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Quantitative Evaluation Model of Carbonate Reservoirs based on Fuzzy Clustering Theory

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Abstract

The quantitative evaluation of carbonate reservoir is one of the key issues of oil and gas exploitation. However, due to the characteristics of carbonate reservoir, such as diverse physical distribution, complex pore-throat structure and strong heterogeneity, its quantitative evaluation is relatively difficult. Take the Jia-2 Member carbonate reservoir of Lower Triassic Jialingjiang Formation in the Moxi gas field of Sichuan Basin as the example. The fuzzy clustering theory is used to build a quantitative evaluation model of carbonate reservoir, and combined with the traditional reservoir classification evaluation scheme in this area, and the reservoirs are classified and evaluated point by point. The evaluation results are well consistent with the actual gas & water capacity, which indicates that the mathematical model is available for quantitatively evaluating the carbonate reservoir and has relatively good feasibility.

Keywords

Fuzzy Clustering Theory; Quantitative Evaluation Model; Carbonate Reservoirs; Jialingjiang Formation.

1. Introduction

With the development of reservoir geology, the trend of reservoir evaluation is to realize the combination of "qualitative and quantitative" aspects, "macro and micro" aspects as well as "general and specific" aspects [1-3]. Due to the characteristics of carbonate reservoir, such as diverse physical distribution, complex pore-throat structure and strong heterogeneity [4], its quantitative evaluation is relatively difficult. Take the Jia-2 Member carbonate reservoir of Lower Triassic Jialingjiang Formation in the Moxi gas field of Sichuan Basin as the example, and the physical property, pore-throat structure, effective reservoir thickness and heterogeneity of carbonate reservoir are comprehensively considered. The fuzzy clustering theory is used to build a quantitative evaluation model of carbonate reservoir, and combined with the traditional reservoir classification evaluation scheme in this area, and the reservoirs are classified and evaluated point by point, achieving the purpose of quantitatively evaluating the quality of Jia-2 Member carbonate reservoir in study area.

2. Geological setting

The Sichuan Basin is a diamond-shaped structural-sedimentary Basin in southwest China[5]. It is situated between the longitude 103°45'~108°43'E and the latitude of 28°42'~33°03'N. It includes eastern Sichuan and western Chongqing, covering an area of approximately $19\times10^4 km^2$. The Moxi gas field is located in the central low-flat belt of the Sichuan Basin, trending roughly in northeast to southwest (Fig.1) [5]. It has succeeded in gas exploration and exploitation since the first well drilling of Moshen 1 in 1977 (Fig.1b). The gas production and proven reserve is about $4.0\times10^8 m^3$ per year

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and $3.3\times10^{10}m^3$, respectively [5]. The Lower Triassic Jialingjiang Formation belongs to marine deposits and can be divided into five lithologic stages ranging from Jia-1 Member to Jia-5 Member. Jia-2 Member is mainly constituted by unequal-thickness limestone, dolomite and gypsum gypsum rock interbeds (Fig. 1), ranging from 0–100 meters. The carbonate reservoir is the main target for gas exploitation in the Jia-2 Member of Jialingjiang Formation in the region.

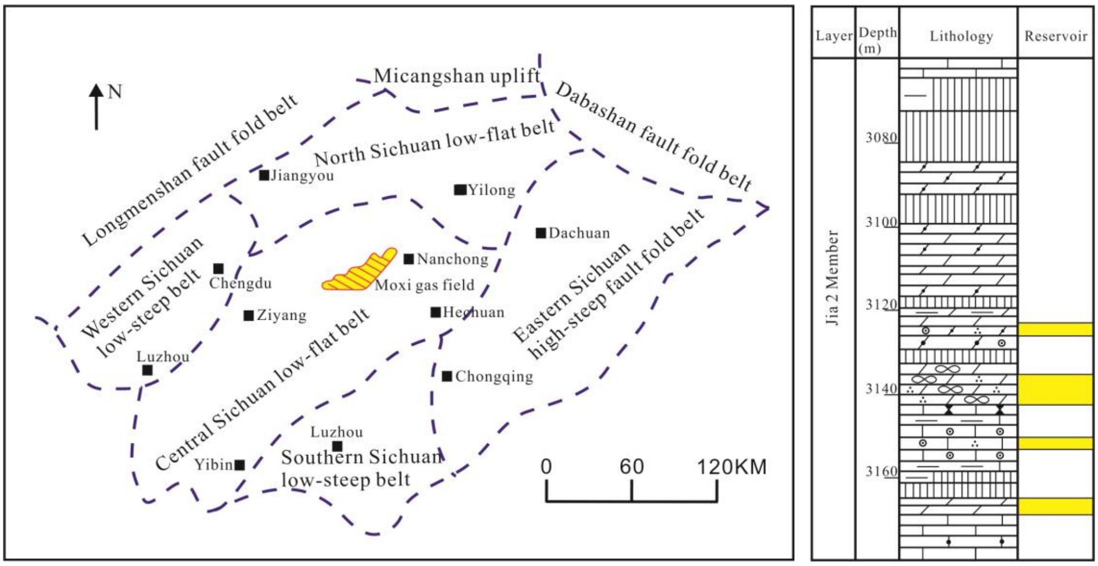

Figure 1. Tectonic units in the Sichuan Basin and the location of the Moxi gas field and generalized stratigraphy of the Moxi gas field

3. Building the quantitative evaluation model for carbonate reservoir

The basic idea of fuzzy cluster analysis is to classify the samples based on the similarity (intimacy relationship) existing between the studied reservoir samples [6-7]. According to multiple observation indicators of a batch of samples, find out some statistics that can measure the degree of similarity between samples or indicators, and use these statistics as the basis for classifying reservoir quality types, and aggregate some samples or indicators with greater similarity. As a category, other samples or indicators that are more similar to each other are aggregated into another category, and proceed in sequence. In the classification process, the dynamic nature of "soft division" is used for classification until all samples are aggregated.

Based on the above-mentioned basic idea of using fuzzy clustering analysis to evaluate the quality of carbonate reservoirs, combined with the general steps of fuzzy clustering analysis, a fuzzy clustering analysis and evaluation of reservoir model is established[8]. It can be seen that the key to using fuzzy cluster analysis to evaluate the quality of carbonate reservoirs is: ①The establishment of the similarity matrix, and the selection of the calibration method directly affects the feasibility of the establishment of the similarity matrix; To reflect the dynamics of clustering is to transform the established similarity matrix into a fuzzy equivalence matrix; ③Establish a reasonable and feasible evaluation set, that is, the fuzzy classification of reservoir quality by each single factor. Among them, the establishment of the similarity matrix through calibration is the most important thing. It is directly related to the uncertainty description of the clustering of each sample data, that is, the degree of aggregation of dynamic clustering, which has a direct impact on the final evaluation result.

3.1 Overview of calibration methods

3.1.1 Correlation coefficient method

The correlation coefficient method is to obtain the correlation coefficient between the sample points, and make them classifiable by spatial conversion of the sample points. Its geometric meaning is as

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follows: When performing correlation analysis on two sample points i and j that are in the same P-dimensional space, since they may not be in the same dimensional space, the similarity cannot be determined by the distance method. At the same time, you can't just consider the distance and ignore their rotation angle in space. We can transform and pass to the same plane at the same time, that is, find their projection distance to the space where they are on this plane and the rotation angle to the space where they are. At this time, the distance between i and j on the plane can be found. This distance is the correlation coefficient of i and j in the P-dimensional space. The calculation formula is as follows (Eq. 1):

$$r_{jk} = \sum_{a=1}^{p} \frac{(x_{ai}-\tilde{x}_j)(x_{aj}-\tilde{x}_k)}{\sqrt{\sum_{a=1}^{p}(x_{ai}-\tilde{x}_j)^2 \sum_{a=1}^{p}(x_{aj}-\tilde{x}_k)^2}} \tag{1}$$

In this formula, $\tilde{x}_k = \frac{1}{p}\sum_{a=1}^{p} x_{ak}$

If the correlation coefficients of the two sample points are calculated, they can be arranged into the sample correlation coefficient matrix (Eq. 2):

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1N} \\ r_{21} & r_{22} & \cdots & r_{2N} \\ \cdots & \cdots & \cdots & \cdots \\ r_{N1} & r_{N2} & \cdots & r_{NN} \end{bmatrix} \tag{2}$$

In this formula, $r_{11} = r_{22} = \ldots = r_{NN} = 1$, In this way, N sample points can be classified according to R.

The correlation coefficient method projects the sample points in the P-dimensional space onto the same surface, and quantifies the pairwise projection distance of the sample points to perform correlation analysis to classify the samples.

3.1.2 Summary

The correlation coefficient method projects the sample points in the dimensional space onto the same surface, and carries out correlation analysis by quantifying the projection distance of the sample points in pairs, thereby classifying the samples. This solves the shortcomings of the Euclidean distance method and the angle cosine method in the sample point classification problem. Therefore, the correlation coefficient method is mostly used to classify the sample points of the vector that has practical significance in the dimensional space.

The author decided to select the correlation coefficient method in this classification evaluation to calculate the similarity matrix of fuzzy cluster analysis by consulting relevant literature, and through trial calculations, combined with the actual situation of the study area.

3.2 Operation steps

3.2.1 Select evaluation parameters

According to the reservoir type in the study area is a porous reservoir with locally developed fractures, combined with the existing data of the Jia 2 Member in the study area, a total of 4 parameters from the logging interpretation results were selected for the classification evaluation in this fuzzy cluster analysis. They are: total porosity (Por), fracture porosity (PF), permeability (Perm), shale content (Sh).

Among them, total porosity (Por) and permeability (Perm) reflect the storage and permeability of the reservoir rock; fracture porosity (PF) reflects the development of fractures and the impact of fractures on reservoir performance improvement; shale The content (Sh) can affect the quality of the reservoir.

3.2.2 Raw data standardization

Before the evaluation, because the different parameters of each sample point have different dimensions, for this problem, the original data needs to be appropriately transformed. According to

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the requirements of the similarity matrix, the data needs to be compressed on [0, 1]. The following transformations are usually adopted:

$$x_{ik}' = \frac{x_{ik}-\bar{X}_k}{s_k}(i = 1,2,\dots,n\,; k = 1,2,\dots,m) \tag{3}$$

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} x_{ik}, S_k = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_{ik} - \bar{X}_k)^2}$$

After the above changes, the value of each variable is 0, the standard deviation is 1, and the influence of dimensions is eliminated. However, the results $X_{ik}{}'$ obtained in this way are not necessarily in the interval [0, 1]. It can be transferred to the interval [0, 1] by using the translation-range formula (Eq.4)

$$x_{ik}{}'' = \frac{x_{ik}{}' - \min\limits_{1\le i\le n}\{x_{ik}{}'\}}{\max\limits_{1\le i\le n}\{x_{ik}{}'\} - \min\limits_{1\le i\le n}\{x_{ik}{}'\}}(i = 1,2,\dots,n; k = 1,2,\dots,m) \tag{4}$$

After the above calculation, it is obvious that there is $0 \le x_{ik}{}'' \le 1$, and the influence of the dimension is eliminated.

3.2.3 Build similarity matrix

The standardized data is calibrated, and this article selects the correlation coefficient method for calibration (Eq.1), after calibration, the similarity coefficient matrix (Eq.2) can be obtained.

3.2.4 Create fuzzy equivalence matrix

Since the calibrated similarity coefficient matrix R is not necessarily transitive, in order to solve the problem of dynamic and random data in cluster evaluation and how to reduce human factors in the classification process, the similarity coefficient matrix R can be transformed into $\tilde{R}$ fuzzy Equivalent relation matrix. This article completes the transformation by passing the closure method. In the process of transferring the closure, the square method is used for the composite operation of the similarity coefficient matrix R, namely: $R \to R^2 \to R^4 \to \dots \to R^{2k}$. When $R^k = R^{2k}$, R^k is the fuzzy equivalence matrix $\tilde{R}$ to be sought.

3.2.5 Cluster analysis

The purpose of clustering analysis is to transform the elements of the fuzzy equivalence matrix R to indicate the degree of similarity between the classified objects. Arrange the elements of R from largest to smallest as the specified level value (Eq.5), so that:

$$C\tilde{R}_\lambda(i,j) = \begin{cases} 0 \quad , & if\, \tilde{R}(\mathrm{i},\mathrm{j}) \ge \lambda \\ 1 \quad , & if\, \tilde{R}(\mathrm{i},\mathrm{j}) < \lambda \end{cases} \tag{5}$$

Use the level cut set of λ of the obtained fuzzy equivalence to classify, and the classification is from coarse to fine. Choose the minimum value of the element $\tilde{R}$ in the fuzzy equivalence relation matrix as the λ value, and then divide it into one category; choose the second minimum value k as the λ value and divide it into two categories; choose the first minimum value as the value and divide it into λ categories; ……. If λ =1, each sample is in its own category. In this way, a dynamic clustering system can be formed from thin to thick, and gradually merged together, and a diagram of the dynamic clustering system can be made, so that the fuzzy clustering analysis is completed and the purpose of classification is achieved.

4. Reservoir evaluation

Use the classification results to find a representative sample point with the properties of the class in each class, analyze the properties of various parameters at this point, and determine the evaluation result. Then, based on the evaluation result, evaluate the quality of all sample points in the category of the point, classify and evaluate gradually, and finally achieve the purpose of reservoir evaluation (Fig.2).

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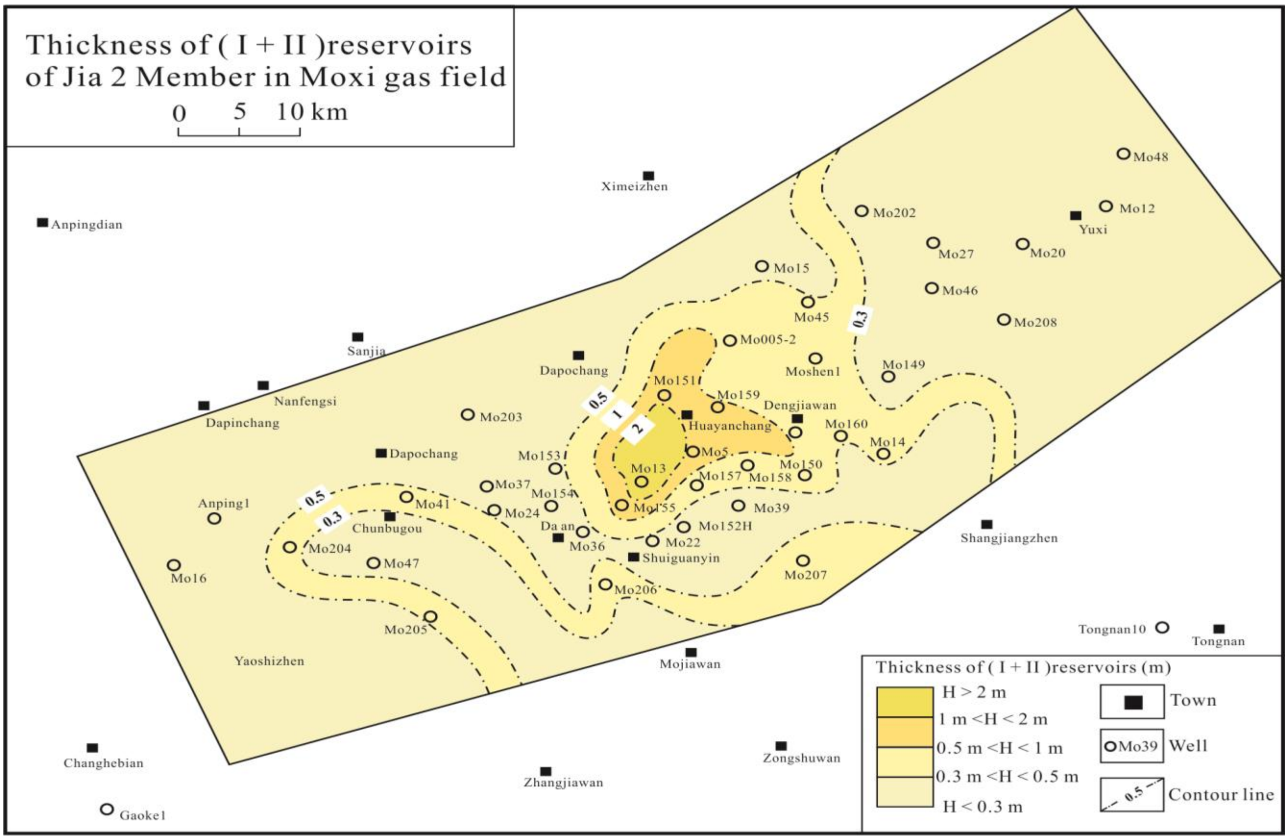

Figure 2. Quality Evaluation Result of Jia-2 Member Carbonate Reservoirs, Moxi gas field

5. Inspection on the evaluation results

Comparison is made between the results of thickness of (I+II) reservoirs quantitative evaluation and the actual gas & water capacity in the Moxi gas field. And the Fig.3 shows the Jia-2 Member carbonate reservoir reservoir daily gas & water production of representative wells. From the Fig.3, the correlation coefficient between the thickness of (I+II) and actual gas & water capacity equals 0.899. These reflect that the actual gas & water capacity is consistent with the result of quantitative evaluation.

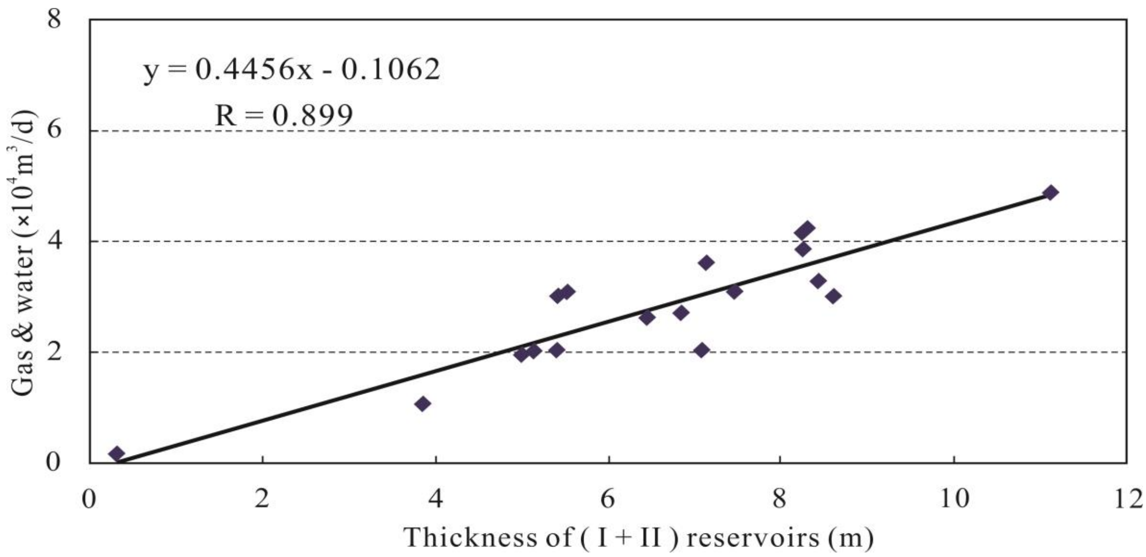

Figure 3. Thickness of (I+II) reservoirs quantitative evaluation and the actual gas & water capacity in the Moxi gas field

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6. Conclusion

The fuzzy cluster analysis method, combined with the traditional reservoir classification and evaluation scheme in this area, to carry out the point-by-point classification and evaluation of the carbonate reservoirs in the second member of the Jia-2 Member in the Moxi area of central Sichuan, using the "soft" in the application of fuzzy set theory. The idea of "partitioning" is used to deal with the clustering problem, which solves the problem of "dynamics" of carbonate reservoir sample points. It has a certain degree of advancement and rationality. The final evaluation result is consistent with the test production in the study area. It shows that it is feasible to use the fuzzy cluster analysis method to evaluate the reservoir sample points one by one.

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