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ORIGINAL PAPER

Improvements to the fuzzy mathematics comprehensive quantitative method for evaluating fault sealing

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Abstract Fuzzy mathematics is an important means to quantitatively evaluate the properties of fault sealing in petroleum reservoirs. To accurately study fault sealing, the comprehensive quantitative evaluation method of fuzzy mathematics is improved based on a previous study. First, the single-factor membership degree is determined using the dynamic clustering method, then a single-factor evaluation matrix is constructed using a continuous grading function, and finally, the probability distribution of the evaluation grade in a fuzzy evaluation matrix is analyzed. In this study, taking the F1 fault located in the northeastern Chepaizi Bulge as an example, the sealing properties of faults in different strata are quantitatively evaluated using both an improved and an un-improved comprehensive fuzzy mathematics quantitative evaluation method. Based on current oil and gas distribution, it is found that our evaluation results before and after improvement are significantly different. For faults in "best" and "poorest" intervals, our evaluation results are consistent with oil and gas distribution. However, for the faults in "good" or "poor" intervals, our evaluation is not completely consistent with oil and gas distribution. The improved evaluation results reflect the overall and local sealing properties of target zones and embody the nonuniformity of fault sealing, indicating the improved method is more suitable for evaluating fault sealing under complicated conditions

Keywords Fault sealing property · Fuzzy mathematics · Dynamic clustering method · Quantitative study

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1 Introduction

Throughout geological history, faults have played a very important role in hydrocarbon migration and accumulation. Large faults, which form the boundaries of oil and gas fields, can generally control hydrocarbon accumulation (Agosta et al. 2012; Allan 1989; Balsamo et al. 2010; Bouvier et al. 1989; Braathen et al. 2009; Brogi and Novellino 2015; Choi et al. 2015; Collettini et al. 2014; Fisher and Jolley 2007). However, small faults generally separate oil and gas, resulting in an increase in well spacing that poses challenges in oil and gas exploration. Thereby, studies of fault sealing have become a very important focus for oil and gas exploration and development (Ciftci et al. 2013; Collettini et al. 2014; Davatzes and Aydin 2005; Fachri et al. 2013a, b). Studies of fault sealing have evolved from trap theory, which is used to identify hydrocarbon sealing mechanism(s) and physical parameters of faults (Hubbert 1953; Smith 1980). Based on different mathematical principles and modes, the sealing properties of one or more given faults are quantitatively identified and predicted by considering various sealing mechanisms and factors. (Childs et al. 2009; Egholm et al. 2008; Fachri et al. 2011; Faulkner et al. 2003; Fisher and Knipe 1998; Wu et al. 2010; Knipe et al. 1997).

With constant improvements in petroleum geology, scholars in China and abroad have gradually realized that fault sealing is jointly controlled by multiple factors, rather than just one or two single factors (Lü et al. 2007; Knott 1993; Knipe et al. 1997; Faulkner et al. 2010; Gibson 1994; Zhang et al. 2013; Pei et al. 2015). With a deepening of quantitative single-factor studies of fault sealing, many scholars tried to comprehensively evaluate fault sealing using mathematical theory methods, including nonlinear mapping methods, gray relational, logical information, fault connectivity probabilistic methods and fuzzy comprehensive evaluation methods (Fu et al. 2005, 2008, 2012; Lü et al. 1995; Lü and Fu 2002; Zhang et al. 2007; Jiang et al. 2008; Li 2009; Zhang et al. 2015). However, for all these methods, some key parameters are difficult to obtain and have regional limitations, so that human factors are generally introduced for value assignment or adjustment. Thus, scholars manage to optimize these parameters using a variety of mathematical approaches. Among them, the fuzzy comprehensive evaluation method, which is strongly systematic and provides definite results, is accepted by many scholars and has been gradually improved over the years.

In this paper, based on the principles of fuzzy comprehensive evaluation, the single-factor membership degree was established using the dynamic clustering method. Then, a single-factor evaluation matrix was constructed using the continuous grading function in order to optimize the probability distribution of the evaluation grade in the fuzzy comprehensive evaluation method. Next, we considered a fault in the Chepaizi Bulge in the northwestern margin of the Junggar Basin as an example, and the sealing properties in the vertical and strike directions were evaluated. Finally, our results are compared with oil and gas exploration results.

2 Un-improved fuzzy mathematics evaluation of fault sealing

The physical principles that affect fault sealing include principal stress sealing, lithological allocation sealing, shale smear sealing, time allocation sealing and occurrence allocation sealing (Liu 1998). Single factors include fault properties, fault plane pressure, lithological allocation, fault dip angle, shale smear and fault active time. Thus, being affected by numerous factors, fault sealing shows very strong complexity and randomness. Fortunately, the fuzzy evaluation method can take various types of single factors that affect fault sealing into consideration, and hence realize a comprehensive evaluation using the principle of fuzzy transformation and maximum membership degree. Using this mathematical method, fault sealing properties can be effectively identified. The process is as follows: First, based on regional geology and fault development, the single factors that affect fault sealing are selected and quantified in order to obtain a single-factor quantization matrix $U_{n\times 1}$ (n is the number of single factors). Then, based on the general division of fault sealing and regional requirements, the number of evaluation grades is divided (m). Finally, a single-factor membership degree matrix is constructed based on the number of evaluation grades and the oil and gas exploration results of the work area, $V_{1\times m}$, based on which, $U_{n\times 1}$ is evaluated in order to construct a fuzzy evaluation matrix $R_{n\times m} = U_{n\times 1} \cdot V_{1\times m}$. Since each single factor has different contributions to fault sealing, once the weighted matrix of each single factor is provided, $W_{1\times n}$, the fuzzy evaluation matrix $B_{1\times m} = W_{1\times n} \cdot R_{n\times m}$ can be obtained. Finally, the maximum value of the fuzzy evaluation matrix $B_{1\times m}$ is taken as the corresponding evaluation grades.

However, there are various methods that can be used to acquire the parameters mentioned above, both qualitatively and quantitatively, and which are constantly optimized (Lü and Fu 2002; Russell et al. 2003; Fu et al. 2012; Li et al. 2009). There are many single factors that affect fault sealing, generally including fault properties, fault plane pressure, fault lithological allocation and shale smear. Evaluation grades can be divided into five ranks: good, better, moderate, fairly poor and poor. The single-factor membership degree can be obtained via a discrete function method and/or a continuous function method. The former applies to qualitative single-factor membership degree, such as fault properties, while the latter applies to quantitative single-factor membership degree, such as fault plane pressure. Weighting coefficients can be obtained via the expert survey method, analytic hierarchy process (AHP), Delphi method and/or the weight matrix method (Ding and Jin 2012; Sun and Wu 1995; Qiu et al. 2007). The larger the weighting coefficient of a single factor, the greater the impact of the single factor on fault sealing. The mathematical model of fuzzy comprehensive evaluation includes the weighted-average type, the main factor highlight type and the main factor determination type (Sun et al. 2010). The weighted-average type can take a variety of single factors into consideration in order to avoid information loss. The main factor highlight type and the main factor determination type emphasize the main controlling factors and prevent interference factors. In the evaluation process of fault sealing, many scholars use the weighted-average type. However, determining the above parameters and effectively predicting fault sealing must be based on the actual petroleum geology of the study area and from suggestions made by local experts in order to reduce exploration risks.

3 Improved fuzzy mathematics of fault sealing

3.1 The establishment of the single-factor membership degree using the dynamic clustering method

In this study, the membership degree of each single factor is established by applying the dynamic clustering method. Based on a large sample dataset, pre-classification is roughly performed. Then, gradual adjustment is made until a reasonable classification is obtained. The maximum and minimum values of each class constitute the range of membership degrees. For fault sealing, the single-factor membership degree is established as follows: Firstly, a large number of samples of one single factor of the work area and their corresponding oil–gas show are constructed. Then, taking best, good, poor and poorest oil and gas show as the standard, the range of the membership degrees of the fault gouge ratio is determined. This means that the fault gouge ratio of a given area is clustered. In the process of clustering, the maximum and minimum values are the range limits of membership degree. The so-called dynamic clustering means the gradual adjustment of a value to a reasonable range using the dynamic clustering principle. This method has the advantages of incorporating the oil and gas geology of the study area, so that it has regional eigenvalues. It is closely related to the fault sealing properties of the study area and hence has a certain degree of predictability. The advantage of this method is that the regional petroleum geology has a regional characteristic value which is related to fault sealing, and is predictive.

3.2 The establishment of a single-factor evaluation matrix using the continuous grading function

After the single-factor membership degree is determined via the dynamic clustering method, fuzzy evaluation should be carried out for all single factors in order to establish a single-factor evaluation matrix. The division of the single-factor membership degree $S(i)$ only gives evaluation results of good and poor intervals, and it does not provide probabilistic evaluation results of each interval. For example, the range of "good" and "poor" is (1–0.5) and (0.5–0). If the single factor value is 0.7, it cannot be regarded simply as "good," thus implying that a further probabilistic evaluation is needed. Hence, the definition "good" accounts for 70% good, and "poor" accounts for 30%. $e(i)$ is the boundary value of the re-probabilistic evaluation. The precise method followed is as follows: First, a range of values for fault sealing is determined using single factors, $S(i)$. Then, the threshold value of each adjacent class is determined, namely the classification representative value $e(i)$, which is determined as per the following principles (Zhao 2001):

$$\left.\begin{aligned} &e(1) = S(1) \\ &e(2) = [S(1) + S(2)]/2 \\ &e(3) = [S(2) + S(3)]/2 \\ &e(4) = S(3) \end{aligned}\right\}$$

Fault properties, fault gouge ratios and fault sealing are not always linearly related with each other. However, they have a piecewise function relation based on single-factor membership degree. According to Newton's iteration principle, it can be assumed that the single-factor evaluation criteria $r(\chi)$ are a linear piecewise function, which can be solved by successive approximation. Then, fuzzy subsets of the fault evaluation criteria can be determined using the following methods:

$$r_1(\chi) = \begin{cases} 1 & \chi \le e(1) \\ \dfrac{e(2) - \chi}{e(2) - e(1)} & e(1) \le \chi \le e(2) \\ 0 & \chi \ge e(2) \end{cases} \quad r_2(\chi) = \begin{cases} 1 - r_1(\chi) & e(1) \le \chi \le e(2) \\ \dfrac{e(3) - \chi}{e(3) - e(2)} & e(1) \le \chi \le e(2) \\ 0 & \chi \le e(1), \chi \ge e(3) \end{cases}$$

$$r_3(\chi) = \begin{cases} 1 - r_2(\chi) & e(2) \le \chi \le e(3) \\ \dfrac{e(4) - \chi}{e(4) - e(3)} & e(3) \le \chi \le e(4) \\ 0 & \chi \le e(2), \chi \ge e(4) \end{cases} \quad r_4(\chi) = \begin{cases} 0 & \chi \le e(3) \\ 1 - r_3(\chi) & e(3) \le \chi \le e(4) \\ 1 & \chi \ge e(4) \end{cases}$$

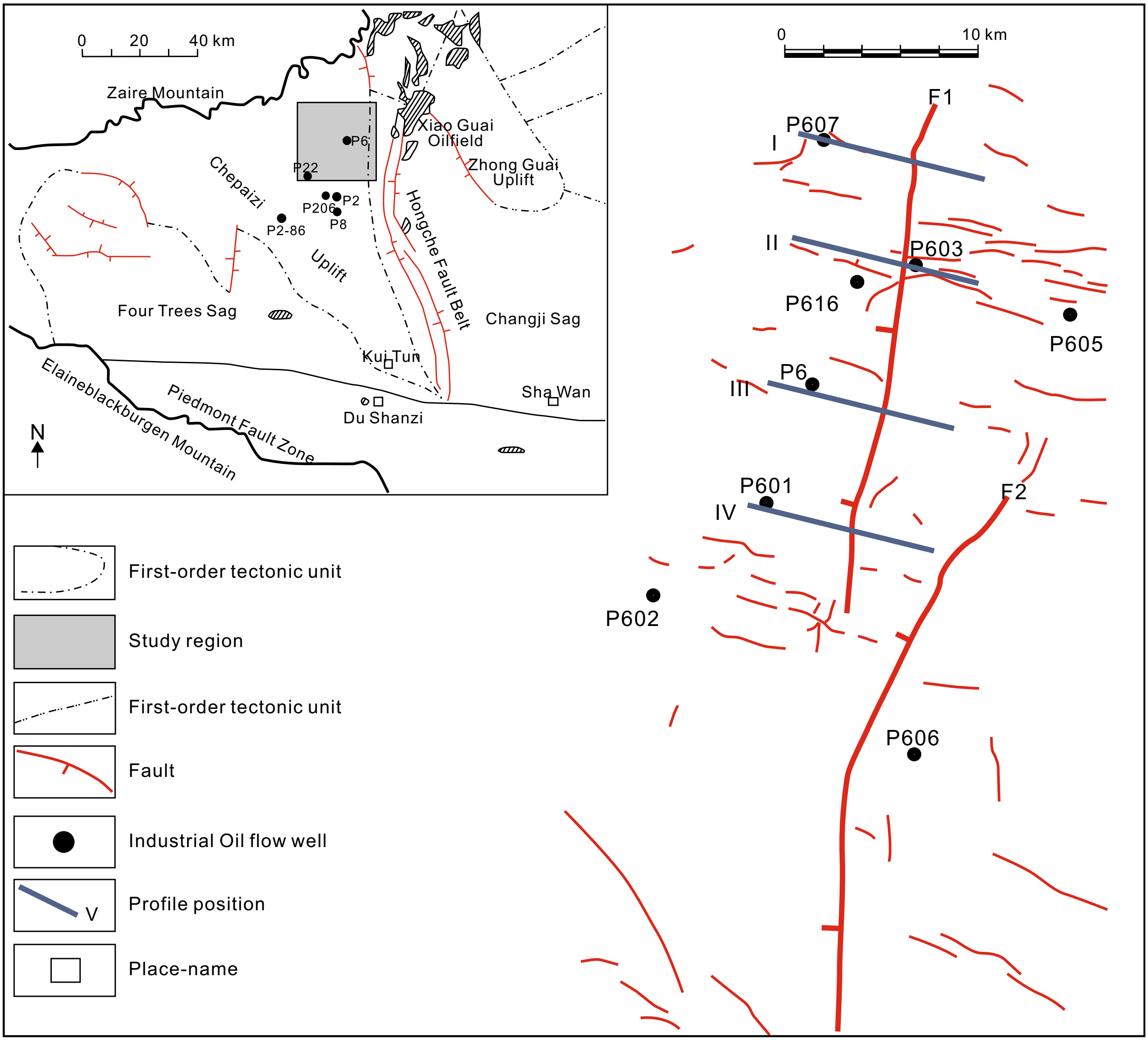

Fig. 1 The position of the seismic profile study of fault sealing

The fuzzy subset obtained based on N single-factor evaluation indices constitutes fuzzy sets:

$$R = \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} \\ \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet \\ r_{n1} & r_{n2} & r_{n3} & r_{n4} \end{bmatrix}_{n\times 4}$$

4 Case studies

Taking the fault F1 located in the northeastern Chepaizi Bulge as an example (Fig. 1), the fault sealing properties of the main target zones were evaluated using both the improved and un-improved methods. This approach was used to determine whether the improved comprehensive evaluation method for fault sealing is more reasonable. The Chepaizi Bulge is located at the southern end of the northwestern margin of the Junggar Basin. It is a secondary structural unit in the western uplift of the Junggar Basin, adjacent to the Changji Sag and the Zhongguai bulge to the east, Sikeshu Sag to the south and Zaire Mountain to the northwest (Fig. 1). Conditions in the Chepaizi Bulge make this a good place for hydrocarbon accumulation. The main reservoirs are Cretaceous (K) and Neogene Sha1 Member (N_1s_1). The F1 fault in the northeastern Chepaizi Bulge is a very important oil control fault, and its sealing properties directly affect hydrocarbon accumulation in this area. The fault has NNE-trending, EW-trending compression in the Yanshanian Period and NWW-trending extension in the

Himalayan Period. Vertically, there are reverse faults in the Cretaceous strata and basement and normal faults in Cenozoic strata, which represent a negative inverted structure as a whole.

4.1 Single-factor selection and quantitative calculation

Since the study area has undergone multiple phases of tectonic evolution, various types of faults with different occurrences have developed. There are many single factors that affect fault sealing in response to tectonic evolution, so that the weighting coefficients of the single factors are different. However, in this paper, and taking fault F1 as an example, the sealing properties in the vertical and strike directions were analyzed. Four single factors with comparable significance were selected, including fault surface normal stress (σ), fault properties, sand/formation ratio (N/G) and the shale content of fault zone fillings. In addition, four seismic profiles vertical to fault F1 were selected (the location is shown in Fig. 1), which were converted into four geological sections via a time-depth conversion. Then, lithological sections were recovered using well logs in order to obtain the quantitative and qualitative values of each single factor (Table 1).

Fault surface normal stress, which is an important parameter used to characterize the fault opening degree, is crucial to fault sealing (Fu et al. 2005). Typically, this value is the vector sum of the gravitational force imparted by the overlying strata, the regional principal compressive stress, the regional principal stress as well as the fault dip angle. Fault F1 is a shovel fault, where the fault plane normal stress increases from the bottom to the top, where the fault sealing properties become better. However, the Chepaizi Bulge is located in a slope belt of a foreland basin, where the buried depth is shallow, so that the fault surface pressure is small.

In general, the sealing properties of compressional, shear and compressional-shear faults are good, while the sealing properties of extensional and extensional-shear faults are poor. Fault F1 is a negative inverted fault, and it is an extensional fault that formed during the Neogene. However, the fault occurrence changes significantly, which is steep in the upper part and gentle in the lower part. That is, regional tensile stress can only cause the Neogene "steep" fault section to extend, but cannot completely make the Cretaceous "gentle" fault section extend. In addition, the pressure experienced by the Cretaceous fault plane is significantly larger than that of the Neogene fault plane, which can also prove this change. After undergoing compressional deformation, the Cretaceous fault section has better sealing properties than the Neogene extensional fault section due to its fault structure and mudstone smearing. Therefore, the Neogene fault section has been assigned as "extensional", while the Cretaceous fault section is assigned as "compressional".

Sand shale contraposition is an important process for oil and gas lateral sealing. In fault dislocation, if sand shale contraposition occurs in one interval, the fault in this interval is closed, while if multiple sand layers are connected in one interval, the fault in this interval is open. The parameter characterizing possible sand shale contraposition is the sand/formation ratio, which is the ratio between the sandstone and layer formation thicknesses, N/G. When N/G is large, the possibility of a sand–sand connection is large, and hence the fault sealing ability is poor. When the N/G ratio is small, the fault sealing ability is in fact good. However, this single factor does not take the fault throw generated by fault slipping into consideration, Therefore, the following single factor is added.

Faults will form fault zones during displacement and dislocation processes. When a given fault zone is filled with shale, it can seal oil and gas laterally due to the plastic flow and compaction of shale. When a fault zone is filled with sandstone, it can act as a hydrocarbon migration pathway since sandstone compacts poorly and has good porosity and permeability. Accordingly, Fu et al. (2012) improved the fault gouge ratio (SGR) proposed by Yielding et al. (1997) and proposed to characterize the sealing property of faults using the ratio between the mudstone thickness of a fault belt and the sum of the fault throw and

Table 1 Evaluation parameter list of single factors on the sealing ability of the F1 fault

Section line no.	Formation	σ, MPa	Fault surface	N/G	Rm	Section line no.	Formation	σ, MPa	Fault surface	N/G	Rm
I	N_1s_3	0.46	Tensile	0.95	0.04	III	N_1s_3	0.66	Tensile	1	0
	N_1s_2	0.52	Tensile	0.02	0.74		N_1s_2	0.77	Tensile	0.12	0.67
	N_1s_1	0.58	Tensile	0.56	0.32		N_1s_1	0.86	Tensile	0.33	0.5
	K	0.82	Compressive	0.24	0.7		K	1.29	Compressive	0.26	0.61
II	N_1s_3	0.25	Tensile	0.99	0.01	IV	N_1s_3	0.09	Tensile	0.99	0.02
	N_1s_2	0.28	Tensile	0	0.79		N_1s_2	0.10	Tensile	0.30	0.70
	N_1s_1	0.31	Tensile	0.46	0.40		N_1s_1	0.11	Tensile	0.28	0.49
	K	0.48	Compressive	0.17	0.79		K	0.19	Compressive	0.28	0.70

faulted formation thicknesses, namely the shale content of the fillings in a given fault belt. Due to the negative inversion of fault F1, Cretaceous shale smeared the fault surface repeatedly. Therefore, the shale in the Cretaceous fault zone fillings was formed in compressional and extensional stages. Hence, the faults that formed in compressional and extensional stages were obtained from structural section restoration.

4.2 Single-factor weighting coefficients and membership degree

Single-factor weighting coefficients are significantly different in different areas. The numerous methods that are used to determine these coefficients are all based on the expert investigation method. Therefore, in this paper, the weighting coefficients of four single factors, including the normal stress of the fault plane (w_1), fault properties (w_2), sand/formation ratio (w_3) and the shale content of the fillings in the fault belt (w_4), were determined using the expert investigation method (Table 2). It is worth mentioning that the formation pressure of the oil and gas discovery wells in this area is abnormal, while the formation pressure of dry wells and water wells is normal, meaning pressure is sensitive to oil and gas accumulation so that the weighting coefficient of fault plane normal stress is the largest.

The statistics used in this study were applied to the well logging data of 85 wells around fault F1 and the corresponding oil and gas shows. Moreover, the values of four single factors were calculated, which were classified into four categories using the dynamic clustering method: best, good, poor and poorest. The maximum and minimum values of each category were taken as the boundary values of each membership degree. Based on the advice of oilfield experts, membership degree was then slightly adjusted. The final results are shown in Table 3.

4.3 Optimized fuzzy evaluation matrix

The advantage of the dynamic clustering method in comprehensive fault sealing property evaluation is to establish a single-factor evaluation matrix. In order to illustrate the establishment process of the un-improved and improved single-factor evaluation matrices, the establishment of the single-factor matrix in the first member of the Shawan Formation in profile I was analyzed.

Table 2 Single-factor weight coefficients of fault sealing in the northeast of Chepaizi Uplift

Influence factor	w_1	w_2	w_3	w_4
Weight coefficient	0.3	0.2	0.25	0.25

Table 3 The single-factor membership list in the study area

Standard	Best	Good	Poor	Poorest
N/G	≤0.3	0.3–0.55	0.55–0.8	≥0.8
Rm	≥0.70	0.55–0.70	0.40–0.55	≤0.40
Fault properties	≥0.9	0.75–0.9	0.5–0.75	≤0.5
σ, MPa	≥1	0.5–1	0.3–0.5	≤0.3

Before improvement, a single value was directly assigned to a single-factor membership degree evaluation matrix using the discrete function and continuous function methods. When the N/G of the first member of the Shawan Formation was 0.56, (i.e., the grade of the maximum membership degree is "poor"), this grade was directly assigned a value of 0.5 when using the discrete function method and 0.3 when using the continuous function method. The single-factor membership degree evaluation matrix is $R_{\mathrm{N/G}} = (0.5)$ or (0.3). However, although a value of 0.56 implies a grade of "poor," which is close to a grade of "good," a value of 0.56 should have some probability evaluation in the grade "good." However, the un-improved single-factor membership degree evaluation matrix does not embody the probability in this transitional type.

Instead, a single-factor evaluation matrix that is constructed by the continuous grading membership function can properly address the problem mentioned above. Its calculation process after improvement is as follows: First, $S(i)$ is determined based on N/G, namely $S(1) = 0.3$, $S(2) = 0.55$, $S(3) = 0.8$. Then, the threshold value of each adjacent evaluation level is calculated, i.e., grading representative value $e(i)$:

$$\begin{cases} e(1) = S(1) = 0.3 \\ e(2) = [S(1) + S(2)]/2 = 0.425 \\ e(3) = [S(2) + S(3)]/2 = 0.675 \\ e(4) = S(3) = 0.8 \end{cases}$$

Finally, when the N/G of the first member of the Shawan Formation is 0.56, the single-factor evaluation matrix is calculated: $e(2) < 0.56 < e(3)$,

$$\begin{cases} r_1 = 0 \\ r_2 = [e(3) - 0.56]/[e(3) - e(2)] = 0.46 \\ r_3 = 1 - r_2 = 0.54 \\ r_4 = 0 \end{cases}$$

After improvement, the evaluation matrix of the sand/formation ratio of the first member of the Shawan Formation is $R_{\mathrm{N/G}} = (0 \quad 0.46 \quad 0.54 \quad 0)$.

The comprehensive evaluation matrix of the four factors of the first member of the Shawan Formation is:

$$R = \begin{bmatrix} 0.00 & 0.51 & 0.49 & 0.00 \\ 0.00 & 0.00 & 0.80 & 0.20 \\ 0.00 & 0.46 & 0.54 & 0.00 \\ 0.00 & 0.00 & 0.00 & 1.00 \end{bmatrix}$$

The fuzzy evaluation matrix of the first member of the Shawan Formation is $B = W \cdot R = (0 \quad 0.27 \quad 0.44 \quad 0.29)$. According to the principle of the maximum membership degree, the evaluation result of the first member of the Shawan Formation is poor. However, the probability distribution of this evaluation grade is scattered, indicating the fuzziness of the fault sealing property is large. Conversely, if the probability distribution of the evaluation grade is concentrated, the evaluation result of fault sealing property is obvious.

4.4 Fuzzy evaluation results and analysis

Using the improved fuzzy evaluation method described above, the sealing properties of fault F1 in the vertical and strike directions were evaluated. The results are shown in Table 4. Cross sections I, II, III and IV are well-tied cross sections that span from south to north along the fault strike. Cretaceous (K), the first member of Shawan Formation (N_1s_1), the second member of Shawan Formation (N_1s_2) and the third member of Shawan Formation (N_1s_3) constitute intervals from top to bottom in the vertical direction. The evaluation results show that the valuation result of Cretaceous faults is "good," but the maximum probability is only 0.58, indicating oil and gas are sealed when they migrate to the footwall, but it may be oil and gas bearing in the hanging wall. The valuation result of the first member of the Shawan Formation is "poor" or "poorest." The probability distribution of the evaluation grade is dispersed, showing the ambiguity of footwalls and hanging walls on its oil-bearing properties. The evaluation result of the second member of the Shawan Formation is "good." A regional survey showed that this interval is a stably distributed shale bed, namely regional caprock. The evaluation result of the third member of the Shawan Formation is "poor," but mud logging results show this interval is conglomerate. There were no oil and gas shows discovered in this interval in the work area.

Next, we compared the variations between the improved and un-improved fuzzy evaluations and their impact on the evaluation results. In this paper, a single-factor membership degree evaluation matrix was directly assigned a value using the discrete function method. The assigned values of evaluation grades $R = (\text{best, good, poor, poorest}) = (1, 0.66, 0.33, 0)$ and the fuzzy evaluation results are shown in Table 4. Upon inspection, the fuzzy evaluation values of the first and second members of the Shawan Formation change significantly, but they do have consistent results. However, the fuzzy evaluation values and evaluation

Table 4 Evaluation form of fault sealing

Section line no.	Formation	Improved evaluation value					Unimproved evaluation value		Oil and gas display	
		Best	Good	Poor	Poorest	Value	Result	Value	Hanging wall	Footwall
I	N_1s_3	0.00	0.05	0.41	0.54	Poorest	0.10	Poorest	Water	Water
	N_1s_2	0.50	0.10	0.36	0.04	Best	0.70	Best	–	–
	N_1s_1	0	0.27	0.44	0.29	Good	0.36	Poor	Oil	Oil
	K	0.58	0.39	0.03	0.00	Best	1.00	Best	Water	Oil
II	N_1s_3	0.00	0.00	0.16	0.84	Poorest	0.00	Poorest	Water	Water
	N_1s_2	0.50	0.00	0.16	0.34	Best	0.50	Good	–	–
	N_1s_1	0.00	0.22	0.22	0.56	Good	0.26	Poorest	Oil–Water	Oil
	K	0.50	0.24	0.26	0	Best	0.80	Best	Water	Water
III	N_1s_3	0.00	0.22	0.24	0.54	Poorest	0.20	Poorest	Water	Water
	N_1s_2	0.42	0.38	0.16	0.04	Best	0.61	Poor	Empty	Empty
	N_1s_1	0.32	0.27	0.37	0.04	Best	0.45	Poor	Oil	Oil
	K	0.55	0.40	0.05	0.00	Best	0.92	Best	Oil	–
IV	N_1s_3	0.00	0.00	0.16	0.84	Poorest	0.00	Poorest	Water	Water
	N_1s_2	0.50	0.00	0.16	0.34	Best	0.5	Good	–	–
	N_1s_1	0.25	0.03	0.38	0.34	Good	0.33	Poor	Oil	Water
	K	0.50	0.18	0.02	0.30	Best	0.7	Best	Oil	–

"–" in the table means there are no drilling test data or wells are not drilled in this horizon

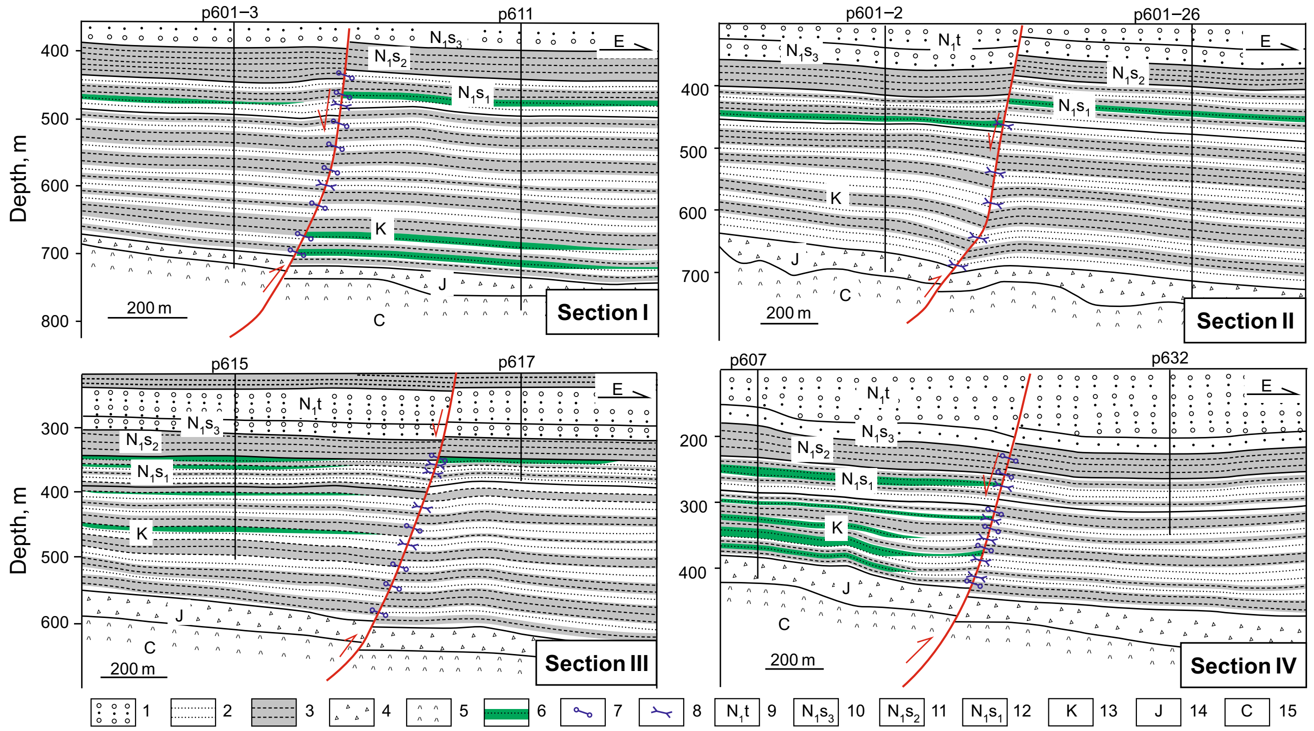

Fig. 2 Analysis of fault sealing and its oil reservoir in sections **I–IV** *1* Conglomerate, *2* Sandstone, *3* Mudstone, *4* Breccia, *5* Igneous rocks, *6* Hydrocarbon migration direction, *7* Faults open, *8* Faults closed

results of the first member of the Shawan Formation change significantly before and after improvement, and the evaluation results before improvement are not well matched with the oil and gas shows in footwall and hanging wall. Taking cross section III as an example, the evaluation results before improvement are poor, but the footwall and hanging walls are both oil bearing. After improvement, the probability distribution of the evaluation grades is scattered, indicating oil and gas may be trapped locally after having continuously migrated from the footwall to the hanging wall in the local open interval (Fig. 2). The above analysis shows that the improved method is more advantageous for regions with larger degrees of vagueness of their fault sealing properties, and hence higher exploration risks.

5 Conclusions

The evaluation of fault sealing properties is an important part of oil and gas exploration and development. Fuzzy comprehensive evaluation is a systematic evaluation method for fault sealing. Since traditional methods are greatly affected by human factors during the establishment of the single-factor membership degree, the assignment method results in fuzzy evaluation values, so that the result only reflects the target interval. In this paper, the dynamic clustering method was introduced to determine the single-factor membership degree. Then, a single-factor evaluation matrix was constructed using the continuous grading function in order to determine the optimum comprehensive evaluation matrix and make a fuzzy evaluation of the fault sealing properties. A comparison of the fuzzy evaluation and its result before and after improvement, combined with current oil and gas distribution regularity, showed that the evaluation results before and after improvement are significantly different. For faults designated as “best” and “poorest,” the evaluation results are consistent with oil and gas distribution. However, for faults designated as “good” or “poor,” the evaluation results of sealing property are not completely consistent with the oil and gas distributions. The improved results reflect the overall and local sealing properties of target zones and embody the fuzziness of fault sealing, indicating the improved method is more precise for evaluating fault sealing properties under complicated conditions.

However, the improved method still has its limitations. First of all, this method still cannot solve the multi-scale fault sealing problem. As mentioned above, the N_1s_1 section in profile III displays strong heterogeneity, and although the evaluation results of large scale are “poor,” the fault sealing properties exist at small scales. Secondly, this method can only explain the sealing properties of the faults in profile. When oil and gas migrate in multiple directions, the evaluation results will not be consistent with drilling results. For example, the evaluation results of section K in the III and IV profiles are good, but the fault is oil bearing in the hanging wall. This phenomenon is related to a two-way oil supply. Oil source comparison shows that the oil and gas migration in the study area is from east to west in the Changji Sag and from south to north in the Sikeshu Sag (Song et al. 2007). Therefore, this method is only applicable for studies of single-scale fault sealing properties. In addition, the direction of oil and gas migration should be vertical to the fault plane.

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