in principle, can be used to serve for the target. However, unfortunately, there have been, at present, few studies on the selection of favorable shale gas regions by these methods, even though they are frequently used in the shale gas development, as well as economic and policy assessment.27,28

To determine the importance of each index with respect to the target object for quantitative evaluation, the index weight must be determined and this can be categorized into three types: subjective, objective, or combinative weight.29 Subjective weights can be determined by an Analytic Hierarchical Process (AHP) or expert consultation method (Delphi feedback method),31 whereas the objective weights can be calculated by, for example, the entropy weight method,29,31,32 coefficient of variation method,32 and gray relational analysis.33

There is a lack of quantification and comparative research about the various evaluation methods, and the shale gas selection methodology must be improved in terms of quantification, systematics, practicality, and comprehensiveness. This paper aims to explore the practical and quantitative evaluation approaches of favorable areas for shale gas to select units or blocks that can be given priority to the drilling engineering for further exploration and development. First, a structural decomposition analysis for the evaluation system with respect to the evaluation index system, weight calculation, and evaluation methods was conducted. Then, 12 typical shale gas research areas of various types in China were evaluated, and some important implications are discussed.

2 | MATERIALS AND METHODS

To assess favorable areas for shale gas exploration, an evaluation indicator system and evaluation criteria were established by dissecting relevant factors in terms of shale gas geology and engineering economic conditions, and corresponding data for the selected 12 areas are shown in Table 1 and Figure 1. Subsequently, index weights were obtained by a subjective weighting method, the Analytic Hierarchical Process (AHP), or objective weighting methods including the gray relational analysis (GRA), the entropy weight method (EWM), and the Euclidean distance method (EDM). Finally, combinative indicator weights (λC) were determined based on the subjective and objective weights. Furthermore, using the fuzzy comprehensive evaluation method (FCEM), fuzzy similarity method (FSM), and TOPSIS method (TM), evaluation was carried out.

2.1 | Index weight acquisition

2.1.1 | Analytic Hierarchy Process

AHP was proposed and developed by Saaty30 to analyze and support decisions that have multiple and even competing objectives. The process consists of four steps. (a) First, a hierarchical evaluation system is created to express the relationship between the factors clearly. (b) Secondly, pairwise comparison matrices are constructed, taking advantage of relative weights that could be obtained by different scales. For the object of study in this paper, the relative importance intensities in comparison are actually not so great. Therefore, the exponential scale can be used to replace 1-9 scale to improve.
the situation smoothly and quantify the judgment matrix accurately,34 and the irrational number “e” is taken as the base to keep an appropriate growth rate and obtain a high degree of consistency in practice. The corresponding relationships are listed in Table 2. (c) Thirdly, the weight vectors, as parameter weights, are computed in MATLAB. (d) Finally, the consistency of the comparison matrix is checked, and the parameter weights, are computed in MATLAB. (d) Finally, the consistency of the comparison matrix is checked, and the

\[ CI = (\lambda_{max} - n)/(n - 1) \]  

(1)

Here, CI represents the consistency index, \( n \) denotes the comparison matrix dimension, the value of \( n \) is 5 in this work, and \( \lambda_{max} \) is the maximum eigenvalue of the comparison matrix.

\[ CR = CI/RI \]  

(2)

Here, CR stands for the random consistency index, and \( RI \) is the average random consistency index.

### 2.1.2 Three objective weighting methods

Table 1 could be abstracted to an \( m \times n \) matrix that is determined by \( m \) objects and \( n \) indicators \((m = 12, n = 25)\), and the

### TABLE 1 Parameters of the chosen assessment areas

| Index                  | Parameters | JSB          | CG            | YC            | HF            | ZM            |
|------------------------|------------|--------------|---------------|---------------|---------------|---------------|
| Background             | Stratigraphy | \( O_{w-S} \) | \( e_{1, n} \) | \( Z_{d} \)   | \( P_{d} \)   | \( C_{2t-P} \) |
| sedimentary environment | Marine      | Marine       | Marine        | Marine        | Marine        |
| Gas generation conditions | Thickness (m) | 80-120/87   | 40-80/60      | 50-120/85     | 30-50/40      | 95            |
|                        | TOC (%)     | 0.6-6.3/3.5 | 1.7-9.6/4.6   | 0.2-3.4       | 0.2-17.3/6.0  | 0.16-10.9/2.2 |
|                        | \( R_{e} \) (%) | 2.4-2.8/2.6 | 2.2-4.4/3.5   | 1.4-2.6/1.9   | 1.8-2.7/2.3   | 3.0-3.8/3.5   |
| Kerogen type           | I           | I           | I             | I             | I             |
| Area (km²)             | 280         | 915         | 1200          | 2306.7        | 1396          |
| Gas storage conditions | Burial depth (m) | 2250-3500 | 1200-2400     | 1500-3500     | 0-2500/1000   | 2000-9000/4500|
|                        | Gas content (m³/t) | 0.63-9.63/4.61 | 0.10-2.88/1.38 | 0.45-5.19/1.97 | 1.04-1.39     | 0.42-4.44/1.93 |
|                        | Gas saturation (%) | 65         | 5-85/50       | –            | –             | 30-74/52      |
|                        | Porosity (%) | 1.17-7.98/4.61 | 0.62-3.34/2.21 | 0.60-2.10/1.48 | 1.46-4.26/2.31 | 0.30-8.80/2.70 |
|                        | Geothermal (°C/100m) | 2.73       | 2.16          | 1.37          | 2.30          | 2.79          |
| Gas preservation       | Structure   | F           | RF            | RF            | RF            |
|                        | Roof-floor  | F           | RF            | RF            | RF            |
|                        | Hydrology   | F           | RF            | F             |
|                        | Fractures   | F           | RF            | F             |
|                        | Magmatic    | RF          | RF            | RF            |
| Gas recoverability      | Permeability (mD) | 0.0015-5.71/0.25 | 0.0007-0.014/0.003 | 0.008-0.545/0.216 | 0.0002-0.0024/0.0008 | 0-0.11/0.00748 |
|                        | Pressure coefficient | 1.55       | 0.93-1.13     | 1-1.1         | 1-1.1         | 1             |
|                        | Free-adsorbed gas ration | 9         | 4             | 1.53          | 0.03-0.043/0.037 | 0.42-1.07/0.75 |
|                        | \( I_{Brit-RC} \) (%) | 50.95-80.30/62.40 | 46.00-78.00/6200 | 19.6-80/52.3 | 50-86/68     | 11-88/51.1   |
|                        | \( I_{Brit-RM} \) (%) | 45.0-63.0 | 44.6-52.1 | 57.3-63.1 | -             | 39.0-49.0    |
| Engineering economic   | Traffic     | F           | RF            | RF            | RF            |
|                        | Terrain     | RF          | RF            | RF            |
|                        | Water source | F           | F             |
|                        | Pipe network | F           | F             |
|                        | Market      | F           | F             |

Note: ‘–’ means no data; data sources are the national shale gas survey (2009-2011), exploration data of various shale gas areas (2012-2018), and references.19,61,62,65

Abbreviations: BJ, Bijie shale gas test area; CG, Cengong Block in Guizhou Province; DC, Dacheng Salient at Jizhong Depression; FX, Fuxin Block in Ordos Basin; FXB, Fuxin Basin; HF, Hefeng Block in Hubei Province; IF, Fuxin Block in Ordos Basin; JSB, Jiaoshiba Block of Fulin Shale Gas Field; KQ, Kuqa Depression in the Tarim Basin; R, favorable; RF, relatively favorable; UF, unfavorable; YC, Yichang Block in Hubei Province; YQ, Yuqia depression in the northern Qaidam Basin; YW, Yushe-Wuxiang Block in Qinhui Basin; ZM, Zhongnou Block in Henan Province.
qualitative factors can be quantified as described in Section 2.2. Furthermore, the $m \times n$ data matrix can be used to calculate index weights by the following three methods.

**Gray relational analysis**

The matrix could be used to analyze uncertainty relationships between individual indicators and calculate index weights by gray relational analysis. The parameter data $a_{ij}$ preprocessed by Min-Max normalization can be expressed by matrix $A$ (Equation 3), and the same operation is conducted for the entropy weight and Euclidean distance methods. Then, the absolute deviation values, $\Delta_i(j)$, and the correlation coefficient, $\epsilon(j)$, between the mother sequence, $a_i(j)$, which is determined by the selected mother factor and comparative sequence, $a_j(j)$, can be calculated using Equations (4) and (5), respectively. The gray relational grade, $r_i$, is computed using Equation (6) to obtain the indicator weights (Equation 7).

\[
A = \begin{pmatrix}
    a_{11} & a_{12} & \cdots & a_{1n} \\
    a_{21} & a_{22} & \cdots & a_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    a_{m1} & a_{m2} & \cdots & a_{mn}
\end{pmatrix}
\]  

(Equation 3)
Here, $a_{ij}$ is the standardized data.

$$\Delta_i(j) = |a_{0j} - a_{ij}| \quad(4)$$

Here, $\Delta_i(j)$ denotes the absolute deviation values between the reference sequence and comparative sequence, and $a_{0j}$ and $a_{ij}$ are the reference sequence and standardization processing results.

$$\varepsilon_i(j) = \frac{\min_{m} \min_n (\Delta_i(j)) + \rho \max_{m} \max_n (\Delta_i(j))}{\Delta_i(j) + \rho \max_{m} \max_n (\Delta_i(j))} \quad(5)$$

Here, $\varepsilon_i(j)$ represents the gray relational coefficient between the reference sequence and comparative sequence, $\rho$ is the distinguish coefficient and ranges from 0 to 1 and is generally considered to be 0.5, and $\min_{m} \min_n (\Delta_i(j))$ and $\max_{m} \max_n (\Delta_i(j))$ are the minimum and maximum deviation between $a_{0j}$ and $a_{ij}$, respectively.

$$r_j = \frac{\sum_{i=1}^{m} \varepsilon_{i}j / m}{\sum_{j=1}^{n} r_j} \quad(6)$$

Here, $r_j$ is the gray relational grade calculated by the correlation coefficient $\varepsilon_i(j)$.

$$\lambda_j = r_j / \sum_{j=1}^{n} r_j \quad(7)$$
Here, $\lambda_j$ is the $j$th indicator weight.

**Entropy weight method**

The entropy is a parameter in thermodynamics that quantitatively characterizes the degree of disorder in a physical system, and its subtypes, such as the statistical entropy and information theoretical entropy, can be used to obtain the potential information about the objective data set, which is regarded as an uncertain information system.\(^3\) Based on the degree of variability of indicators, the entropy weights can be computed using Equations (8)–(10).

The entropy, $h_j$, of the $j$th indicator is computed as follows.

$\begin{align*}
    h_j &= -\left( \sum_{i=1}^{m} f_{ij} \ln f_{ij} \right) / \ln m \\
    f_{ij} &= \left( 1 + a_{ij} \right) / \sum_{i=1}^{m} \left( 1 + a_{ij} \right)
\end{align*}$

(8) (9)

Here, $f_{ij}$ is scaled as follows. It should be noted that the improved formula (9) is adopted to ensure that the value of $f_{ij}$ makes sense because the result calculated by the traditional entropy method may be equal to zero.\(^3\)\(^5\) Here, $f_{ij}$ denotes the $j$th object weight of the $i$th indicator, and $a_{ij}$ is the standardized data.

$\lambda_j = (1 - h_j) / \sum_{j=1}^{n} (1 - h_j) \quad (10)$

**Euclidean distance method**

The Euclidean distance is defined as the absolute difference between two vectors and is applied in diverse fields.\(^3\)\(^6\) Here, we adopt the square Euclidean distance to measure the parameter variability (Equation 11) and the indicator weights are given by Equation (12).

$R_k^2 = \sum_{i=1}^{m} (a_{ik} - \overline{a}_k)^2 \quad (11)$

Here, $R_k$ denotes the Euclidean distance between the individual and the holistic level of the $k$th factor, $a_{ik}$ scales the $i$th object of the $k$th factor, $\overline{a}_k$ is the mean $a_{ik}$ of the $k$th factor, and $m$ is the number of objects.
Here, $\lambda_k$ is the $k$th indicator weight, and $n$ is the number of indicators.

### 2.1.3 Combinative weighting method

The final index weights should be determined using both the subjective and objective weights to reflect the importance of evaluation indicators fully and to synthesize advantages and disadvantages of the two methods. The combinative weighting method has been proposed and applied in previous studies.\(^{29,32}\) Here, the combinative weights are calculated according to the suggested formula in Equation (13).

$$\lambda_{Cj} = \lambda_{Sj}\lambda_{Oj}/(\sum_{j=1}^{n}\lambda_{Sj}\lambda_{Oj})$$

Here, $\lambda_{Cj}$ is the combinative weights of the $j$th index, and $\lambda_{Sj}$ and $\lambda_{Oj}$ represent the subjective and objective weights of the $j$th index, respectively.

### 2.2 Evaluation approaches

#### 2.2.1 Fuzzy comprehensive evaluation method

Fuzzy theory is applied extensively to the fuzzy system to support the multicriteria group decision-making and tends to generally combine with other theories to encourage a broader range of applications.\(^{37,38}\) The fuzzy comprehensive evaluation method, which consolidates the comprehensive evaluation methodology (commonly regarded as a multicriteria decision issue) and fuzzy theory (managing vagueness or information full of uncertainties),\(^{25}\) is widely applied for decision support, prediction analysis, and risk assessment in many fields. The result of FCEM is expressed as the fuzzy judgment vector, $S$, which is obtained from fuzzy evaluation matrix $R$ and weight vector $W$ (Equation 14). It should be noted that several membership functions, such as Gaussian, bilateral Gaussian, $\pi$, $S$, $Z$, trapezoid, and triangular, could be exploited to calculate the $R$ matrix, but those approaches fail to characterize the sensitivity of geological parameters to shale gas evaluation. In fact, the individual value domains of each parameter have distinct effects on the evaluation result, but existing membership functions tend to be unable to express the relationship accurately. Taking the TOC as an example, let us suppose that there are two shale samples with TOC increasing from 1% to 2% and 9% to 10%, respectively. As a rule, the former improvement, from the viewpoint of shale evaluation, is more meaningful because it is indicative of a major change of kerogen quality from fair to good, whereas the latter is high but belongs to very good source rock.

Because four typical piecewise-linear whitenization weight functions in gray system can summarize the value preference of various parameters, improved whitenization weight functions constructed from frequently used functions, including the Langmuir function, Gaussian distribution function, and trigonometric function, in the field of energy geology, can be used for the assessment of quantitative indicators (Figure 2). Because some factors, such as the terrain, transportation, hydrogeology, and pipe network, are quite difficult to quantify, the qualified value ranges of 0.8-1, 0.5-0.8, and 0.5-0 are assigned to represent factor memberships, that is, “favorable,” “relatively favorable,” and “unfavorable,” respectively, and the objects without data are estimated to have...
TABLE 3  The evaluation standards of the previous and this work

| Parameters               | Previous works       | This work |
|--------------------------|----------------------|-----------|
| Thickness (m)            | 3643,46,47           | 30        |
| TOC (%)                  | 25,43,47             | 2         |
| $R_o$ (%)                | 1.443,47             | 1.5-3.0   |
| Area (km²)               | 200-500              | 500       |
| Burial depth (m)         | 1500-350011,1000-300044, (2000-2700) to (4200-4400)51 | 1000-3500 |
| Gas content (m³/t)       | 0.515, 243,47        | 1         |
| Gas saturation (%)       | 50³,6043,47          | 80        |
| Porosity (%)             | 4³, 243, 347         | 4         |
| Geothermal (°C/100 m)    | 110³43               | 2.5       |
| Permeability (mD)        | 100 nD43,47          | 0.1       |
| Pressure coefficient     | 13                   | 1         |
| Free-adsorbed gas ration | 1-1.8645             | 1         |
| $I_{R_{Bt,RC}}$ (%)      | 4043,47              | 40-60     |
| $I_{R_{Bt,RM}}$ (%)      | Poisson's ratio < 0.25, Young's modulus > 3.0 MMPSIA43 | 40       |

Here, $S$ denotes fuzzy judgment vector of $m$ objects, $W$ is the weight vector, and $R$ is the fuzzy evaluation matrix.

2.2.2 | Fuzzy similarity method

The FSE works by computing the interval distance and similarity coefficient between the evaluation object and standard to evaluate objects quantitatively.39 Assuming that $n$ indicators are contained in an evaluation system, $I = (I_1, I_2, \ldots, I_n)$ and $I_0 = (I_{01}, I_{02}, \ldots, I_{0n})$, and these are defined as the evaluation object interval and evaluation standard interval, respectively, both of which have been normalized by division by the respective maximum values, and the interval distance $d(I, I_0)$ and the similarity coefficient $S(I, I_0)$ can be determined using Equations (15) and (16).

$$d(I, I_0) = \frac{1}{n} \sum_{j=1}^{n} \left| I_j - I_{0j} \right|$$

(15)

$$S(I, I_0) = 1 - k \sum_{j=1}^{n} [\lambda_j d(I_j, I_{0j})]$$

(16)

Here, an appropriate value of $k$ is selected to satisfy $S(I, I_0) \in [0,1]$, and $\lambda_j$ is the $j$th indicator weight.

2.2.3 | TOPSIS method

The TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) method was first proposed by Hwang and Yoon in 198140 to rank a limited number of evaluation objects on the basis of their closeness to an idealized target. After dealing with the statistics in the same trends by means of the improved whitenization weight functions, the Euclidean distances $D_i^+$ and $D_i^-$ between each object are evaluated, and both the positive-ideal solution $Z^+ = [Z_1^+, Z_2^+, \ldots, Z_n^+]$ and the negative-ideal solution $Z^- = [Z_1^-, Z_2^-, \ldots, Z_n^-]$, respectively, are determined using Equations (17) and (18), thus yielding the relative approach coefficient to the ideal solution, $L_i$ (Equation 19), which is used to rank the considered objects.41,42

$$D_i^+ = \sqrt{\sum_{j=1}^{n} (Z_{ij}^+ - Z_{ij})^2}$$

(17)

$$D_i^- = \sqrt{\sum_{j=1}^{n} (Z_{ij}^- - Z_{ij})^2}$$

(18)

Here, $D_i^+$ and $D_i^-$ represent the Euclidean distance between each object, $Z_{ij}$, and both the positive-ideal solution $Z_{ij}^+$ and negative-ideal solution $Z_{ij}^-$, respectively.

The relative approach to ideal solution $L_i$ is defined as

$$L_i = D_i^- / (D_i^+ + D_i^-)$$

(19)

3 | RESULTS AND DISCUSSION

3.1 | Index system and evaluation criterion

As shown in Figure 3, based on the shale gas geological characteristics, five types of indicators, including gas generation, storage, preservation, recoverability, and economy conditions, are marked off the operable subindexes that form
TABLE 4  Membership functions of all quantitative indexes

| Index | Scoring criterion | Whitenization function type |
|-------|-------------------|-----------------------------|
| $a$: Shale thickness, m | $f(a) = \begin{cases} 0 & a < 3 \\ 4(a - 3)/(4a + 15) & a \geq 3 \end{cases}$ | Type IV |
| $w_{TOC}$: TOC mass percentage, % | $f(w_{TOC}) = \begin{cases} 0 & w_{TOC} < 0.3 \\ 4(2w_{TOC} - 1)/(8w_{TOC} - 1) & w_{TOC} \geq 0.3 \end{cases}$ | Type IV |
| $R_o$: Vitrinite reflectance, % | $f(R_o) = \begin{cases} 0 & R_o < 0.25 \\ \sin(\pi R_o/5) & 0.25 \leq R_o < 2.5 \\ \exp[-0.715 \times (R_o - 2.5)^2] & R_o \geq 2.5 \end{cases}$ | Type III |
| $A$: Gas-bearing area, km$^2$ | $f(A) = \begin{cases} 0 & A < 50 \\ 2(A - 50)/(2A + 125) & A \geq 50 \end{cases}$ | Type IV |
| $D$: Burial depth, m | $f(D) = \begin{cases} \sin(\pi D/2000) & D < 1000 \\ 1 & 1000 \leq D < 2500 \\ \exp[-2.2 \times 10^{-7} \times (D - 2500)^2] & D \geq 2500 \end{cases}$ | Type I |
| $V$: Gas content, m$^3$/t | $f(V) = \begin{cases} 0 & V \in [0, 0.2] \\ 4V/(4V + 1) & V \in [0.2, +\infty] \end{cases}$ | Type IV |
| $S_g$: Gas saturation, % | $f(S_g) = S_g/(S_g + 20)$ | Type IV |
| $\phi$: Porosity, % | $f(\phi) = \phi/(\phi + 1)$ | Type IV |
| $G$: Geothermal gradient, °C/100m | $f(G) = \exp(-0.0257G^2)$ | Type II |
| $K$: Permeability, mD | $f(K) = 40K/40K + 1$ | Type IV |
| $P$: Pressure gradient, Mpa/100m | $f(P) = 4P/(4P + 1)$ | Type IV |
| $FAR$: Free-adsorbed gas ration | $f(FAR) = 4FAR/(4FAR + 1)$ | Type IV |
| $I_{brit-MC}$: Mineral brittleness, % | $f(I_{brit-MC}) = \begin{cases} 0 & I_{brit-MC} \in [0, 20] \\ \sin\left[\frac{\pi}{20}\left(I_{brit-MC} - 20\right)\right] & I_{brit-MC} \in [20, 50] \\ \exp\left[-0.002 \times (I_{brit-MC} - 50)^2\right] & I_{brit-MC} \in [50, 100] \end{cases}$ | Type III |
| $I_{brit-RM}$: Rock mechanical brittleness, % | $f(I_{brit-RM}) = \begin{cases} 0 & I_{brit-RM} \in [0, 20] \\ (I_{brit-RM} - 20)/(I_{brit-RM} - 15) & I_{brit-RM} \in [20, 100] \end{cases}$ | Type IV |

the evaluation indicator system with a hierarchical structure. Then, the evaluation standard of quantitative indexes was established (Table 3). Based on the evaluation standard and improved whitenization weight functions, the undetermined coefficient method was adopted to determine the membership functions of each index that can act as the evaluation criteria (Table 4), in which the corresponding function value of the evaluation standard is 0.8.

3.1.1  Gas generation conditions

Gas generation conditions are affected by the material composition and the degree of thermal evolution, and the relative parameters are composed of the shale thickness and area, TOC, Ro, and kerogen type. Previously, a shale thickness of 30 m has been used as the lowest effective thickness because the huge shale gas resources require a certain shale thickness and area. However, thinner lower thickness might be reasonable because a thickness of less 10 m (about 30 ft) of Antrim shale in Michigan Basin has been exploited. The TOC content in dark shales not only acts as the material foundation for gas generation but also affects pore structure, adsorbability, gas-bearing properties, and gas production, and high-quality shales with TOC > 2% tend to be expected for shale gas evaluation. The hydrocarbon expulsion process of shales with various types of kerogens can be divided into different stages, and studies indicate that thermogenic gas of industrial importance tends to be associated with an appropriate thermal maturity in relation to subsidence/burial history.

3.1.2  Gas storage conditions

Favorable gas storage conditions are related to the available reservoir space and gas occurrence environments and are generally assumed to be moderate burial depth, high
gas content, high porosity, high gas saturation, and low stratum temperature. As a factor influencing the shale gas content, the depth of major shale gas producing areas is <3500 m, and the Antrim shale gas field, which contains biogenic methane at less 200 m depth, is developed; a “sweet window” in the shale gas reservoir depth for artificial fracture network formations might be nonexistent. In most cases, high gas contents and corresponding high gas production rates tend to be associated with a high reservoir quality, and a lower limit value should be set for shale gas evaluation. Shales with the low degree of water saturation, indicative of high gas saturation, have been successfully developed in the USA, and a water saturation below 40% has been suggested as favorable. A suitable porosity providing free gas within gathering space, and the commercially viable critical value might be considered to be 4%.

### Table 5: Importance coefficient of the index layer relative to the target layer

| Evaluation index and matrix | Maximum eigenvalue | Eigenvector | Consistency ratio |
|-----------------------------|--------------------|-------------|------------------|
|                            | $\lambda_{max}$    | WB | CR |
| A-B B1                     | 5.0077             | 0.3680 | 0.0017 |
| B2 1.000                   | 5.0498             | 0.2777 | 0.0111 |
| B3 0.670                   | 5.0743             | 0.2462 | 0.0166 |
| B4 0.368                   | 5.0758             | 0.2852 | 0.0169 |
| B5 0.202                   | 5.0063             | 0.2935 | 0.0014 |
| B1-C1 C11                  | 5.0481             | 0.3546 | 0.0107 |
| C12 1.000                  |                   |     |     |
| C13 0.368                  |                   |     |     |
| C14 0.549                  |                   |     |     |
| C15 0.247                  |                   |     |     |
| B2-C2 C21                  |                   |     |     |
| C22 1.000                  |                   |     |     |
| C23 0.368                  |                   |     |     |
| C24 0.549                  |                   |     |     |
| C25 0.301                  |                   |     |     |
| B3-C3 C31                  |                   |     |     |
| C32 1.000                  |                   |     |     |
| C33 0.301                  |                   |     |     |
| C34 0.549                  |                   |     |     |
| C35 0.202                  |                   |     |     |
| B4-C4 C41                  |                   |     |     |
| C42 1.000                  |                   |     |     |
| C43 0.549                  |                   |     |     |
| C44 0.670                  |                   |     |     |
| C45 0.368                  |                   |     |     |
| B5-C5 C51                  |                   |     |     |
| C52 1.000                  |                   |     |     |
| C53 0.549                  |                   |     |     |
| C54 0.247                  |                   |     |     |
| C55 0.301                  |                   |     |     |
3.1.3 | Gas preservation conditions

Considering the shale gas preservation conditions, the structural conditions, roof and floor plate conditions, hydrogeology, and fracture features have been the focus of the previous studies, and it is emphasized that the metamorphism, fracture development, fluid migration and preservation resulting from magmatism must be known to make a definite analysis of particular conditions.52

3.1.4 | Gas recoverability conditions

Gas recoverability conditions largely depend upon shale reservoir fracability, and the difficulty of gas extraction and the specific indexes include the permeability, reservoir pressure, free-to-adsorbed ratio, mineral composition, and rock mechanical properties. The correlation between gas production and permeability, reservoir pressure, and free-to-adsorbed ratio has already revealed by previous studies and development practices, and brittleness indexes calculated based on the mineral content and rock mechanical parameters have been developed and applied to understand shale reservoir fracability.17,28,53

3.1.5 | Engineering economic conditions

The ideal engineering economic conditions, in terms of the transportation, terrain, water source, pipe network and market, are necessary to reduce preconstruction costs.27,54

3.2 | Index weight determination

Although the Analytic Hierarchy Process is considered to be a subjective weighting approach, it should be noted that only evaluating a pairwise comparison matrix needs subjective analysis according to experience, and the matrix tends to be achieved through comparison between two parameters in the same level with one another. In terms of the AHP comparison matrix, the calculated CR value of each hierarchy varies from 0.0014 to 0.0169 with a cumulative value of 0.0584, in which low CR values far <0.1
indicate the calculation results pass a consistency check of rationality and reliability (Table 5). As shown in Figure 4 and Table 6, the indicator weight values obtained by AHP show distinct differences, and the TOC has the largest weight value of 0.135, followed by the gas content and shale thickness ranking second with weights of more than 0.1. Indicators with weight values exceeding 0.03 include $R_o$, organic matter type, burial depth, porosity, structural characteristics, fracture development, permeability, reservoir pressure, and mineral composition; in contrast, other factors, for example, the economic conditions, have lower weight values. Furthermore, $\lambda_{EWM}$ ranging from 0.005 to 0.099 is very close to $\lambda_{EDM}$, which has a range of 0.007-0.101, and both have a similar overall distribution to $\lambda_{AHP}$. However, the results using $\lambda_{GRA}$ that show poor importance differentiation of each parameter are almost around the average of 0.004, and the gas content as the mother factor has the largest weight value.

The degree of consistency of the weight calculation results obtained using various methods was assessed using the coefficient of determination, $R^2$ (0 $\leq$ $R^2$ $\leq$ 1), for the two different approaches and the angle, $\theta$ (0 $\leq$ $\theta$ $\leq$ 0.7854, unit: radians), between the fitted line and the $y = x$ line. A high $R^2$ and low $\theta$ are suggestive of a strong correlation (Figure 5). Among the weight calculation approaches mentioned in this study, the AHP is commonly considered to be a subjective decision-making method, not only because of numerous qualitative factors but also because of the discrete scale used to handle the uncertainty and ambiguity in deciding the factor attribute characteristics of the comparison matrix.28 However, EWM, EDM, and GRA are based on objective data, and the calculation of the relevant parameters depends little on the subjective or sensory components.32,33,36 Figure 5 implies that $\lambda_{AHP}$ might be correlated with $\lambda_{EWM}$ ($R^2 = 0.2628$, $\theta = 0.3957$), indicating that the subjective and

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FIGURE 5  Relationships between various index weights obtained by different approaches

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FIGURE 6  Relationships between the entropy weight method weights ($\lambda_{EWM}$) and the Euclidean distance weights ($\lambda_{EDM}$), and parameter standard deviations
objective consequences have a certain degree of uniformity. Meanwhile, there is strong correlation between $\lambda_{EWM}$ and $\lambda_{EDM}$ ($R^2 = 0.9055$, $\theta = 0.0509$) in Figure 5, both of which show remarkable power function correlation with the parameter variance (Figure 6). In the entropy method, the indexes with higher weight values are quite distinct from the others and make a significant difference in the ranking outcomes of the evaluation object. The EDM, which is similar to the entropy approach, determines the weights of the indexes in terms of their variability via Equations (11) and (12). Nevertheless, there is a weak correlation between $\lambda_{GRA}$ and both $\lambda_{AHP}$ and $\lambda_{EWM}$, having $R^2 = 0.1694$, $\theta = 0.7140$; and $R^2 = 0.0468$, $\theta = 0.7385$, respectively.

Figure 7A shows that the results of $\lambda_{GRA}$, which are obviously affected by both the selected mother factor and the resolution coefficient $\rho$. The weight value of the chosen mother factor is the highest for a given $\rho$ value and increases with decreasing $\rho$ at an ever-increasing rate (Figure 7B). Previous studies have pointed out that the rank order of index weights is always same though different values of $\rho$ are adopted, but the use of $\rho = 0.5$, which is often used, should be discussed rationally to achieve effective evaluation results for a particular field. The suitability of these methods in approaching the research questions is related to their fundamental principles, advantages, and disadvantages (Table 7). From this perspective, there exist at least two reasons for the poor differentiation of $\lambda_{GRA}$. On the one hand, the number of the indicators is greater than the number of the evaluation objects, which leads to an erroneous understanding of relationships between the mother factor and other subfactors determined by the comparability sequence and the reference sequence; on the other hand, some subfactors actually have no correlation with the mother factor in a geological sense, for example, the relationship between transportation and gas content. Thus, efforts to optimize the GRA methodology for immediate application to shale gas evaluation are required to obtain more reliable results.

**TABLE 7** Fundamental principles, advantages, and disadvantages of various weight determination approaches

| Approaches of index weight acquisition | Fundamental principles | Advantages | Disadvantages |
|---------------------------------------|------------------------|------------|---------------|
| AHP                                   | Relative importance of indexes | Simple in principle and clear hierarchy structure | Subjective approaches to the comparison matrix |
| Gray relational analysis              | Correlation degree of parameters | No special requirements for the parameter distribution | Limited applicability of quantitative models, and aiming at the gray system |
| Entropy weight method                 | Variability of parameters | Strong objectivity and applicability | Overdependence on samples, lack of the comparison among indexes |
| Euclidean distance method             | Variability of parameters | Strong objectivity and applicability | Overdependence on samples, lack of the comparison among indexes |
| Combinative weighting method          | Weighting method         | Comprehensive consideration of both subjective and objective weights | Moderate subjectivity and objectivity |
On the basis of the above discussion, combinative weights ($\lambda_C$) were calculated using $\lambda_{AHP}$ and $\lambda_{EW}$ and Equation (10), which combines the subjective and objective approaches, surface and underground factors, geological and economic conditions, hierarchical and logical structure, and quantitative and qualitative indexes (Figure 8). Additionally, the factors serving as the key indexes for shale gas favorable area evaluation, such as TOC, shale thickness, $Ro$, burial depth, and gas content, possess higher weight values because China’s shale gas selection area, at the present stage, mainly focuses on the optimization of shale gas geological conditions, which is consistent with the previous standard evaluation workflow for unconventional shale gas. Compared with the previous works aimed at shale gas development, market conditions possess lower weigh values in this work, and the reference 44 in which the weigh values calculated by AHP presented the relevant information.

### 3.3 Evaluation results

The relative approach degree values obtained via TM vary from 0.4167 to 0.8133 (Table 8) and present a significant linear positive correlation with the scores obtained by FCE ($R^2 = 0.9695$), suggesting that the results of these two methods have a high degree of conformance (Figure 9).
However, the evaluation results obtained using the FSE reveal that the relatively favorable level for each evaluation subject has higher coefficient similarity values than both favorable and unfavorable levels (Figure 10), which differs from conclusions obtained using the FCE and TOPSIS methods because it would be unfeasible to depend on extreme indicator values while neglecting characteristics of the parameter distribution. Based on the fuzzy evaluation scores ranging from 0.7054 to 0.9002 (Table 8), the chosen evaluation areas could be ranked as JSB, YC, FX, YW, DC, YQ, FXB, HF, BJ, CG, KQ, and ZM in descending order of the favorability, and the evaluation results also show that marine shale gas regions are characterized by favorable gas generation and storage conditions, as well as complex and changeable preservation and recoverability conditions. Considering transitional shale gas, the geological conditions vary largely between different areas and strata. Furthermore, the engineering economic conditions in some continental shale regions, subject to geographic location, are relatively poor, but the complexity of other geological conditions usually falls somewhere between those of marine and transitional shale gas (Figure 11).

To summarize the above evaluation results, it is necessary to have a good understanding of the key characters of various types of shale gas in favorable areas. Favorable areas of marine shale gas possess the two basic conditions: a good material basis with high TOC and brittle minerals in advantageous sedimentary facies belts, in which the depositional controls on the organic matter enrichment have a great effect on the reservoir properties, and it is important to note that the biogenic silicon might be the main reason why the marine shales are more brittle than the transitional and

| Evaluation units | Scores obtained by FCE | Relative approach degree obtained by TM | Similarity coefficients computed by FSM |
|------------------|------------------------|----------------------------------------|----------------------------------------|
|                  | FCE                    | TM                                     | Favorable | Relatively favorable | Unfavorable |
| JSB              | 0.900                  | 0.813                                  | 0.971     | 0.981               | 0.970       |
| CG               | 0.755                  | 0.486                                  | 0.967     | 0.986               | 0.980       |
| YC               | 0.872                  | 0.794                                  | 0.966     | 0.986               | 0.978       |
| HF               | 0.763                  | 0.473                                  | 0.969     | 0.983               | 0.977       |
| ZM               | 0.705                  | 0.417                                  | 0.962     | 0.985               | 0.981       |
| YW               | 0.832                  | 0.686                                  | 0.972     | 0.981               | 0.974       |
| BJ               | 0.762                  | 0.498                                  | 0.973     | 0.979               | 0.974       |
| DC               | 0.812                  | 0.625                                  | 0.963     | 0.988               | 0.978       |
| FXB              | 0.769                  | 0.564                                  | 0.970     | 0.982               | 0.977       |
| FX               | 0.865                  | 0.768                                  | 0.970     | 0.986               | 0.978       |
| YQ               | 0.772                  | 0.553                                  | 0.963     | 0.986               | 0.980       |
| KQ               | 0.749                  | 0.502                                  | 0.962     | 0.984               | 0.981       |

**FIGURE 9** Relationship between scores obtained by fuzzy comprehensive evaluation and the relative approach degree obtained using the TOPSIS method

**FIGURE 10** Distribution of similarity coefficients computed using the FSM
continental shales. Importantly, good preservation conditions and relatively low thermal maturity are essential because marine shales, which are mainly developed in the middle-upper Proterozoic to lower Paleozoic strata, have experienced more tectonic periods and long-term thermal evolution, resulting in stronger reformation and higher thermal maturity. In contrast, continental shales are well developed in the Meso-Cenozoic strata in northern China, which leads to the low overall maturity and coexisting multiple origin of shale gas, including thermogenic and biogenic methane. These are present in different locations and depths of the subsiding basins because of the broad burial depth range and thermal maturity gradient (Figure 12). Therefore, shallow reservoirs are suitable for the exploring biogenic gas and shale oil, and a certain burial depth for prospecting thermogenic shale gas is required. Transitional shales, principally formed in delta, tidal flat, and lagoon, are frequently interbedded with coal, sandstone, and carbonate rocks (Figure 13), and different types of coal measure gas (CMG) could exist simultaneously, which suggests that coexploration and conining of the CMG would be promising because the coexistence of CMG is a reflection of favorable gas generation and preservation conditions.

3.4 | Implications for China’s exploration strategy

It should be noted that various types of shale gas show the large differences in the regional distribution, geological conditions, and development history in China, in which these factors result in the evaluation results, and therefore that can also be indicative of the exploration strategy. Previous studies have shown that the Sichuan Basin and its periphery in South China are the favorable zones for marine shale gas. Generally, marine-continental transitional shale gas typically coexists with coalbed methane and tight sandstone gas occurred in the upper Proterozoic Carboniferous-Permian strata of the coal-bearing basins nationwide, such as the Southern North China, Ordos, Qinshui, Jungar, and Tarim Basins in the central and western regions. Continental shale is mainly distributed in the sedimentary basins in North China, such as...
3.4.1 Marine shale gas

In the early stages of China’s shale gas exploration, the Jiaoshiba Block was chosen as a Class I target area of the Lower Silurian Wufeng-Longmaxi Formation in Fuling area because of the simple structural conditions and favorable sedimentary environment. The Cengong Block is considered as a relatively favorable area for shale gas accumulation of the Lower Cambrian Niutitang Formation in northern Guizhou, but it is important to note that the organic matter has a high thermal maturity despite the advantageous shale gas geological conditions, and the results of this study are consistent with those made previously. The rationality of the evaluation results is also proved by exploration and development practices. The Jiaoshiba Block, the leading area of the shale gas industry in China, possesses the extremely advantageous shale gas geological conditions and has yielded remarkable breakthroughs in the geological theory of highly evolved marine shale gas, and the first commercial shale gas field with the capability to produce 203,000 m³/d was obtained from Well JY1. In the Precambrian Sinian Doushantu Formation, which is regarded as the oldest formation with shale gas potential, the discovery of shale gas in the Yichang area of Hubei
Province in 2017 was an important breakthrough, and subsequent well exploration was extensively carried out (Figure 1). Recently, significant effort has been put into the study on shale gas potential of the lower Cambrian Nuititang Formation and the upper Permian Dalong Formation, which are regarded as two of prime targets of shale-bearing strata in the South China. Compared with marine shale gas, the exploration and development of the marine-continental transitional shale gas in China is still in its infancy. Well MY-1, which is located in the Zhongmu Block of Henan Province, was the first well drilled in 2011 and aimed at revealing the transitional shale gas potential of the Southern North China Basin.

### 3.4.2 Marine-continental transitional shale gas

Almost simultaneously, the integrated exploration of coalbed methane and shale gas in the same strata as Zhongmu Block was conducted in the Yushe-Wuxiang Block of the Qinshui Basin, Shanxi Province, and the detected total gas resources exceeded $1.8 \times 10^{11} \text{ m}^3$. In some parts of the South China, the upper Permian Longtan Formation transitional shale gas has also drawn attention, and a comprehensive exploration test area for shale gas in northern Guizhou covering an area of 36 000 km$^2$ was established by the Ministry of Land and Resources in 2014, and Well Yangmeican 1 achieved a stable gas flow of over 3600 m$^3$/d from coal, shale, and tight sandstone.

### 3.4.3 Continental shale gas

In the last few years, major breakthroughs have been made in the continental shale gas exploration, and we have obtained a better understanding of accumulation mechanism and evaluation of terrestrial shale gas. The Yanchang area was selected as a national demonstration zone for shale gas in 2012, and the LP177 well with the tested gas production of 2350 m$^3$/d in the upper Triassic Chang7 Member after fracturing in 2011 is the first continental shale gas well in China. Since then, potential shale oil and biogenic shale gas in continental basins in northern China have been extensively proven and evaluated.

In conclusion, a relatively low maturity and weak degree of reformation are expected for favorable marine shale gas areas in the South China region, and continental and transitional shale-bearing basins are promising for the prospecting of multiple-origin shale gas/oil and various types of CMG, respectively.
4 | CONCLUSIONS

In this study, a structural decomposition analysis for the evaluation of favorable shale gas areas with respect to the index system, evaluation criteria, weight determination, and evaluation methods was conducted. Five types of indicators, considering gas generation, storage, preservation, recoverability, and economic conditions, were marked off 25 subindexes that formed the indicator system, and subsequently, improved whitenization weight functions were proposed to establish evaluation criteria for assigning quantitative indicators.

The index weights of the EWM and EDM were consistent and showed good correlation with the AHP weights ($\lambda_{AHP}$), indicating that subjective and objective consequences have a high degree of uniformity, whereas weights determined by GRA are significantly affected by the relative number of indexes and evaluation objects, selected mother factor, and resolution coefficient ($\rho$). Consequently, combinative weights were determined using $\lambda_{AHP}$ and $\lambda_{EWM}$, which represent the subjective and objective weights, respectively. The relative approach degree values calculated by TOPSIS showed a significant linear positive correlation with the scores obtained by fuzzy comprehensive evaluation ($R^2 = 0.9695$), which suggests that the evaluation of the two methods shows a high degree of conformance, and the conclusions drawn from these models are consistent with geological understanding, previous evaluation results, and development practices. Although it should be noted that the results of FSE are highly susceptible to the upper and lower limits of the parameters, this approach is more meaningful on the condition of understanding the characteristics of the parameter distribution.

On the basis of the procedure and results of evaluation, some important implications for exploration strategy of China’s shale gas can be summarized as follows: (a) a relatively low thermal maturity and good preservation conditions related to a weak degree of deformation in the advantageous sedimentary facies zone are critical for the classification of favorable areas of marine shale gas, (b) continental shale-bearing basins could contain shale gas/oil of various origins of in different locations and basin depths, and (c) coexploration and comining of CMG are extremely promising for the exploitation of marine-continental transitional coal-bearing strata.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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REFERENCES

1. Chu S, Majumdar A. Opportunities and challenges for a sustainable energy future. Nature. 2012;488(7411):294-303.
2. Hu DS, Xu SQ. Opportunity, challenges and policy choices for China on the development of shale gas. Energy Pol. 2013;60:21-26.
3. Mcfarland E. Unconventional chemistry for unconventional natural gas. Science. 2012;338(6105):340-342.
4. Mcjeon H, Edmonds J, Bauer N, et al. Limited impact on decadal-scale climate change from increased use of natural gas. Nature. 2014;514(7523):482-485.
5. Schwietzke S, Sherwood OA, Bruhwiler L, et al. Corrigendum: upward revision of global fossil fuel methane emissions based on isotope database. Nature. 2017;543(7645):452-452.
6. Mackenzie AS, Leytheauser D, Muller P, et al. The movement of hydrocarbons in shales. Nature. 1988;331(6151):63-65.
7. Curtis JB. Fractured shale-gas systems. AAPG Bull. 2002;86(11):1921-1938.
8. Boyer C, Kieschnick J, Suarez-Rivera R, et al. Producing gas from its source. Oilf Rev. 2006;18:36-49.
9. Ross D, Bustin RM. Shale gas potential of the lower Jurassic Gordondale Member, northeastern British Columbia, Canada. Can Petrol Geol. 2007;55(1):51-75.
10. Hu HY, Fang H, Lin JF, et al. Organic matter-hosted pore system in the Wufeng-Longmaxi (O$_2$w–S$_1$1) shale, Jiaoshiba area, Eastern Sichuan Basin, China. Int J Coal Geol. 2017;173:40-50.
11. Guo XS, Hu DF, Li YP, et al. Technologies in discovery and exploration of Fuling shale gas field, China. Nat Resor. 2016;7:271-286.
12. Guo TL, Zhang HR. Formation and enrichment mode of Jiaoshiba shale gas field, Sichuan Basin. Petrol Explor Dev. 2014;41(1):31-40.
13. Dong DZ, Zou CN, Dai JX, et al. Suggestions on the development strategy of shale gas in China. J Nat Gas Geosci. 2016;1(6):413-423.
14. Wang S. Shale gas exploitation: status, problems and prospect. Nat Gas Ind B. 2018;5(1):60-74.
15. Zhang JC, Lin LM, Li YX, et al. The method of shale gas assessment: probability volume method. Earth Sci Front (CUGB; PKU). 2012;19(2):184-191. (in Chinese).
16. Li YX, Zhang JC, Jiang SL, et al. Geologic evaluation and targets optimization of shale gas. Earth Sci Front (CUGB; PKU). 2012;19(5):332-338. (in Chinese).
17. Jarvie DM, Hill RJ, Ruble TE, et al. Unconventional shale-gas systems: the Mississippian Barnett Shale of north-central Texas as one model for thermogenic shale-gas assessment. AAPG Bull. 2007;91(4):475-499.
18. Burnaman MD, Shelton J. Shale gas play screening and evaluation criteria. Chin Petrol Explor. 2009;14(3):51-64.
19. Zhou Z, Ren SM, Wu YL, et al. Evaluation of shale gas resources in Yuqi sag of Qaidam Basin. Geol Bull Chin. 2016;35(2/3):242-249. (in Chinese).
20. Assad G, Ralf L, Garri G, et al. Assessment of unconventional shale gas potential of organic-rich Mississippian and Lower Pennsylvanian sediments in western Germany. Int J Coal Geol. 2018;198:29-47.
21. Guo XS, Hu DF, Li YP, et al. Geological factors controlling shale gas enrichment and high production in Fuling shale gas field. Petrol Explor Dev. 2017;44(4):481-491.
22. Ma YS, Cai XY, Zhao PR. China's shale gas exploration and development: understanding and practice. Petrol Explor Dev. 2018;45(4):589-603.
23. Jin ZI, Nie HK, Liu QY, et al. Source and seal coupling mechanism for shale gas enrichment in upper Ordovician Wufeng Formation – Lower Silurian Longmaxi Formation in Sichuan Basin and its periphery. Mar Pet Geol. 2018;97:78-93.
24. Li XQ, Zhang JZ, Wang Y, et al. Accumulation condition and favorable area evaluation of shale gas from the Niutitang Formation in northern Guizhou, South China. J Nat Gas Geosci. 2018;3:1-10.
25. Liu HH, Sang SX, Wang GG, et al. Evaluation of the synergetic gas-enrichment and higher-permeability regions for coalbed methane recovery with a fuzzy model. Energy. 2012;39(1):426-439.
26. Billig E, Thraen D. Renewable methane – a technology evaluation by multi-criteria decision making from a European perspective. Energy. 2017;139(15):468-484.
27. Ren IZ, Tan SY, Goodsite ME, et al. Sustainability, shale gas, and energy transition in China: assessing barriers and prioritizing strategic measures. Energy. 2015;84:551-562.
28. Sui LL, Ju Y, Yang Y, et al. A quantification method for shale fracability based on Analytic Hierarchy Process. Energy. 2016;115(1):637-645.
29. Alemi-Ardakani M, Milani AS, Yannacopoulos S, et al. On the effect of subjective, objective and combative weighting in multiple criteria decision making: a case study on impact optimization of composites. Expert Syst Appl. 2016;46:426-438.
30. Saaty TL. How to make a decision: The analytic hierarchy process. Eur J Oper Res. 1990;48(1):9-26.
31. Kaldellis JK, Anestis A, Koronaki I. Strategic planning in the electricity generation sector through the development of an integrated Delphi-based multi-criteria evaluation model. Energy. 2013;106(2):212-218.
32. Jahan A, Mustapha F, Sapuan SM, et al. A framework for weighting of criteria in ranking stage of material selection process. Int J Adv Manuf Technol. 2012;58(1-4):411-420.
33. Kadier A, Abdeshahian P, Simayi Y, et al. Grey relational analysis for comparative assessment of different cathode materials in microbial electrolysis cells. Energy. 2015;90:1556-1562.
34. Zhang W, Sun K, Lei CZ, et al. Fuzzy Analytic Hierarchy Process synthetic evaluation models for the health monitoring of shield tunnels. Comput-Aided Civ Inf. 2014;29(9):676-688.
35. Wu JH, Li PY, Qian H, et al. On the sensitivity of entropy weight to sample statistics in assessing water quality: statistical analysis based on large stochastic samples. Environ Earth Sci. 2015;74(3):2185-2195.
36. Singha J, Das K. Indian sign language recognition using eigen value weighted Euclidean distance based classification technique. Int J Adv Comp SCI Appl. 2013;4(2):188-195.
37. Wang L, Peng JJ, Wang JQ. A multi-criteria decision-making framework for risk ranking of energy performance contracting project under picture fuzzy environment. J Clean Prod. 2018;191:105-118.
38. Wang L, Wang XK, Wang Peng JJ, et al. The differences in hotel selection among various types of travellers: A comparative analysis with a useful bounded rationality behavioural decision support model. Tourism Manage. 2020;76:103961.
39. Wang SH, Tian XL, Wang CK, et al. Application of fuzzy similarity methods for evaluating the district of shale gas: a case of marine shale gas in Sichuan Basin. Reserv Eval Dev. 2018;8(1):71-75. (in Chinese).
40. Hwang CL, Yoon K. Multiple attribute decision making: methods and applications. Berlin, Germany: Springer; 1981.
41. Wang JQ, Han ZQ, Zhang HY. Multi-criteria group decision-making method based on intuitionistic interval fuzzy information. Group Decis Negot. 2014;23(4):715-733.
42. Nie RX, Tian ZP, Wang JQ, et al. Water security sustainability evaluation: applying a multistage decision support framework in industrial region. J Clean Prod. 2018;196:1681-1704.
43. Sondergeld CH, Newsham KE, Comisky JT, et al. Petrophysical considerations in evaluating and producing shale gas resources. SPE unconventional gas conference, February, 23–25, Pittsburgh, Pennsylvania, USA; 2010.
44. Yang Y, Wang LM, Fang YB, et al. Integrated value of shale gas development: a comparative analysis in the United States and China. Renew Sust Energ Rev. 2017;76:1465-1478.
45. Montgomery SL, Jarvie DM, Bowker KA, et al. Mississippian Barnett Shale, Fort Worth basin, north-central Texas: gas-shale play with multitierrillion cubic foot potential. AAPG Bull. 2005;89(2):155-175.
46. Bowker KA. Barnett Shale gas production, Fort Worth Basin: issues and discussion. AAPG Bull. 2007;91(4):523-533.
47. Li YZ, Wang XZ, Wu B, et al. Sedimentary facies of marine shale gas formations in Southern China: the Lower Silurian Longmaxi Formation in the southern Sichuan Basin. J Earth Sci. 2016;27(5):807-822.
48. Tan IJQ, Weniger P, Krooss B, et al. Shale gas potential of the major marine shale formations in the Upper Yangtze Platform, South China, Part II: Methane sorption capacity. Fuel. 2014;129:204–218.
49. Yang YT, Liang C, Zhang JC, et al. A developmental model of lacustrine shale gas genesis: a case from T3y7 shale in the Ordos Basin. China. J Nat Gas Sci Eng. 2015;22:395-405.
50. Li J, Zhou S, Gaus G, et al. Characterization of methane adsorption on shale and isolated kerogen from the Sichuan Basin under pressure up to 60 MPa: experimental results and geological implications. Int J Coal Geol. 2018;189:83-93.
51. He ZL, Li SJ, Nie HK, et al. The shale gas “sweet window”: “The cracked and unbroken” state of shale and its depth range. Mar Pet Geol. 2019;101:334-342.
52. Zhang W, Wang Q, Ye JG, et al. Fracture development and fluid pathways in shales during granite intrusion. Int J Coal Geol. 2017;183(1):25-37.
53. Grieser B, Halliburton JB. Identification of production potential in unconventional reservoirs. SPE 106623, 2007.
54. Ma ZW, Pi GL, Dong XC, et al. The situation analysis of shale gas development in China-based on Structural Equation Modeling. Renew Sust Energ Rev. 2017;67:1300-1307.
55. Li S, Tang DZ, Pan ZJ, et al. Evaluation of coalbed methane potential of different reservoirs in western Guizhou and eastern Yunnan, China. Fuel. 2015;139:257–267.
56. Wang YS, Li Z, Gong JQ, et al. An evaluation workflow for shale oil and gas in the Jiyang Depression, Bohai Bay Basin, China: a...
case study from the Luojia area in the Zhanhua Sag. *Petrol Res.* 2016;1:70-80.

57. Liang C, Jiang ZX, Cao YC, et al. Deep-water depositional mechanisms and significance for unconventional hydrocarbon exploration: a case study from the lower Silurian Longmaxi shale in the southeastern Sichuan Basin. *AAPG Bull.* 2016;100(5):773-794.

58. Wu J, Liang C, Hu ZG, et al. Sedimentation mechanisms and enrichment of organic matter in the Ordovician Wufeng Formation-Silurian Longmaxi Formation in the Sichuan Basin. *Mar Pet Geol.* 2019;101:556-565.

59. Moore TA. Coalbed methane: a review. *Int J Coal Geol.* 2012;101:36-81.

60. Wang ZC, Liu JJ, Jiang H, et al. Lithofacies paleogeography and exploration significance of Sinian Doushantuo depositional stage in the middle-upper Yangtze region, Sichuan Basin, SW China. *Petrol Explor Dev.* 2019;46(1):41-53.

61. Wang YF, Zhai GY, Wu YL, et al. Evaluation of Sinian Doushantuo formation shale gas content and fracturing property of Eyangye1 well in Hubei Province. *Chin Min Mag.* 2017;26(6):167-172. (in Chinese).

62. Xu LL, Liu ZX, Zhang YL, et al. Shale gas reservoir potential evaluation of Dalong Formation in Hefeng of western Hubei Province. *Spec Oil Gas Reserv.* 2018;23(2):13-18.

63. Liu Y, Tang X, Zhang JC, et al. Geochemical characteristics of the extremely high thermal maturity transitional shale gas in the Southern North China Basin (SNCB) and its differences with marine shale gas. *Int J Coal Geol.* 2018;194:33-44.

64. http://www.sxmtdz.com/info/1015/7751.htm. Accessed October 2019.

65. Qu XR, Zhu YM, Zhang QH. Reservoir characteristics and co-exploration and concurrent production analysis of unconventional natural gases in transitional facies coal measures: taking Yushe-Wuxiang block as an example. *J Xi’an Shiyou Univ: Nat Sci.* 2017;32(3):1-8. (in Chinese).

66. Qin Y. Research progress of symbiotic accumulation of coal measure gas in China. *Nat Gas Ind B.* 2018;5(5):466-474.

67. Xiong FY, Jiang ZX, Chen JF, et al. The role of the residual bitumen in the gas storage capacity of mature lacustrine shale: a case study of the Triassic Yanchang shale, Ordos Basin, China. *Mar Pet Geol.* 2016;69:205-215.

68. Wang XZ, Gao SL, Gao C. Geological features of Mesozoic lacustrine shale gas in south of Ordos Basin, NW China. *Petrol Explor Dev.* 2014;41(3):326-337.

69. Zhang SC, Shuai YH, Huang L, et al. Timing of biogenic gas formation in the eastern Qaidam Basin, NW China. *Chem Geol.* 2013;352:70-80.

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