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تسلسل الإنتاج الأمثل لخزانات النفط في مكامن خطأ معقدة

***جنرال بى، *لونج-شين مو، *شيانغ هونغ وو، *شين تاو يوان، *تشينغ يان شو، *تشنغ لي، *مين وانغ و**هوى لو**

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الخلاصة

حاليا، تسلسل الإنتاج في خزانات النفط في مكامن خطأ معقدة مازالت تعتمد على الخبرة، وهي تعتمد على عملية التقييم النوعي. ولذلك، فإنه مطلوب طريقة مسلسلة أكثر فعالية للإنتاج الكمي للنفط. لذلك من خلال مزيج من التحليل الحسابي الهرمي والطريقة الغامضة للتقييم الشامل، تم بناء نموذج أمثل وتطبيقه على مكامن النفط في حقول النفط المعقدة. ومع التحسين، يتم احتساب الترتيب العام للخزانات في المكامن الخطأ المعقدة ويتم الحصول على تسلسل إنتاج الخزانات وفقا للتصنيف الشامل. وقد أظهرت النتائج أن الخزان DI1 يتلقى أعلى الترتيب العام، وينبغي أن يوضع أولا في الإنتاج. وقد تم التحقق من النتائج وفقا لتاريخ الإنتاج الفعلي للحقل AGD.

Production sequence optimization of complex fault block oil reservoirs

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ABSTRACT

So far, production sequence determination of fault block oil reservoirs of a complex fault block oilfield still depends on the experience of experts, which is a totally qualitative evaluation process. Therefore, a more effective and quantitative production sequence determination method is required. Through the hybrid of analytic hierarchy process method and fuzzy comprehensive evaluation method, a production sequence optimization model is built and applied to the complex fault block oil reservoirs of AGD oilfield. With the optimization, overall rankings of fault block reservoirs are calculated and the production sequence of fault block reservoirs is obtained according to the overall rankings. The results show that fault block reservoir DI1 receives the highest overall ranking and should be put into production first. The results are verified by the actual production history of AGD oilfield.

Keywords: Analytic hierarchy process (AHP); complex fault block oilfield; fuzzy comprehensive evaluation (FCE); overall ranking; production sequence optimization.

NOMENCLATURE

a_{ij}	The value of index j, fault block reservoir i
a_{jmax}	The largest value of index j in all fault block reservoirs
a_{jmin}	The smallest value of index j in all fault block reservoirs
CI	Consistency index
CR	Consistency ratio
E_i	Standard factor set of reservoir i
e_{ij}	Standard factor after normalization of index j, fault block reservoir i

p_i	Overall ranking of fault block reservoir i
RI	Random index
V	Weight vector
v_j	Overall weight of index j
W	Maximum eigenvector of a matrix
λ_{max}	Maximum eigenvalue of a matrix

INTRODUCTION

Development of complex fault block reservoirs with high economic efficiency is a great challenge in petroleum industry especially for international oilfields. As a result of great differences among fault block reservoirs (Yu *et al.*, 1995), the development sequence of fault block reservoirs has a decisive influence on the economic benefits of the development of entire oilfield. Therefore, production sequence of complex fault block reservoirs should be determined before oilfield development.

So far, production sequence determination of complex fault block reservoirs still depends on the experience of experts. It is a totally qualitative evaluation process and only focuses on original oil in place (OOIP) and estimated ultimate recovery (EUR). In the process of production sequence determination, many important factors are not considered, such as distance to central processing facility (CPF), oil property, natural energy, reservoir depth, reservoir property, uncertainty factor, well productivity and complexity.

Many sequence optimization applications have been done in petroleum industry, such as in decision-making of regional petroleum exploration (Cheng *et al.*, 1998), oilfield development plan optimization (Zhang *et al.*, 2002) and reservoir quantitative evaluation (Tan *et al.*, 2008). However, no research on production sequence optimization of complex fault block reservoirs was reported.

Production sequence optimization of fault block reservoirs is a multi-attribute comprehensive evaluation process. Based on detailed analysis of reservoir characteristics and oilfield development strategy, a hybrid optimization model is built and applied to the 89 complex fault block oil reservoirs of AGD oilfield. And the optimization result is verified by the actual production history of AGD oilfield.

OPTIMIZATION MODEL BUILDING AND APPLICATION TO AGD OILFIELD

Fuzzy comprehensive evaluation (FCE) is a method that can solve problems, which are vague and difficult to quantify (Dubois & Prade, 1980; Kaufmann & Gupta, 1988;

Kaufmann & Gupta, 1991; Klir & Yuan, 1995), and does not take a lot of computation work. One prerequisite of FCE calculation is to determine the weight of each evaluation index, which is generally given directly by experts. For a complex problem, the evaluation indices may have influences between each other. Thus, it is difficult to assign weights of evaluation indices directly. However, analytic hierarchy process (AHP) is good at solving this kind of problems (Saaty, 1977; Saaty, 1980; Golden *et al.*, 1989). AHP is widely used for the determination of weights in multi-level and multi-factor systems. Through the hybrid of the two methods, the shortcoming of FCE method can be overcome. Thus, the evaluation can be more reasonable for a very complex problem.

The general principle of complex fault block reservoirs development is that, the fault block reservoir with the highest comprehensive quality should be developed first (Yu, 1998), which is also the principle of production sequence optimization. Optimization of fault block reservoir production sequence is a multi-attribute comprehensive evaluation process. Every fault block reservoir is an evaluation object, and the sequence is an array based on the evaluation result of fault block reservoirs. With the hybrid of AHP and FCE, a production sequence optimization model is built. The optimization model includes 4 basic parts: index system building, indices normalization, weights determination and overall ranking calculation.

Evaluation indices selection

Comprehensive evaluation has no universal indices. The selection of indices depends on the evaluators (White *et al.*, 2014; Sagbas & Mazmanoglu, 2014). Besides the common indices, some other indices are selected due to the large differences among the 89 fault block reservoirs in AGD oilfield. The selection is based on the actual geological and development situation of AGD oilfield and the importance of each index to the overall target, which demands smaller investment scale, larger profit and faster investment recovering speed. Some indices are demonstrated as follows. Higher uncertainty factor means higher probable reserves ratio, which increases the investment risk of oilfield development. Higher well productivity means that investment can be recovered in a shorter time. Reservoir properties and oil properties can affect oilfield development difficulty and oil price. The fault block, which has sufficient natural energy will save a lot of investment. Complexity, reservoir depth, development mode, drilling scale, development strata, injection scale and well pattern have influences on investment scale. Distance to CPF is also an important index, which can affect pipeline construction cost. Surface conditions and environmental requirements also have influences on cost of development engineering. In a word, every index is essential. Finally, a fuzzy evaluation index set, which includes 17 indices is established. The 17 indices include OOIP, EUR, uncertainty factor, well productivity, reservoir properties, oil properties, natural energy, complexity, reservoir depth, development mode, drilling scale, development strata, injection scale, well pattern, distance to CPF, surface conditions and environmental requirements. In the evaluation process, every index plays its role.

Index type analysis

Index type analysis can help to make indices ranked and normalized. From different perspectives, the indices can be divided into different categories. Evaluation indices can be divided into quantitative indices and qualitative indices. Quantitative indices are objective and quantifiable. Qualitative indices are subjective indices. Evaluation indices can also be divided into positive indices and negative indices. A positive index is the index, which is better with a bigger value. A negative index is the index, which is better with a smaller value.

Index system building

According to the factors affecting development benefits of complex fault block reservoir, a multi-layer comprehensive evaluation index system is built. The decision hierarchy for comprehensive evaluation is shown in Figure 1.

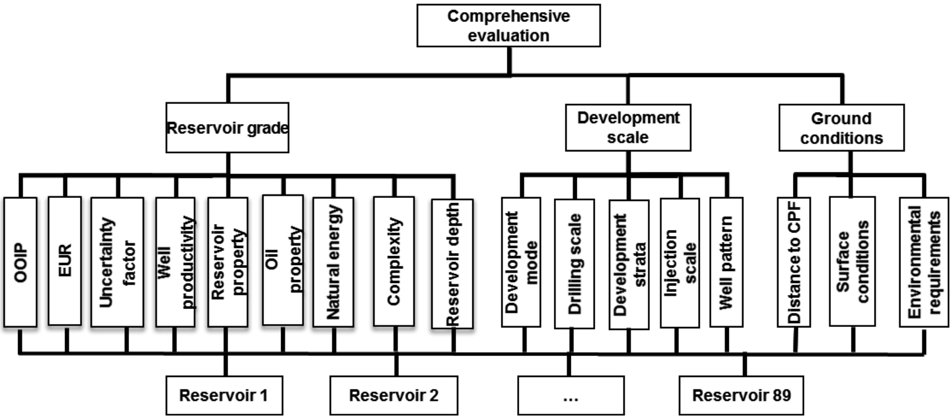

Fig. 1. Decision hierarchy for comprehensive evaluation

The index system can be divided into four layers. Each layer contains elements, which have direct impact on the upper layer. The impact recurrences to the top, layer by layer. The first layer is the layer of overall target, i.e., comprehensive evaluation of fault block reservoirs. The second layer is the layer of operation elements, including three aspects, which have major influences on fault block reservoir development benefits. The third layer is the layer of indices. The 17 indices belong to three groups corresponding to the operation elements of the upper layer. The first group includes OOIP, EUR, uncertainty factor, well productivity, reservoir property, oil property, natural energy, complexity and reservoir depth. The second group includes development mode, drilling scale, development strata, injection scale and well pattern. The third group includes distance to the CPF, surface conditions and environmental requirements. The fourth layer is the layer of programs. It consists of evaluated objects with all the attributes listed in the third layer, i.e., 89 fault block reservoirs in AGD oilfield.

Indices normalization

Through the analysis of 17 evaluation indices used in this case, problems can be found in the comprehensive evaluation process with the participation of various indices. Firstly, quantitative indices have different dimensions and different magnitudes; secondly, subjective indices need to be quantified. Therefore, indices must be normalized. The objective of normalization is to establish comparability between indices. Quantitative indices and qualitative indices have different methods on normalization.

For quantitative indices, normalization formulas of positive and negative indices are as follows.

For a positive index a_{ij}, standard factor e_{ij} is:

$$e_{ij} = \frac{a_{ij} - a_{jmin}}{a_{jmax} - a_{jmin}} \tag{1}$$

For a negative index a_{ij}, standard factor e_{ij} is:

$$e_{ij} = \frac{a_{jmax} - a_{ij}}{a_{jmax} - a_{jmin}} \tag{2}$$

Qualitative indices are normalized by using the values in Table 1.

Table 1. Value assignment for qualitative indices

Grade	Good	Better	Moderate	Poor	Bad
Standard factor value	1	0.75	0.5	0.25	0

Weights determination

In order to determine the weights of indices, the judgment matrix is established. The so-called judgment matrix refers to the matrix formed by pairwise comparison of elements. For each set of comparison results, a score is assigned.

For element i to element j, the values for pairwise comparison are assigned as follows:

1	Equally preferred
2	Equally to moderately preferred
3	Moderately preferred
4	Moderately to strongly preferred
5	Strongly preferred
6	Strongly to very strongly preferred
7	Very strongly preferred
8	Very to extremely strongly preferred
9	Extremely preferred

Otherwise, for element j to element i, the score equals to the reciprocal of the score for element i to element j.

(1) Judgment matrix of operation elements

Through pairwise comparison of the three operation elements, the judgment matrix B shown in Table 2 is obtained.

Table 2. Judgment matrix of operation elements to comprehensive evaluation

Operation element	B	i=1	i=2	i=3
Reservoir grade	j=1	1	4	4
Development scale	j=2	0.25	1	2
Ground conditions	j=3	0.25	0.5	1

(2) Judgment matrix of indices

Through pairwise comparison, the judgment matrix M1 (Table 3), M2 (Table 4), M3 (Table 5) are obtained.

Table 3. Judgment matrix of the indices to reservoir grade

Index	M1	j=1	j=2	j=3	j=4	j=5	j=6	j=7	j=8	j=9
OOIP	i=1	1	1	1	2	3	4	5	7	8
EUR	i=2	1	1	1	2	3	4	5	7	8
Uncertainty factor	i=3	1	1	1	2	3	4	5	7	8
Well productivity	i=4	0.5	0.5	0.5	1	2	4	5	7	8
Reservoir property	i=5	0.33	0.33	0.33	0.5	1	2	4	5	8
Oil property	i=6	0.25	0.25	0.25	0.25	0.5	1	3	5	7
Natural energy	i=7	0.2	0.2	0.2	0.2	0.25	0.33	1	5	7
Complexity	i=8	0.14	0.14	0.14	0.14	0.2	0.2	0.2	1	5
Reservoir depth	i=9	0.13	0.13	0.13	0.13	0.13	0.14	0.14	0.2	1

Table 4. Judgment matrix of the indices to development scale

Index	M2	j=1	j=2	j=3	j=4	j=5
Development mode	i=1	1	1	3	4	4
Drilling scale	i=2	1	1	2	2	5
Development strata	i=3	0.33	0.5	1	2	6
Injection scale	i=4	0.25	0.5	0.5	1	7
Well pattern	i=5	0.25	0.5	0.17	0.14	1

Table 5. Judgment matrix of the indices to ground conditions

Index	M3	j=1	j=2	j=3
Distance to CPF	i=1	1	8	9
Surface conditions	i=2	0.13	1	5
Environmental requirements	i=3	0.11	0.2	1

(3) Matrix consistency

For arbitrary elements a_{ik}, a_{kj} and a_{ij} of matrix H_{n*n}, if they have the relationship that $a_{ij} = a_{ik} * a_{kj}$ (i = 1, 2, ···, n; j = 1, 2, ···, n; k = 1, 2, ···, n), the matrix is called a consistency matrix. For a consistency matrix, weights of indices can be obtained by the maximum eigenvector of the matrix.

Matrix consistency discriminant is as follows.

$$\mathrm{CI} = (\lambda_{max} - \mathrm{n})/(\mathrm{n} - 1) \tag{3}$$

$$\mathrm{CR} = \mathrm{CI}/\mathrm{RI} \tag{4}$$

When CI = 0, the matrix is called a complete consistency matrix; when CI ≠ 0 and CR < 0.10, the matrix is called a consistency matrix; otherwise, the matrix is not a consistency matrix.

In this case, judgment matrices of all the layers meet CI = 0, i.e., they are all complete consistency matrices. Therefore, weights of indices can be calculated.

(4) Weights calculation

As the judgment matrices in this study are all complete consistency matrices, the weight vector of every judgment matrix equals the maximum eigenvector of the matrix. Thus, the weights calculation can be carried out step by step.

Firstly, weights of operation elements are calculated to determine the relative importance of the three operation elements to comprehensive evaluation. Secondly, weights of indices to operation elements are calculated to determine the relative weight of each index. Finally, overall weight of each index is determined by the product of respective weights in the last two steps. Overall weight calculation is shown in Table 6.

Table 6. Overall weight calculation

Target layer	Operation element		Index		Overall weight	
	Operation element	Weight	Index	Weight	Symbol	Overall weight
Comprehensive evaluation	Reservoir grade	0.661	OOIP	0.201	v1	0.133
			EUR	0.201	v2	0.133
			Uncertainty factor	0.201	v3	0.133
			Well productivity	0.146	v4	0.097
			Reservoir property	0.095	v5	0.063
			Oil property	0.068	v6	0.045
			Natural energy	0.048	v7	0.032
			Complexity	0.025	v8	0.016
			Reservoir depth	0.015	v9	0.010
	Development scale	0.208	Development mode	0.342	v10	0.071
			Drilling scale	0.269	v11	0.056
			Development strata	0.184	v12	0.038
			Injection scale	0.148	v13	0.031
			Well pattern	0.057	v14	0.012
	Ground conditions	0.131	Distance to CPF	0.785	v15	0.103
			Surface conditions	0.162	v16	0.021
			Environmental requirements	0.053	v17	0.007

Overall ranking calculation

The last part of the optimization is to calculate overall rankings of fault block reservoirs. Then production sequence of fault block reservoirs can be obtained according to the overall rankings.

According to standard factors of all reservoirs, the best virtual reservoir and the worst virtual reservoir are constructed.

The standard factor set of the best virtual reservoir is constructed as follows:

$$\begin{cases} H = \{h_j\} \\ h_j = \max\{e_{ij}\} \\ i = 1, 2, ..., 89 \\ j = 1, 2, ..., 17 \end{cases} \tag{5}$$

The standard factor set of the worst virtual reservoir is constructed as follows:

$$\begin{cases} C = \{c_j\} \\ c_j = \min\{e_{ij}\} \\ i = 1, 2, ..., 89 \\ j = 1, 2, ..., 17 \end{cases} \tag{6}$$

Distance between each reservoir and the virtual reservoir is calculated. For reservoir i, the distance to the best virtual reservoir is $|V *(H - E_i)|$, and the distance to the worst virtual reservoir is $|V* (E_i - C)|$.

$$|V *(H - E_i)| = \sqrt[2]{\sum_{j=1}^{17} [v_j * (h_j - e_{ij})]^2} \tag{7}$$

$$|V* (E_i - C)| = \sqrt[2]{\sum_{j=1}^{17} [v_j * (e_{ij} - c_j)]^2} \tag{8}$$

Finally, overall ranking of reservoir i is obtained as follows.

$$p_i = \left\{1 + \left[\frac{|V* (H - E_i)|}{|V* (E_i - C)|}\right]^2\right\}^{-1} \tag{9}$$

RESULTS AND DISCUSSION

The 89 fault block reservoirs have large differences in the 17 indices. For example, the biggest OOIP is $36159*10^3$ m^3; the smallest OOIP is $143.1*10^3$ m^3; the longest distance to CPF is 183.2 kilometers; the shortest distance to CPF is 0 kilometers. Thus, with so many indices be considered, the comprehensive quality of a reservoir should be represented by an overall ranking. For the overall target, which demands smaller investment scale, larger profit and faster investment recovering speed, the reservoir with the highest comprehensive quality should be developed first to recover the investment as quickly as possible.

Overall rankings of the 89 fault block reservoirs are shown in Figure 2. The fault block reservoir, which has the biggest overall ranking should be put into production first. Thus, the production sequence of the 89 fault block reservoirs is obtained according to the overall rankings.

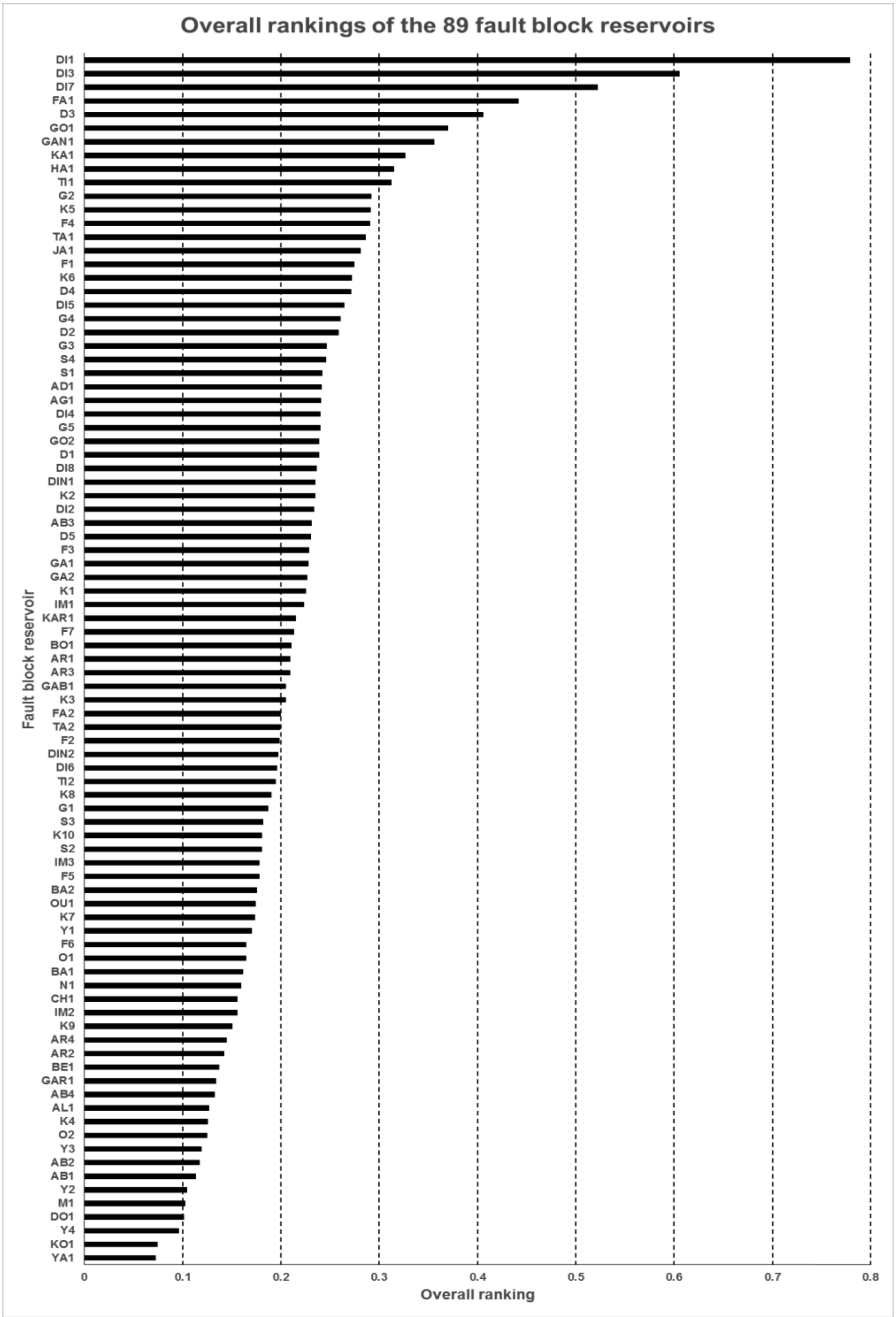

Fig. 2. Overall rankings of the 89 fault block reservoirs.

Through the analysis of the results, we have found that the dominant factors to decide the overall ranking are OOIP, uncertainty factor, EUR, well productivity and distance to CPF. Of course, other 12 indices also have influence on the overall ranking. Dominant factors of the overall ranking are listed in Table 7. Reservoir DI1, GAN1 and YA1 are taken for analysis. Reservoir DI1 get the highest overall ranking with 4 best indices except the uncertainty factor. Reservoir GAN1 has the smallest uncertainty factor, which means a high ratio of proved reserves. For reservoir YA1, each index is very bad, such as the longest distance to CPF and the biggest uncertainty factor, which means a high ratio of probable reserves. Due to the worst comprehensive quality of reservoir YA1, it should be developed last, when the early investment has been recovered.

Table 7. Dominant factors of the overall ranking

Fault block oil reservoir		DI1	GAN1	YA1
Dominant factors	OOIP (10^3 m^3)	36159	2368	956
	Uncertainty factor	0.7	0.3	1
	EUR (10^3 m^3)	10812	429.3	238.5
	Well productivity (m^3)	238.5	127.2	63.6
	Distance to CPF (10^3 m)	0	44.2	172.1
Overall ranking		0.78	0.36	0.07
Production sequence		1	7	89

According to the actual field production history, fault block reservoir DI1 is the best reservoir among those reservoirs that are in production now. DI1 was put into production first 3 years ago. At present, there are 26 production wells and no injection well in DI1. Daily production of DI1 is 19,000 barrels per day, and the water cut is 21%. Pressure drop is relatively slow. Formation pressure maintain level is 87% now. The development effect of DI1 is the best among the fault block reservoirs, which are in production now, which is consistent with previous optimization results.

CONCLUSIONS

A hybrid production sequence optimization model is built and applied to the complex fault block reservoirs of AGD oilfield. According to the optimization results, the production sequence of the 89 fault block reservoirs is determined. The results demonstrate that this optimization is very essential in the development of complex fault block reservoirs, as it is extremely difficult for human experience to deal with this kind of complicated optimization.

The production sequence optimization of complex fault block reservoirs overcomes some drawbacks of the conventional experience method. This is a big step that the determination of production sequence of complex fault block reservoirs is developed to be a semi-quantitative process. However, subjectivity still exists in this study, which needs to be further addressed in future research.

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