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The Open Petroleum Engineering Journal, 2016, *9*, 207-215

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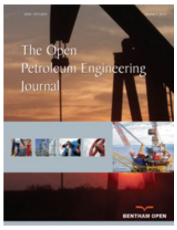
The Open Petroleum Engineering Journal

Content list available at: www.benthamopen.com/TOPEJ/

DOI: 10.2174/1874834101609160207



RESEARCH ARTICLE

Investigation of the Main Factors During Shale-gas Production Using Grey Relational Analysis

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Received: December 1, 2015 Revised: April 8, 2016 Accepted: May 22, 2016

Abstract: Shale gas is one of the primary types of unconventional reservoirs to be exploited in search for long-lasting resources. Production from shale gas reservoirs requires horizontal drilling with hydraulic fracturing to achieve the most economic production. However, plenty of parameters (*e.g.*, fracture conductivity, fracture spacing, half-length, matrix permeability, and porosity, *etc*) have high uncertainty that may cause unexpected high cost. Therefore, to develop an efficient and practical method for quantifying uncertainty and optimizing shale-gas production is highly desirable. This paper focuses on analyzing the main factors during gas production, including petro-physical parameters, hydraulic fracture parameters, and work conditions on shale-gas production performances. Firstly, numerous key parameters of shale-gas production from the fourteen best-known shale gas reservoirs in the United States are selected through the correlation analysis. Secondly, a grey relational grade method is used to quantitatively estimate the potential of developing target shale gas reservoirs as well as the impact ranking of these factors. Analyses on production data of many shale-gas reservoirs indicate that the recovery efficiencies are highly correlated with the major parameters predicted by the new method. Among all main factors, the impact ranking of major factors, from more important to less important, is matrix permeability, fracture conductivity, fracture density of hydraulic fracturing, reservoir pressure, total organic content (TOC), fracture half-length, adsorbed gas, reservoir thickness, reservoir depth, and clay content. This work can provide significant insights into quantifying the evaluation of the development potential of shale gas reservoirs, the influence degree of main factors, and optimization of shale gas production.

Keywords: Correlation analysis, Grey correction grade method, Main factors, Oil and gas development, Shale gas reservoir.

1. INTRODUCTION

Shale-gas production has drawn worldwide attention over past several years and has changed the energy equation around the world. Shale gas refers to natural gas that is trapped within fine gained sedimentary rocks called shale or mudstone, which can be rich source rocks for oil and natural gas. Shale gas reservoirs are organic-rich formations, and the natural gas in shale gas reservoirs is stored by two mechanisms, free gas and adsorbed gas, which is different from conventional gas reservoir. The permeability of shale gas reservoirs is extremely low on the order of micro-darcy to nano-darcy [1 - 5].

In order to increase well productivity, production from shale gas reservoirs requires horizontal drilling with hydraulic fracturing to achieve the most economic production. However, there are many uncertain parameters [6 - 9]. Shale gas reservoirs exhibit complexity across several factors, which can have significant impact on productivity, depending on the production technologies employed. Therefore, to develop an optimal way for quantifying uncertainties and optimization of shale gas production is highly desirable.

Many works have examined the influencing factors on the productivity of shale gas reservoirs. Many researchers [10 - 12] studied the influencing factors of production performance focus on the geologic features and petro-physical properties of tight gas reservoirs. Wei *et al.* concerned the impact of TOC on the potential of shale gas in southern

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China [13]. Fullmer *et al.* used a pore geometry characterization approach to investigate the influences of micro-porosity on oil recovery [14]. However, Yu and Sepehrnoori paid attention to the impacts of the exclusive features in shale gas reservoirs, such as non-darcy flow behavior, gas desorption, and geomechanics [7]. However, Joshi simulated various fracture models using a fracture simulator to observe their impacts on the well productivity [15]. Previous works show that many scholars have evaluated the development potential of shale gas reservoirs through various methods, but the selected parameters are not comprehensive, or the weight of parameters is determined by subjective assignment method, leading to the reduction in objectivity and accuracy of parameters.

This work focuses on analyzing the main factors during shale-gas production, including petro-physical parameters, hydraulic fracturing parameters, and work conditions on shale gas production performances. Firstly, the key influencing parameters on shale-gas production, from the fourteen best-known shale gas reservoirs in the United States, are selected through the correlation analysis method. Secondly, grey relational analysis (GRA), which is a new analysis method and proposed in the Grey system theory, is used in this work, and the objective weight of each parameter is determined by the grey correlation degree theory. Then, the multiple-attribute evaluation model is established for quantitatively estimating the development potential of target shale gas reservoirs and the impact ranking of main factors. The objective is to provide significant insights into quantifying the uncertainty, characterization of main factors, and optimization of shale-gas production.

2. KEY PARAMETERS FOR DEVELOPMENT OF SHALE GAS RESERVOIRS

Fourteen North American shale plays are used as units of analysis in this paper. The map of them is shown in Fig. (**1**), and their stratigraphy and depositional environments are labeled in Table **1**.

Fig. (1). Map of North American shale plays [16].

Table 1. Stratigraphy and depositional environments of the 14 shale plays [16].

Shale play	Stratigraphy	Depositional environment
Bakken	Mississippian	Marine environment
Barnett	Mississippian	Marine environment
Duvernay	Upper Devonian	Deep-water environment
Eagle Ford	Upper Cretaceous	Marine environment

(Table 1) contd.....

Shale play	Stratigraphy	Depositional environment
New Albany	Late Devonian	Marine environment
Niobrara	Upper Cretaceous	Foreland basin environment
Utica/Point Pleasant	Upper Ordovician	Basin environment
Wolfcamp/Bone Springs	Lower Permian	Marine environment
Woodford	Devonian	Shallow marine environment
Fayetteville	Mississippian	Shoreface environment
Haynesville/Bossier	Middle Cretaceous	Marine environment
Marcellus	Later Devonian	Marine environment
Montney/Doig	Lower Triassic/Middle Triassic	Marine environment
Muskwa	Upper Devonian	Shallow marine environment

In order to study the impacts of the main factors on gas production, reservoir depth (RD), reservoir thickness (RT), clay content (CLT), reservoir pressure (RP), matrix permeability (MP), porosity (POR), Young's modulus (YM), total organic carbon (TOC), thermal maturity (TM), adsorbed gas (AG), water saturation (S_w), horizontal well length (HWL), density of hydraulic fractures (N_f), fracture half-length (h_f), fracture conductivity (F_C), bottom hole pressure (BHP), and the first year decline rate (1st DR) which are easily quantified are selected. These key parameters are obtained from fourteen typical shale gas reservoirs in the United States [17 - 32], as shown in Table **2**.

Table 2. Parameters of fourteen shale gas reservoirs.

Parameters	Unit	Shale Gas Reservoirs													
		Bakken	Barnett	Duvernay	Eagle Ford	New Albany	Niobrara	Utica/ Point Pleasant	Wolf -Bone	Wood -ford	Fayett -eville	Haynesville/ Bossier	Marcellus	Montney /Doig	Muskwa
Depth	ft	9500	6750	10500	8500	3500	7500	6500	8000	10000	3950	10500	6250	10000	8000
Thickness	ft	49.5	300	115	150	125	312.5	150	350	170	125	250	175	170	450
Clay content	wt%	25	35	25	22.5	23.50	27.50	35.00	25.00	17.50	35	40	20	15	20
Reservoir Pressure	psi	5400	3200	7950	10500	850.00	5000	3250	5200	3500	3500	2850	7600	7510	3500
Matrix Permeability	10^{-3}mD	3	0.225	0.29	0.128	0.008	0.5	0.0225	0.55	0.25	0.65	0.55	1.1	2.5	0.025
Porosity	%	8.00	5.00	6.75	8.50	11.00	8.00	5.00	6.00	5.50	5.00	9.00	6.50	7.00	4.00
Young'S Modulus	10^6 psi	4.00	6.00	3.80	2.88	2.50	3.20	2.30	4.80	2.51	2.45	3.50	5.50	5.07	4.50
TOC	%	10.00	5.00	6.50	4.00	13.00	5.50	2.05	5.00	6.50	7.00	2.25	6.50	5.00	5.00
Thermal Maturity	%*R*o	0.75	1.45	1.80	1.38	0.96	0.98	1.65	0.90	1.30	2.50	2.15	1.60	1.83	1.90
Adsorbed Gas	%	25.00	35.00	10.00	15.00	15.00	35.00	20.00	40.00	25.00	50.00	15.00	50.00	20.00	10.00
Water Saturation	%	27.5	30	20	25	40.00	35.00	18.00	35.00	22.50	32.50	17.50	25.00	30.00	35.00
Horizontal Length	ft	5000	3250	4300	4800	1800	4250	6500	6050	4200	3000	5800	3500	6300	6800
Fracturing Density	1/ft	0.006	0.00246	0.00512	0.00313	0.00167	0.00259	0.00185	0.00182	0.00262	0.00267	0.00259	0.002	0.00254	0.002353
Frac Half Length	ft	450	140	180	230	320	165	280	150	160	420	380	175	260	210
Frac Conductivity	md-ft	160	55	70	140	25	80	130	100	60	250	185	75	180	70
BHP	psi	1000	320	2000	2600	350	500	325	520	350	350	350	1500	500	300
1st Year Decline Rate	%	65.00	50.00	55.00	70.00	60.00	80.00	70.00	60.00	65.00	60.00	50.00	64.00	54.00	71.00

Among all the main factors, some parameters may have similarities in data structure, which may result in an increase of workload and the interference of data accuracy. Therefore, in order to make all the main factors be independent, some derivative parameters can be abandoned based on the criterion of correlation coefficient. The correlation coefficient matrix of all the main factors is obtained using the SPSS statistical analysis software, as shown in Table **3**. Subsequently, combining with the field experience and setting the liminal value as 0.9, we can see that the selected seventeen parameters have well independence.

Table 3. Partial correlation analysis results of the main factors.

	Depth	Thickness	Clay content	Reservoir Pressure	Porosity	Young'S Modulus	TOC	Thermal Maturity	Adsorbed Gas	Water Saturation	Horizontal Length	Frac Density	Frac Half Length	Frac Conductivity	BHP	1st Year Decline Rate
Depth	1.000															
Thickness	0.192	1.000														
Clay content	-0.147	-0.091	1.000													
Reservoir Pressure	0.367	-0.117	-0.383	1.000												
Porosity	-0.067	-0.362	0.013	-0.007	1.000											
Young'S Modulus	0.099	0.618	-0.107	0.170	-0.344	1.000										
TOC	-0.518	-0.360	-0.289	-0.327	0.428	-0.219	1.000									
Thermal Maturity	0.041	-0.033	0.297	0.034	-0.373	0.010	-0.422	1.000								
Adsorbed Gas	-0.541	0.088	0.201	-0.057	-0.321	0.219	0.021	0.024	1.000							
Water Saturation	-0.582	0.390	-0.281	-0.284	0.114	0.148	0.561	-0.343	0.242	1.000						
Horizontal Length	0.570	0.505	-0.021	0.154	-0.384	0.093	-0.745	0.172	-0.401	-0.312	1.000					
Fracturing Density	0.416	-0.351	0.105	0.271	0.058	-0.208	0.155	-0.066	-0.384	-0.340	-0.083	1.000				
Frac Half Length	-0.338	-0.422	0.566	-0.448	0.298	-0.644	0.197	0.339	-0.159	-0.072	-0.134	0.141	1.000			
Frac Conductivity	-0.071	-0.158	0.555	0.030	-0.139	-0.408	-0.458	0.681	0.138	-0.258	0.220	-0.052	0.619	1.000		
BHP	0.266	-0.396	-0.280	0.888	0.242	0.017	-0.023	-0.072	-0.168	-0.326	-0.093	0.519	-0.181	-0.045	1.00	
1st Year Decline Rate	-0.118	0.103	-0.317	0.178	-0.047	-0.362	0.026	-0.384	0.058	0.201	0.175	0.019	-0.095	-0.115	0.115	1.00

Note: The matrix permeability is taken as the control variable in the SPSS correlation analysis.

3. MODELING OF GREY RELATIONAL GRADE

Assume that the number of shale gas reservoirs to be evaluated is *n*, denoted as, $X=\{x_1,x_2,x_3,\cdot,x_n\}$, is *m*, denoted as, $V=\{v_1,v_2,v_3,\cdot,v_m\}$, also known as evaluation indices. Thus, x_{ij} (i=1, 2, ·, n; j=1, 2, ·, m) means the *j*-th parameter of the *i*-th shale gas reservoir. Then, *n* shale gas reservoirs and *m* parameters compose the matrix $Z=(x_{ij})_{n\times m}$, which is the so called evaluation matrix.

To have a uniform standard, the evaluation matrix Z should be normalized in the grey relational analysis [33]. In this paper, the indices are classified into three types: benefit index, cost index, and fuzzy index. The value of the benefit index is the larger the better. The value of the cost index is the smaller the better. The value of the fuzzy index is optimal at the intermediate number.

3.1. Determination of Reference and Comparison Sequences

Denote the attribute value of parameter v_j to the corresponding ideal target shale gas reservoirs x as x_j, then;

$$x_{0j}=\begin{cases}\max(x_{1j},x_{2j},x_{3j},\cdots,x_{nj}), & j\in I_1;\\ \min(x_{1j},x_{2j},x_{3j},\cdots,x_{nj}), & j\in I_2;\\ x_{cj},\left|x_{cj}-x\right|=\min\left(\left|x_{1j}-x_j\right|,\cdots,\left|x_{nj}-x_j\right|\right), & j\in I_3.\end{cases}\quad (i=1,2,\cdots,n;\ j=1,2,\cdots,m). \tag{1}$$

where I_1, I_2, I_3 represent the subscript set of the benefit type, cost type, and fuzzy type, respectively. x_j is the theoretical optimal value of parameter v_j. The matrix $A=(x_{ij})_{(n+1)\times m}$ is the so called evaluation matrix of the set *X* of target shale gas reservoirs to the set *V* of parameters.

3.2. Treatment of the Initial Data

In order to cancel out the dimensions, the initial data is non-dimensionalized firstly using the following equation:

$$x_{ij}^{'} = \begin{cases} x_{ij} / x_{0j}, & \text{if } j \in I_1; \\ x_{0j} / x_{ij}, & \text{if } j \in I_2; \\ \min(x_{ij}, x_{0j}) / \max(x_{ij}, x_{0j}), & j \in I_3. \end{cases} \tag{2}$$

Thus, $A'=(x_{ij}^{'})_{(n+1)\times m}$ is the initialized matrix of A.

Meanwhile, the range can be calculated using the following equations. The maximal range is

$$\Delta_{\max} = \max_{1\le i\le n} \max_{1\le j\le m} \left| x_{ij}^{'} - x_{0j}^{'} \right|, \tag{3}$$

and the minimal range is

$$\Delta_{\min} = \min_{1\le i\le n} \min_{1\le j\le m} \left| x_{ij}^{'} - x_{0j}^{'} \right|. \tag{4}$$

3.3. Calculation of the Correlation Coefficients

The ideal shale gas reservoir is regarded as the primary sequence, and the shale gas reservoirs to be evaluated are regarded as the subsequence. Then, the correlation coefficient r_{ij} can be calculated as follows;

$$r_{ij} = \frac{\Delta_{\min} + \rho\Delta_{\max}}{\left| x_{ij}^{'} - x_{0j}^{'} \right| + \rho\Delta_{\max}}, \tag{5}$$

where ρ is the identification coefficient, and it is between 0 and 1. Generally, it is set as 0.5 [34].

3.4. Determining the Weight of Parameters

Choose the parameter which most significantly impacts on the evaluation result as the primary index, and assume the c-th parameter has the most significant influence on the evaluation result. It is denoted as $\overline{X}_c = (x_{1c}, x_{2c}, \cdots, x_{nc})^T$. . Based on the experiences of shale gas development, the matrix permeability is selected as the primary index in this work. The other parameters are sub-indexes and are denoted as $\overline{X}_j = (x_{1j}, x_{2j}, \cdots, x_{nj})^T$, in which j=0, 1, 2, ·, m, but $j\neq c$. The correlative grade between the primary index and the sub-indexes reflects the influence degree of every parameter to the evaluation result, and can be set as the weight of parameter. First, the initial data is also non-dimensionalized firstly using the following equation:

$$x_{ij}^{'} = \begin{cases} x_{ij} / x_{0j}, & \text{if } j \in I_1; \\ x_{0j} / x_{ij}, & \text{if } j \in I_2; \\ \min(x_{ij}, x_{0j}) / \max(x_{ij}, x_{0j}), & j \in I_3. \end{cases} \quad (i=1, 2, \cdots, n; j=1, 2, \cdots, m). \tag{6}$$

Then, the correlation coefficient of the primary index and the subindex:

$$y_{ij} = \frac{\min\limits_{1\le j\le m} \min\limits_{1\le i\le n} \left| x_{ij}^{'} - x_{ic}^{'} \right| + \rho \max\limits_{1\le j\le m} \max\limits_{1\le i\le n} \left| x_{ij}^{'} - x_{ic}^{'} \right|}{\left| x_{ij}^{'} - x_{ic}^{'} \right| + \rho \max\limits_{1\le j\le m} \max\limits_{1\le i\le n} \left| x_{ij}^{'} - x_{ic}^{'} \right|}. \tag{7}$$

Calculate the average value according to the column of matrix $Y=(y_{ij})_{n\times m}$, and then normalization processing is performed:

$$y_j = \frac{1}{n} \sum_{i=1}^{n} y_{ij}, \ (j=1,\ 2,\ \cdots,\ m), \tag{8}$$

$$w_j = y_j / \sum_{j=1}^{m} y_j \text{ , } (j=1, 2, \cdots, m), \quad \textbf{(9)}$$

where the matrix $W=(w_1,w_2\cdot,w_m)^T$ is the weight of each parameter. The synthetically weighted value, $f_{ij} = r_{ij} \times w_j$, can be regarded as the evaluation value of the exploitation potential of the shale gas reservoirs. A larger weighted value indicates that the shale gas reservoir to be evaluated is closer to the ideal target shale gas reservoir and the development efficiency will be better.

4. RESULTS AND DISCUSSION

According to the Grey Relational Grade model, we select the matrix permeability as the primary index and then the weight of every parameter is obtained as: W = (0.0583, 0.0610, 0.0567, 0.0662, 0.1029, 0.0564, 0.0522, 0.0661, 0.0551, 0.0613, 0.0526, 0.0558, 0.0678, 0.0646, 0.0686, 0.0543, 0.0488)^T. The correlative grade of every shale gas reservoir is shown in Table **4**. Calculate the synthetically weighted value to achieve $F=(f_{ij})_n$, and then F=(0.6712, 0.5293, 0.5978, 0.5798, 0.6217, 0.5222, 0.5914, 0.5312, 0.5536, 0.6437, 0.6379, 0.5302, 0.6421, 0.6251). We can see that the ranking exploitation potential of each target shale gas reservoir from large to small is Bakken, Fayetteville, Montney/Doig, Haynesville/Bossier, Muskwa, New Albany, Duvernay, Utica/Point Pleasant, Eagle Ford, Woodford, Wolf Bone, Marcellus, Barnett, and Niobrara. This is in accordance with their recovery efficiency 14.0%, 13.5%, 13.0%, 12.5%, 11.0%, 10.0%, 8.5%, 7.0%, 6.8%, 6.6%, 6.0%, 5.6%, 5.3%, and 5.0%, respectively. The calculating results is in accordance with the field result, as shown in Fig. (**2**), which indicates that the established grey relational grade model is accurate and reliable. Therefore, it can be applied for the evaluation of the exploitation potential of shale gas reservoirs, and the evaluation of the impacting degree of main factors for optimizing the production of shale gas reservoirs.

Table 4. Calculated correlative grade of every target shale gas reservoir.

Parameters	Shale Gas Reservoirs													
	Bakken	Barnett	Duvernay	Eagle Ford	New Albany	Niobrara	Utica/Point Pleasant	WolfBone	Woodford	Fayett-eville	Haynesville/Bossier	Marcellus	Montney/Doig	Muskwa
Depth	0.4412	0.5088	0.4279	0.4588	1.0000	0.4832	0.5193	0.4699	0.4341	0.8140	0.4279	0.5312	0.4341	0.4699
Thickness	0.3591	0.5994	0.4011	0.4279	0.4084	0.6201	0.4279	0.6917	0.4449	0.4084	0.5287	0.4493	0.4449	1.0000
Clay Content	0.5549	0.4660	0.5549	0.5994	0.5796	0.5231	0.4660	0.5549	0.7773	0.4660	0.4438	0.6661	1.0000	0.6661
Reservoir Pressure	0.5066	0.4177	0.6725	1.0000	0.3517	0.4877	0.4193	0.4970	0.4279	0.4279	0.4063	0.6436	0.6365	0.4279
Matrix Permeability	1.0000	0.3503	0.3557	0.3425	0.3333	0.3744	0.3344	0.3791	0.3523	0.3890	0.3791	0.4405	0.7495	0.3346
Porosity	0.6464	0.4776	0.5634	0.6869	1.0000	0.6464	0.4776	0.5231	0.4993	0.4776	0.7328	0.5493	0.5783	0.4393
Young'S Modulus	0.5399	0.4471	0.5582	0.7123	0.8618	0.6394	1.0000	0.4891	0.8563	0.8907	0.5926	0.4615	0.4772	0.5049
TOC	0.6836	0.4476	0.4993	0.4187	1.0000	0.4636	0.3719	0.4476	0.4993	0.5193	0.3762	0.4993	0.4476	0.4476
Thermal Maturity	0.4160	0.5428	0.6404	0.5256	0.4466	0.4498	0.5946	0.4379	0.5095	1.0000	0.7808	0.5807	0.6487	0.6751
Adsorbed Gas	0.4539	0.4111	1.0000	0.5994	0.5994	0.4111	0.4993	0.3994	0.4539	0.3840	0.5994	0.3840	0.4993	1.0000
Water Saturation	0.5783	0.5448	0.7996	0.6244	0.4699	0.4993	0.9472	0.4993	0.6917	0.5193	1.0000	0.6244	0.5448	0.4993
Horizontal Length	0.6532	0.4885	0.5756	0.6290	0.4041	0.5708	0.9187	0.8189	0.5660	0.4716	0.7723	0.5068	0.8715	1.0000
Fracturing Density	1.0000	0.4582	0.7720	0.5100	0.4084	0.4672	0.4187	0.4171	0.4695	0.4730	0.4671	0.4279	0.4637	0.4507
Frac Half Length	1.0000	0.4199	0.4539	0.5049	0.6332	0.4405	0.5690	0.4279	0.4362	0.8821	0.7622	0.4493	0.5415	0.4832
Frac Conductivity	0.5807	0.3900	0.4092	0.5312	0.3565	0.4231	0.5095	0.4539	0.3962	1.0000	0.6573	0.4160	0.6404	0.4092
BHP	0.4160	0.8886	0.3697	0.3605	0.7773	0.5549	0.8664	0.5410	0.7773	0.7773	0.7773	0.3840	0.5549	1.0000
1st Year Decline Rate	0.6836	1.0000	0.8458	0.6357	0.7495	0.5708	0.6357	0.7495	0.6836	0.7495	1.0000	0.6951	0.8707	0.6277

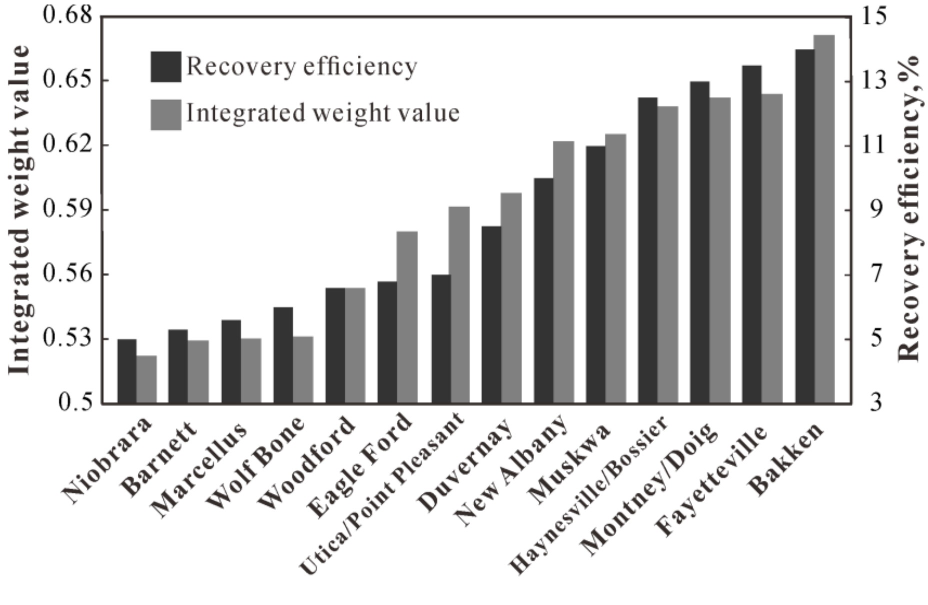

Fig. (2). The relation between integrated weight value and recovery efficiency of the fourteen shale gas reservoirs.

According to the calculated weight of every parameter, the impact ranking of main factors from more important to less important is the matrix permeability, fracture conductivity, fracture density of hydraulic fracturing, reservoir pressure, TOC, fracture half length, adsorbed gas, reservoir thickness, reservoir depth, clay content, porosity, horizontal length, thermal maturity, BHP, water saturation, and Young's modulus, as shown in Fig. (**3**).

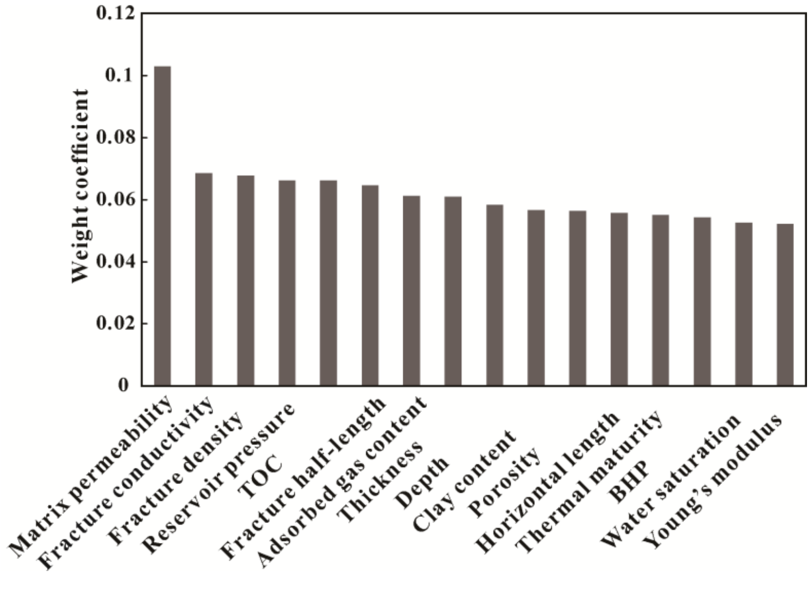

Fig. (3). The impact ranking of main factors for the development of shale gas reservoirs.

CONCLUSION

In this paper, we put forward a new tool to analyze the main factors of shale gas production. Both the definitions and steps are described. The subjective factors and objective factors as well as the interrelation of every parameter are considered synthetically, making the calculation of the weight and evaluation model more reliable. Then, fourteen shale gas reservoirs are used to verify this method and some conclusions are achieved:

1. The established grey correction grade model can reasonably, effectively, and objectively reflect the exploitation potential of shale gas reservoirs; it reduces the inaccuracy of shale gas reservoir selection.
2. The ranking exploitation potential of the fourteen shale gas reservoirs from large to small is Bakken, Fayetteville, Montney/Doig, Haynesville/Bossier, Muskwa, New Albany, Duvernay, Utica/Point Pleasant, Eagle Ford, Woodford, Wolf Bone, Marcellus, Barnett, and Niobrara.
3. According to the parameters of fourteen shale gas reservoirs in the United State, the impact ranking of main factors from more important to less important is the matrix permeability, fracture conductivity, fracture density of hydraulic fracturing, reservoir pressure, TOC, fracture half length, adsorbed gas, reservoir thickness, reservoir depth, clay content, porosity, horizontal length, thermal maturity, BHP, water saturation, and Young's modulus.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

This work was supported by the Natural Sciences Foundation of China (Project No. 51474226), the National Basic Research Program of China (2015CB250906) and Important National Science & Technology Specific Projects (2016ZX05047004001).

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