Limitation of fault-sealing and its control on hydrocarbon accumulation—An example from the Laoyemiao Oilfield of the Nanpu Sag

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Abstract: Based on previous studies on the internal structures of fault belts, the fault belts in the Laoyemiao Oilfield of the Nanpu Sag can be divided into three units, a crushed zone, an upper induced fracture zone and a lower induced fracture zone according to the log response characteristics. The upper induced fracture zone is characterized by the development of pervasive fractures and has a poor sealing or non-sealing capability. It therefore can act as pathways for hydrocarbon migration. The lower induced fracture zone consists of fewer fractures and has limited sealing capability. The crushed zone has a good sealing capability comparable to mudstone and can thus prevent lateral migration of fluid. Through physical modeling and comparing laboratory data with calculated data of oil column heights of traps sealed by faults, it is concluded that the fault-sealing capability for oil and gas is limited. When the oil column height reaches a threshold, oil will spill over from the top of reservoir along the lower induced fracture zone under the action of buoyancy, and the size of reservoir will remain unchanged. Analysis of the formation mechanisms of the fault-sealed reservoirs in the Nanpu Sag indicated that the charging sequence of oil and gas in the reservoir was from lower formation to upper formation, with the fault playing an important role in oil and gas accumulation. The hydrocarbon potential in reverse fault-sealed traps is much better than that in the consequent fault-sealed traps. The reverse fault-sealed traps are favorable and preferred exploration targets.

Key words: Limitation of fault-sealing, fault belt, oil column height, hydrocarbon accumulation, Nanpu Sag

1 Introduction

The Laoyemiao Oilfield in the Nanpu Sag is a typical fault-fracture controlled reservoir and the area of hydrocarbon trap is controlled by faults and stratigraphy. Drilling data indicate that the oil-water boundaries of the reservoirs in different strata sealed by the same fault are consistent. The oil and gas distribution in the cross section looks like a “brush”, such as the reservoirs of Miao36×1 well (Fig. 1). In addition, when the dip directions of the formation and the fault are the same, i.e., the fault is the up-dipping barrier of the formation in the upper wall, the trap has generally poor hydrocarbon accumulation. What has caused this phenomenon? What is the role of the fractures in the process of hydrocarbon accumulation? If the nature of the fault is sealing, why do the traps in the upper wall of the fault have poor hydrocarbon accumulation when the dip directions of the fault and the

formation are the same? If the fault is non-sealing, how can it serve as the seal for the reservoirs in the lower wall? It is therefore of great significance to understand the cause of this phenomenon and the control of faults on hydrocarbon accumulation in order to search for favorable exploration targets and achieve a higher exploration success rate in the Nanpu Sag.

Fig. 1 Reservoir profile in M36×1 well in the Laoyemiao Oilfield

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2 Geological background

The Nanpu Sag is a small hydrocarbon generating sag developed since the Mesozoic-Cenozoic in the north of the Huanghua Depression of Bohai Bay Basin. It is located in the south of Tangshan city, and is adjacent to the southern boundary of the east-west striking Yanshan Fold Belt. In the north it is limited by the Xinanzhuang and the Baigezhuang fracture zones, and in the south it overlaps the Shaleitian Uplift (Zhou et al, 2005a). The Laoyemiao structure in the northwest of the Nanpu Sag is a secondary structural unit controlled by the Xinanzhuang boundary fault in the north of the sag. It is an inheritedly developed rollover anticline in nature. The strata from bottom to top are the Eocene Shahejie (Es) and Dongying (Ed) Formations, and the Neogene Guantao (Ng) and Minghuazhen (Nm) Formations. Among these formations, unconformable contacts exist between the Guantao Formation and the Dongying Formation, as well as between the Dongying Formation and the Shahejie Formation (Zhou et al, 2005b). The major source rock in the Laoyemiao Oilfield is the Es₁-Ed₃ dark mudstone. The Laoyemiao Oilfield comprises several reservoirs, in which the major productive beds are Ed₁, Ed₂, Ng and Nm₁. A series of faults developed in this area and most of them are normal faults. Exploration results show that most of the reservoirs are related to faults, which play an important role in controlling the distribution of oil and gas (Zhou et al, 2005a; 2005b).

3 Zonation of fault belts and limitation of fault-sealing

3.1 Internal structure and zonation of fault belts

The internal structure of the fault belts and fault-sealing have been investigated. Based on the geometric study of the internal structure of fault belts, a number of authors have demonstrated that the internal structure of fault belts has zonation (Faulkner et al, 2003; Micarelli et al, 2006; Fu et al, 2005; Zhou, 2005; Song, 2005), including three units: a crushed zone in the center and two induced fracture zones on two sides. The physical characteristics of different zones inside the fault belt are different owing to different lithology and different degrees of deformation/metamorphism. Based on tests of sealing capability of rock samples in different units of fault belts, a number of authors have reached a consensus that the sealing capability of the crushed zone is better than that of original rock and is the best in a fault belt because of the development of fault gouge (Evans et al, 1997; Wibberley and Shimamoto, 2003; Tsutsumi et al, 2004; Géraud et al, 2006). The induced fracture zones with higher permeability than that of original rock on both sides of the crushed zone have poor sealing capability. The permeability of the induced fracture zone in the upper wall of the fault is much higher than that in the lower wall (Fig. 2).

It has been found that the fault belt in the Laoyemiao Oilfield of the Nanpu Sag has zonation as shown on the wireline response signature. Taking Miao28-1 well for example, a fault at 2740-2812m was encountered, and

Fig. 2 Experiment results: comparison of permeability of different units in fault belts (Evans, 1997)

the characteristics of the logging curves in the fault belt change markedly (Fig. 3). In the section of 2763-2785m, the fluctuation of the logging curves is weak with a short acoustic travel time averaging 255μs/m, and a high compensated density averaging 2.56g/cm³. It indicates that the rock is compact and has a good sealing capability. In the section of 2740-2763m, the curves of acoustic travel time and compensated density fluctuate greatly with their amplitudes jumping from 208μs/m to 294μs/m and 1.86g/cm³ to 2.44g/cm³, respectively. This suggests that the rock has a low structure density, a series of fractures and relatively high permeability. In the interval of 2785-2812m, the fluctuations of logging curves become weaker and then return back to normal gradually. It can be found that the rock has relatively fewer fractures but still has some sealing capability. Therefore, the fault belt can be divided into a crushed zone, an upper induced fracture zone and a lower induced fracture zone. The upper induced fracture zone can act as the pathway for hydrocarbon migration because of its abundant fractures, relatively high permeability and poor sealing capability. The sealing capability of the lower induced fracture zone with fewer fractures and some permeability is between that of mudstone and sandstone. The middle crushed zone has the best sealing and confining capability, which can prevent fluid from leaking. This can be verified by formation water analysis. There is huge difference in the degree of mineralization in the formation water on different sides of the fault.

3.2 Limitation of fault-sealing

The oil and gas boundaries on one side of the fault in the Laoyemiao Oilfield have good coincidence vertically. What has caused this phenomenon? Is it caused by oil and gas in different beds from different sources or the limitation of the fault sealing? If it is caused by the former, different beds should have equal supplies of oil and gas. However, it is difficult to explain in the real geological condition. If it is caused by the latter, the reservoir would be under the condition of critical saturation. In other words, even if there is continued hydrocarbon supply, the extra hydrocarbons would spill over under the force of buoyancy. Then the size of the reservoir will remain unchanged. If there is little change in lithology and its proportion, the sealing of different strata in the same fault zone should be consistent

Fig. 3 Log response characteristics of fault belt in M28-1 well in the Laoyemiao Oilfield

or only change gradually, which would result in a consistent oil-water boundary on one side of the fault like a “brush”. The following sections present the analysis about the relationship between oil column height at present and oil column boundary height sealed by the fault.

The fault sealing capability could be evaluated by the displacement pressure of the fault belt. Acoustic travel time is dependent on lithology, and its response to the rock pore configuration is sensitive. Thus there is normally a good correspondence between acoustic travel time and sealing capability of faults. The displacement pressure can be calculated directly from acoustic travel time. Some researchers have made studies on this subject in the Songliao Basin, Tarim Basin and Qiongdongnan Basin. Taking the data of the Songliao Basin for example, the corresponding relationships between the displacement pressure and porosity, acoustic travel time and porosity of mudstone, silty mudstone as well as argillaceous siltstone have been established. An empirical equation between the displacement pressure and acoustic travel time for mudstone, silty mudstone as well as argillaceous siltstone has been presented (Qu et al, 2005). According to the lithological characteristics of fault belts in the Nanpu Sag area, the empirical equation for silty mudstone is chosen to calculate the displacement pressure of the fault belt.

$$Pc = 108 / (0.0745\Delta t - 13.5745) - 40 \quad (1)$$

where Pc is the displacement pressure of the fault, MPa; Δt is the acoustic travel time of the fault belt, $\mu s/m$.

Based on the sealing principle of capillary pressure, the highest oil column that the fault could seal is:

$$H = Pc / g(\rho_w - \rho_o) \quad (2)$$

where H is the highest oil column sealed by the fault, m; g is the acceleration of gravity, m/s^2 ; ρ_w is the water density in the reservoir, g/cm^3 ; ρ_o is the oil density in the reservoir, g/cm^3 , which is $0.8 g/cm^3$ in this area.

The critical height of an oil column sealed by the fault can be calculated according to the above empirical equations and the statistical data are showed in Table 1. The measured data of nine reservoirs in two wells in the study area are compared with the calculated values sealed by the corresponding faults. It indicates that the deviations between oil columns in the lower reservoirs and the calculated values are small, below 7%. The good agreement of measured oil column values and calculated critical height values indicates that the reservoir is in critical saturation condition. However, the differences between the oil column heights in the upper reservoirs and the calculated values are above 8%. It indicates that they are not in the critical saturation condition. Generally speaking, the hydrocarbon sealing capability of the fault is limited. Hydrocarbons would spill over along the fault and migrate to the upper reservoirs if the oil column height in the reservoir reaches the critical value which could be sealed by the fault.

The limited sealing capability of the faults can be inferred from the above discussion. The fault does not have complete sealing capability and is only effective within a limited oil column height. Smith (1966) demonstrated a theory by displacement pressure. He believed that hydrocarbon would migrate along the fault and accumulate in the lower wall of the fault if there was a difference between displacement pressures of fault belts and that of the reservoir beds (the displacement pressure of the fault belt is larger than that of the reservoir bed) until the buoyancy force caused by oil column height balanced the displacement pressure difference.

Table 1 Comparison between measured data and calculated data of oil column heights sealed by fault

Number	Well number	Depth m	SDT $\mu\text{s/m}$	Displacement pressure MPa	The height of oil column, m		Calculated value –measured value m	(Calculated value – measured value) $\times 100$ / measured value %
					Measured value	Calculated value		
1	Miao39-2	2015	322.999	6.30	29.00	31.48	2.48	8.56
2	Miao39-2	2130	334.285	5.53	27.00	27.66	0.66	2.45
3	Miao39-2	2157	275.492	11.54	55.00	57.70	2.70	4.91
4	Miao39-2	2169	322.572	6.33	31.00	31.64	0.64	2.06
5	Miao36 $\times$ 1	1660	363.255	4.01	18.00	20.04	2.04	11.31
6	Miao36 $\times$ 1	1744	377.69	3.42	16.00	17.08	1.08	6.74
7	Miao36 $\times$ 1	1796	391.798	2.92	14.00	14.58	0.58	4.17
8	Miao36 $\times$ 1	1903	412.37	2.30	11.00	11.49	0.49	4.48
9	Miao36 $\times$ 1	2054	376.575	3.46	17.00	17.29	0.29	1.72

4 Effects of fault-sealing on hydrocarbon accumulation

4.1 Types and oil-bearing properties of fault-sealed traps

Fault-sealed traps can be divided into two types: reverse fault-sealed trap and consequent fault-sealed trap on the basis of the dip relationship between fault and strata. When the dips of the fault and the formation are in the same direction, it is referred to as consequent fault-sealed traps. In this circumstance, the fault and the formation in the upper wall of a fault belt constitute a fault-sealed trap (Fig. 4(a)). If the dips of the fault and the formation are in opposite directions, it is referred to as reverse fault-sealed trap, which consists of the fault and the formation in the lower wall of the fault (Fig. 4(b)). In the consequent fault-sealed traps, the upper induced fracture zone acts as the barrier; whereas in the reverse fault-sealed traps, the lower induced fracture zone acts as the barrier. As described above, the upper induced fracture zone has a higher permeability than the lower one. It therefore has poor sealing capability and the hydrocarbons tend to migrate through or leak along the upper permeable zone of the fault.

Fig. 4 Types of fault-sealed traps

There is a difference in the sealing effectiveness between two types of fault-sealed traps. The drilling data in the area have confirmed that consequent fault-sealed traps have poor oil saturation and hence have a relatively high exploration risk.

4.2 Hydrocarbon charging physical modeling

As described above, the oil-water boundaries of traps in the lower wall of a fault are consistent and look like a “brush”, which is caused by the limited sealing capability of the fault. We need to find out 1) What is the hydrocarbon charging sequence of these reservoirs distributed in different formations along the fault? and 2) What is the control of the fault on the accumulation process?

Hydrocarbons will firstly charge into the stratigraphic interval with the highest permeability and lower displacement pressure (England et al, 1987). There is a general agreement that capillary pressure acts as the resistance against the migration and accumulation of hydrocarbons. Hydrocarbons always migrate along the direction with least capillary pressure which can be measured by displacement pressure of pores. Displacement pressures of pores in the formations with different properties are different (e.g. the displacement pressure of sandstone reservoir bed is much smaller than that of mudstone caprock). There is also a great difference between the displacement pressures of different zones in fault belts. Combining the permeability experiments of different units in fault belts carried out by Evans et al (1997), Wibberley and Shimamoto (2003), Tsutsumi et al (2004) and Géraud et al (2006), it can be seen that the crushed zone in the fault belt has a high displacement pressure similar to mudstone. However, the upper induced fracture zone has a lower displacement pressure than the sandstone reservoir bed and the displacement pressure of the lower induced fracture zone is somewhere between that of mudstone and the sandstone reservoir bed.

Based on the characterization of hydrocarbon accumulation in the Laoyemiao Oilfield, we built a physical geological model (Table 2 and Fig. 5). The model was 50cm long, 30cm high and 2.2cm thick. The sand layers 1-6 were filled with glass beads whose grain diameter was 0.25-0.3mm, the porosity was 33% and the permeability was $3476 \times 10^{-3} \mu\text{m}^2$. Sand layers 1-3 had a dip of 22° and layers 4-6 had

a dip of 17° . The fault was filled with glass beads whose grain diameter was 0.15-0.2mm, the porosity was 33% and the permeability was $2266.3 \times 10^{-3} \mu\text{m}^2$. The other parts of the model were impervious rubber. Oil entry is on the bottom of the fault. The sand edge and the top of the fault were both equipped with exits and each exit had the same height 4cm higher than the model. We first filled the model with distilled

Table 2 Limitation of fault-sealing experimental parameters

	Size mm	Media size mm	Porosity %	Permeability $\times 10^{-3} \mu\text{m}^2$	Average pore radius mm
Fault	0.15-0.2	0.175	33	2266.3	0.0725
Sand layer	0.25-0.3	0.275	33	3476	0.1139

Fig. 5 Limitation of fault-sealing experimental model

water to drive out any air and then injected the oil through the oil entry. The oil we used was colored kerosene (density $0.75\text{g}/\text{cm}^3$) and the injection rate was $0.1\text{ml}/\text{min}$.

Fig. 6 shows photographs, taken at different times, of the model simulating reservoirs being formed by the fault. The two yellow lines are connections of the oil/water boundaries

on the same side and they are parallel to the fault plane. Through the experiment, three conclusions can be reached: 1) The largest column heights sealed by the fault block trap are basically the same, when the difference of displacement pressure of the reservoir bed and the fault are small; 2) The oil column height will increase no further, even if

Fig. 6 Photographs at different times of the physical model of reservoirs formed by a fault

hydrocarbon is injected again, when the oil column height reaches the threshold, and at this point the fault is relatively open; 3) The oil-bearing area (or width) is affected by the reservoir bed inclination, at a specific difference between displacement pressures of the reservoir bed and the fault.

Fig. 7 illustrates that with increasing thermal evolution and hydrocarbon generation of the Ed₁-Es₃ source rock in the Laoyemiao area, the driving force for expulsion of oil and gas from the source rock also increases. When the driving force is greater than the displacement pressure of reservoir bed near the top of Ed₃, hydrocarbon begins to charge from the bottom of the reservoir bed, and the lower wall of the fault acts as a seal at this time (Fig. 7(a)). With increasing hydrocarbon accumulation in the nearby reservoir bed, the hydrocarbon column height also increases, which results in the increase of buoyancy force at the top of hydrocarbon column. Oil and gas then begin to spill over from the top of the reservoir along the lower fracture zone when buoyancy force is greater than the difference between the displacement pressures of reservoir bed and the lower fracture zone. At this stage, the lower fracture zone is in the condition of limited sealing. The reservoir may become critically saturated, reaching its maximum capacity allowed by the sealing capability in the lower wall of the fault and reaches an equilibrium state. At this point, the size of the reservoir remains unchanged because the accumulation in the bottom and spill at the top reach

equilibrium (Fig. 7(b)). The hydrocarbon spilled from the top of the reservoir migrates upwards along the lower fault zone and accumulates again in another sandstone reservoir with lower displacement pressure because of the better sealing of the middle crushed zone, which can prevent hydrocarbon from leaking through the fault entirely. In addition, the hydrocarbon can also migrate along the lower fracture zone when the driving force for hydrocarbon expulsion from the source rock is greater than the capillary pressure of the lower fracture zone (Fig. 7(c)). Likewise, if the reservoir is big enough to get into the state of critical saturation adjustment caused by the limited sealing capability of the lower fracture zone of the fault, the hydrocarbon would continue to migrate upwards and accumulate in the upper traps (Fig. 7(d)). This can explain why the fault-sealed hydrocarbon reservoirs such as in Miao36×1 well occur like a “brush”. Therefore, the charging sequence of reservoirs in different formations is from the lower to the upper. During the process, the lower reservoir will always be in critical saturation state while the upper reservoir may be in an unsaturated state. This is consistent with the oil testing data from Miao36 well, which shows the absence of oil and gas in the upper strata except for the top of Ed₃. It is unlikely that the hydrocarbon has migrated laterally because there would be remnants in the reservoir during migration of hydrocarbons (Xin et al, 2002).

Fig. 7 Map showing the formation process of fault-sealed reservoir in M36×1 well in the Laoyemiao Oilfield

5 Conclusions and recommendations

1) Based on the review of previous theoretical studies, the fault belts in the Laoyemiao Oilfield of the Nanpu Sag can be divided into three units including a crushed zone, an

upper induced fracture zone and a lower induced fracture zone according to the logging response characteristics of the fault belts. The upper induced fracture zone can act as pathways for hydrocarbon migration because of the presence of pervasive fractures and poor sealing capability; the sealing

capability of the lower induced fracture zone with fewer fractures and some permeability is found to be between that of mudstone and sandstone; the middle crushed zone has the best sealing and confining capability, which can prevent fluids from leaking.

2) The physical simulation, geological statistics and theoretically calculated data indicate that the fault-sealing for hydrocarbons in the Nanpu Sag is limited. Hydrocarbons will spill over along the lower induced fracture zone when the buoyancy force caused by oil column is greater than the difference between displacement pressures of the reservoir and the lower induced fracture zone. In this situation, the reservoir is in its critical saturation state, and its size reaches a maximum. The charging sequence of the fault-sealed reservoirs in the lower wall of the fault is from lower formation to upper formation. The size and saturation of the upper reservoirs depends on hydrocarbons supplied.

3) Fault-sealed hydrocarbon reservoirs in the Nanpu Sag can be divided into consequent fault-sealed trap and reverse fault-sealed traps according to the dips of the fault and the formation. The former trap is sealed by the upper induced fracture zone, whereas the latter is sealed by the lower induced fracture zone. The difference in sealing capability between upper and lower induced fracture zones results in a huge difference of oil-bearing properties between these two kinds of fault-sealed traps. The consequent fault-sealed trap has a poor reservoir sealing capability and should be avoided in future selection of drilling targets. It is suggested that the reverse fault-sealed traps should be the favorable and preferred exploration targets in the Nanpu Sag.

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