Relationship between wellbore instability and rock mechanics when drilling in the fault area of Shunbei Formation

Jingtao Liu¹, Yang Yu¹, Pengju Ren², Zhou Zhou²

¹Sinopec Northwest Oilfield Branch, Urumqi, Xinjiang, China
²State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum (Beijing), Beijing, China

Zhou Zhou: zhouzhou.cn@hotmail.com

Abstract. The Tarim Basin is one of the most important oil formations in China, and it is prospected to exceed 110 billion barrels. Recently, some fault areas were drilled to achieve high potential oil reservoirs in the Tarim Basin. However, during drilling, wellbore stability is difficult to ensure in the fault areas. Wellbore collapse and lost circulation may unexpectedly occur. Therefore, analysis of wellbore stability according to the formation characteristics of the fault zone is necessary. On the basis of the formation mechanism of the fault zone, the stratigraphic characteristics corresponding to the internal structure of different fault zones were analyzed in this work. As a result of the formation characteristics, the corresponding logging identification methods of the induced fracture zone and sliding crushing zone formed, and the differences in wellbore instability in different internal structures were compared. The formation characteristics and mechanical properties of the sliding crushing zone were characterized by XRD, SEM, linear expansion rate test, rolling recovery test, and other physical experiments. Logging calculations were also conducted to assess the phenomenon of collapse that often occurs in the sliding crushing zone, and the collapse mechanism was analyzed accordingly. In view of the leakage phenomenon in the induced fracture zone, the complex mechanism of the leakage was analyzed, and the traditional minimum principal stress model was modified to obtain the leakage pressure calculation model suitable for the fault zone. Finally, taking the F1 fault zone in Shunbei area as an example, the internal structure of the fault zone was divided by using the summarized logging identification method. The wellbore instability of the different internal structures was compared, and the newly established loss pressure model was applied in the SHBX1 well, thereby proving that the model has a good application effect.

1. Introduction
The fault zone plays an important role in the formation and storage of oil and gas in Shunbei area. Many studies have been made on the formation mechanism, geometric characteristics, and reservoir physical properties of the fault zone [1,2]. However, systematic and in-depth research on the wellbore instability that often occurs in the drilling process of the fault zone is insufficient.
Wellbore stability was first studied in the 1940s. Over the past decades, many experts and scholars have conducted in-depth studies on the mechanism of wellbore instability, and a series of achievements has been made [3,4,5]. In general, the causes of wellbore instability can be divided into two categories: physicochemical factors and geomechanical factors. The physical and chemical factors mainly consider the influence of engineering operations and drilling fluids on the formation rock properties, while the mechanical factors mainly consider the stress imbalance around the wellbore. On the basis of the mechanism of wellbore instability in the strata in the fault zone, some experts and scholars have also conducted further research. Zhang Peifeng [6] believed that the collapse in pressure, reduction in rupture pressure, and mud-plastic deformation caused by the abrupt transition of the strata stress in the fault zone were the main reasons for the wellbore instability in the Longmen Shan fault zone. Deng Jingen et al. [7,8] believed that the weak structural plane in the strata in the fault zone leads to the strong heterogeneity and anisotropy of the strata, which can affect the mechanical properties and ground stress distribution of the strata, thereby resulting in the stress imbalance around the wellbore and the instability of the wellbore. However, these studies did not start from the formation mechanism of the fault zone and did not distinguish the wellbore instability mechanism of different internal structures. Thus, the analysis of wellbore instability mechanism of the fault zone was not comprehensive and in-depth enough.

In terms of the formation leakage mechanism, a large number of previous studies have been conducted [9,10,11,12]. Three main causes of leakage have been reported: fracturing leakage, fracture extensibility leakage, and large fracture-cavern leakage. However, given the complexity and heterogeneity of the fracture network structure, the single leakage mechanism cannot explain the loss of continuous well segments in the fault zone, so the traditional loss pressure calculation model cannot be applied to the fault zone. Thus, the author divided the internal structure of the fault zone from the formation mechanism, characterized the formation characteristics and mechanical properties of the fault zone in combination with physical experiment and logging calculation, and comprehensively analyzed the wellbore instability mechanism of different internal structures and formations. Moreover, as the traditional leakage pressure model could not be applied to the strata in the fault zone, the author revised the minimum principal stress model and obtained the calculation model suitable for the strata leakage pressure in the fault zone. With a well in the F1 fault zone in Shunbei area as an example, this work proved that the modified model could be applied well in the fault zone.

2. Characteristics of fault zone
Fault is a tectonic deformation phenomenon in which rock strata fracture under the action of stress and produce obvious relative movement along the fracture plane [13,14,15]. Each movement does not follow a plane due to the strain hardening effect of fault rocks. The deformation surrounding rocks between multiple sliding planes are called fault zones. Compared with the normal formation, fractures are developed in the fault zone and the rock is broken to a large degree, which makes the wellbore stability more likely to occur in the drilling process.

2.1. Internal structure unit of fault zone
The fault zone is a 3D geological body with complex internal structure. According to the degree of deformation inside the fault zone, the fault zone can be generally divided into induced fracture zone and sliding crushing zone [13,16,17,18].

When the fault is formed, the rock fracture is caused by the stress action. With the strengthening of the fault activity, the two plates of the fracture surface slip relative to each other, and the broken rock particles fill in the space caused by the two dislocations to form the sliding crushing zone. At the same time, the surrounding rock of the fault zone is accompanied with a large number of fractures due to stress concentration, forming an induced fracture zone. The formation mechanism of different internal structures leads to obvious differences in the characteristics of strata in the fault zone.
Located at the center of the fault, the sliding crushing zone is a combination of complex, grouped, and cross-arranged fault slip surfaces and corresponding fault bodies within a certain rock volume; it consumes most of the energy released by the fault development and concentrates most of the deformation of the fault development [19]. When the fault staggers to form the fracture space, the original rock gravel and part of the loose sediments fill the fracture space together. With the fault activity, the strong extrusion and friction force makes the rock gravel grind into fine particles, with large degree of breakage and smooth gravel. At the same time, the strong plastic sediments bind the gravel under the action of compaction. Thus, the rock particles in the sliding crushing zone are fine, densely arranged and generally have good homogeneity. Moreover, due to the filling and compaction of sediments, the porosity and permeability of the strata are poor and the sealing performance is good. The induced fracture zone is mainly distributed in the transition zone between normal stratum and sliding crushing zone and is located in the finite area on both sides of the fault or the stress release zone at the end of the fault. The induced fracture zone retains the basic characteristics of parent rock and is only cut by transverse and longitudinal fractures. A large number of fractures are developed in rocks located in the induced fracture zone, including open fractures and closed fractures filled by veins (including strong brittle calcite, quartz particles, and plastic clay minerals). The formation heterogeneity in the induced fracture zone is strong and the sealing ability is poor, and the porosity and permeability are obviously higher than those in the sliding crushing zone.

2.2. Logging characteristics of the internal structure

Through the difference in formation characteristics of the fault zone, the internal structure of the fault zone can be identified by using conventional logging data. In conventional logging curves, acoustic logging, density logging, compensated neutron logging, and caliper logging can all be used to identify the internal structure of the fault zone [18,20,21].

In the induced fracture zone, the propagation of sound wave between the fractures must undergo multiple reflection and refraction, and the sound wave will be greatly attenuated. The corresponding time difference curve of sound wave shows the abnormal peak value and periodic jump. In the sliding crushing zone, due to the compression effect of fault development, the broken rock particles are small and arranged in a compact manner, and the corresponding acoustic time difference curve shows a small value and small fluctuation.

In the induced fracture zone, the porosity corresponding to the well segments with high fracture density is also large, and the density logging value reflects the extremely low abnormal value. In the sliding crushing zone, the compaction makes the porosity smaller, the formation becomes more homogeneous and extremely dense, and the corresponding density value is large and the fluctuation is small.

Fracture development in the induced fracture zone leads to the increase in the total pore space of the formation, and the corresponding compensated neutron log value is large. However, the rock particles in the sliding crushing zone are compact, with small pore space and uniform distribution, and the corresponding compensating neutron value is small with low fluctuation.

In general, for the induced fracture zone, the logging curve generally shows that the acoustic time difference is large or periodic wave jump occurs, the compensated neutron value and borehole diameter are large, and the density log value is small. For the sliding crushing zone, the acoustic time difference value, compensated neutron value, and borehole diameter value are usually small, and the density logging value is large. Meanwhile, the logging curve of the fractured zone is relatively stable, and the variation range is significantly smaller than that of the induced fracture zone. The difference of structural units is affected by fracture activity strength, fracture mechanics property, fracture zone lithology, and development stage. For different blocks and lithologies, the value of logging curves will vary, but the variation trend of logging curves is similar. In the identification of the internal structure of the fault zone, multiple logging curves should be used for a comprehensive assessment to ensure the accuracy of identification.
3. Analysis of wellbore stability in fault zone

The stress state of the strata in the fault zone changes due to the fault activity in the early stage. As a result of fracture development, formation fragmentation, and poor integrity, wellbore instability often occurs during the drilling process, which can seriously affect drilling safety. On the basis of the above characteristics of fault formation in the process of drilling, the strata with different internal structures show different situations of wellbore instability. For the sliding crushing zone, the drilling hole destroys the wall of the compaction state of surrounding rock, and the effect of drilling fluid made of plastic cement dispersal expansion greatly reduces the formation of cohesive force. Moreover, the formation strength is reduced, resulting in rock debris and collapse of impellers and wellbore. However, for the induced fracture zone, the fracture network structure is complex, the formation bearing capacity is low, and the fracture can easily open and spread, resulting in lost circulation.

3.1. Analysis of collapse mechanism

Wellbore collapse is the most common and serious condition of wellbore instability in the fault zone, especially in the sliding crushing zone. On the basis of the analysis of the formation characteristics of the fault zone, the collapse mechanism of the sliding crushing zone involves three aspects:

(1) The drilling operation destroyed the original environment of sedimentation and overstock, which deformed the sediments with strong plasticity. The stratum that was tightly compacted was only supported by the broken and fine original rocks and boulders, which could easily induce wellbore collapse. As shown in Figure 1, the detritus in one of the fault zones in Shunbei formation was highly fragmented, and the maximum particle diameter was only about 10 mm.

![Figure 1. Detritus in fault zone.](image)

(2) The sliding crushing zone featured closed fractures filled with argillaceous materials (Figure 2). The content of expansive clay minerals was high, and the rocks exhibited strong expansive and dispersive properties.
XRD analysis was conducted to analyze the microcomponents of the detritus from a fault zone in Shunbei formation, including the mineral components of the whole rock (Table 1) and the clay mineral components (Table 2). The content of clay minerals in the fracture zone rocks in the study area exceeded 1/5, and the proportion of expansive clay minerals (including I/S and C/S) was more than 1/2. Thus, the rocks had strong expansive property.

Table 1. Mineral components of the whole rock

|         | Quartz | Plagioclase | Calcite | Dolomite | Hematite | Clay minerals | Other |
|---------|--------|-------------|---------|----------|----------|---------------|-------|
| Average content (%) | 10.639 | 2.506 | 32.250 | 26.611 | 4.378 | 22.422 | 1.194 |

Table 2. Clay mineral components

|         | S (Smectite) | It (Illite) | Kao (Kaolinite) | C (Chlorite) | I/S (Illite/smectite formation) | C/S (Chlorite/Smectite formation) |
|---------|--------------|-------------|-----------------|--------------|---------------------------------|----------------------------------|
| Average content (%) | 0 | 31.286 | 9.143 | 5.000 | 53.143 | 1.429 |

Moreover, the linear expansion rate and rolling recovery of the above detritus from the fault zone in Shunbei formation were further determined to analyze the expansibility and dispersion of the rock. The linear expansion rate experiment could obtain the expansion ratio of the rock sample in water. Through multiple experiments, the average linear expansion rate of the test sample was 8.44%, which further proved that the rocks in the fault zone had certain expansibility. The rolling recovery of the test sample was low at only 23.71%, indicating that the rock presented strong dispersion and the formation had poor cementation. Therefore, the hydration expansion and dispersion of the strata in the fault zone may easily occur under the action of drilling fluid, reducing the stability of the wellbore and easily causing wellbore collapse.

(3) The fracture degree of the strata in the sliding crushing zone was large and the compressive strength of the rocks was low. Moreover, the drilling hole destroyed the compaction environment, which worsened the formation rock cementation and lowered the cohesive force. Previous calculations of uniaxial compressive strength ($\sigma_c$) and cohesive force ($C$) of rocks have led to empirical formulas with good application effects [22,23,24]:

Figure 2. Closed fractures filled with argillaceous materials.
\[
\sigma_c = (0.0045 + 0.0035 V_{cl}) E_d \tag{1}
\]
\[
C = 3.54 \times 10^9 \times (1 - 2 \mu_d) \times \left(\frac{1 + \mu_d}{1 - \mu_d}\right)^2 \times \rho^2 \times \left(\frac{1}{\Delta t_p}\right)^4 \times (1 + 0.78 V_{cl}) \tag{2}
\]

where \(\sigma_c\) is uniaxial compressive strength, \(V_{cl}\) is argillaceous content, \(E_d\) is dynamic Young’s modulus, \(C\) is cohesive force, \(\mu_d\) is dynamic Poisson’s ratio, \(\rho\) is rock skeleton density, and \(\Delta t_p\) is longitudinal wave offset time.

where the argillaceous content \(V_{cl}\) can be obtained according to the statistical relation [25]:
\[
V_{cl} = -5.18 \times \frac{1}{\Delta t_s} + 2.88 \times \frac{1}{\Delta t_p} + 0.9 \tag{3}
\]

\(\Delta t_s\) and \(\Delta t_p\) are transverse wave offset time and longitudinal wave offset time, respectively.

Dynamic elastic modulus \(E_d\) and dynamic Poisson’s ratio \(\mu_d\) can be obtained according to the relationship between parameters and acoustic time:
\[
E_d = \left[\rho \times \left(3 \Delta t_s^2 - 4 \Delta t_p^2\right)\right]^{\frac{1}{2}} \left[\Delta t_s^2 \left(\Delta t_s^2 - \Delta t_p^2\right)\right]^{\frac{1}{2}} \tag{4}
\]
\[
\mu_d = 0.5 \times \left(\Delta t_s^2 - 2 \Delta t_p^2\right) \div \left(\Delta t_s^2 - \Delta t_p^2\right) \tag{5}
\]

\(\rho\) is rock skeleton density.

According to the established calculation model, the uniaxial compression strength and cohesion profiles of the strata in the sliding crushing zone were established. Figure 3 presents the parameter profile of a well section in the sliding crushing zone in Shunbei area. The uniaxial compression strength and cohesion of the strata significantly decreased after entering the strata in the sliding crushing zone. With the decrease in uniaxial compressive strength and cohesive force, the stability of the wellbore decreased and the risk of wellbore collapse greatly increased.
3.2. Analysis of lost circulation mechanism

Lost circulation has been a global problem in drilling engineering. In the fault zone, especially in the induced fracture zone, leakage is particularly serious due to the development of fractures and the complex structure of the fracture network. Previous research reported that the causes of lost circulation are mainly divided into three categories [9,10,11,12]: fracturing leakage, fracture extensibility leakage, and large fracture-cavern leakage. However, based on the above study on the formation characteristics of fracture zones, the fracture network structure is considered highly complex as it is induced to open fractures and close fractures and even the small pore space derived from fracture intersection. As a result of the presence of closed joints filled with mud, the action of drilling fluid will promote the hydration expansion of clay minerals and further reduce the strength of the weak surface of the fracture, allowing cracks to expand the fracture. Therefore, the traditional loss mechanism cannot be used to induce fracture zones.

The loss pressure is an important parameter to characterize lost circulation. For the calculation of continuous formation loss pressure, the minimum principal stress model can be used:

$$p_L = \sigma_h$$  \hspace{1cm} (5)

Previous studies showed that the model has a good application effect for the complete stratum or the stratum with only closed fractures. However, based on the above analysis of the formation loss
mechanism in the induced fracture zone, the minimum principal stress model is obviously not applicable to the prediction of loss pressure in the induced fracture zone. For continuous formations, which fracture structure is responsible for the loss of each small well segment is almost impossible to determine. For this reason, the pressure of the actual loss point in the formation was fitted with the loss pressure calculated by the minimum principal stress model. When the fitting shows a good correlation, then the fitting relation truly reflects the actual bearing capacity of the formation.

With the leakage of several wells in a fault zone in Shunbei formation as an example, the minimum principal stress and the loss pressure of the leakage point were obtained by using Huang’s crustal stress model [24] and the statistical-based model [26], respectively. The relationship curve between the actual leakage point pressure and the calculated loss pressure of the minimum principal stress model was established, as shown in Figure 4, and the correlation of different fitting methods was compared, as shown in Table 3.

![Figure 4. Curve between the actual value and the calculated value.](image)

| Fitted method            | Fitted equation         | Fitted correlation $R^2$ |
|--------------------------|-------------------------|-------------------------|
| Linear fitting           | $y = 0.7421x + 8.9971$  | 0.9361                  |
| Power function fitting   | $y = 1.293x^{0.9044}$   | 0.9361                  |
| Exponential fitting      | $y = 33.666e^{0.009x}$  | 0.9246                  |
| Logarithmic fitting      | $y = 74.216\ln(x) - 258.35$ | 0.9440                |

The pressure at the actual loss point has the greatest correlation with the loss pressure calculated by the minimum principal stress model in logarithmic relation, that is, the correction of the minimum principal stress model through logarithmic relation best reflects the lost circulation. Thus, a modified minimum principal stress model suitable for induced fracture zones is obtained:

$$p_L = A\ln(p_L) + B = A\ln(\sigma_n) + B \quad (6)$$
where \( p_L \) is corrected loss pressure, \( p_L \) is the loss pressure calculated by the minimum principal stress model, \( \sigma_h \) is the minimum horizontal ground stress of the formation, and \( A \) and \( B \) are the fitting coefficients.

In practice, only the section in the fault zone with a drilling leakage situation is analyzed, and the actual leak point pressure corresponding to the minimum horizontal stress for fitting of depth can be used to determine the fitting coefficient and obtain a continuous interval of loss pressure calculation. The fitting may then be used to predict the pressure loss coefficient of adjoining wells.

4. Application example

4.1. Introduction of the study area

The Shunbei oil field is located in Shuntuoguole low uplift in Tarim Basin, and it is a unique deep carbonate fracture-cavern reservoir controlled by the strike-slip fault zone. Thirteen main fault zones have been identified in the work area.

An analysis of the logging response characteristics revealed that the internal structure of the fault zone in Shunbei area was divided. In a well located in the F1 fault zone in Shunbei area of SHBX1, the internal structure division of the formation in SHBX1 was identified based on the logging response characteristics, as shown in Figure 5. Moreover, through the study of the F1 fault zone and the fault zone strata in the whole Shunbei area, the internal structure of the fault zone in Shunbei area was similar, that is, the sliding crushing zone was developed in O2yj and O1-2y of the Ordovician, and the induced fracture zone was developed in Silurian and O3s to O3q of the Ordovician.

4.2. Wellbore instability in F1 fault zone

![Figure 5. Internal structure division of the formation in SHBX1.](image-url)
On the basis of the above division of the internal structure of the fault zone in Shunbei area, the wellbore instability of the sliding crushing zone and the induced fracture zone on the F1 fault zone were analyzed, as shown in Table 4.

**Table 4. Wellbore instability in F1 fault zone**

| Internal structure          | Number | Strata          | Trip Time/d | Profile                                                                 |
|-----------------------------|--------|-----------------|-------------|-------------------------------------------------------------------------|
| **Sliding crushing zone**   | 1      | O2yj to O1-2y   | 242         | Wellbore instability occurs in both vertical and sidetrack sections, but it is more serious and difficult to solve the problem in sidetrack sections |
|                             | 2      | O2yj to O1-2y   | 184         |                                                                         |
|                             | 3      | O1-2y           | 124         |                                                                         |
|                             | 4      | O1-2y           | 49          |                                                                         |
|                             | 5      | O2yj            | 70          |                                                                         |
| **Induced fracture zone**   | 1      | S1t to S1k      | 110         | Loss 22 times                                                           |
|                             | 2      | S1t to S1k      | 134         | Loss 19 times                                                           |
|                             | 3      | S1t to S1k      | 50          | Loss 17 times                                                           |
|                             | 4      | S1t             | 22          | Loss 7 times                                                            |
|                             | 5      | S1t             | 40          | Loss 10 times                                                           |
|                             | 6      | S1t to S1k      | 21          | Loss 7 times                                                            |

The complex statistics also confirmed the conclusion of the analysis of wellbore stability in Chapter 2. In the formation of the sliding crushing zone, wellbore instability was mainly manifested as wellbore collapse, especially in the sidetrack section. In the induced fracture zone, wellbore instability was mainly manifested as lost circulation, especially in Silurian formation, where multiple points of leakage occurred randomly.

### 4.3. Calculation of loss pressure in F1 fault zone

On the basis of the analysis of the loss mechanism in section 2.2, the loss pressure model in the F1 fault zone was constructed:

\[ p_L = 74.216 \ln (\sigma_h) - 258.35 \]  

With SHBX1 on the F1 fault zone as examples, the formation loss pressure profile was calculated by using the minimum principal stress model and the modified minimum principal stress model. The application effects of the two models combined with the drilling fluid density in the drilling process were compared, as shown in Figure 6.
Figure 6. Loss pressure profile.

In accordance with the drilling conditions, serious leakage occurred at the bottom of the O3s to O3q in the Ordovician of SHBX1. As shown in Figure 6, the red curve and the green curve represent the loss pressure calculated by the modified minimum principal stress model and the minimum principal stress model, respectively. A comparison with the actual drilling fluid density revealed that the calculated value of the modified model was consistent with the formation leakage situation.

5. Conclusions
The fault zone can be generally divided into induced fracture zone and sliding crushing zone. Sonic logging, density logging, compensated neutron logging, and caliper logging can all be used to identify the internal structure of the fault zone. In Shunbei area, the sliding crushing zone was developed in O2yj and O1-2y of the Ordovician, and the induced fracture zone was developed in Silurian and O3s to O3q of the Ordovician.

In the formation of the sliding crushing zone, wellbore instability is mainly manifested as wellbore collapse, especially in the sidetrack section. By contrast, wellbore instability is mainly manifested as lost circulation in the induced fracture zone.

The modified minimum principal stress model proposed in this paper can be applied to the fault zone, and it has been successfully applied to the F1 fault zone in Shunbei area.

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References

[1] Ma Qingyou, Sha Xuguang, Li Yulan. 2012. Characteristics of strike-slip fault and its controlling on oil in Shuntuoguole region, middle Tarim Basin[J]. Petroleum Geology & Experiment, 34(2):120−124.

[2] Yang Shengbin, Liu Jun, Li Huili. 2013. Characteristics of the NE-trending strike-slip fault system and its control on oil accumulation in north pericline area of the Tazhong paleouplift[J]. Oil & Gas Geology, 34(6):797-802.

[3] Jin Yan, Chen Mian. 2012. Wellbore stability mechanics [M]. Beijing: Science Press, 2012.

[4] Yu M. 2002. Chemical and Thermal Effects on Wellbore Stability of Shale[J]. SPE71366, 2001:1-11.

[5] Abass H, Shebatalhamd A, Khan M. 2006. Wellbore instability of shale formation; Zuluf field, Saudi Arabia[C]. SPE71366, 2006:1-9.

[6] Zhang Peifeng. 2012. In-situ stress distribution and its effects on borehole stability in the Longmenshan earthquake fault zone[J]. Geology and Exploration, 48(2):379-386.

[7] Deng Jingen, Lin Hai, Hu Lianbo. 2013. Variations of In-situ Stress and Wellbore Stability for Kingfisher Block Through the Fault[J]. Science & Technology Review, 23:53-56.

[8] Lin Hai, Xu Jie, Xing Xuesong. 2017. Study on wellbore stability of well sections through a fault[J]. China Offshore Oil and Gas, 29(001):110-115.

[9] Li Chuanliang, Kong Xiangyan. 2000. A theoretical study on rock breakdown pressure calculation equations of fracturing process[J]. Oil Drilling & Production Technology, 22(2):54-56.

[10] Jin Yan, Zhang Xudong, Chen Mian. 2005. Initiation pressure models for hydraulic fracturing of vertical wells in naturally fractured formation[J]. Acta Petrolei Sinica, 26(6):113-114,118.

[11] Aadnoy B S, Belayneh M, Arriado M. 2007. Design of well barriers to combat circulation losses[R]. SPE 105449.

[12] Xu Tongtai, Liu Yujie, Shen Wei. 1997. Technology of lost circulation prevention and control during drilling engineering[M]. Beijing: Petroleum Industry Press, 1997:1-4.

[13] Wu Zhiping, Chen Wei, Xue yan. 2010. The structural characteristics of the fault zone and its transport and plugging property to oil and gas [J]. Acta Geologica Sinica, 84(4):570-578.

[14] McGrath A G, Davison I. 1995. Damage zone geometry around fault tips. Journal of Structural Geology, 17(7):1011-1024.

[15] Kim Y S, Peacock D C P, Sanderson D J. 2004. Fault damage zone[J]. Journal of Structural Geology, 26(3):503-517.

[16] Caine J S. 1996. Fault zone architecture and permeability structure. Geology, 24(11):1025-1028.

[17] Gudmundsson A, Berg S, Lyslo K B, Skurtveit E. 2001. Fracture networks and fluid transport in active fault zone. Journal of Structure Geology, 23:343-353.

[18] Feng Dongxiao, Tian Meirong, Zhang Huicai. 2010. Study on the geological structure characteristics and hydrocarbon accumulation in The West Part of Huimin Depression. Shanghai Land & Resources.

[19] Sun Yimei, Tian Shicheng. 2001. New progress in the study of fault migration of oil and gas.
Earth Science Frontiers, 8(4):36.

[20] Shen Zhongshan, He Xin, Mei Mei, Li Ping. 2016. Geological characteristics of the faulted zone in north Xingshugang Oilfield of Songliao Basin[J]. *Petroleum Geology & Oilfield Development in Daqing*, 035(003):22-25.

[21] Liu Wei, Zhu Liufang, Xu Donghui. 2013. Study on structural element characteristics of fault zone and logging identification method[J]. *Well Logging Technology*, (05):43-46.

[22] Deere D U, Miller R P. 1996. Engineering classifications and index properties for intact rocks [R]. *Air Force Weapons Laboratory*.

[23] Ding Ciqian. 2007. Field geophysics [M]. Beijing: China university of petroleum press, 2007.

[24] Chen Mian, Jin Yan, Zhang Guangqing. 2008. Petroleum related rock mechanics[M]. Beijing: Science Press, 2008: 40.

[25] Qiao Wenxiao. 1995. Effects of porosity, argillaceous content and saturation on rock acoustic waves [J]. *Well Logging Technology*, 19(3):194-198.

[26] Jin Yan, Chen Mian, Liu Xiaoming. 2007. Statistical analysis of loss pressure in Ordovician carbonate formation in Tazhong Basin [J]. *Oil Drilling Production Technology*, 29(5):82-84.