The quantitative research and application of the fault lateral sealing ability of structural traps in Weixinan Sag

Kui Chen, Jiaxiong Zhou, Xibing Yang, Jun Gan, Lin Hu, Zhenzhen Wang, Anqi Li, Ming Li
Zhanjiang Branch, CNOOC China Limited, Zhanjiang, China

*Corresponding author e-mail: chenkui3@cnooc.com.cn

Abstract. The Weixinan sag in Beibuwan basin experienced strong tectonic movement during late Oligocene, which formed a number of fault-block and fault-nose structural traps. The fault sealing ability, especially the fault lateral sealing ability, plays an important role in the process of structural trap accumulation. The fault lateral sealing ability mainly depends on the AFPD between the material in the fault zone and the target plate. This paper considers the contribution of two fault plates to the muddy content of the fault zone and quotes the geological model of $R_m$, which can quantitatively evaluate the fault sealing ability. Through analysing the shale content ($R_m$) and mudstone smear factor (SSF) of the drilled wells of the Member 3 of Weizhou formation in A oilfield, the quantitative chart of $R_m$-SSF is established. A quantitative prediction technology of the fault sealing oil column height is established by using the principle of the equilibrium between the appearance of fault press difference (AFPD) and the parallel stratigraphic phase of the resultant force. This paper applies the quantitative analysis technology of the fault lateral sealing ability to the A oil field in the WeiXinan sag, and solves the problem why the oil-water interface of each fault block is inconsistent in the A oil field.

1. Introduction
Faults play an important role in the process of oil migration and accumulation to structural traps [1-7]. The fault sealing state is not constant in different geological and historical periods, alternating between open and close. When the fault is open, it has the effect of transporting oil; when the fault closes, it has the effect of sealing oil. The key factor to determine the fault lateral sealing ability is the difference of permeability on both plates of the fault [1-2]. When the displacement pressure of the fault zone or the opposite plate is greater than the target plate, the fault has the effect of sealing oil. On the contrary, the oil loses through the fault zone when the fault is open [8].

The lateral sealing analysis of control faults is very important in the main structural traps of the Weixinan sag, Beibuwan basin [9-12]. The current researches of the fault lateral sealing analysis focus on the qualitative or semi-quantitative analysis methods, such as the analysis of the connection relationship of sandstone and mudstone between the two plates (Allen graphic method) and the analysis of mudstone smear factor (SSF) [13-16]. The evaluation accuracy of such methods is low. However, the quantitative analysis technology of fault lateral sealing with high evaluation accuracy is rarely used in Weixinan sag [17]. In order to improve the accuracy of the fault lateral sealing, the “shale content” ($R_m$)
geological model is introduced by considering the contribution of the two fault plates to the mud-stratum ratio of fault zones [18], and the relationship between $R_m$ and SSF is comprehensively analyzed. The $R_m$-SSF quantitative chart of the fault lateral sealing is established. A quantitative prediction technology of the oil column height in structural traps is established by applying the principle of the equilibrium between the appearance of fault press difference (AFPD) and the component force paralleled to strata of the resultant force. This paper applies the $R_m$-SSF quantitative chart of the fault lateral sealing and the quantitative prediction technology of the oil column height to the A oil field in the Weixinan sag.

2. The quantitative analysis technology of fault lateral sealing ability

The quantitative analysis technology of fault lateral sealing ability mainly includes the $R_m$-SSF quantitative chart to assess fault lateral sealing ability and the quantitative prediction technology of the oil column height. The $R_m$-SSF quantitative chart can ascertain the fault lateral sealing ability. The quantitative prediction technology of the oil column height focuses on the potential area with good fault lateral sealing ability and predicts the height of the oil column. The basis of the two quantitative analysis technologies is the AFPD analysis technology.

2.1. AFPD analysis technology

The fault lateral sealing ability mainly depends on AFPD between the material in the fault zone and the target plate. AFPD is the difference between the displacement pressure of the fault zone ($P_f$) and the displacement pressure of the target plate ($P_t$) [8]. When $P_f > P_t$, oil can’t break through the fault and the fault lateral sealing ability is good (Figure 1); When $P_f < P_t$, oil can break through the fault and the fault lateral sealing ability is poor (Figure 1). The key factor influencing for the fault lateral sealing ability is the filling material in the fault zone. When the mud-stratum ratio of fault zones is higher, the AFPD is higher, and the fault lateral sealing ability is better [19].

![Figure 1. The sketch map of fault lateral sealing.](image)

Yielding et al [17] counted AFPD on both faults sides of drilled reservoirs in basins such as the North Sea, Norway, Mexico, Vietnam, and Thailand. And by searching for the enclosure line between the fault sealing data area and the data blank area, Yielding established the relationship between AFPD and fault mud ratio SGR (Shale gouge ration):

$$AFPD = 10^{SGR/d-c}$$

In the formula: AFPD unit is MPa, $c$ depends on the maximum depth of the fault, when depth< 3.0 km, $c=0.5$; when depth between 3.0km and 3.5km, $c=0.25$; when depth> 3.0 km, $c=0$. SGR is the ratio of the total thickness of the muddy matter in the mudstone and sandstone to the fault throw; It is a common parameter for calculating the mud-stratum ratio of fault zones [20], $SGR = \frac{\sum_{i=1}^{n} h_{1i} + \sum_{i=1}^{n} C_{1i}}{L}$; $h_{1i}$ is the number i set of mudstone thickness of the opposite plate, the unit is m; $C_{1i}$ is the
number i set of the muddy matter in the sandstone of the opposite plate, the unit is m; and L is the fault throw, the unit is m. D is constant. SGR/d is the slope of the enclosure line.

This paper uses $R_m$ instead of SGR and establishes the relationship between AFPD and $R_m$:

$$\text{AFPD} = 10^{(\frac{R_m}{d}-c)} \quad (2)$$

2.2. $R_m$-SSF quantitative chart technology

The advantage of SGR lies in the comprehensive consideration of the mud ratio of mudstone and sandstone in fault zone rocks. However, the SGR only considers the contribution of opposite plate to mud-stratum ratio without considering the contribution of target plate.

For the insufficient of SGR, the $R_m$ geological model is introduced to consider the contribution of the two fault plates to mud-stratum ratio of fault zones [8, 18]. Assuming that the lithology of the fault zone is average distributed, and the mudstone thickness of the two fault plates contributes to the mud ratio of fault zone. Based on this principle, a geological model of the relationship between mudstone of the two plates and mud-stratum ratio of fault zones is established (Figure 2):

$$R_m = \frac{h}{H+L} = \frac{\sum h_{1i} + \sum h_{2j}}{2(H+L)} \quad (3)$$

In the formula: $h$ is the cumulative mudstone thickness of both fault plates, the unit is m; $H$ is the thickness of the broken strata, the unit is m; $L$ is the fault throw, the unit is m; $h_{1i}$ represents the number i set of mudstone thickness of target plate, the unit is m; $h_{2j}$ represents the number j set of mudstone thickness of opposite plate, the unit is m.

![Figure 2. The muddy content of fillings in fault zone ($R_m$).](image)

Another parameter is SSF which indicates the continuity degree of the mudstone smear [21]. SSF is positively related to the fault throw and is negatively related to the thickness of mudstone in the course of fault zone formation. The smaller the SSF, the better the continuity degree of the mudstone smear:

$$\text{SSF} = \frac{L}{\sum h_{2j}} \quad (4)$$

Considering the different effects of $R_m$ and SSF on fault lateral sealing ability, a quantitative chart of $R_m$-SSF fault lateral sealing ability is established with $R_m$ as horizontal coordinate and SSF as ordinate coordinate. First of all, taking the F, G, and H oil fields in the eastern part of No. 2 fault zone in Weixinan sag as an example, $R_m$, SSF of multiple faults, multiple lines are obtained by analyzing the main controlling fault lateral sealing ability of the drilled traps. And the eastern part of the No. 2 fault zone $R_m$-SSF quantitative chart is established (Figure 3). Then, the $R_m$-SSF quantitative chart is divided into
oil zone, transition zone and water zone which bases on oil-water interface at each line, and is applied to the quantitative prediction of fault lateral sealing ability in potential area (Figure 3).

Figure 3. The $R_m$-SSF chart of fault lateral sealing ability for eastern part of No.2 fault zone in Weixinan sag.

2.3. Quantitative prediction technology of oil column height

Based on the $R_m$-SSF quantitative analysis of the fault lateral sealing ability, the oil column height was quantitatively predicted by selecting the trap of good fault lateral sealing ability. The oil column height depends on the fluid quality of the trap and AFPD [22-24] (Figure 4).

$$H = \frac{AFPD}{(\rho_w - \rho_o)\sin\theta} = \frac{10^{(R_m-0.5)}}{(\rho_w - \rho_o)\sin\theta}$$  \hspace{1cm} (5)

In the formula: $H$ represents prediction of oil column height, the unit is m; $\rho_o$ represents the density of oil, the unit is kg/m$^3$; $\rho_w$ represents the density of water, the unit is kg/m$^3$; $\theta$ is the inclination of the formation, the unit is $\degree$; $g$ represents gravitational acceleration, $g=9.8m/s^2$.

Figure 4. Quantitative prediction of oil column height.
3. Application of technologies
The research area A oil field is located in the eastern part of No. 1 fault zone in Weixinan sag of Beibuwan basin in the northern part of the South China Sea (Figure 5). A oil field mainly develops the main faults in the strike of east-west and the branch faults in the strike of south-north. The main faults, which are long-term active, break through the Paleogene layer. The branch faults, which are lately-active faults, break through the Weizhou formation and form in the Oligocene. The sedimentary evolution from the Member 3 of Liushagang (L3) formation to the Member 3 of Weizhou (W3) formation experiences the alluvial fan deposition of L3 formation, the deep lake facies deposition of L2 formation, and the fan delta-shallow lake deposition of W3 formation. Overall, the process is transgression-regressive. Hydrocarbon source rock is deep lake facies oil shale in L2 formation, and forms multiple sets of reservoir-cap rock assemblages [25]. And drilling shows that it has the oil characteristics and has great resource potential.

3.1. Problems and countermeasures of research area
The A oil field develops structural traps, such as fault nose trap, which is controlled by fault F1. It is divided into S1, S2, S3, and S4 fault block traps by the branch faults F2, F3, F4. Because the fault throw of each branch fault is small, the conventional analysis shows that the branch fault lateral sealing ability is poor, and the S1, S2, S3, and S4 fault block traps are the same reservoir and have the same oil-water interface. However, the drilled wells show that the fourth oil series (W3Ⅳ) and fifth oil series (W3Ⅴ) for W3 formation of S2 drilled oil layer, and the third oil series for W3 formation (W3Ⅲ) drilled water layer. The W3Ⅲ of S3 drilled thin oil layer, and W3Ⅳ and W3Ⅴ drilled water layer. The W3Ⅴ of S4 drilled oil layer, and the W3Ⅲ and W3Ⅳ drilled water layer. Actual drilling results show the different fault blocks contained different oil and water layers, and the same oil series has different oil-water interface (Figure 6), it indicates that the branch faults F2, F3, F4 have good fault lateral sealing ability, and the actural drillings results are different from conventional understanding.
In order to solve this problem, $R_m$-SSF quantitative chart technology and oil column height quantitative prediction technology are applied to analyze the fault lateral sealing characteristics for W3 formation of developed blocks in A oilfield. And then the oil column height is predicted. The fault lateral sealing ability of branch fault F2, F3 and F4 are determined by comparing oil column height predicted with oil column height drilled. And the maximum oil column heights of S2, S3 and S4 are predicted, which solve the problem of oil-water interface inconsistence between S2, S3 and S4.

3.2. The application of $R_m$-SSF quantitative chart technology

$R_m$ and SSF values are sensitive factors that affect fault lateral sealing ability. Based on the main faults data of developed blocks in A oilfield, $R_m$-SSF quantitative chart of fault lateral sealing ability is established with $R_m$ as horizontal coordinate and SSF as ordinate coordinate (Figure 7). And then the quantitative analysis of the fault lateral sealing ability is carried out.

$R_m$ and SSF have the following relationship:

- The oil zone: $R_m > 0.64$, SSF < 2. Statistical results show that there are 22 oil sites (56%) and 17 potential sites (44%) in the oil area. The ratio of oil sites is dominant and the statistical results are highly credible.
- The transition zone: $0.59 < R_m < 0.64$, SSF < 2.3 or $R_m > 0.64$, 2 < SSF < 2.3. The water zone: $R_m < 0.59$ or SSF > 2.3.
Fault lateral sealing ability of S2 is researched, and it is found that the traps of W3 I, W3 IV and W3 V oil series have good fault lateral sealing ability, and the high site of W3 II and W3 III oil series structural traps have good fault lateral sealing ability. The W3 I and W3 V oil series of S3 have good fault lateral sealing ability, and the high site of W3 III and W3 IV oil series structural traps have good fault lateral sealing ability, while the trap of W3 II oil series has poor fault lateral sealing ability. As to the S4, the trap of W3 V oil series has good fault lateral sealing ability, and the high site of W3 III and W3 IV oil series structural traps have good fault lateral sealing ability, while the trap of W3 I and W3 II oil series have poor fault lateral sealing ability (Figure. 7). These understandings above are consistent with the drilling results of the S2, S3, and S4 blocks, and conformed to the understanding of the geological reservoir. The understandings above prove that the branch faults F2, F3 and F4 between the S2, S3, and S4 blocks have good fault lateral sealing ability. Different fault block traps are different reservoirs, which have different oil-water systems.

3.3. The application of oil column height quantitative prediction technology
According to the relationship between AFPD and oil column height, the oil column height of each oil series in the developed blocks is calculated. Because the W3 V oil series of S2 drilled the oil-water interface, taking its Rm and the oil column height as reference values. Through the formula (5), d is calculated to 0.1208. Based on the reservoir analysis data of the oil field, $\rho_w = 1000 \text{ kg/m}^3$, $\rho_o = 779.7 \text{ kg/m}^3$.

The oil column height of each oil series in the developed blocks is calculated through the formula (5). Because the fault lateral sealing characteristics of different blocks and different oil series are different, the Rm value bases are different:

1) When all sample points are within the oil zone, the minimum value of Rm is selected according to the short plate effect.

2) When a sample point is within the oil-water interface, it’s Rm is selected for calculation according to the principle of force balance.

3) When the sample points are distributed in both the oil zone and the water zone, if high site of structural traps are located in the water zone, there are no reservoirs; If high site of structural traps are located in the oil zone, the minimum value of Rm is chosen.
The $R_m$ selected by each oil series in the development zone are substituted to the formula (5), and obtain the predicted oil column height (table.1). Compared with the results of drilling, these understandings above are conformed to the understanding of the geological reservoir (Figure. 8). The results show that the predicted oil column height of the same oil series for different fault blocks are different, which further solve the problem of oil-water interface inconsistence between S2, S3 and S4.

**Table 1.** Prediction of the oil column height for developed blocks in A oilfield.

| Block | Oil series | $R_m$ | SSF | Formation inclination $\theta$ | Oil column height m | Prediction of oil column height m | Profile of drilled well |
|-------|------------|-------|-----|-------------------------------|---------------------|----------------------------------|-------------------------|
| S2    | W3I        | 0.64  | 1.32 | 14.92                         | 108                 | 30                               | The water layer, closed height of A-S1 well is 145 |
|       | W3II       | 0.58  | 2.15 | 17.72                         | 30                  |                                   | The water layer, closed height of A-S1 well is 170 |
|       | W3III      | 0.58  | 1.80 | 16.15                         | 34                  |                                   | The water layer, closed height of A-A2hSa well is 50 |
|       | W3IV       | 0.69  | 1.73 | 18.01                         | 244                 |                                   | The oil layer, oil column height of A-S1 well is 225.8m |
|       | W3V        | 0.64  | 1.95 | 18.68                         | 84                  |                                   | Reference layer of d |
| S3    | W3I        | 0.69  | 1.22 | 15.35                         | 268                 | 264                              | No well drilled this oil series |
|       | W3II       | 0.59  | 1.60 | 14.38                         | 43                  |                                   | No well drilled this oil series |
|       | W3III      | 0.60  | 1.61 | 12.18                         | 28                  |                                   | The oil layer, oil column height of A-A3 well is 11.5m |
|       | W3IV       | 0.60  | 1.99 | 14.31                         | 10                  |                                   | The water layer, closed height of A-A3 well is 60 |
|       | W3V        | 0.69  | 2.24 | 15.58                         | 292                 |                                   | The oil layer, oil column height of A-A3 well is 80m |
| S4    | W3I        | 0.55  | 1.52 | 19.77                         | 16                  |                                   | The water layer, closed height of A-A1hSa well is 20 |
|       | W3II       | 0.57  | 1.93 | 16.87                         | 25                  |                                   | The water layer, closed height of A-A1hSa well is 30 |
|       | W3III      | 0.58  | 1.87 | 15.67                         | 38                  | 110                              | The water layer, closed height of A-A1hSa well is 50 |
|       | W3IV       | 0.59  | 1.85 | 16.45                         | 43                  |                                   | The water layer, closed height of A-A1hSa well is 50 |
|       | W3V        | 0.65  | 2.25 | 17.36                         | 120                 |                                   | The oil layer, oil column height of A-A1hSa well is 85m |

**Figure 8.** Comparison of predicted column height and drilled height of developed block in A oilfield.
4. Conclusion

$R_m$-SSF quantitative chart technology and oil column height quantitative prediction technology are applied to analyze the fault lateral sealing characteristics for W3 formation of developed blocks in A oil field. Different fault block traps have different fault lateral sealing ability and different predicted oil column height, which are confirmed to drilling results. It shows that branch faults can also play an important role in sealing oil. The key influencing factors of fault lateral sealing ability are $R_m$ and SSF. The fundamental research of fault lateral sealing ability is AFPD, which is closely related to $R_m$. The larger of the $R_m$, the smaller of the SSF and the greater of the AFPD, the fault lateral sealing ability will be better, and the oil column height will be greater. The mudstone is extraordinarily developed in the research area, mudstone smear factor is strong, and the $R_m$ of the fault zone is large, so the research area has good fault lateral sealing ability, and the oil column height is predicted to be large.

Through the study of the quantitative analysis of the fault lateral sealing ability and its application in A oilfield, the conclusions are drawn:

1) Considering the contribution of the two fault plates to the mud ratio of the fault zone, the $R_m$ geological model is introduced, and $R_m$-SSF quantitative chart of fault lateral sealing ability is established, which improves the accuracy of the fault lateral sealing ability analysis.

2) According to the principle of reaching the maximum oil column height when the appearance of fault pressure of the two fault plates are balanced, a quantitative oil column height prediction technology is introduced to predict oil column height for the potential area with good fault lateral sealing ability.

3) $R_m$-SSF quantitative chart technology and oil column height quantitative prediction technology are used to analyze the fault lateral sealing ability of developed blocks in A oil field. The research shows that the branch faults F2, F3 and F4 have good fault lateral sealing ability. The maximum oil column height of the same oil series for S2, S3 and S4 are different. Compared with the results of drilling, these understandings are conformed to the understandings of the geological reservoir, which solve the problem of oil-water interface inconsistence between S2, S3 and S4.

Acknowledgments

This work was financially supported by “National science and technology major projects- Formation conditions and exploration technology of offshore large and medium-sized oil and gas fields (2016ZX05024-006)” fund.

References

[1] Chen F J, Tian S C. Compaction and migration of oil and gas, M. Wuhan: China Geological University Press, 1989.

[2] LV Y F, Fu G, Fu X F, et al. The effect of fault on oil and gas transport and sealing, M. Beijing: Petroleum Industry Press, 2013.

[3] Niu S Y, Zhang F X, Chen C, et al. Geometry, kinematics and dynamics of the houjiayao fault in yangyuan county, Hebei, J. Marine Geology and Quaternary Geology. 2016,36(3):103-114.

[4] Feng Y, Liu G D, Yang W W, et al. Characteristics and models of hydrocarbon accumulation in Xinglongtai oilfield, LiaoHe depression, J. Marine Geology and Quaternary Geology. 2014,34(1):137-143.

[5] Xie D, Wu S M, Sun P. Paleostrass inversion for the onshore north margin of south china sea since late mesozoic: Takeing Zhangmutou, Guangdong province as a case, J. Marine Geology and Quaternary Geology. 2016,36(3):91-102.

[6] Xia Q L, Xu C G. New geological understandings and major hydrocarbon discoveries in the complex fault zone of Bohai Sea, J. Acta Petrolei Sinica. 2016,37(S.1):22-33.

[7] Zhu W L, Cui H Y, Wu P K, et al. New development and outlook for oil and gas exploration in passive continental margin basins, J. Acta Petrolei Sinica. 2017, 38(10): 1099-1109.

[8] Huang J S, LV Y F, Liu C G, et al. Quantitative evaluation method discussion of fault sealing by use of different displacement pressure between fault and reservoir : taking Bei 3-1 block in Beier depression Hailaer as example, J. Science Technology and Engineering.
[9] Li C R, Zhang G C, Liang J S, et al. Characteristics of fault structure and its control on hydrocarbons in the Beibuwan Basin, J. Acta Petrolei Sinica. 2012,33(2):195-203.
[10] Xie J H, Xia B, Zhang Y H, et al. Study on Formation and Evolution of the South China Sea, J. Advances In Marine Science. 2005, 23(2):212-218.
[11] Chen K, Zhou J X, Zhang H, et al. The research and application of the reservoir controlling mechanism for the No 2 fracture zone, Weixinan Sag, J. Acta Oceanological Sinica. 2019,41(7):92-102.
[12] Liu B, Pan X H, Wan L K, et al. Structural evolution and main controlling factors of the Palaogen hydrocarbon accumulation in Termit Basin, eastern Niger, J. Acta Petrolei Sinica. 2012,33(3):394-403.
[13] Jiang D H, Hu F. Research on sealing capacity of faults in Weixinan sag, Beibuwan basin based on evaluation factors, J. Offshore Oil. 2012,32(1):7-12.
[14] Fu X F, Li W L. Quantitative estimation of lateral fault seal and application in hydrocarbon exploration, J. Geological Review. 2011,57(3):57-63.
[15] LV Y F. Analysis on the difference of fault seals, J. Journal of DaQing petroleum institute. 1996,20(4):7-11.
[16] Wang K, Dai J S. A quantitative relationship between the crustal stress and fault sealing ability, J. Acta Petrolei Sinica. 2012,33(1):74-81.
[17] Yielding G, Freeman Band Needham D T. Quantitative fault seal prediction, J. AAPG Bulletin, 1997,81(6):907-917.
[18] Fu G, Yang M. Improved method for studying fault closure by using shale content in fault filling materials, J. Journal of Jianghan Petroleum Institute. 2002, 24(1):1-4.
[19] Fu G, Xue Y C, Yang M. Research method to sealing of fault by the percentage of mudstone in filling material of fault, J. Fault-Block Oil& Gas field. 1999,6(1):9-12.
[20] LV Y F, Li G H, Wang Y W. Quantitative analyses in fault sealing properties, J. Acta Petrolei Sinica. 1996,17(3):39-45.
[21] Fu G, Cao C R, Chen Z M. Mudstone daubing coefficient and its application in studying the lateral sealing of faults, J. Petroleum Exploration And Development. 1996,23(6):38-41.
[22] Xiao Y X, Gong X L, He X Y. Analysis of fault sealing and estimate of height of hydrocarbon column in fault trap by SGR meathod: A case of application in G fault block in eastern China, J. Marine Origin Petroleum Geology. 2005,10(4):51-58.
[23] LV Y F, Huang J S, Fu G, et al. Quantitative study on fault sealing ability in sandstone and mudstone thin interbed, J. Acta Petrolei Sinica. 2009,30(6):824-829.
[24] Chen K, Li M, Zou M S, et al. The validity quantitative evaluation technology and its application to structural trap in Weizhou Formation,Weixinan sag, J. Acta Petrolei Sinica. 2018,39(12):1370-1378.
[25] Zhu W L, Jiang W R. Relations between fractures and hydrocarbon reservoirs in Weixinan sag, J. Acta Petrolei Sinica. 1998,19(3):6-10.