A Quantitative Study of Fault Zone Sealing

LI Yang1, * and ZHAO Mifu2

1 Department of Exploration and Development, SINOPEC, Beijing 100029, China
2 Dongxin Production Factory, Shengli Oilfield Branch Company, SINOPEC, Dongying 207068, China

Abstract: A fault is not simply a plane, but a zone consisting of a series of broken planes or lower faults. The greater the scale of faults, the wider and more complex the fault zone is. Fault-sealing properties are influenced by the fault zone itself, whose fault displacement, depth, net-to-gross-ratio of mudstone, fault plane angle, and fault mechanical properties play important controlling roles. The sealing of hydrocarbon by the fault zone depends on whether the fault zone can form a continuous sealing zone and if the pore throats connecting those fault zones are small enough. The concept of fault zone-sealing potential is proposed here, and a quantitative formula is established by using a great amount of practical statistical data as well as the fuzzy comprehensive evaluation method, which is a comprehensive characterization parameter to judge whether or not fault zones could seal oil hydrocarbon. The greater the value of the fault zone-sealing potential, the better sealed the fault is. For example, with increasing depth, the sealing degree of the Xin 68 Fault in the Dongxin 1 oilfield changes greatly, reflecting the complexity of fault-sealing properties.

Key words: fault, fault-sealing properties, fault zone-sealing potential, Xin 68 Fault

1 Introduction

The phenomenon of fault-sealing properties has aroused great attention among geological workers at home and abroad. Common cognition about the fault-sealing mechanism has been reached (Smith, 1966, 1980; Schowalter, 1989). Methods for prediction and evaluation of fault-sealing properties, such as clay smear (Bouvier et al., 1989; Lindsay and Murphy, 1993; Yielding et al., 1997; Weber, 1978), lithologic allocation (Watts, 1978; Allan, 1989; Knipe, 1997), and fault plane normal stress (Lun et al., 1996; Liu et al., 1998; Tong, 1998) have been used widely. However, it can not be denied that sometimes big failures and even opposite results may be obtained when those methods mentioned for evaluating fault-sealing properties are applied, because the fault-sealing properties of the fault zone itself are neglected. Fault zone-sealing properties can only be determined qualitatively and cannot be solved by giving semiquantitative-quantitative characterization. The quantitative evaluation at fault-sealing properties is of great importance.

2 Characteristics of Fault Zones

* Corresponding author: E-mail: liyang@sinopec.com.cn

Fault zones consist of a set of deformed bodies surrounding those faults and are largely displaced. They result from the faults extending, moving, and connecting to one another in the fault development process (Engelder, 1974). Generally, the greater the scale of faults, the more complicated and wider the fault zone is. The width of the fault zone extends from less than 1 m to several kilometers. Plenty of geological surveys and studies of faults reflect that fillers in fault zones include not only sandstone, mudstone, and faulted tectonite, but many other kinds of fillers. For example, some faults are filled with syntectonic crystallization minerals and some are filled with magma, mineralizing liquids, or late sediments at a later stage, the latter forming sedimentary dykes. Faults within oilfields are mainly filled with sandstone, mudstone, and tectonite, whose distribution also influences the sealing properties of the fault zone.

Confined by the seismic resolution, geological drawings or data on physical explorations usually simplify the faults as a plane or a curved face, but after fine characterization, many faults are actually deemed fault zones with different widths and play an important role in controlling fault-sealing properties (Fig. 1).
3 Factors Influencing the Sealing Properties of Fault Zones

In sedimentary basins, the thickness of the fault zone usually extends from tens of centimeters to hundreds of meters. The development degree of the fault zone depends on the lithology of two fault walls, the scale of the fault, occurrence, mechanical properties, active history, and its relation with a regional tectonic stress field. Now only the tectonic significance of a fault zone has been cognized, but its effect on liquid movement has been neglected. According to its relation with permeability of fluid (mainly hydrocarbon), the properties of fault zones can be qualitatively classified into three types: penetrative type, non-penetrative type, and transitional type, which shows that fault zones have influence on the sealing properties. The greatest difference between single fault-sealing properties and fault zone-sealing properties is that the former is mainly influenced by such factors as lithologic allocation of two walls of the fault, clay smear, fault plane normal stress, and the physical properties of reservoirs on both sides of the fault. For fault zones, apart from the controlling factors that influenced the single fault-sealing properties, the fault-sealing properties are closely relative to and mainly influenced by the physical properties of the fault zone itself because of the great thickness of the fault zone.

3.1 Fault displacement

For given type of rock, the longer the displacement of epigenetic extension fault, the wider the fault zone (Aydın and Johnson, 1987). Longitudinally, fault angles in different parts of the fault change differently, which leads to the part where the fault angle that becomes smaller bears more gravity component. The mechanical decrease of porosity and permeability then become greater so that rocks modified by the fault will have lower porosity and permeability than that of the original rock, for instance, faulted tectonic rocks in sandstones have lower porosity and permeability than original rocks (Fig. 2), which is good for the formation of fault-sealing properties (Aydın and Johnson, 1987) and hydrocarbon accumulation (Fig. 3). On the part with larger fault angle, the mechanical properties of the movement of the fault are mainly extensional hence the part doesn’t develop tectonic rocks, but the extension space is mostly filled by rocks on both sides of the fault at a later stage (Liu et al., 2006), which makes the fault-sealing properties difficult to determine. The properties are filled with mudstone; it is good for the faults to be sealed (precondition is that the fault zone is closed). The depth of faults discussed in this article are mostly more than 1500 m, in other words, the fault zones bear a relatively large gravity component, so that longer fault displacement indicates that two walls of a fault bear stronger friction and are more probable to form fault gouges, enabling them to be easily sealed. On the earth’s surface, the longer the displacement of epigenetic extension fault, the wider the fault zone and the better the extensional fractions. With a depth of more than 1000 m after the movement of the fault (it may be open in the active state and a short time after that), the fault zone is mainly closed or the fault plane normal stress should be positive. The analysis of production and geological data of hundreds of faults in Shengli oilfield which shows the sealing properties of large extensional faults are far better than that of the small ones. This suggests that the former has a large fault zone width and the probability of the development of mudstones (generally mudstones squashed into both sides of the fault), fault gouge, and fine cataclastic rock is
bigger, which is beneficial for the formation of fault-sealing properties. When studying the Brent oil region in the North Sea, Knott (1993) found that 90% of faults whose fault displacement was bigger than the thickness of reservoirs have sealing properties, thereby realizing the importance of fault displacement.

Many studies by authors including Knott (1993) and Evans (1990) show that the thickness of deformed zones of the faults roughly has a linear relation with the fault displacement, and the thickness is approximately 0.01–0.1 times that of fault displacement. The relation between the thickness of the fault zones and fault displacement is established on the basis of data on faults of Dongxin oilfield, from the Jiyang Depression, from which a positive correlation between the logarithm for fault displacement and the width of the fault zone can be derived (Fig. 4).

It has been proven by plenty of researchers that there are obviously more sealed faults than unsealed ones below the depth of 2500 m (Knott, 1993). The reason is that the deeper the faults are, the greater the overburden static pressure is, the better the fault zone will seal, and the better the fault-sealing properties are. On the contrary, the shallower the faults are, the worse the fault-sealing properties will become. According to physical simulation experiments, pressures borne by clays and sands have a logarithmic relation with porosity (Zheng and Pang, 1989), so it can be held that the increase of depth (increase of overburden forces) has approximately a logarithmic relation with the stratum porosity. With the decrease of this porosity, the entry pressure of rocks increases, which is beneficial for the formation of fault-sealing properties.

3.3 Net-to-gross-ratio of mudstone

In the sequence of clastic rocks, the percentage and distribution of clay rocks indicate the likelihood of plastic smear or clay rocks infusing the fault zone. The value also shows the possibility that sandstones on both sides of the fault could contract each other, but sandstones may not belong to the same unit. The greater the net-to-gross-ratio of sandstones, the poorer the fault seal (Gibson, 1994). A survey in the field shows that sandstones inside the fault zone become thin and may even disappear from top to bottom in the faulted sandstones. That is, on the site where both sides of fault zone are shales, sandstones mostly do not appear inside the faults. While on the site of heavily-bedded sandstones, most sandstone inside the fault is thick. In contrast, in the opposite condition, sandstones are thin. When the net-to-gross-ratio of sandstones decreases, not only will the clayish component increase in the fault zone, but easy deformation of mud rocks block the vacancies among the sands and rubbles, which reduces the permeability of the fault zone and changes it into the sealing zone of hydrocarbon migration. The inner composition of fault zone of larger scale, the Tanlu Fault for example, not only is relevant with lithology of two fault walls, but also has relations with the fillers from extraneous materials and tectonic activation. So this kind of fault is not included in this discussion.

3.4 Fault plane angle

Fault-sealing properties to some degree are controlled by fault plane normal stress. When fault planes bear extensional stress, the fault will become unsealed, but the fault needs to bear fairly large compressional stress to seal, because closing is a necessary condition for faults to seal.
It is very important for evaluating the fault-sealing properties to determine how much the stress borne by the fault plane is. In extensional circumstances, the smaller the fault plane angle, the greater the fault plane normal stress becomes and the better the fault zone will seal, which is beneficial for fault sealing. However, the greater the fault plane angle, the worse the fault-sealing properties will become. Generally, fault angles tend to be small in ductile beds and steep in brittle ones. Although the occurrence of faults has different forms, no matter what form it is, the extensional fault is always close in the gentle part and has good sealing properties, but is open in that steep part and has poor sealing properties. Concave fault planes are gentle at the low part, but steep at the upper part so the sealing properties of the lower part are better than those of the upper part. For convex faults, it is the other way round. The sealing properties of the upper part are better than that of the lower part; the reverse-S fault is gentle in the middle part and steep at both the upper and lower parts so that the middle part has good sealing properties (Chen et al., 1997). Special attention should be paid to extensional faults whose fault plane angle is gentle and mostly develop fault gouges (local stress conditions are compressional); on the contrary, most compressional and compresso-shear faults develop fault breccia (Fig. 2).

In extensional stress circumstances, one of the reasons that why the place with small fault plane angle has good sealing properties could be found by stress analysis. The stress condition where the normal fault developed in is: \( \sigma_3 \) is vertical, \( \sigma_2 \) and \( \sigma_3 \) are horizontal, \( \sigma_2 \) is in accordance with the fault strike and hanging wall slides down along the fault slope (Barnett and Watterson, 1987; Zhu, 1996). That is, the condition favorable for the formation of normal faults is that maximum principle stress (\( \sigma_1 \)) increases in the vertical direction or minimum principle stress (\( \sigma_3 \)) decreases in the horizontal direction. Consequently, horizontal extension and vertical upthrow are the most favorable stress condition to form the normal faults. Through further presumption it certainly can be known that at the place with low fault angle, the fault plane normal stress will increase rapidly compared with other parts. And this part where rocks abrade more strongly is good for the formation of such fault rocks as fault gouge that have fine grains and well-proportioned pore throats, so is good for the formation of fault-sealing properties. This is an important reason for a great amount of hydrocarbon accumulating at the place with small fault angle (Fig. 3).

3.5 Mechanical properties of faults

Different types of faults have different mechanical mechanisms, so they have different abilities of sealing off hydrocarbon. It has been proven by practices that strike-slip faults (torsion faults) has the best sealing properties, while the sealing properties of compressional faults are better, and that of extensional faults are worse. There are two reasons for this: (1) the tightness degree of the fault. The extensional fault is the product of tensile stress and the fault plane is coarse. The compressional fault is formed under the effect of compression, but after the formation of the compressional fault, the elastic rebound created in the stress relaxation stage is the most obvious and this kind of stress release can develop extensional fractures, which is not good for sealing the faults. While strike-slip faults' elastic rebound is not as strong as that of compressional faults, it has good sealing properties (Zhong, 1991). The physical properties of fault zones include: compressional and compresso-shear faults that usually develop compressional fault rocks that are dense and have closely ranged grains, extremely non-developed fractures and cavities, as well as bad poroperm characteristics, and in particular, fault gouges or mylonites developed within them have worse poroperm characteristics and good sealing properties. Tensile and tenso-shear faults mainly develop fault breccias and coarse cataclasites that have irregular shapes, clear-edge angles, miscellaneous sizes, astatism, loose consolidation, good poroperm characteristics, and bad sealing properties.

4 Fault Zone-Sealing Mechanisms

If the entry pressure in the fault zone is stronger than that of the hydrocarbon migration and both walls of the fault contact each other with thick fault zone, the fault zone can prevent hydrocarbon from parallel migration (Lun and Fu, 2002). Entry pressures are pressures needed for compelling the non-wetting liquid phase to pass the biggest connected pore throats of sealed zones (Smith, 1966; Schowalter, 1979; Watts, 1987). Consequently, whether the fault zone can seal hydrocarbon is relevant to the pore throat radius of the fault zone-sealing materials.

Many researchers judge the sealing quality by capillary entry pressure and hold that the entry pressure changes with different liquid–rock systems. The method adopted in this essay is to use the biggest radius of interconnected pore throats (inversely proportional to the displacement pressure) to indicate the sealing quality. The universal equation of the height of the sealable hydrocarbon column (\( h \)) and the pore throat radius (\( r \)) is (Berg, 1975):

\[
h = \frac{500 \gamma \rho_s}{(\rho_w - \rho_s)g}
\]

where \( h \) is the height of hydrocarbon (m), \( \gamma \) is the tensile force of hydrocarbon–water interface (N/m), \( g \) is gravitational acceleration (m/s²), \( \rho_s \) is the density of water
in the reservoir \((kg/m^3)\), \(\rho_s\) is the density of hydrocarbon in the reservoir \((kg/m^3)\), and \(r\) is the radius of the pore throat in the fault zone (\(\mu m\)).

These suggest that the ability of the fault zone to seal hydrocarbon depends on two aspects: (1) whether the fault zone could form a continuous sealing zone in space; and (2) whether pore throats connecting fault zones are small enough to seal hydrocarbon, both of which are indispensable. It is obvious that fault gouges have better sealing properties than that of fault breccia.

5 Quantitative Study on Fault Zone-Sealing Properties

At present, only qualitative interpretation for effects that fault zone exert on the movement of fluid is given. The lack of quantitative formula forecasting fault zone-sealing abilities is absent, restricting geological workers in evaluating fault-sealing properties. The concept of fault zone-sealing potential is proposed and is associated with a relevant characterization formula developed by Shi (2004). However, the formula is not based on a great deal of statistical data. Therefore, further analysis is conducted here, suggesting that the fault zone-sealing potential is a comprehensive characterization parameter for the fault zone-sealing hydrocarbon. According to those factors influencing the fault-sealing properties mentioned earlier, fault displacement, the net-to-gross-ratio of mudstone, depth, fault plane angle, and fault properties have important effects on fault-sealing properties. On the basis of the features that fault displacement has a logarithmic relation with the thickness of the fault zone, as is the case between depth and strata porosity, logarithms for the fault displacement and depth were chosen as the values of thickness of fault zones and stratum porosity.

The sealing properties of fault zones are controlled by the key factors mentioned earlier. In order to demonstrate that there are many factors influencing sealing properties and the fault zone sealing, a quantitative formula of fault zone-sealing potential is established here by adopting the fuzzy comprehensive evaluation methodology. It is necessary to point out that through this method, comprehensive effects from all factors are taken into consideration, and values of all factors depend on the cognitions of practical geological conditions that geologists have, so geological knowledge is still the premise and also a crucial step of the study.

5.1 Mathematical model of fuzzy comprehensive evaluation

Suppose the set of all evaluation factors considered is: $U=(U_1, U_2, \ldots, U_m)$ \(i=1, 2, \ldots, m\) is the evaluation factors, and \(m\) is the integer.

In the fuzzy comprehensive evaluation for fault-sealing properties, five key factors are taken into consideration, that is: $U_1$ is the logarithm of vertical fault displacement, $U_2$ is the net-to-gross-ratio of mudstone, $U_3$ is the fault mechanical properties, $U_4$ is the stratum angle, and $U_5$ is the logarithm of depth.

Suppose the single-factor evaluation matrix is $R=(r_{ij})$ \(m \times n\), where $r_{ij}$ is the membership degree for the factor number $i$ to comment number $j$. Suppose the weighing of each factor in the single factor set is $A=(a_1, a_2, \ldots, a_m)$, then the fuzzy comprehensive equation is:

$B=AoR$ \(..................(3)\)

where $B=(b_1, b_2, \ldots, b_n)$ is the result of the comprehensive evaluation and $o$ is the fuzzy operator.

5.2 Establishment of a single-factor evaluation matrix

The membership function chosen in the work falls into two forms:

5.2.1 Discrete membership function

$\mu(x)=\mu(0, \mu_1, \mu_2, \ldots, 1)$ \(..................(4)\)

where $0<\mu_1, \mu_2, \ldots, \mu_n<1$.

5.2.2 Continuous membership function

$\mu(x)=f(x)$ \(..................(5)\)

For the qualitative index, such as fault properties, the discrete membership function is adopted to determine the evaluation membership degree of each single factor, while for the quantitative index, such as the net-to-gross-ratio of mudstone, the continuous membership function is adopted to calculate the evaluation membership degree of each single factor. In practical work, it is a fuzzy process to determine the membership degree in which a plethora of statistical data is needed as a basis. In this study, all faults in many oil-bearing and non-oil-bearing blocks are anatomized, which made the evaluation of membership scientifically and universally meaningful. The specific process is listed in Table 1.

5.3 Establishing weighing vector

The evaluation matrix analysis is adopted to determine weighing factors. The basic idea of this method is that evaluation factors of number $m$ are arranged to a set of $m$ exponential evaluation matrixes, and through pairwise comparisons, the factors in the matrix can be determined on the basis of the importance degree of each factor. Then, the biggest characteristic roots of the evaluation matrix and corresponding characteristic vector are calculated. This characteristic vector is the importance degree.
Table 1 Membership degree for the controlling factors of fault zone-sealing properties

<table>
<thead>
<tr>
<th>Influencing factor</th>
<th>Evaluation standard</th>
<th>Statistic number</th>
<th>Number sealed faults</th>
<th>Membership degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Logarithm of vertical fault displacement</td>
<td>The larger the fault throw, the better the fault-sealing properties</td>
<td>Calculation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net-to-gross-ratio of mudstone</td>
<td>Fault with high net-to-gross-ratio of mudstone has better sealing properties</td>
<td>Calculation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault properties</td>
<td>Extensional fault</td>
<td>60</td>
<td>30</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Compressional fault</td>
<td>50</td>
<td>35</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Shear fault</td>
<td>50</td>
<td>45</td>
<td>0.9</td>
</tr>
<tr>
<td>Stratum angle</td>
<td>Extensional fault: the smaller the fault angle, the greater the fault-sealing properties</td>
<td>Calculation</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Compressional fault: the greater the fault angle, the better the fault-sealing properties</td>
<td>Calculation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Logarithm of depth</td>
<td>The deeper the stratum, the relatively better the fault-sealing properties become</td>
<td>80</td>
<td>64</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 2 Degree of controlling factors

<table>
<thead>
<tr>
<th>Grades for importance of ( u_i ) in comparison with ( u_j )</th>
<th>( f_{ui}(u_j) )</th>
<th>( f_{ui}(u_i) )</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u_i ) and ( u_j ) are &quot;of equal importance&quot;</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>( u_i ) is &quot;a bit more important than&quot; ( u_j )</td>
<td>3</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>( u_i ) is &quot;obviously more important than&quot; ( u_j )</td>
<td>5</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>( u_i ) is &quot;strongly more important than&quot; ( u_j )</td>
<td>7</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>( u_i ) is &quot;absolutely more important than&quot; ( u_j )</td>
<td>9</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Degree of ( u_i ) compared with ( u_j ) is between every 2 grades</td>
<td>One of 2, 4, 6, 8</td>
<td>1</td>
<td>Medium value of every 2 grades' values</td>
</tr>
</tbody>
</table>

Coefficient \( a_i \) of the controlling factor that is required. The calculating formula is as follows:

\[
b_{ij} = \frac{f_{ui}(u_i)}{f_{ui}(u_j)} \quad (i, j = 1, 2, 3, 4, 5) \quad \ldots \quad (6)
\]

where \( f_{ui}(u_i) \) shows how important the factor \( u_i \) is compared with the factor \( u_j \). The method that determines the values of \( f_{ui}(u_i), f_{ui}(u_j) \) is listed in Table 2. For example, if factor \( u_i \) is considered obviously more important than \( u_j \), then \( f_{ui}(u_i) = 5, f_{ui}(u_j) = 1 \). It can be seen that the determination of the weighing vector subjectivity exists, but subjective knowledge is built up on the basis of analyzing plentiful objective examples.

Through the anatomy of plenty of faults and experience for many years, the relative importance degree among various factors influencing the fault-sealing properties were obtained after the pairwise comparisons.

\[
\begin{align*}
&f_{u1}(u_2) = 9, f_{u2}(u_1) = 1, f_{u3}(u_2) = 3, f_{u2}(u_3) = 1, f_{u1}(u_3) = 3, f_{u3}(u_1) = 1, f_{u4}(u_5) = 1, f_{u5}(u_4) = 3, f_{u5}(u_2) = 1, f_{u4}(u_2) = 1, f_{u5}(u_3) = 1, f_{u3}(u_5) = 1, f_{u2}(u_1) = 1, f_{u3}(u_1) = 7, f_{u1}(u_3) = 1, f_{u2}(u_5) = 3.
\end{align*}
\]

where, \( u_i, i = 1, 2 \ldots 5 \) separately represent five factors considered in the fault-sealing property evaluation. The evaluation equation structured by \( b_{ij} \) of number \( m \times m \) is:

\[
\begin{bmatrix}
1 & 1 & 1 & 1 & 1 \\
9 & 3 & 3 & 3 & 3 \\
9 & 1 & 5 & 5 & 9 \\
3 & 1 & 3 & 7 & 7 \\
3 & 1 & 3 & 7 & 7 \\
1 & 1 & 1 & 1 & 1 \\
3 & 9 & 7 & 3 & 3
\end{bmatrix}

B =
\begin{bmatrix}
1 & 1 & 1 & 1 & 1 \\
9 & 3 & 3 & 3 & 3 \\
9 & 1 & 5 & 5 & 9 \\
1 & 1 & 1 & 1 & 1 \\
3 & 9 & 7 & 3 & 3
\end{bmatrix}
\]

\[
\begin{bmatrix}
1 & 1 & 1 & 1 & 1 \\
9 & 3 & 3 & 3 & 3 \\
9 & 1 & 5 & 5 & 9 \\
3 & 9 & 7 & 3 & 3
\end{bmatrix}
\]

The calculation of the biggest characteristic root \( \lambda_{max} \) of the evaluation matrix, that is, the biggest " \( \lambda \)" meeting the formula was based on:

\[
\begin{bmatrix}
1 & 1 & 1 & 1 & 1 \\
9 & 3 & 3 & 3 & 3 \\
9 & 1 & 5 & 5 & 9 \\
3 & 9 & 7 & 3 & 3
\end{bmatrix}
\]

\[
B =
\begin{bmatrix}
1 & 1 & 1 & 1 & 1 \\
9 & 3 & 3 & 3 & 3 \\
9 & 1 & 5 & 5 & 9 \\
3 & 9 & 7 & 3 & 3
\end{bmatrix}
\]

Equation 9 gives \( \lambda_{max} = 3.7276 \), and calculates the characteristic vector \( \xi \) as \( \lambda_{max} = 3.7276 \), that is, the solution of the subsystem of linear equations according to the following equation:

\[
\begin{align*}
(1 - 3.7276)x_1 + \frac{1}{9} x_2 + \frac{1}{3} x_3 + \frac{1}{3} x_4 + 3 x_5 & = 0 \\
9 x_1 + (1 - 3.7276) x_2 + 5 x_3 + 5 x_4 + 9 x_5 & = 0 \\
3 x_1 + \frac{1}{3} x_2 + (1 - 3.7276) x_3 + 3 x_4 + 7 x_5 & = 0 \\
3 x_1 + \frac{1}{3} x_2 + \frac{1}{3} x_3 + (1 - 3.7276) x_4 + 3 x_5 & = 0 \\
\frac{1}{3} x_1 + \frac{1}{9} x_2 + \frac{1}{7} x_3 + \frac{1}{3} x_4 + (1 - 3.7276) x_5 & = 0
\end{align*}
\]
where $x_i$ is chosen as the importance degree coefficient $a_i$ of factor $u_i$.

$$A=(x_1, x_2, \ldots, x_m) = (a_1, a_2, \ldots, a_m) \quad \ldots \ldots \ldots \ldots \ldots (11)$$

gives $x_1=0.00373$, $x_2=0.06318$, $x_3=0.01840$, $x_4=0.00884$, and $x_5=0.00141$

$$\zeta=(0.00373, 0.06318, 0.01840, 0.00884, 0.00141) \quad \ldots \ldots \ldots \ldots \ldots (12)$$

when $\sum x_i > 1$, the characteristic vector $\zeta=(x_1, x_2, \ldots, x_m)$ must be normalized.

$$\zeta = \left( \frac{x_1}{\sqrt{\sum x_i^2}}, \frac{x_2}{\sqrt{\sum x_i^2}} , \ldots, \frac{x_m}{\sqrt{\sum x_i^2}} \right) \quad \ldots \ldots \ldots \ldots \ldots (13)$$

Normalization of the characteristic vectors gives: (0.039, 0.661, 0.193, 0.093, 0.015).

Then the set of weighing coefficient of each factor influencing fault-sealing properties is obtained:

$$A=(0.039, 0.661, 0.193, 0.093, 0.015).$$

It can be seen that the most important factors influencing the fault zone-sealing properties are the net-to-gross-ratio of mudstone, fault angle, and fault properties. The comprehensive evaluation formula of the fault zone-sealing potential is then further established (Fig. 5):

$$FZSP=\log(L) \times 0.039 + (1-W) \times 0.661 +$$

$$F \times 0.093 + \cos \theta \times 0.193 + \log(H) \times 0.01 \quad \ldots \ldots \ldots \ldots \ldots (14)$$

where $F$ is the fault properties, $H$ is the depth (m), $L$-vertical fault displacement (m), $W$ is the net-to-gross-ratio of sandstone, and $\theta$ is the fault plane angle. All parameters in the formula are the values obtained after the normalization.

6 Fault Zone-Sealing Potential of the Xin 68 Fault

The Xin 68 Fault is located on the northern part of the Xin 68 faulted block in the Dongxin oilfield. It is of a large scale, has had a long active period, and its displacement is located at the Dongying Formation with a range of approximately 100–200 m. It can be seen from the seismic profile that the fault zone in the Xin 68 Fault has a great width and influences fault-sealing properties, where a great amount of hydrocarbon accumulated (Fig. 6).

On the basis of the fault zone-sealing potential formula established above, the sealing properties of the Xin 68 Fault in the Dongxin oilfield were evaluated. Fault displacement and strata depth were read directly on the reservoir profile. The net-to-gross-ratio of mudstone was obtained by well logging and the electrical logging curve. The fault plane angle is obtained mainly by seismic profile, and the fault mechanical properties of the Xin 68 Fault, analyzed by associating the regional geological setting, ought to be extensional and does not have too many changes longitudinally. Because fault-sealing properties in the vertical direction vary greatly, the different depth ranges were calculated separately (Table 3).

A referenced standard is made based on the geological condition of this region and experiences, that is, when $b_2<0.6$, the fault is a hydrocarbon-migrating fault; when $0.7>b_2>0.6$, it is fault with bad-sealing conditions; when

| Fault | Depth (m) | N (%) | SFV (%) | Displacement (m) | NGRM | SFV (%) | N (%) | SFV (%) | FP | N (%) | SFV | FA (%) | N (%) | SFV | Comprehensive value ($b_2$) |
|-------|-----------|-------|---------|------------------|------|---------|-------|---------|----|-------|------|-------|-------|---------------------|
| Xin 68 | 1400 | 0.80 | 0.012 | 95 | 0.85 | 0.033 | 30 | 0.70 | 0.463 | 1 | 1 | 0.093 | 55 | 0.57 | 0.110 | 0.711 |
| | 1450 | 0.82 | 0.012 | 140 | 0.92 | 0.036 | 35 | 0.81 | 0.535 | 1 | 1 | 0.093 | 42 | 0.74 | 0.143 | 0.819 |
| | 1500 | 0.86 | 0.013 | 155 | 0.95 | 0.037 | 40 | 0.93 | 0.615 | 1 | 1 | 0.093 | 30 | 0.87 | 0.168 | 0.926 |
| | 1550 | 0.89 | 0.013 | 165 | 0.96 | 0.037 | 43 | 1.00 | 0.661 | 1 | 1 | 0.093 | 25 | 0.91 | 0.176 | 0.980 |
| | 1600 | 0.91 | 0.014 | 180 | 0.97 | 0.038 | 42 | 0.97 | 0.641 | 1 | 1 | 0.093 | 55 | 0.57 | 0.110 | 0.896 |
| | 1650 | 0.94 | 0.014 | 195 | 0.98 | 0.038 | 38 | 0.88 | 0.582 | 1 | 1 | 0.093 | 55 | 0.57 | 0.110 | 0.837 |
| | 1700 | 0.97 | 0.015 | 200 | 0.99 | 0.039 | 36 | 0.84 | 0.555 | 1 | 1 | 0.093 | 55 | 0.57 | 0.110 | 0.812 |
| | 1750 | 1.00 | 0.015 | 210 | 1 | 0.039 | 40 | 0.93 | 0.615 | 1 | 1 | 0.093 | 54 | 0.59 | 0.114 | 0.876 |

0.8 > b > 0.7, it is fault with moderate sealing conditions; and when b > 0.8, it is fault with good sealing conditions.

The fault-sealing properties of the Xin 68 Fault have great variability vertically (Fig. 7). With increased depth, the seal intensity changes greatly, which reflects the complexity of the fault seal, but b 1 are all more than 0.7, which shows that the fault is sealed under present conditions. The best evidence is that a large amount of hydrocarbon was sealed by Xin 68 (Fig. 6).

7 Conclusions

In conclusion, a fault is not simply a plane, but a zone consisting of a series of broken planes or secondary faults. The greater the scale of faults, the wider and more complex the fault zone becomes. The fault zone itself has great influence on the fault-sealing properties.

The sealing of hydrocarbon by fault zones depends on whether the fault zone can form a continuous seal and whether the pore throats connecting those fault zones are small enough to seal the hydrocarbon.

The primary controlling factors influencing fault zone-sealing properties are the net-to-gross-ratio of mudstone, fault plane angle, the mechanical properties of faults, fault displacement, and depth. The characterization formula of the fault zone-sealing potential is then established by using a great amount of practical statistical data as well as fuzzy comprehensive evaluation. The greater the value of the fault zone-sealing potential, the better the fault-sealing will become.

The fault-sealing properties of the Xin 68 Fault have undergone great changes vertically. With the increase in depth, the sealing degree of the Xin 68 Fault changes greatly, which reflects the complexity of fault-sealing properties is in accordance with the facts and also proves that it is feasible to study the fault-sealing properties by using the fault zone-sealing potential.

Acknowledgements

These research results are part of the project “Study on Technology to Increase the Recovery Ratio in Oilfields with Complex Fault Block” (P01035), a Science and Technology Promotion Project in the Tenth Five-Year Plan of SINOPEC. The authors wish to thank the Shengli Petroleum Administration Bureau for providing excellent working conditions and permission to publish this paper.

Manuscript received May 29, 2008
accepted Sept. 16, 2008
edited by Fei Hongcai

References


