ISSN 2616-5872 Vol.6, Issue 4: 26-36, DOI: 10.25236/AJEE.2024.060404

Faults Internal Structure and Its Influence on Hydrocarbon Migration

Douxing Zhu[1,a,*], Siyu Wang[1,b], Jianxiong Zheng[1,c], Yongli Wang[1,d], Cunying Shi[1,e], Ruifeng Zhao[1,f], Chaolong Ding[1,g], Xujiao Zang[1,h], Yang Meng[1,i], Bing Han[1,j], Ning Sun[2,k], Zhe Liu[3,l]

[1]Geological Research Center, GRI, BGP Inc., CNPC, Zhuozhou, Hebei, 270750, China
[2]School of Earth Sciences, Northeast Petroleum University, Daqing, Heilongjiang, 163000, China
[3]School of Petroleum Engineering, Guangdong University of Petrochemical Technology, Maoming, Guangdong, 525000, China
[a]zhudouxing@cnpc.com.cn, [b]1310297706@qq.com, [c]zhengjianxiong@cnpc.com.cn,
[d]wangyongli01@cnpc.com.cn, [e]shicunying@cnpc.com.cn, [f]zhaoruifeng@cnpc.com.cn,
[g]dingchaolong@cnpc.com.cn, [h]zangxujiao@cnpc.com.cn, [i]mengyang1@cnpc.com.cn,
[j]hanbing01@cnpc.com.cn, [k]sn@nepu.edu.cn, [l]liuzhe@gdupt.edu.cn
[*]Corresponding author

Abstract: *Faults is the main channels for hydrocarbon migration. The internal structure characteristics of fault zones have always been the focus and difficulty in petroleum geology. Fault includes interlaced fracture plane or fault zone which showing as deformation based-band, joint-based faulting and brittle faulting. The property of a fault and its formed stages control fault architecture, which may be divided into host rock, induced fracture zone with main slip plane, and fault damage zone. Fault architecture control the migration and sealing properties which showing complex permeability and displacement pressure in geological events. These properties could evaluation by clay content, fault zone width, depth and other feature. Fluid migration in fault zone follows porosity seepage characteristics as it does in reservoir. Cross-fault pressure and petroleum column height cannot be converted to seal capacities because charge history and sealing type influence sealing. In the future, with the innovation of research methods, logging data will be used to characterize the internal structure of faults more effectively. Meanwhile, quantitative fluorescence analysis of hydrocarbon fluid inclusions will be used to analyze reservoir plugging evolution history more quantitatively.*

Keywords: *Fault Zone, Internal Structure, Hydrocarbon Migration, Permeability, Displacement Pressure*

1. Introduction

Hydrocarbon often encounters fault planes during migration, which sometimes can serve as channels for oil and gas migration, and sometimes act as barriers. The introduction and application of fault sealing and permeability have enabled people to have a deeper understanding of the mechanism of oil and gas accumulation. The study of fault sealing involves the vertical and horizontal sealing and connectivity under static conditions, which is a complex issue involving multiple factors. The factors that affect the sealing of fault zones vary in different regions. Lv Yanfang (2002) summarized ten main factors that affect fault sealing: mechanical properties of faults, dip angle of fault planes, fault strike, burial depth of faults, fault displacement, fault activity, fault density, cementation and lithification of filling materials in fault zones, lithology of opposing walls of faults, and mudstone smear on fault planes [1].

The study of fault sealing mechanisms and the prediction of sealing performance are extremely important, as they are the key to revealing the laws of oil and gas migration and accumulation. Downey (1984) and Watts (1987) conducted extensive research and found that lithological sealing, where non-permeable strata and reservoir strata abut against each other in faults, is the primary mechanism of fault sealing [2,3]. For clastic strata, the sealing capacity of fault zones is often related to the mud content mixed into them. During fault activity, extremely fine-grained non-permeable mud deposits distributed along the fault, due to dragging, compression, grinding, and plastic flow, adhere to the fault plane, enhancing the sealing capacity of the fault. Relevant prediction formulas include the fault gouge ratio

ISSN 2616-5872 Vol.6, Issue 4: 26-36, DOI: 10.25236/AJEE.2024.060404

(SGR), CCR [4,5], shale smear factor (SSF) [6], and shale smear potential (CSP) [7]. However, in some cases, sandstone-to-sandstone abutments with extremely low SGR ratios have also shown an impediment to fluid migration [8,9], indicating that it is not the abutment sealing effect of the strata on both sides of the fault but other mechanisms that provide effective sealing. Fisher (1998) and Doughty (2003) pointed out that in areas with long-term fault activity or high crustal stress, particles in the fault zone undergo compression and crushing, and coarser fault breccia and cataclasites are refined into fault gouge, reducing porosity and permeability within the zone, sealing the reservoirs on both sides [9-11]. In deep sandstone with high quartz content, cataclasis in the fault zone is often accompanied by the development of primary quartz cementation, reducing porosity and permeability in the fault zone. In the absence of shale smear layers; this can effectively seal fluid migration [12].

Current discussions on the impact of faults on oil and gas migration mainly focus on the geometric morphology of fault structures, the internal structural characteristics of faults, the identification of various sealing effects in fault zones, and the quantitative evaluation of the physical properties of fault rocks. This article will review and compare the progress of research on the development process and internal structural characteristics of faults. Finally, from the perspective of the essence of sealing, the expulsion pressure of fault zones will be quantitatively predicted to evaluate the impact of faults on fluid migration during quiescence.

2. Types of Fault Zones

The traditional methods to characterize the sealing mechanisms of fault zones mainly rely on the abutment sealing of low-permeability mudstones and high-permeability sandstones, as well as the formation of a continuous, low-permeability clay material known as shale smear along the fault plane. However, various methods to assess the sealing capacity of fault zones do not take into account the formation patterns of faults and the formation mechanisms of fault rocks, which play an important role in fluid migration. Fault structures are tectonic deformations that occur when rock layers or rock masses undergo significant displacement along rupture surfaces under stress. They can manifest as a single or multiple intersecting rupture surfaces or as fault zones. There are three common types of fault zones: deformation zone faults, joint faults, and brittle faults (Figure 1).

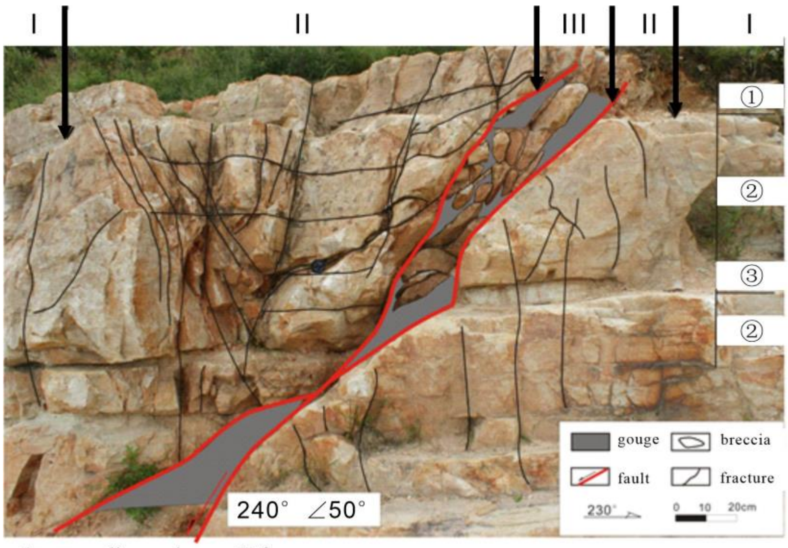

Figure 1: Internal structure diagram of normal fault

2.1 Deformation Zone Faults

In areas with long-term fault activity or high crustal stress, porous sandstone particles a few micrometers thick undergo compression and crushing, accompanied by the destruction of intergranular pores and the sequential development of fine microcracks into a deformation zone. The displacement of a single shear deformation zone is approximately 1-10 mm. As the displacement increases, individual deformation zones intersect and connect, forming a complex set of multiple deformation zones [13,14].

ISSN 2616-5872 Vol.6, Issue 4: 26-36, DOI: 10.25236/AJEE.2024.060404

2.2 Joint Fault Zones

Joints, shear joints, tensile fractures, cataclasites, and fault breccias are all products of joint faulting. Joint faulting occurs when shear forces act on geologically weak planes under discontinuous deformation, resulting in fractures with no significant displacement. It is caused by stress micro-disturbances at the tips of discontinuities [16]. Since the formation of joint faults is the result of stress concentration, the number of joints near faults increases significantly, with a relative increase in density and a relatively larger width of the joint zone. In complex fault structures, such as in the fold belt above a fault, joints often develop superimposed on deformation zones. In practical work, joint faults are usually treated as crack models and can be roughly evaluated through mechanical models and borehole stress analysis.

2.3 Brittle Faults

Brittle faults are the most common type of fault zone in brittle rock formations. The growth stage of the fault is the most important factor controlling the truncation and smearing of mudstones from the source rock layer [10].

Tensional faults have segmented characteristics in both strike and dip, a view that has been confirmed through ground surveys, underground studies, and theoretical experiments [5,7,16]. From high-precision 3D seismic volumes, different segments within a fault can be clearly distinguished based on their different displacements. For convenience, the segmented characteristics within a single fault are often ignored, but the conclusions drawn from analyzing the abutment relationship between the rocks on both sides of the fault can be vastly different. It is particularly crucial to use the combined method of Allan diagram and shale smear to evaluate fault sealing, as it allows for the identification of fault segments and tensile buffers on the profile, further determining the distribution of shale smear and fault rocks[15].

3. Internal Structure of Fault Zones

3.1 Classification of Fault Internal Structure

Scholars at home and abroad have discovered through extensive field observations that faults have complex internal structures and often appear as fault zones with varying widths or as one or multiple intersecting rupture surfaces. Caine (1996) proposed a three-part model for the internal structure of fault zones when studying the hydrogeological characteristics of faults, such as their conductivity and resistance to fluids in their vicinity [17]:

Fault Core: This includes the fault sliding surface and the fault rocks that fill it, such as fault gouge, mylonite, and cataclasite.

Fracture Zone: This is the subordinate structure outside the fault core, consisting of secondary faults, fissures, and fault fold development zones.

Surrounding Rock: This is the normal rock stratum outside the fracture zone, with basically unchanged properties.

The internal structure of fault zones is often divided into three parts from an applied perspective: fractured zone, induced fracture zone, and surrounding rock (Figure 1). These basically correspond to Caine's fault core, ruptured zone, and surrounding rock. The fractured zone includes fault rocks, internally associated small faults, fractures, and small folds. There is a relationship of 1:10 to 1:100 between the width of the fractured zone and the fault displacement [6]. Typically, the width of the fault fractured zone is narrow, with small faults possibly only 2-3cm wide, and large faults up to 10-20m wide [18]. Despite its generally narrow width, the fractured zone absorbs most of the deformation of the fault. During intense tectonic activities, fault gouge and tectonic lenses are formed, which are usually truncated by internally associated fractures and intersect with them at a large angle [19]. The scale of the induced fracture zone is larger than that of the fractured zone, with a width of several hundred meters, but the degree of deformation is relatively low, and the rock strata are mostly fractured.

3.2 Types of Fault Rocks in Brittle Faults

The nature of faulting affects the internal structure of fault zones. Ramsay (1980) classified shear

ISSN 2616-5872 Vol.6, Issue 4: 26-36, DOI: 10.25236/AJEE.2024.060404

zones into three major categories based on their geometric morphology: brittle shear zones, ductile shear zones, and transitional brittle-ductile shear zones [20]. Although they manifest as ductile shear zones in deep strata, they always appear as brittle shear zones in shallow strata or at the surface. The relevant fault rocks discussed in this article only include fault gouge, fault breccia, and some cataclastic rocks in brittle shear faults. By comprehensively evaluating factors such as the nature of surrounding rocks, stress effects, and formation temperature and pressure conditions [21-22], the fault rocks in the fractured zone can be classified into five types [25]:

(1) Fault breccia, which are rock fragments that retain the characteristics of the original rock within the fault zone and are surrounded by fractures in the surrounding rock. Fault breccia does not have a bonded structure.

(2) Cataclastic rocks, which undergo fracturing and block rotation due to fault friction. These rocks retain their bonding during the fragmentation process and exhibit fine grain size. In high-confining pressure strata, consolidated cataclastic rocks can form a good barrier for fluid migration.

(3) Deformation zones, where the intergranular pores of porous sandstone are destroyed, and fine micro-fractures develop sequentially into a deformation zone. The deformation zone is thin and has good continuity, effectively hindering fluid migration.

(4) Fault gouge and clay smear layers, which are extremely fine-grained, non-permeable mud-like substances distributed along the fault plane due to drag, extrusion, grinding, and plastic flow during fault activity. These are present as veins or bands along the fault plane [21]. Fault gouge, as a weak interlayer, significantly affects the strength of the geological body, imparting high displacement pressure to the fault zone and enhancing its sealing ability.

(5) Fault cementation and lithification, where the dissolution process of clay minerals is controlled by temperature. When the burial depth exceeds 2-3Km and the temperature is above 80-100℃, montmorillonite undergoes dissolution. Kaolinite and potassium feldspar dissolve at temperatures above 130℃, forming illite and quartz while releasing interlayer water [23]. The migration of high-pressure fluids accompanies water-rock interactions, and the resulting cementation greatly increases the sealing capacity and shear strength of the fault [12,23].

3.3 Factors Influencing the Development of Induced Fractures in Brittle Faults

Within the internal structure of faults, although the porosity of fractures accompanying fault formation is not significant, they have a remarkable effect on fluid permeation, significantly improving oil and gas storage and transportation space and performance [1], making them a focus of research and evaluation. Under the action of tectonic stress fields, a series of shear fractures parallel to the faults are often generated. The induced fractures and the faults are products of the same stress field, differing only in scale [16]. The distribution of induced fractures is not only influenced by secondary tectonic stress fields but also related to the mechanical properties of rocks. The orientation of fracture development depends on the mechanical properties of rocks and the scale of fault activity [24]. Induced fractures are most prominent in the central part of the fault zone, while stress release zones at fault tips, fault intersections, branches, and outwardly convex bending sections are areas of relatively concentrated stress, often forming complex fracture systems [25-28]. In addition, due to the asymmetry of the internal structure of the fault zone, its density and width are also inconsistent.

4. Control of Faults on hydrocarbon Migration

4.1 Evaluation of Fault Zone Permeability

Evaluating the permeability of fault zones is crucial for analyzing preferential fluid migration channels and reservoir development. In the early stages, this area of work was relatively sparse, limited to qualitative analysis. Evans et al. (1997) tested the permeability of natural gas through reverse faults developed in Precambrian granite in Wyoming [29]. Under simulated stratigraphic conditions with an effective stress of 3.4 MPa, the permeability of surrounding rocks was measured to be around 10-6 to 10-5 Darcy (d). The induced fracture zone exhibited a 2-3 order of magnitude increase in permeability compared to the original rock, reaching 10-4 to 10-2 d. In contrast, the permeability of fault rocks decreased by 1-3 orders of magnitude, ranging from 10-8 to 10-5 d (Figure 2). The presence of "diagenetic healing" processes such as iron oxide and calcite cementation can further reduce the permeability of fault rocks [14]. The influence of cataclasis on the permeability of fault rock zones falls between these two extremes. Further research has shown that the permeability within deformation zones is generally slightly higher in the direction parallel to the fault plane than in the vertical direction (Kmax > Kmin in Figure 3). This is attributed to the parallel alignment of clay mineral particles and the increased vertical curvature caused by compaction, leading to the compaction or crushing of many interconnected pores [14]. The determination of porosity and permeability in fault rocks is crucial for reservoir development. However, due to limitations in fault rock coring and testing conditions, it is unrealistic to extensively measure the displacement pressure within the strata on both sides of the fault and within the fault zone.

The permeability of fault zones depends on the spatial distribution of fractures and deformation zones, as well as the permeability of the original rock. The permeability of deformation zones developed in high-porosity strata is relatively complex, generally related to the probability of the occurrence and connectivity of internally low-permeability deformation zones and high-permeability slip surfaces [30]. Since deformation fault zones are rarely observed in practical oilfield work, the permeability and displacement pressure described below are only applicable to common brittle faults in sandstone-mudstone interbeds. The permeability of faults in terrestrial clastic strata is directly related to the type of fault rock filling the fractures. The higher the content of clay (or clay-grade minerals) within the fault, the lower the permeability. Many scholars have established empirical formulas for the relationship between clay content and permeability during single-phase fluid flow in fault zones through experimental and fieldwork.

(1)Manzocchi et al.(1999)[31]

$$log\, K_f = 4CCR - 0.25\, log\, D \cdot (1 - CCR)^5 \quad (1)$$

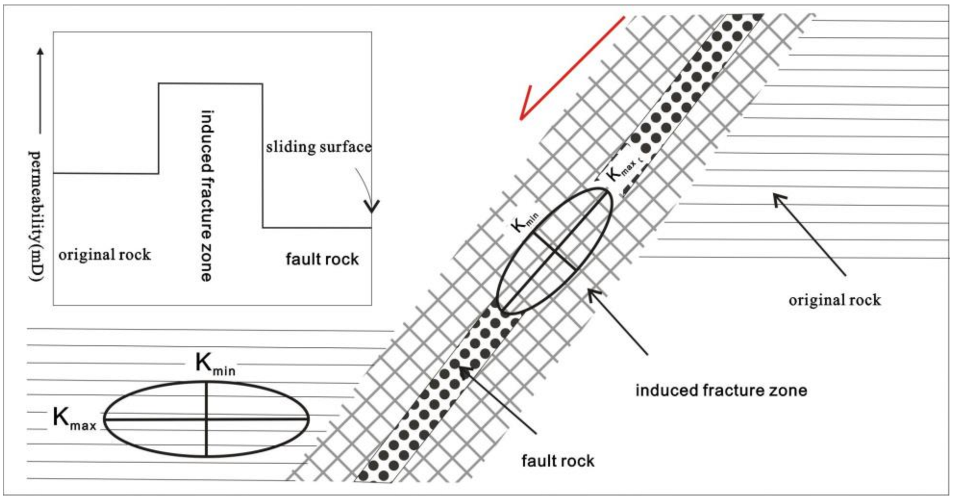

Figure 2: Model of single-phase permeability distribution in clastic reservoir (Fowles, 1994; Evans, 1997, James, 1997)

(2)Badleys Earth Sciences FAPS

$$k_f = 10^{-5\times SGR} \quad (2)$$

(3)Sperrvik et al.(2002)[32]

$$K_f = a \cdot e^{[-b\cdot ccR + c\cdot Z_{max} + (dZ_f - e)\cdot(1-CCR)^7]} \quad (3)$$

The permeability of fault zone rock (Kf) is related to the clay content (CCR and SGR, ranging from 0 to 1), fault displacement (D in meters), and burial depth (Zf and Zmax, in meters, representing the burial depth of fault zone rock at the time of fault formation and the maximum burial depth of fault zone rock, respectively). Empirical constants (a to f) are also involved. Higher clay content, larger fault displacement, and deeper burial depth of fault rocks all lead to lower permeability. When the clay content exceeds 15%, the permeability of fault zone rock is primarily controlled by the maximum burial depth. The empirical formula takes into account factors such as mud content and depth. The burial depth of fault rocks reflects the pressure state of the surrounding strata, and the mud content filling the fracture space obstructs the migration space. The confining pressure and porosity of the strata are both proportional to the permeability, exhibiting clear geological implications.

Strata with high clay content typically exhibit low porosity and low permeability, and oil and water

ISSN 2616-5872 Vol.6, Issue 4: 26-36, DOI: 10.25236/AJEE.2024.060404

layers often show characteristics such as high bound water content, which corresponds well with rock conductivity. Based on the influence of clay content on rock conductivity, Hipper (1997) established a relationship between the conductivity model and permeability for low-porosity, low-permeability argillaceous sandstones in fault zones [33]:

$$K = C \times L_c^2 \times \frac{\sigma}{\sigma_0} \tag{4}$$

Where Lc is the capillary connection radius (in micrometers), σ0 and σ are the conductivity of saltwater solution and the conductivity of the rock sample containing saltwater solution, respectively, and C is a constant. By considering the effective wettability phase saturation, a model can also be established with the displacement pressure [38].

4.2 Displacement Pressure in Faults and Fluid Migration

(1) Calculation of Displacement Pressure in Faults during Static Periods

The displacement pressure in fault zones is a key factor controlling the migration of two-phase (or multi-phase) fluids. It represents the minimum driving force required for secondary hydrocarbon migration and is a crucial indicator for studying secondary hydrocarbon migration and evaluating the sealing capacity of fault zones. When two or more immiscible fluids coexist in a rock pore system or seep through it, capillary phenomena occur, generating a capillary pressure directed towards the interior of the non-wetting phase fluid. The sealing capacity of the fault side and vertical direction depends on the difference in displacement pressure between the reservoir in the target formation, the opposing formation, the fault fillings, and the overlying caprock. However, due to significant limitations in drilling and coring, it is not possible to extensively test the displacement pressure in fault zones. Therefore, employing reasonable methods to predict the displacement pressure in fault zones is crucial for judging fault sealing and evaluating fault traps.

Since Purcell (1949) established the quantitative relationship between rock capillary pressure, capillary (throat) radius, interfacial tension, and wetting angle, many researchers have used capillary displacement pressure to assess the sealing quality of fault zones. Pittman developed an equation linking the sealable hydrocarbon column height in fault zones to the pore throat radius [34]:

$$h = \frac{2\gamma}{rg(\rho_w - \rho_o)} \tag{5}$$

Where h is the hydrocarbon column height (in meters), γ is the hydrocarbon-water interfacial tension (in N/m), g is the gravitational acceleration, ρw and ρo are the densities of water and hydrocarbons (in kg/m^3), rw is the well radius, and rt is the throat radius (in micrometers). Gibson (1998) studied the migration characteristics of two-phase fluids in fault zones [35] and measured pore throat radii ranging from 0.18 to 13.3 micrometers, corresponding to sealed oil column heights of 137 to 2 meters.

In reality, determining parameters such as γ and r in fault zones is challenging, prompting reservoir engineers to seek alternative methods for determining displacement pressure in fault zones. Two common methods exist. One involves establishing a correlation between the displacement pressure in the adjacent reservoir and the fault zone. For example, Lu Yanfang et al. (2002) indirectly analyzed the displacement pressure and lithology ratio of the reservoir on both sides of the fault and estimated the displacement pressure within the fault based on the series principle [1]:

$$\mathrm{P_c} = \frac{P_s * P_m}{R_m * P_s + R_s * P_m} \tag{6}$$

In the formula, Pc, Pm, and Ps represent the displacement pressures of the fault zone, the surrounding mudstone, and sandstone of the target stratum, respectively. Rm and Rs represent the mud content and sand content within the fault zone, which are approximately substituted by the mud content and sand content in the surrounding rocks on both sides of the fault. Fu Guang (2009) introduced a correlation coefficient to evaluate the vertical sealing capacity of the fault zone. This coefficient is related to the fault dip angle, and the displacement pressure of the mudstone within the fault zone is the product of the correlation coefficient and the displacement pressure of the surrounding mudstone [36].

Another method to evaluate the displacement pressure within the fault zone is by analyzing the relationship between the mud content of the fault zone and the pressure of proven reservoirs [5,37] or the pressure directly measured in the laboratory [32] to establish a prediction model. Bretan et al. (2003) analyzed the relationship between the shale gouge ratio (SGR) and the fluid pressure on both sides of the fault trap. They established a quantitative prediction equation based on the mud content and the failure envelope of the plug. For a given SGR value, the fault zone displacement pressure (FRPc) can be estimated as:

$$\mathrm{FRPc}=10^{(\mathrm{SGR}/27-\mathrm{C})} \tag{7}$$

In this formula, C is a constant. When the burial depth is less than 3000m, C is 0.5; when the burial depth is between 3000m and 3500m, C is 0.25; and when the burial depth exceeds 3500m, C is 0. The critical SGR value representing fault sealing or leakage is between 15% and 20%. When the buoyancy of the oil column exceeds the minimum displacement pressure of the fault zone, the fault leaks. By determining the critical displacement pressure to ascertain the maximum fluid buoyancy that the fault can preserve, we can infer the potential hydrocarbon column height supported by each part of the fault. Based on the consideration of the structural spill point, an accurate evaluation of the hydrocarbon resources in the fault block trap can be made, and the practical application effect is good.

Since both permeability and displacement pressure reflect the physical properties of hydrocarbons in the pores of rocks, oil reservoir engineers have been trying to establish a quantitative relationship between permeability and displacement pressure since Purcell (1994) proposed this theory. Sperrevik et al. (2002) studied the relationship between the permeability of a single-phase fluid and the displacement pressure measured by mercury injection experiments on some sandstone reservoirs and fault zone samples from the North Sea oilfield [32]. They derived the following relationship:

$$\mathrm{FRPc}=31.838*K_f^{-0.3848} \tag{8}$$

It must be noted that the above prediction methods have relatively large errors. Sorkhabi (2005) summarized analysis and test data on the displacement pressure and permeability of surrounding rocks and fault zones [22]. He believed that the correlation coefficient between the displacement pressure and permeability of fault rocks is approximately 0.65, while the correlation coefficient between these two properties in the sandstone surrounding the fault is slightly higher, at 0.72.

(2) The impact of displacement pressure within the fault zone on fluid migration

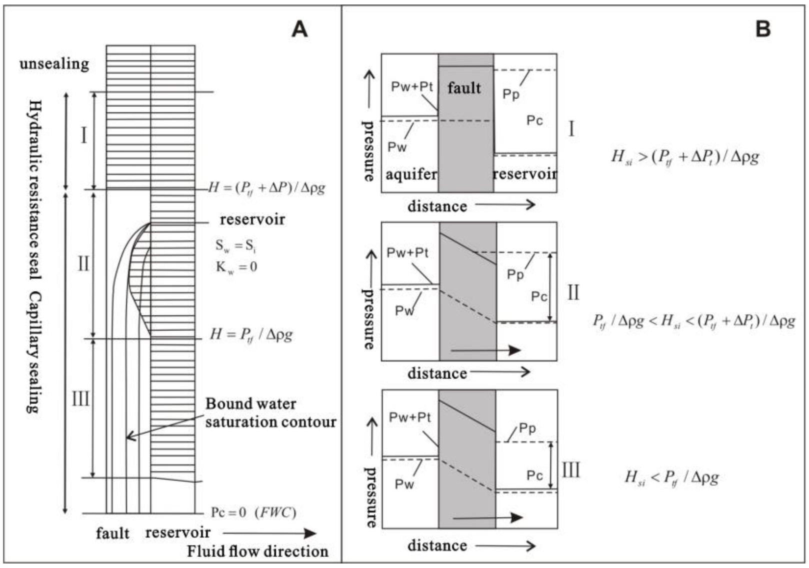

Figure 3: Schematic diagram of sealing mechanism of overpressure fracture fill

There is a similar exponential relationship between the permeability and displacement pressure of both the reservoir sandstone and the fault zone, indicating that both follow the seepage characteristics of porous media. Therefore, the impact of displacement pressure within the fault zone on hydrocarbon migration can be evaluated by comparing the effect of displacement pressure in the reservoir on fluids. As shown in Figure 3, the relevant parameters in the figure are: Ptf and Ptr represent the minimum displacement pressure of the fault fill and the reservoir, respectively; Pp and Pw represent the fluid pressure and pure water pressure, respectively; Pc represents the capillary pressure; Sw and Si represent the water saturation and bound water saturation, respectively; PWC represents the oil-water interface, where the displacement pressure is equal to the minimum displacement pressure; FWC represents the free water interface, where the displacement pressure is 0; Hsi represents the height above the free water surface where the bound water saturation is formed in the reservoir; Ht represents the height above the free water surface where the capillary pressure is equal to the minimum displacement pressure.

(A) Sectional view of the faulted fill and adjacent reservoir. The figure reflects the distribution of oil saturation with depth H. The horizontal line graph shows the distribution of hydrocarbons; (B) refers to the cross-sectional pressure profile of the same reservoir - fault zone fill - aquifer, and the cross-sectional pressure characteristics correspond to stages I, II and III in(A).

(2) There are two sealing mechanisms for fault fillings: film sealing and hydraulic resistance sealing. Film sealing is caused by the surface tension between water and oil and gas, while hydraulic resistance sealing is essentially a "relative" sealing with low permeability. Assuming uniform filling within the fault zone with hydrophilic properties, the fault filling material has a lower effective permeability than the reservoir, resulting in steeper potential gradients and hydrodynamic inclined fluid levels within the filling material compared to the reservoir. The minimum displacement pressure (Ptf) of the fault filling material is greater than the minimum displacement pressure (Ptr) of the reservoir. As oil and gas are injected, both the water saturation and permeability within the fault zone increase with increasing fluid pressure. The sealing effect of the fault zone on oil and gas occurs in three stages: In stage III, the lower boundary of the bound water saturation in the reservoir is below $Ht = Pt/\Delta\rho g$, so the contact surface between the reservoir and the caprock is completely sealed. In stage II, the lower boundary of the bound water saturation is above $Ht = Pt/\Delta\rho g$, and the sealing layer extends to the fault filling material. However, due to $\Delta\rho g < Ptf + \Delta P$, film sealing plays a role. In stage I, the critical displacement pressure of the fault zone is greater than that of the reservoir. With increasing fluid pressure, the relative permeability of multiphase fluids causes a smooth transition from film sealing to leakage, and hydraulic resistance sealing may occur after film sealing is destroyed. The lower boundary of hydraulic resistance sealing is the depth where the capillary pressure is equal to the critical capillary pressure and the oil and gas permeability is zero. Overpressured fluids alter the depth at which these critical values occur. As the fluid pressure gradient on both sides of the fault increases, leakage intensifies. When significant leakage occurs on both sides of the fault, hydraulic resistance sealing fails, and the leakage rate must be less than the injection rate to form oil and gas accumulations.

When the fluid pressures on both sides of the fault are different, many scholars have directly used the pressure difference or the height of the oil and gas column on both sides of the fault to explain the sealing capacity. This explanation actually underestimates the sealing capacity of the fault. As long as there is effective oil and gas permeation through the fault, the hydrocarbon column will seep through the fault filling material. When the capillary pressure at the seepage point drops below the minimum displacement pressure of the fault filling material, pressure equilibrium is maintained [12]. This is similar to the effect of reservoir displacement pressure on oil and gas. The difference in oil-water interfaces is caused by the difference in minimum displacement pressure of the sandstone that crosses the fault. The sealing capacity of different oil-water interfaces should be evaluated based on the capillary pressure of the highest hydrocarbon column [40].

5. Research Prospects and Trends

5.1 Greater emphasis on logging data

Due to technological limitations, the study of internal structural characteristics of fault zones has long been limited to surface surveys and partial laboratory tests. The accurate measurement of mudstone content within fault zones is constrained by factors such as the number of wells drilled into the fault and the availability of core samples. The SGR and SSF calculated based on the lithology of the displaced strata and the fault displacement represent "possible trend values" for the mud content of the fillings, while natural gamma logging and neutron logging responses provide "approximate true values" for the mud content of the fillings within the fault zone. Recent experimental studies have shown that vertical stress, mechanical strength-consolidation state of rock strata, mineral composition, water content, and deformation rate can all affect the formation and continuity of clay smear layers [34]. Other factors include the thickness of the original strata and the fault displacement [4], as well as the pore fluid pressure of the strata [10].

Corrected logging data can reflect the true conditions inside the fault zone. A large number of domestic and foreign literature indicate that there is a clear negative correlation between the acoustic time difference and the displacement pressure of rocks in logging. The greater the acoustic time difference is, the smaller the displacement pressure of rocks will be. Using acoustic time difference data to study the displacement pressure of rocks is essentially to analyze how the propagation speed of sound waves in faults is affected by the lithology of the fillings and the size of spatial pores, which is a direct reflection of the mud content, porosity, and the degree of fault-associated fracture development of the fault fillings. The principles of other logging curves in studying fault features are also based on this, such as combining compensated density logging with acoustic time difference logging to study the development of fault fractures. The compensated density above the breakpoint is significantly reduced, and the acoustic time difference jumps, indicating that there are a large number of fractures distributed along the fault above the breakpoint. The decrease in the degree of fracture development above the breakpoint is manifested in the characteristics of the restored compensated density and the reduced acoustic time difference jumps [31]. It can be predicted that logging data has great applicability in studying the internal structural characteristics of fault zones.

5.2 More emphasis on fluid inclusions

During the migration of oil and gas along faults, hydrocarbon fluids or hydrocarbon-bearing fluids are captured by cementation and fillings to form structural thermal fluid inclusions. Fluid inclusions in calcite, quartz, and various other dykes developed in the caprock and damage zone related to fault hydrocarbon reservoirs, as well as in cracks of quartz particles, record the environmental changes and evolution processes of faults from different perspectives, providing information on underground oil and gas migration and accumulation [39]. Quantitative fluorescence analysis of clastic rock reservoirs is an important means for rapid identification of oil layers, dry layers, and oil and gas migration channels. In recent years, quantitative grain fluorescence (QGF) and non-hydrocarbon quantitative fluorescence (QGF-E) have made significant progress in studying the ancient oil, gas, and water distribution in fault block hydrocarbon reservoirs and inferring the sealing evolution of faults. The oil column height at present and in geological history indicates the current sealing capacity of the fault, while the ancient oil column and residual oil column reveal the sealing and leakage in geological history. Combining the study of hydrocarbon-bearing fluid inclusions with the analysis of fault activity patterns is expected to reveal the sealing evolution of fault block hydrocarbon reservoirs. Gartrell (2006) once used this technique to evaluate the relationship between fault activity history, trap integrity characteristics, and hydrocarbon preservation probability [24], with a geological verification rate of 80%.

6. Conclusions

It is very important and difficult to study the mechanism and ability of fracture to prevent hydrocarbon fluid migration, which can reveal the law of hydrocarbon migration and accumulation. The fault usually exists in the form of fault zone, and its interior is very complicated. According to the historical stage of fault formation and evolution, it can be divided into surrounding rock, induced fracture zone and fracture zone. The characteristics of fluid seepage in the fault zone are the same as those in the reservoir, and the parameters such as the content of mud in the fault zone, the width of the fault zone and the buried depth will affect the ability of the fault to seal or transport oil and gas migration. With the innovation of technical means, logging technology and fluid inclusion quantitative fluorescence technology have become effective means to study the seepage fluid capacity in fracture zone.

References

[1] Lv yanfang, Fu guang, Zhang yunfeng, et al. Fault sealing study [M]. Petroleum Industry Press, 2002:142-146.
[2] Watts N L. Theoretical aspects of cap-rock and fault seals for single and two phase hydro-carbon columns [J]. Marine and Petroleum Geology, 1987, 4(4): 274-307.
[3] Downey M W. Evaluating seals for hydrocarbon accumulation [J]. AAPG Bulletin, 1973, 68(11): 1752-1763.
[4] Yielding G, Freeman B, Needham D T. Quantitative fault seal prediction [J]. AAPG Bulletin, 1997, 81(6): 897-917.
[5] Koledoye B A. Aydin A, May E. A new process-based methodology for analysis of shale smear

along normal faults in the Niger Delta [J]. AAPG Bulletin, 2003, 87(3): 445-463.

[6] Gibson R G. Fault-zone seals in siliciclastic strata of the Columbus Basin, Offshore Trinidad [J]. AAPG Bulletin, 1994, 78(9): 1372-1385.

[7] Bouvier J.D, Kaars-Sijpesteijn C.H, Kluesner D.F. et al. Three-dimensional seismic interpretation and fault sealing investigation,Nun River field,Nigeria [J]. AAPG Bulletin, 1989, 73(11): 1397-1414.

[8] N.G. Lindsay, F.C. Murphy, J.J.Walsh, J. Watterson . Outcrop studies of shale mear on fault surface [J]. Special Publication of the International Association of Sedimentologists 15, 1993, 113-123.

[9] Fisher Q.J., Knipe R.J. K R J. Fault sealing processes in siliclastic sentiments, in Faulting , Fault sealing and Fluid Flow in Hydrocarbon Reservoirs [M]. London: Geological Special Publication, 1998.

[10] Doughty, P. T. Clay smear seals and fault sealing potential of an exhumed growth fault, Rio Grande rift, New Mexico [J]. AAPG Bulletin, 2003, 87(3): 427-444.

[11] N.C. Davatzes, A.Aydin. Distribution and Nature of fault Architecture in a Layered Sandstone and Shale Sequence: An Example from the Moab Fault, Utah [C]// R. Sorkhabi and Y.Tsuji ed. Faults, fluid flow, and petroleum traps. AAPG Memoir 85. 2005: 154-180.

[12] Fisher, Q. J.Harris, S. D.McAllister, et al. Hydrocarbon flow across faults by capillary leakage revisited [J]. Marine and Petroleum Geology, 2001, 18(2): 251-257.

[13] Aydin, A., A. M. Johnson. Development of faults as zones of deformation bands and as slip surfaces in sandstone [J]. Pure and Applied Geophysics, 1978, 11(6): 931-942.

[14] Antonellini, M.Aydin, A. Effect of faulting on fluid flow in porous sandstones; petrophysical properties [J]. AAPG Bulletin, 1994, 78(3): 355-377.

[15] Peacock, D.C.P., Zhang Xing. Field examples and numerical modelling of oversteps and bends along normal faults in crosssection [J]. Tectonophysics, 1994, 234(1): 147-167.

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

[17] Yehuda Ben-Zion, Charles G S. Characterization of fault zone [J]. Pure and Applied Geophisics, 2003, 160(3-4): 677-715.

[18] Gudmundsson,Berg S,Lyslo K B,et al. Fracture networks and fluid transport in active fault zone [J]. Journal of Structure Geology, 2001, 23(2-3): 343-353.

[19] Ramsey, J. G. Shear zone geometry: a review [J]. Journal of Structural Geology, 1980, 2(1-2): 83-99.

[20] Gartrell, A. Bailey, W. R. Brincat, M. A new model for assessing trap integrity and oil preservation risks associated with postrift fault reactivation in the Timor Sea [J]. AAPG Bulletin, 2006, 90(12): 1921-1944.

[21] Sorkhabi, R.B., S.Hasegawa, S.Iwanaga, et al. Sealing assessment of normal faults in clastic reservoirs: The role of geometry and shale smear parameters [J]. Journal of Japanese Associlation of Petroleum Technology, 2002, 67(6): 576-589.

[22] Hesthammer, J.Bjorkum, P. A. Watts, L. The effect of temperature on sealing capacity of faults in sandstone reservoirs: Examples from the Gullfaks and Gullfaks Sor fields, North Sea [J]. AAPG Bulletin, 2002, 86(10): 1733-1751.

[23] Wu hongling. analysis on the mechanical properties of a tensile structure plane and its relationship to principal stresses [J]. Geological Review, 1999, 45(5): 449-455.

[24] Sun huanquan, Wang Jiaying. Distribution law of underground structural fissures and their forecasting [J]. Journal of daqing petroleum institute, 2000, 24(3): 83-85.

[25] Luo qun, Jiang zhenxue, Pang xiongqi. Mechanism and model of hydrocarbon control by fault [M]. Petroleum Industry Press, 2007:279-303.

[26] Fu xiaofei, Fang deqing, Lv yanfang. et al. Method of Evaluating Vertical Sealing of Faults in Terms of the Internal Structure of Fault Zones [J]. Journal of Earth Science, 2005, 30(3): 328-336.

[27] Wu zhiping, Chen wei, Xue yan. et al. Structural Characteristics of Faulting Zone and Its Ability in Transporting and Sealing Oil and Gas [J]. Acta Geologica Sinica, 2010, 84(4): 570-578.

[28] Evans, J. P. Thickness disolacement relationships for fault zones [J]. Journal of Structural Geology, 1990, 12(8): 1061-1065.

[29] Lunn, R.J. Wilson, J.P. Shipton, Z.K. et al. Simulating brittle fault growth from linkage of pre-existing structures [J]. Journal of Geophysical Research-solid Earth, 2008, 113(B043):12-19.

[30] Manzocchi, T. Walsh, J. J. Nell, P. et al. Fault transmissibility multipliers for flow simulation models [J]. Petroleum Geoscience, 1999, 5(1): 53-63.

[31] Sperrvik, S.,P.A.Gillespie,Q.J.Fisher, et al. Empirical estimation of fault rock properties [M]. Norwegian Petroleum Society Special Publication, 2002: 103-140.

[32] Hipper S.J. Microstructures and diagenesis in North Sea fault zone:Implications for fault-seal

ISSN 2616-5872 Vol.6, Issue 4: 26-36, DOI: 10.25236/AJEE.2024.060404

potential and fault-migration rate [M]. AAPG Memoir 67, 1997:85-100.
[33] Pittman E.D. Relationship of porosity and permeability to various parametes derived from mercury injection capillary pressure curves for sandstone [J]. AAPG Bulletin, 1992, 76(2): 191-198.
[34] Gibson R.G. Physical character and fluid-flow properties of sandstone-derived fault zones, Structural geology in reservoir characterzation [J]. Geological Society Special Publication, 1998, 127(1): 83-97.
[35] Fu guang, Zhang nan. Quantitative evaluation for vertical sealing ability of faults in overpressure mudstone cap rock [J]. Fault-Block oil & gas field, 2009, 16(4): 1-3.
[36] Zhou xingui. the study of fault closure by use of entry pressure and its application in north tarim [J]. Jouranl of geomechanics, 1997, 3(2): 47-53.
[37] Brown A. Capillary effects on fault-fill sealing [J]. AAPG Bulletin, 2003, 87(3): 381-395.
[38] Heum, O. R. A fluid dynamic classification of hydrocarbon entrapment [J]. Petroleum Geoscience, 1996, 2(2): 145-158.
[39] Smith, D.A. Sealing and nonsealing faults in Lousiana Gulf Coast salt basin [J]. AAPG Bulletin, 1980, 64(1): 145-172.
[40] Yang weiran, Zhang wenhuai. Tectonic fluids a new research domain[J]. Earth Science Frontiers (China University of Geosciences,Beijing),1996,3(3-4):124-130