Energy Proceedings
Vol 52, 2025
ISSN 2004-2965

Application of Grey Correlation-multivariate Classification in Comprehensive Classification and Evaluation of Low Permeability Reservoirs with Different Geological Genesis

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ABSTRACT

In the comprehensive classification and evaluation of low permeability reservoirs with different geological genesis, the correlation between the classification results with gas permeability as the classification standard and the oil well productivity is low. In order to improve the correlation between the classification results of low permeability reservoirs with different geological genesis and the productivity of oil wells, the grey correlation degree (r_i) between the evaluation parameters of low permeability reservoirs with different geological genesis and the reservoir seepage capacity (*RQI*) is calculated based on the grey correlation method. According to the size of r_i, the main control evaluation parameters affecting *RQI* are obtained. Then the multivariate classification coefficient (*Feci*) of the main control evaluation parameters is calculated by the multivariate classification method, and the size of *Feci* is compared to comprehensively classify and evaluate the low permeability reservoirs with different geological genesis. Taking the three types of low permeability reservoirs with geological genesis in the S oilfield as an example, the main control evaluation parameters affecting the *RQI* of the three types of low permeability reservoirs with geological genesis are as follows : shale content, mainstream throat radius, crude oil viscosity, starting pressure gradient, movable fluid saturation and fracturing adaptability parameters. The *Feci* of the main controlling factors is calculated, and the reservoirs are classified into four categories. *Feci*>0.8 is class I reservoir, 0.4-0.8 is class II reservoir, 0.2-0.4 is class III reservoir, < 0.2 is class IV reservoir ; the R^2 value of *Feci* and oil well productivity is 0.795, and the R^2 value of gas permeability and oil well productivity is 0.0219.Grey correlation-multiple classification comprehensive classification results have better correlation with oil well productivity.

Keywords: different geological causes ; low permeability reservoir ; comprehensive classification evaluation ; grey correlation ; multivariate classification

NONMENCLATURE

Abbreviations	
RQI	Reservoir Quality Index
Symbols	
r_i	Grey Correlation Degree
k	Reservoir Permeability
Feci	Multivariate Classification Index

1. INTRODUCTION

For medium and high permeability reservoirs with different geological genesis, the comprehensive classification and evaluation of reservoirs are usually carried out by geological experience methods such as gas permeability of reservoir rocks. The results of reservoir classification have a good correlation with oil well productivity[1,2]. Zhu Chunjun et al.[3] used the geological experience method to optimize the geological evaluation parameters from the aspects of sedimentary facies, petrological characteristics, diagenesis, porosity and permeability characteristics, and divided four types of reservoirs in the target layer. The biggest advantage of the geological experience method is that it fully reflects the influencing factors of reservoir genesis, and the evaluation criteria are derived from exploration and production practice. It has a good effect in the comprehensive classification and evaluation of medium and high permeability reservoirs with different geological genesis[4]. However, in low permeability reservoirs with different geological genesis,

This is a paper for the 16th International Conference on Applied Energy (ICAE2024), Sep. 1-5, 2024, Niigata, Japan.

the correlation between reservoir classification results and oil well productivity is low by using geological experience method, which forms an engineering problem that the oil well productivity of low permeability reservoirs with different geological genesis varies greatly under the same gas permeability.

The main reason for this engineering problem is that the low permeability reservoirs with different geological causes are quite different in six types of evaluation parameters, such as geology, micro pore throat structure, fluid physical properties, nonlinear seepage, two-phase displacement and transformation adaptability[5].

In order to improve the correlation between the classification results of low permeability reservoirs with different geological causes and the productivity of oil wells, the main control evaluation parameters affecting the reservoir seepage capacity (RQI) should be screened out, and then the main control evaluation parameters should be comprehensively classified and evaluated. Through the understanding of previous studies, the main control factors are screened by grey correlation method [6]. Liu Jiyu et al.[7] used the grey correlation analysis method to determine the weight coefficient in the process of reservoir evaluation, which solved the problem that the evaluation results appeared in the process of single factor evaluation were crossed and not unique. Tuyi et al.[8] selected the grey correlation method to rank the grey correlation degree of 9 geological parameters, and the reservoir was classified and evaluated. In the comprehensive classification and evaluation, the predecessors used the multivariate classification method[9]. Yang Qiulian et al.[10] used multivariate classification method to calculate the multivariate classification coefficients of four ultra-low permeability reservoir classification and evaluation parameters: porosity, mainstream throat radius, movable fluid saturation and starting pressure gradient, and carried out reservoir classification and evaluation in 9 blocks. Xu Yongqiang et al.[11] selected porosity, permeability, surface porosity, average pore throat radius, mean coefficient, displacement pressure, movable fluid saturation and oil displacement efficiency as evaluation parameters, and used multivariate classification coefficient method to classify and establish tight reservoir evaluation criteria.

When the predecessors used the multivariate classification method for comprehensive classification and evaluation, the selected evaluation parameters were mostly determined by the correlation with permeability, and were only applicable to a single geological reservoir. Therefore, it is impossible to comprehensively classify and evaluate low-permeability reservoirs of different geological origins. Therefore, in this paper, based on the grey correlation method, the grey correlation degree between RQI and 6 kinds of 14 evaluation parameters such as geology, micro pore throat structure, fluid physical properties, nonlinear seepage, two-phase displacement and transformation adaptability in low permeability reservoirs with different geological genesis is calculated. According to the grey correlation degree, the 6 main control evaluation parameters affecting RQI are obtained, and then the Feci of the 6 main control evaluation parameters are calculated according to the multivariate classification method, and the Feci size is compared to comprehensively classify and evaluate the This should explore the significance of the results of the work, not repeat them. A combined Results and Discussion section is often appropriate. Avoid extensive citations and discussion of published literature.

2. GREY CORRELATION-MULTIPLE CLASSIFICATION COMPREHENSIVE CLASSIFICATION EVALUATION METHOD

2.1 Grey correlation

As a main control factor analysis method, grey correlation is used to analyze the correlation degree of each factor in the system. Its basic idea is to judge the degree of correlation between the sub-factors and the main factors according to the correlation degree r_i. The main factor is denoted by x_0 (*k*), *k* = 1,2,3... n, and the sub-factor is denoted by x_i (*k*), *k* = 1,2,3... n ; *i* = 1, 2, 3... m. The correlation coefficient between the sub-factors and the main factors is calculated, and then the correlation degree r_i is obtained.

The correlation coefficient between x_0 and x_i (*k*) is Eq. (1) .

$$\xi_i(k) = \frac{\min_i \min_k |x_0(k) - x_i(k)| + \rho \max_i \max_k |x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \rho \max_i \max_k |x_0(k) - x_i(k)|} \quad (1)$$

Denote, $\Delta_i(k) = |x_0 - x_i(k)|$, $\Delta_i(k)$ is the absolute difference between xi and x_0 at point k, then Eq.(1) becomes Eq.(2).

$$\xi_i(k) = \frac{\min_i \min_k \Delta_i(k) + \rho \max_i \max_k \Delta_i(k)}{\Delta_i(k) + \rho \max_i \max_k \Delta_i(k)} \quad (2)$$

Where, ρ is the resolution coefficient, the smaller the ρ is, the greater the resolution is. Generally, the value range of ρ is (0,1), usually ρ = 0.5.

Correlation degree ri is Eq.(3).

$$r_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \quad k = 1,2,\cdots,n \qquad (3)$$

The larger the correlation degree r_i is, the greater the influence of the sub-element on the main element is.

2.2 Multivariate Classification

The geological experience method, which takes reservoir physical properties such as permeability as the classification standard, comprehensively evaluates the quality of the reservoir, but all of them are single factor division. The classification and evaluation of reservoirs are restricted by multiple factors, so it is necessary to comprehensively reflect the characteristics of evaluation parameters and quantify the comprehensive parameters of reservoir classification. Yang et al.[10] proposed the concept of 'quaternary classification coefficient ', which is based on the single factor analysis, and the parameters are normalized. The formula is Eq. (4).

$$Feci = \ln\frac{(\phi_0/\phi_{0\max})(s_o/s_{osmx})(r_m/r_{m\max})}{(\lambda/\lambda_{\max})} \qquad (4)$$

The Eq.(4) is the 'four-element classification coefficient method'. However, due to the small number of sub-elements considered, it cannot effectively reflect the complex geological characteristics of low-permeability reservoirs with different geological causes, and does not consider the influence of main elements. Therefore, more parameters need to be considered.

Due to the large differences in the six types of evaluation parameters such as geology, microscopic pore throat structure, fluid physical properties, nonlinear seepage, two-phase displacement and transformation adaptability of low permeability reservoirs with different geological genesis, it is necessary to consider the main elements and increase the number of sub-element evaluations to correct Eq.(4). The main elements and their maximum values are x_0 and $x_0$max. The six main controlling sub-elements and their maximum values are x_1 and $x_1$max, x_2 and $x_2$max, x_3 and $x_3$max, x_4 and $x_4$max, x_5 and $x_5$max, x_6 and $x_6$max.

Eq. (4) is modified to ' seven-element classification coefficient method ', and the formula is Eq.(5).

$$Feci = \ln\left[(x_0/x_{0\max})(x_1/x_{1\max})^{a_1}(x_2/x_{2\max})^{a_2}(x_3/x_{3\max})^{a_3}(x_4/x_{4\max})^{a_4}(x_5/x_{5\max})^{a_5}(x_6/x_{6\max})^{a_6}\right] \qquad (5)$$

Where a_1, a_2, a_3, a_4, a_5, a_6 are the correlation index of x_1, x_2, x_3, x_4, x_5, x_6 and x_0. If xi is positively correlated with x_0, $a_i = 1$; if xi is negatively correlated with x_0, $a_i = -1$.

The larger the value of multivariate classification coefficient *Feci*, the better the classification results.

3. COMPREHENSIVE CLASSIFICATION AND EVALUATION OF THREE TYPES OF LOW PERMEABILITY RESERVOIRS IN THE EASTERN OILFIELD OF SOUTH CHINA SEA

3.1 Evaluation parameters

When applying the grey correlation method to screen the main control sub-factors, the most important thing is the selection of the main factors. The correlation between gas permeability and oil well productivity is low, so gas permeability cannot be selected as the main element. By understanding previous studies, Kozeny-Carmen[12,13] proposed the *RQI* coefficient to characterize the reservoir seepage capacity, and the correlation between *RQI* and gas permeability and oil well productivity is improved.

The *RQI* coefficient formula is Eq. (6).

$$RQI = 0.0314\sqrt{\frac{k}{\phi}} \qquad (6)$$

Where, *k* is the gas permeability, $10^{-3}\mu m^2$; φ is porosity, %.

Therefore, *RQI* is selected as the main factor in the comprehensive classification and evaluation of low permeability reservoirs with different geological genesis. The 6 sub-factors are : geological evaluation parameters (p_i-formation pressure and c_m-shale content), microscopic pore throat structure parameters (p_{c}-displacement pressure, r_{50}-median radius , r_z -mainstream throat radiusand ; r_{pt}-pore throat ratio), fluid physical parameters (μ_o -crude oil viscosity and r_s-dissolved gas oil ratio), nonlinear seepage parameters (tpg-starting pressure gradient and α-stress sensitivity coefficient), two-phase displacement parameters (s_m-movable fluid saturation and η-final oil displacement efficiency) and transformation adaptability parameters (k_{ai}-acidification permeability improvement multiple and fb-fracturing brittleness index).

There are three types of typical low permeability reservoirs with different geological genesis in the S oilfield, which are A-deep sandstone low permeability reservoir, B-middle-shallow shaly sandstone low permeability reservoir and C-limestone low permeability reservoir. The gas permeability $<50\times10^{-3}\mu m^2$ is low permeability reservoir. According to the actual development experience, the gas permeability of low permeability reservoir is divided into three grades : $1\text{-}10\times10^{-3}\mu m^2$, $10\text{-}20\times10^{-3}\mu m^2$ and $20\text{-}50\times10^{-3}\mu m^2$. The *RQI* and six sub-factor parameters of three gas permeability grades in three types of low permeability reservoirs are shown in table 1.

Table. 1 Three types of low permeability reservoir RQI and six types of evaluation parameters

Low permeability reservoir	k $10^{-3}\mu m^2$	ϕ %	p_i MPa	c_m	p_c MPa	r_{50} μm	r_z μm	r_{pt}	μ_o mPa·s	r_s m^3/m^3	tgp MPa/m	α 1/MPa	s_m	η	k_{ai}	f_b
	1-10	0.10		0.13	0.12	0.32	1.26	2.96			0.02	0.02	0.26	0.38		
A	10-20	0.10	32.06	0.11	0.03	0.47	4.11	3.68	0.70	31.09	0.01	0.01	0.28	0.43	1.34	42.9
	20-50	0.12		0.08	0.03	0.67	5.33	3.39			0.01	0.01	0.31	0.45		
	1-10	0.14		0.17	0.16	0.15	0.65	2.40			0.05	0.02	0.24	0.36		
B	10-20	0.17	15.31	0.16	0.09	0.23	1.36	2.63	4.37	38.85	0.02	0.01	0.24	0.37	1.82	26.2
	20-50	0.17		0.12	0.04	0.49	2.19	2.79			0.01	0.01	0.24	0.37		
	1-10	0.16		0.11	0.29	0.26	0.44	1.73			0.12	0.03	0.09	0.32		
C	10-20	0.17	14.47	0.10	0.14	0.45	0.78	1.94	5.42	28.18	0.05	0.02	0.24	0.40	2.44	45.6
	20-50	0.20		0.08	0.05	0.72	2.60	2.78			0.02	0.01	0.25	0.43		

3.2 Screening of main control evaluation parameters

The grey correlation method is used to screen the main control evaluation parameters of three types of low permeability reservoirs in the S oilfield. The grey correlation degree between each evaluation parameter and *RQI* is shown in table 2.

Table.2 R_i-Six evaluation parameters of three types of low permeability reservoirs

low permeability reservoir	k $10^{-3}\mu m^2$	ϕ %	r_i-p_i MPa	r_i-c_m	r_i-p_c MPa	r_i-r_{50} μm	r_i-r_z μm	r_i-r_{pt}	r_i-μ_o mPa·s	r_i-r_s m^3/m^3	r_i-tgp MPa/m	r_i-α 1/MPa	r_i-s_m	r_i-η	r_i-k_{ai}	r_i-f_b
	1-10	0.10	0.68	0.70	0.68	0.86	0.72	0.69	0.70	0.69	0.70	0.66	0.71	0.71	0.71	0.69
A	10-20	0.10	0.93	0.86	0.91	0.89	0.82	0.94	0.93	0.93	0.93	0.91	0.90	0.90	0.92	0.87
	20-50	0.12	0.83	0.84	0.84	0.90	0.85	0.82	0.83	0.85	0.83	0.81	0.85	0.85	0.83	0.85
	1-10	0.14	0.77	0.77	0.76	0.79	0.81	0.77	0.77	0.75	0.77	0.75	0.79	0.78	0.80	0.80
B	10-20	0.17	0.92	0.92	0.92	0.93	0.93	0.91	0.92	0.92	0.91	0.91	0.92	0.92	0.92	0.92
	20-50	0.17	0.94	0.95	0.89	0.96	0.97	0.92	0.93	0.94	0.94	0.93	0.96	0.95	0.96	0.96
	1-10	0.16	0.89	0.91	0.87	0.95	0.95	0.91	0.91	0.98	0.91	0.91	0.92	0.91	0.90	0.91
C	10-20	0.17	0.89	0.91	0.87	0.95	0.95	0.91	0.91	0.98	0.91	0.91	0.92	0.91	0.90	0.91
	20-50	0.20	0.88	0.90	0.89	0.90	0.90	0.89	0.92	0.89	0.81	0.81	0.94	0.95	0.88	0.89

According to the ri value of the six evaluation parameters, six main control evaluation parameters with high correlation between the three types of low permeability reservoirs and RQI are obtained : shale content, mainstream throat radius, crude oil viscosity, starting pressure gradient, movable fluid saturation and fracturing adaptability parameters.

3.3 Evaluation parameters

According to the formula (5), the *RQI* of three types of low permeability reservoirs under three types of gas permeability levels and the *Feci* of six main control evaluation parameters are calculated, and the calculation results are shown in figure 1.

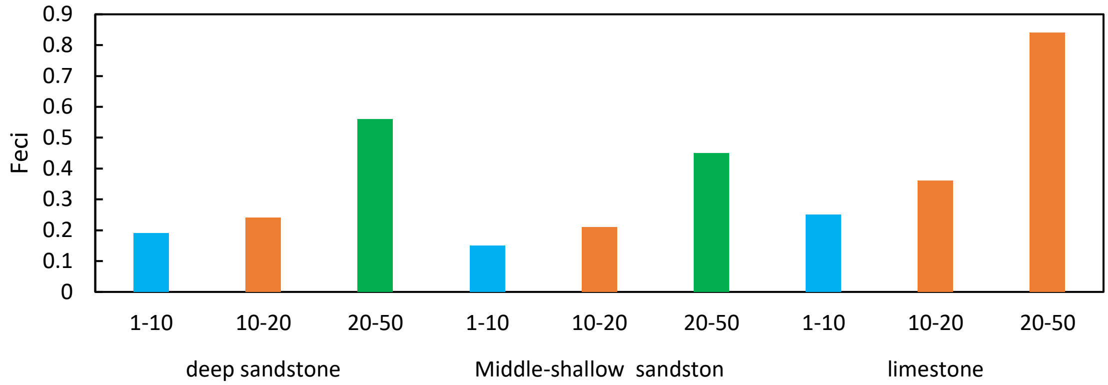

Fig. 1 Feci of three types of low permeability reservoirs under three permeability levels

As shown in Fig.1, the *Feci* of limestone low permeability reservoir under three permeability grades is the largest, and the Feci of low permeability reservoir with mud sandstone in middle and shallow layers is the smallest. Therefore, the limestone low permeability reservoir is the best under the three permeability grades, the deep low permeability sandstone reservoir is the second, and the low permeability reservoir with mud sandstone in middle and shallow layers is the worst.

4. VERIFICATION OF GREY CORRELATION-MULTIVARIATE CLASSIFICATION COMPREHENSIVE CLASSIFICATION EVALUATION METHOD

4.1 Correlation between Feci and productivity

The correlation between *Feci* and gas permeability and oil well productivity of three types of low permeability reservoirs under three permeability grades is compared. In order to eliminate the influence of production pressure difference and reservoir thickness on the classification results, the specific oil production index is selected as the verification object, and the verification results are shown in Fig.2.

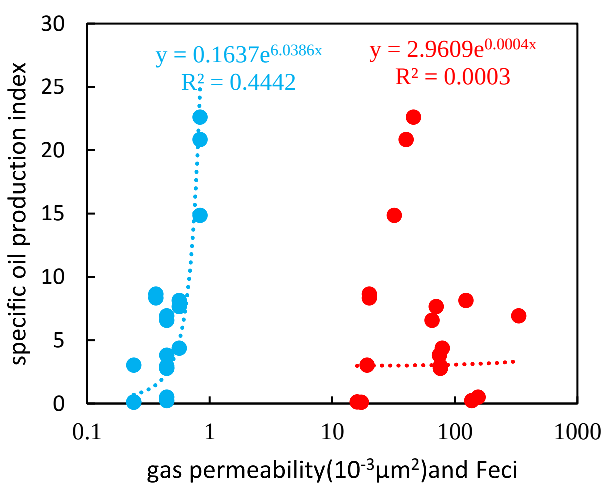

Fig. 2 Verification of correlation between Feci and gas permeability and oil well productivity

As shown in Figure 2, the correlation between gas permeability and oil well productivity is 0.0219, while the correlation between Feci and oil well productivity is 0.795, and the correlation between Feci and oil well productivity is higher.

4.2 Reservoir classification

According to the size of *Feci* of three types of low permeability reservoirs under three permeability grades, the reservoirs are classified into four categories. *Feci* > 0.8 is type I reservoir, 0.4-0.8 is type II reservoir, 0.2-0.4 is type III reservoir, <0.2 is type IV reservoir. The classification of three types of low permeability reservoirs in the S oilfield is shown in Table 3.

Table.3 Classification of three types of low permeability reservoirs in the S oilfield

low permeability reservoir	k 10-3μm2	ϕ %	reservoir classification
deep sandstone	1-10	0.10	Ⅳ
	10-20	0.10	Ⅲ
	20-50	0.12	Ⅱ
Middle-shallow argillaceous sandstone	1-10	0.14	Ⅳ
	10-20	0.17	Ⅲ
	20-50	0.17	Ⅱ
limestone	1-10	0.16	Ⅲ
	10-20	0.17	Ⅱ
	20-50	0.20	Ⅰ

5. CONCLUSIONS

According to the grey correlation method, the main control evaluation parameters affecting the three types of low permeability reservoirs in the S oilfield are shale content, mainstream throat radius, crude oil viscosity, starting pressure gradient, movable fluid saturation and fracturing adaptability parameters. According to the size of Feci, the reservoirs are classified into four categories.

Feci > 0.8 is type I reservoir, 0.4-0.8 is type II reservoir, 0.2-0.4 is type III reservoir, and <0.2 is type IV reservoir. The correlation between gas permeability and oil well productivity is 0.0219, while the correlation between Feci and oil well productivity is 0.795, and the correlation between Feci and oil well productivity is higher.

REFERENCE

[1] Zou Caineng, Zhu Rukai, Wu Songtao, et al. Accumulation types, characteristics, mechanisms and prospects of conventional and unconventional oil and gas : A case study of tight oil and gas in China [J]. JOURNAL OF PETROLEUM SCIENCE, 2012,33 (02) : 173-187.

[2] Wang Min, Cao Yue, Li Wancai, etc. Based on pore structure and nuclear magnetic logging, the classification standard of volcanic reservoir is established-Taking Chaganhua gas field in Songnan fault depression as an example [J].Oil and gas reservoir evaluation and development, 2024,14 (02) : 216-223 + 236.

[3] Zhu Chunjun, Wang Yanbin. Genesis and evaluation of low permeability reservoir in Daniudi gas field [J].Journal of Southwest Petroleum University (Natural Science Edition) 2011,33 (01) : 49-56 + 11-12.

[4] Kuang Hui, Du Guichao, Wang Cong 'e, et al. Characteristics and classification evaluation of pore throat structure of Chang 7 tight reservoir in Ganquan Oilfield [J].Journal of Chengdu University of Technology (Natural Science Edition), 2023,50 (05) : 525-536.

[5] Zhang Zhonghong, Yang Zhengming, Liu Xiangui, et al. Low permeability reservoir classification evaluation method and its application [J].Petroleum Journal, 2012,33 (03) : 437-441.

[6] Zhao Jiafan, Chen Xiaohong, Zhang Qin. Application of grey relational analysis in reservoirevaluation [J].Progress in exploration geophysics, 2003 (04) : 282-286.

[7] Liu Jiyu, Peng Zhichun, Guo Xiaobo. Application of Grey Relational Analysis in Reservoir Evaluation - - A Case Study of North II Area of Daqing Saertu Oilfield [J].Oil and Gas Geology and Recovery, 2005, (02) : 13-15 + 82.

[8] Tu Yi, Xie Chuanli, Liu Chao, etc. Application of grey correlation analysis in reservoir evaluation of Qingdong Sag [J].Natural Gas Geosciences, 2012,23 (02) : 381-386.

[9] Zhao Jun, Cao Gang, Wu Yanliang. Application of multivariate membership function in tight sandstone reservoir classification [J].Natural Gas Geosciences, 2018, 29 (11) : 1553-1558.

[10] Yang Qiulian, Li Aiqin, Sun Yanni, etc. Discussion on the classification method of ultra-low permeability reservoirs [J].Lithologic reservoirs, 2007, (04) : 51-56.

[11] Xu Yongqiang, He Yonghong, Bu Guangping, et al. Based on the microscopic pore throat structure and seepage characteristics, the classification and evaluation criteria of tight reservoirs are established-Taking Chang 7 reservoir in Longdong area of Ordos Basin as an example [J].Petroleum Experimental Geology, 2019,41 (03) : 451-460.

[12] Kozeny J. Ueber kapillare Leitung des Wassers im Boden. Sitzungsber Akad. Wiss., Wien 1927; 136(2a): 271-306.

[13] Carman P C .Fluid flow through granular beds[J].Trans. Inst. Chem. Eng, 1937, 15.