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Research Status and Development Trends of Fault Seal in Petroleum Geology

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Abstract

Fault sealing and opening properties are crucial to hydrocarbon migration and accumulation. Fault sealing and opening properties refer to the displacement pressure difference caused by the lithological and physical property differences between the hanging wall and footwall of a fault, and this pressure difference controls the fluid flow capacity between the two sides of the fault. In terms of migration direction, fault sealing and opening properties are divided into vertical sealing and opening and lateral sealing and opening; in terms of the nature of the isolation zone, they are divided into fault plane sealing and opening and lithologic sealing and opening. The controlling factors of sealing and opening properties include juxtaposition, cataclasis, cementation, smear and filling, as well as asphaltene precipitation. The research methods for this property include the Allan plot method, fault plane pressure method, shale smear method and fuzzy mathematics method. At present, all the research methods are quantitative or semi-quantitative analyses with a single means from a certain perspective. Therefore, the breakthrough direction of research methods for fault sealing and opening properties will be comprehensive quantitative analysis from different perspectives.

Keywords

Fault Sealing; Fault Sealing Mechanism; Displacement Pressure; Mudstone Smearing; Controlling Effect of Faults on Hydrocarbons.

1. Introduction

The controlling effect of faults on hydrocarbons is mainly reflected in their impacts on the processes of hydrocarbon migration and accumulation as well as the distribution laws, and its essence lies in the issue of fault seal. Fault seal is often controlled by multiple factors, and there are significant differences in the fault sealing mechanisms and the dominant controlling factors of seal among different regions, different strata and different geological periods[1]. At present, a complete research system for fault seal, sealing mechanisms and evaluation methods has not yet been established, and the accuracy of its evaluation still needs to be improved[2]. Based on a comprehensive and systematic investigation of the research hotspots in fault seal in recent years, this paper summarizes the fault sealing mechanisms, analyzes the dominant controlling factors of fault seal, sorts out the evaluation methods of fault seal, discusses the practical problems faced in the research of fault seal, and puts forward the future research and development trends. Currently, the fault sealing mechanisms can be divided into vertical sealing mechanisms and lateral sealing mechanisms. The former includes the fault plane sealing mechanism and the displacement pressure difference sealing mechanism of the fault zone, while the latter includes the sandstone-mudstone juxtaposition sealing mechanism, the lateral sealing mechanism formed by shale smearing and the high displacement pressure sealing mechanism of the fault zone. The main factors affecting fault seal include fault development characteristics, lithology of the two fault walls, stress field environment, and diagenetic processes such as compaction, cementation and dissolution[3]. Different factors exert their

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effects on fault seal in different ways, and the sealing performance of faults varies significantly at different positions and in different periods.

The future research directions of fault seal include the fault sealing and opening mechanisms and seal evaluation in carbonate formations, the influence mechanism of stress, fluid and their coupling effects on fault seal, the comprehensive quantitative evaluation of fault seal considering multiple factors, and the spatiotemporal evolution of fault seal and the assessment of hydrocarbon source connectivity capacity[4]. Since faults can act as pathways, barriers, or combined pathway-barrier structures for subsurface hydrocarbon migration, their presence increases the risks associated with hydrocarbon drilling, exploration, and development[5-7]. To accurately assess whether faults function as migration pathways or barriers to hydrocarbon movement, intense discussions have been conducted within the petroleum industry and among geologists. With the continuous breakthroughs in hydrocarbon exploration and development technologies, the available subsurface geological and geophysical data have become increasingly abundant, including seismic data, core physical property data, core microstructures, core mechanical properties, logging data, and production performance data of hydrocarbon wells[8]. These data have made it possible to predict and evaluate fault seal in petroliferous basins.

The degree of fault sealing is affected by multiple factors. There are significant differences in fault sealing mechanisms and the dominant controlling factors of sealing among different regions and strata[9]. A complete research system for fault seal evaluation methods has not yet been established, and the accuracy of such evaluation still needs to be improved[10].

Therefore, summarizing fault sealing mechanisms, influencing factors of sealing performance, and sealing evaluation methods, as well as analyzing future research directions, is of great significance for evaluating the timing and capacity of hydrocarbon migration through source-connecting faults, reconstructing hydrocarbon accumulation processes, predicting favorable hydrocarbon accumulation zones, analyzing hydrocarbon distribution patterns, and reducing hydrocarbon exploration risks.

2. Research Progress and Influencing Factors of Fault Seal

A fault is a complex three-dimensional geological body, and the dissection of its internal structure is the basis for studying fault sealing and opening properties. Due to the complexity of fault internal structure and the practical problems arising in hydrocarbon exploration and development, scholars have conducted extensive research on this topic. The fault core refers to a shear zone composed of fault slip surfaces, structural lenticles and fault rocks. The formation of a fault core is affected by factors such as fault activity intensity, stress nature, burial depth, surrounding rock and lithology, and is manifested as a combination of one or more of the above-mentioned fault rocks. The fractured zone is located on both sides of the fault core, characterized by high fracture density and higher permeability than the surrounding rock and the fault core. Typical binary and ternary structures are commonly observed in normal faults or reverse faults. However, the internal structures of the strike-slip faults differ from those of normal and reverse faults. This is because strike-slip faults typically feature a main fault that cuts directly into the basement, bifurcates upward, and spreads out, forming a flower-like shape with a narrow lower part and a wide upper part of the fractured zone. This characteristic may result in differences between the internal structure of the wide upper fractured zone of strike-slip faults and the typical binary and ternary structures of other faults. Studies have shown that the internal structure of the translational segments of strike-slip faults remains a ternary structure.

The farther away from the fault center, the lower the fracture density and the lower the degree of filling. Fractures at corresponding positions on the active wall are more developed than those

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on the passive wall. The deformation of different types of fault rocks inside the fault and the heterogeneity of fracture distribution exert a significant impact on the sealing properties of different positions of the fault. Therefore, the study of the differences in the internal structure of faults is the basis for analyzing the influencing factors of fault sealing properties.

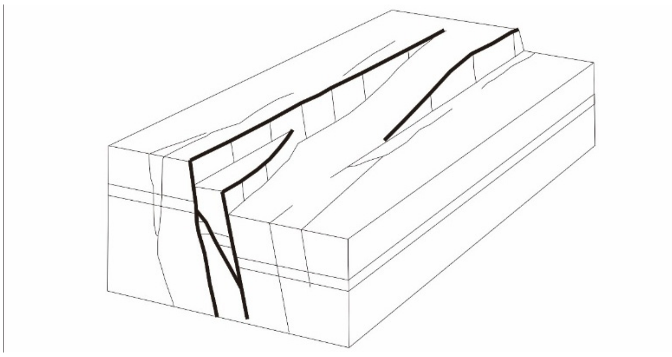

Fig 1. Binary structure of normal faults

Previous studies have systematically analyzed the influencing factors of sealing properties of normal faults and reverse faults in sandstone-mudstone formations. These factors mainly include the mechanical properties of faults, strike, dip angle, displacement, burial depth, formation period, activity period, activity intensity, the configuration relationship between fault occurrence and stratum occurrence, fault density, fault combination pattern, lithology of the opposing wall, sandstone-mudstone thickness ratio, shale smear factor, properties of fault zone fillings, cementation and diagenesis of fault zone fillings, fluid action, compaction, dissolution, and internal fault structure. Different factors exert their effects on fault sealing properties in distinct ways.

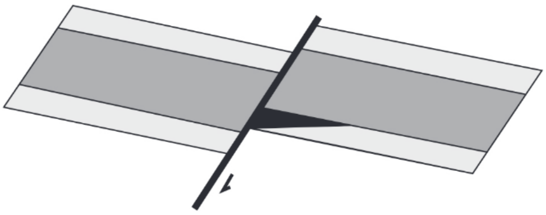

Fig 2. Schematic Diagram of Fault Seal

According to the structural state and lithological differences of faults, the sealing and opening properties can be divided into two categories: Fault plane sealing and opening properties: the sealing and opening properties generated by the juxtaposition of the two fault walls; Lithological sealing and opening properties: the sealing and opening properties resulting from pore-permeability pressure differences, which are caused by lithological changes of the two fault walls induced by fault activities or shale smearing.

3. Fault Seal Evaluation Methods

Over the past 50 years, based on the understanding of fault zone structures, fault sealing and opening types, fault sealing and opening processes, and fault rock generation, geologists have proposed a large number of models and methods to evaluate the sealing and opening behavior of fault zones. Among these methods, nine are the most representative, namely the Allan plot method, fault plane pressure method, shale smear method, acoustic interval transit time method, seismic velocity spectrum identification method, logical information method,

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nonlinear mapping analysis method, fuzzy mathematics method, and connectivity probability method.

3.1. ALLAN Diagram

Due to the variations in stratum occurrence and fault displacement along the fault strike, the stratum contact relationships differ at different positions of the fault. The locations where permeable reservoirs are juxtaposed will form spill points, leading to hydrocarbon seepage. Therefore, fault-block structures are not necessarily traps. To delineate genuine fault traps and reduce the exploration risks of fault-block structures, Allan proposed a cross-section mapping method. Specifically, based on high-resolution seismic data and drilling data, the strata of the hanging wall and footwall of the fault are divided in detail. Then, the lithology of the hanging wall and footwall cut by the fault plane is accurately plotted on a single map, and the contact conditions between permeable and impermeable layers at different positions are analyzed. In this way, the truly effective trap locations can be delineated, and the risks of hydrocarbon exploration can be mitigated.

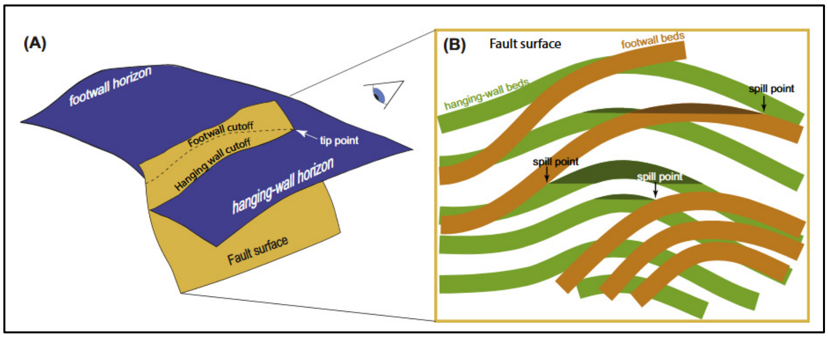

Fig 3. Schematic Diagram of Allan Method

The workflow of this method is as follows: the fault plane is used as the base map, and the strata of the two fault walls in contact with the fault plane are projected onto the fault plane. Then, the fault planes of several faults are superimposed on a single map using the fault plane as the overlapping surface. This enables three-dimensional characterization of stratal juxtaposition and fault structures, which helps to understand stratal contact points, fault geometric structures, and trap styles.

Its advantage lies in the intuitive evaluation of the lithology on both sides of the fault through mapping, so as to quickly identify hydrocarbon spill points and assess the lateral sealing capacity of the fault. However, it cannot finely characterize the juxtaposition of sandstone and mudstone, and treats the fault plane as a hypothetical surface that is neither open nor sealed.

3.2. Shale Gouge Ratio

According to the research by Lindsay et al. in 1993, shale smearing refers to a process where, during fault activity, mudstones (including gypsum-mudstones and salt rocks), due to their high plasticity, are crushed into clays or undergo plastic deformation under the action of tectonic compressive stress and gravity, thus forming a shear zone composed of clay interlayers. This shale smear zone seals laterally migrating hydrocarbons by virtue of its own high displacement pressure. Although shale smearing can enable faults to form lateral seals, it may not necessarily produce vertical sealing effects. Parameters such as shale smearing capacity, smear factor, and fault gouge ratio can be used to evaluate the degree of lateral sealing of faults.

Shale Gouge Ratio: It refers to the ratio of the product of the thickness of the strata displaced by the fault and the shale content of the corresponding strata to the vertical displacement. The larger the SGR value, the higher the shale content in the fault zone, the stronger the ability of fault rocks to seal hydrocarbons laterally, and the more difficult it is for hydrocarbons to seep. The smaller the SGR value, the lower the shale content in the fault zone, the weaker the ability of fault rocks to seal hydrocarbons laterally, and the easier it is for hydrocarbons to seep.

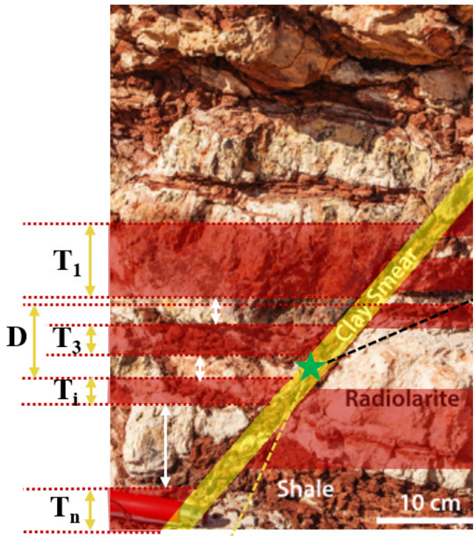

Fig 4. Schematic Diagram of Fault Gouge Ratio Method

3.3. Fuzzy Mathematics Method

Fuzzy mathematics is an important method for the semi-quantitative and quantitative evaluation of fault sealing and opening properties in reservoirs. To study fault sealing and opening properties more accurately, on the basis of previous research, Dong improved the comprehensive quantitative evaluation method of fuzzy mathematics: first, the dynamic clustering method was adopted to determine the membership degree of single factors; then, the continuous scoring function was used to construct the single-factor evaluation matrix; finally, the probability distribution of evaluation grades in the fuzzy evaluation matrix was analyzed.

This method decomposes the evaluation object into multiple factors and evaluates each of them separately to obtain the fuzzy evaluation vector; ultimately, the comprehensive evaluation value is derived through fuzzy transformation. This method involves three key elements, namely the factor set, the evaluation set, and the single factor. In the evaluation of geological phenomena, many qualitative indicators are fuzzy in nature. Forcing them to be quantified may lead to the loss of intermediate information, resulting in evaluation deviations. However, the fuzzy comprehensive evaluation method can simulate the way the human brain processes fuzzy information, and effectively avoid such losses by establishing the fuzzy relationship between the evaluation factor set and the evaluation set.

3.4. Nonlinear Mapping Analysis Method

The nonlinear mapping analysis method is a mathematical approach that transforms high-dimensional data into low-dimensional representations through nonlinear conversion while preserving the original geometric relationships as much as possible. This enables us to directly observe the interrelationships among high-dimensional samples in a low-dimensional space. In the study of fault seal, Q-mode nonlinear mapping analysis is commonly adopted, where the term "Q-mode" indicates that a distance coefficient matrix is used to characterize the relationships between sample points. When applying this method to study fault seal, the first step is to accurately identify the main factors affecting fault seal and select a certain number of known faults with or without sealing capacity as reference samples. On the two-dimensional plane generated by nonlinear mapping analysis, faults that are close to the reference samples tend to have similar sealing properties.

3.5. Normal Stress Method of Fault Plane

The magnitude of the normal stress acting on the fault plane determines the tightness of the fault plane structure, thereby governing the sealing and opening properties of the fault. Fault plane pressure is a qualitative method for characterizing the vertical sealing and opening properties of faults. The higher the pressure exerted on the fault plane, the better the tightness of the fault plane; conversely, the lower the pressure, the poorer the tightness.

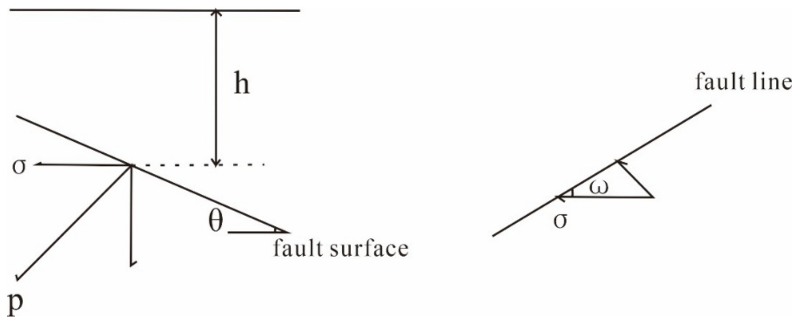

Fig 5. Schematic Diagram of Fault Normal Stress Method

In any stress field, we can identify a normal stress field where the shear stress is zero. Based on the principle that rocks deform under applied forces, mudstones will undergo plastic deformation when the applied pressure reaches the upper limit of their elastic range. According to the data from the compressive strength experiments conducted by Li Defa et al., mudstones exhibit plastic deformation when subjected to a pressure ranging from 5 to 10 MPa. Therefore, most scholars regard the pressure range of 5–10 MPa as the minimum threshold required for the initiation of vertical sealing in faults.

If the strata on both sides of the fault plane are dominated by argillaceous rocks, the argillaceous rocks will undergo plastic deformation and flow when the fault plane pressure meets or exceeds this range, thereby forming a favorable vertical seal. Conversely, if the strata on both sides of the fault plane are dominated by arenaceous rocks, the fault plane may close under pressure, but the juxtaposition of sandy layers will leave seepage pores, resulting in a generally vertically open fault.

It is evident that when using fault plane pressure to evaluate the vertical sealing and opening properties of faults, it is essential to combine this parameter with the sand-shale ratio of the displaced strata. Evaluation criteria for the vertical sealing and opening properties of faults in the study area should be established based on existing practical data, so as to classify the sealing and opening levels accordingly.

4. Research Limitations and Future Directions

According to the research status of fault sealing and opening properties by scholars at home and abroad, there are generally the following future development directions. Although scholars worldwide have conducted systematic and in-depth research on fault sealing properties in recent years, and achieved many new understandings and results, it remains an extremely challenging problem to accurately evaluate fault sealing properties. This is mainly due to the highly complex geological structure of fault zones. By reviewing previous research on the history, sealing mechanisms, main controlling factors, and evaluation methods of fault sealing properties, the authors hold that there are still many unsolved problems in the research of fault sealing properties. At the current stage, research on the mechanisms controlling fault sealing

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and opening properties remains insufficiently in-depth. For example, the formation mechanism of shale smearing proposed by Lindsay et al. especially how it generates fault seals in three-dimensional space, is still not clearly elaborated. Therefore, further deepening the research on the influence mechanisms of factors such as shale smearing and cementation in three-dimensional space will be an important development direction in the study of fault sealing and opening properties.

Early research on fault sealing properties mainly focused on sealing mechanisms such as sand-mudstone juxtaposition, shale smearing, and high displacement pressure in fault zones. In addition, the evolution of multi-stage tectonic stress fields, fault properties, fault occurrence (strike and dip angle), the angle between fault strike and the maximum horizontal principal stress, and the internal filling characteristics of fault zones have significant impacts on fault sealing properties. If a fault zone has high shale content and a high degree of filling, the fault tends to have relatively poor openness. In contrast, if a fault zone is heavily filled with brittle minerals such as calcite and silica, affected by later tectonic activities and fluid activities, the brittle fillings will undergo secondary or multiple tectonic fracturing and re-dissolution, generating a large number of micro-fractures with good openness, which results in heavily filled fault zones still possessing favorable openness. This is because they not only affect the redistribution of hydrocarbons in paleo-reservoirs, but also control the present-day hydrocarbon distribution patterns, as well as the fluid migration pathways and modes during the development process.

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