

Research Progress on the Structure and Permeability of Fault Zones

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Abstract

The fluid dynamics of fault zones have long been a cutting-edge scientific issue in geological research, focusing on characterizing the fracture structure and permeability of fault zones. Fault zones consist of rocks that are spatially close, genetically related, and exhibit varying degrees of deformation, which can be divided into two distinct structural units: the fault core and the damage zone. The structure of fault zones is not static; it continuously evolves under the influence of tectonic stress, fluids, protolith lithology, and evolutionary stage. The permeability of each structural unit in a fault zone is primarily determined mainland by the internal structural features that develop, significantly influenced by the evolution of fault activity. During active faulting periods, permeability in both the fault core and damage zone rapidly increases, while during quiescent periods, the permeability of the fault core declines sharply, and that of the damage zone decreases more gradually. Additionally, fault type, thermal history, protolith lithology, and fluid-rock interactions are also important factors affecting fault permeability. Despite the numerous findings regarding fault zone structures and permeability, it is still necessary to analyze the spatiotemporal evolution of fault structure and permeability from the perspective of their coupling with the dynamics of fluid flow. This understanding will aid in addressing related issues such as energy exploration, disaster forecasting, and management.

Keywords

Fault core, damage zone, permeability, fluid dynamics of fault zones.

1. INTRODUCTION

Fault zones serve as important conduits for subsurface fluid flow, and the associated fluid activities influence the migration and accumulation of hydrocarbons and mineralizing fluids (Cox et al., 2016; Curzi et al., 2023), CO₂ geological sequestration (Tueckmantel et al., 2012), regional hydrology and hydrogeological conditions (Bense et al., 2013), crustal mechanical properties and earthquake models (Valoroso et al., 2014; Shelly et al., 2015), among other geological conditions and processes. Consequently, the fluid dynamics of fault zones have become a frontier scientific issue in geoscience research.

Permeability and its heterogeneity are the primary factors affecting fluid flow in porous media. Therefore, a key aspect of studying fluid dynamics in fault zones is to characterize the permeability and its heterogeneity and evolution within these zones. In recent years, researchers have discovered that fault zones typically exhibit complex internal structures, which can be divided into two distinct structural units: the fault core and the damage zone. The permeability of these structural units is primarily controlled by the internal structural features (Faulker et al., 2010). Additionally, it has been found that the fluid-rock interactions within fault

zones cause the permeability to exhibit temporal and spatial variations, and these interactions can alter the strength and permeability of the fault, further affecting the evolution and structural characteristics of the fault zone. Clearly, fluid flow in fault zones is a complex process involving interactions among multiple physical fields. Therefore, analyzing the structure and permeability of fault zones, along with their temporal and spatial evolution patterns, is crucial for exploring the mechanisms of fluid conduction and/or obstruction in these zones.

Due to the widespread distribution of faults, the complexity of their formation mechanisms, the transient nature of their activity, the multi-phased evolution, and the strong heterogeneity of their internal structures and permeabilities, studies on fault zone structures and permeabilities are often conducted on specific real-world examples to develop conceptual models. This has resulted in numerous research outcomes in the field, but also ongoing controversies. Thus, it is urgent and necessary to periodically review the extensive body of research in this area and summarize the consensus reached and the key scientific questions that remain unresolved.

2. FAULT ZONE STRUCTURE

Modern tectonic geology theory posits that fault zones are banded geological entities composed of spatially adjacent, genetically related rocks that exhibit varying degrees of deformation. Therefore, the essence of studying fault zone structure is to analyze the deformation and distribution characteristics of the rocks within the fault zones.

2.1. Formation Process of Fault Zones

Extensive field observations, experimental simulations, and theoretical studies indicate that tectonic faults are the products of rocks reaching the rupture stage under stress (Crider, 2015). When the stress on the rocks exceeds the yield point, shear displacement occurs along weak planes between mineral grains or within crystals, forming conjugate Luder's bands that exhibit an X-shaped distribution, creating a potential shear rupture network. As strain increases, when the shear stress surpasses the rock's shear strength, the Luder's bands rupture, forming an X-shaped conjugate microfracture system. The ends of microfractures are typically favorable locations for stress concentration and propagation, rapidly expanding and connecting to form the main fault surface. Once the main fault surface is established, if the stress exceeds the frictional force, the two sides of the fault will slide relative to each other along the main fault surface, causing the rocks distributed along the fault to fracture and become finer-grained, resulting in fault rocks with varying deformation characteristics. Additionally, the ellipsoidal strain field generated by fault shear can pull surrounding rocks into the deformation process, leading to the formation of an asymmetrically distributed outer rupture zone (Choi et al., 2016).

In recent years, many researchers have recognized that fluid involvement profoundly influences the formation and evolution of fault zones (Caine et al., 2010; Cox et al., 2016). During the fault's quiescent period (Figure 1a), fluids are stored in the voids of the rocks surrounding the fault zone (including pores and fractures). As the minimum principal stress decreases, the differential stress controlling the tectonic deformation gradually increases, causing the fractures formed during early fault activity to open first as stress concentration zones, facilitating the generation of new fractures, while the local fluid flow produced promotes the development of hydraulic fractures. When the differential stress reaches the rupture limit (Figure 1b), the fault enters the active phase, with shear sliding and strain propagation causing the entire fault zone to widen, creating cavities within the fault core and extending fractures to form a network of fractures that serve as a low-pressure, high-permeability fluid flow channel. At this point, high-pressure fluids stored in the surrounding rock enter the fault zone due to the pressure difference. The fractured rocks within the fault core undergo rupture, rotation, and fluidization, resulting in fault rocks with distinct characteristics and strong heterogeneity.

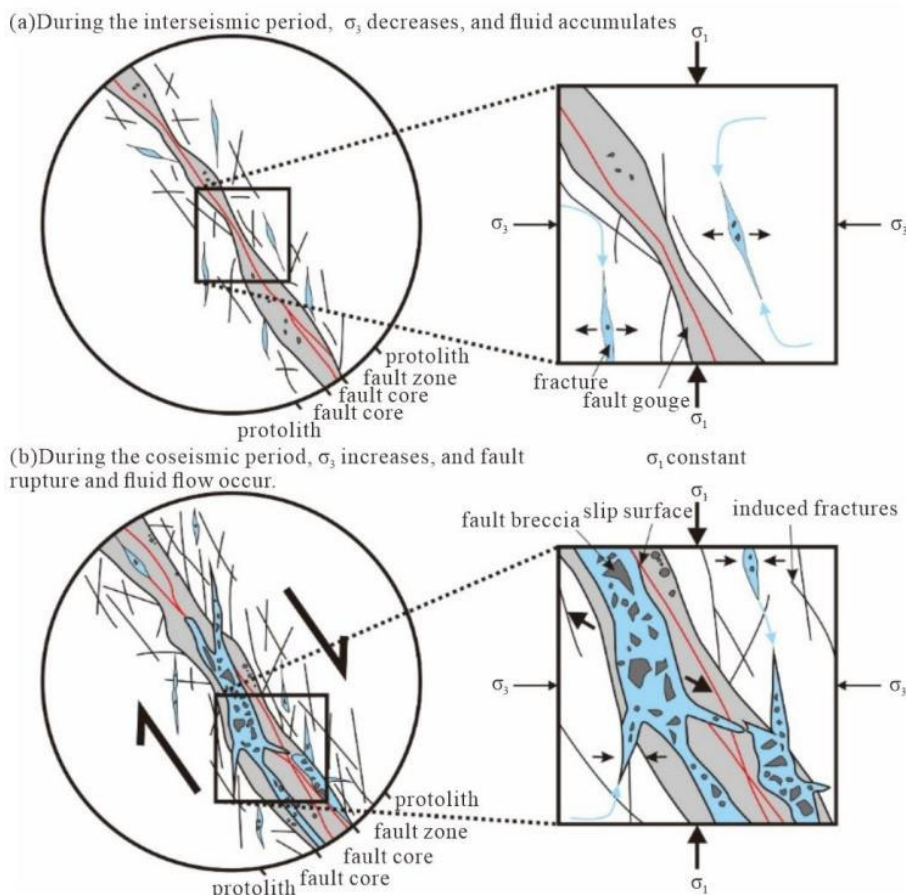


Figure 1. Geological model of fault-fluid interaction (after Caine et al., 2010).

Calculations indicate that the formation of a mature fault zone requires approximately 103 episodes of faulting. Consequently, the width of the fault zone, the heterogeneity of the fault rocks, and the extent of the surrounding rupture zone will continuously increase with repeated faulting activities, leading to the evolution of the fault zone into a three-dimensional banded geological entity with a complex internal structure.

2.2. Structural Characteristics of Fault Zones

Based on the deformation characteristics of rocks within fault zones, they are typically divided into strongly deformed fault cores, characterized by permeable or semi-permeable deformation, and low-strain rupture zones, dominated by non-permeable or dispersed deformation (Bastesen et al., 2010; Marinković et al., 2023). The fault core is a narrow zone located at the center of the fault zone where intense rock deformation occurs. It absorbs most of the energy released during faulting activities and concentrates the majority of the strain in the fault zone. The fault core usually consists of one or more slip surfaces, fault gouge, fault breccia, shattered rocks, structural lenses, and smeared clay. The rupture zone, found in the limited area surrounding the fault core or at the stress re-lease zones at the ends of the fault, does not exhibit complete rock fracturing, and the original rock fabric remains identifiable. Its width varies significantly, and the rupture zones are asymmetrically distributed on either side, primarily developing structures such as fractures, deformation zones, small faults, cleavage, dikes, and minor folds (Figure 2; Faulker et al., 2010; Chen et al., 2010). Additionally, Kim et al. (2004) classified rupture zones based on their locations into wall rock rupture zones, connecting rupture zones, and terminal rupture zones. In nature, not every fault develops all the aforementioned structural features, and the fault structure often changes along the strike and dip.

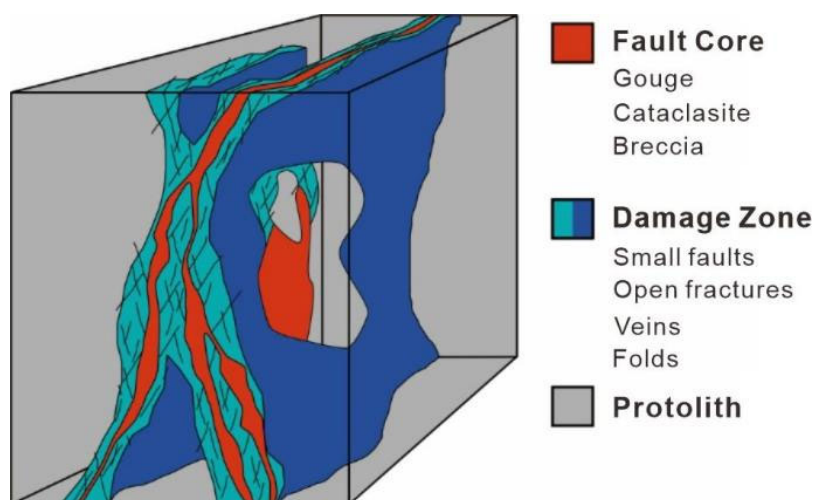


Figure 2. Structural model of fault zones

The tectonic stress field controls the properties, formation, and evolution of faults, making it a major factor influencing fault structure characteristics (Faulker et al., 2010). Normal faults formed in extensional stress fields (Figure 3) typically develop fault rocks that are fragmented, loose, fine-grained, and weakly cemented in the fault core; the rupture zone, on the other hand, features shorter and less continuous structural fractures, but due to the higher density of fractures, it often forms interconnected fracture network systems (Berg et al., 2005). In contrast, reverse faults developed in compressional stress fields show fault core rocks that are dense, fine-grained, and rich in fault gouge due to intense shear rotation and fracturing; the rupture zone, in this case, tends to develop multiple sets of long, well-connected structural fractures (Tesei et al., 2014).

Traditional studies of fault structures have primarily focused on the strongly deformed fault core, while researchers have paid more attention in the last 20 years to the weakly deformed rupture zones surrounding the fault core. Studies indicate that rock porosity significantly controls the deformation behavior of rupture zones; rupture zones in high-porosity rocks commonly develop deformation bands, where rock particles undergo extensive fragmentation, leading to a significant reduction in local permeability, which may impact fluid flow in high-quality reservoirs (Fachri et al., 2013; Ballas et al., 2015). In contrast, rupture zones in low-porosity rocks are typically dominated by fracture development, which often forms interconnected fracture systems, thereby effectively improving the rock's permeability (Sagi et al., 2016). As one moves away from the fault core, the density of deformation bands or fractures in the rupture zone decreases (Wibberley et al., 2008). Additionally, researchers have found a clear positive correlation between the width of the rupture zone and fault displacement, with statistical analyses of various scale fault data suggesting that the relationship between rupture zone width and displacement is approximately linear on a logarithmic scale (Wibberley et al., 2008). Furthermore, some researchers believe that current definitions and determinations of rupture zones are highly subjective, and indiscriminate comparison of fault data from different backgrounds (such as lithology, structure, and depth) may lead to unrelated comparisons. Therefore, establishing a quantitative relationship between rupture zone width and displacement through statistics needs improvement (Wibberley et al., 2008; Choi et al., 2016).

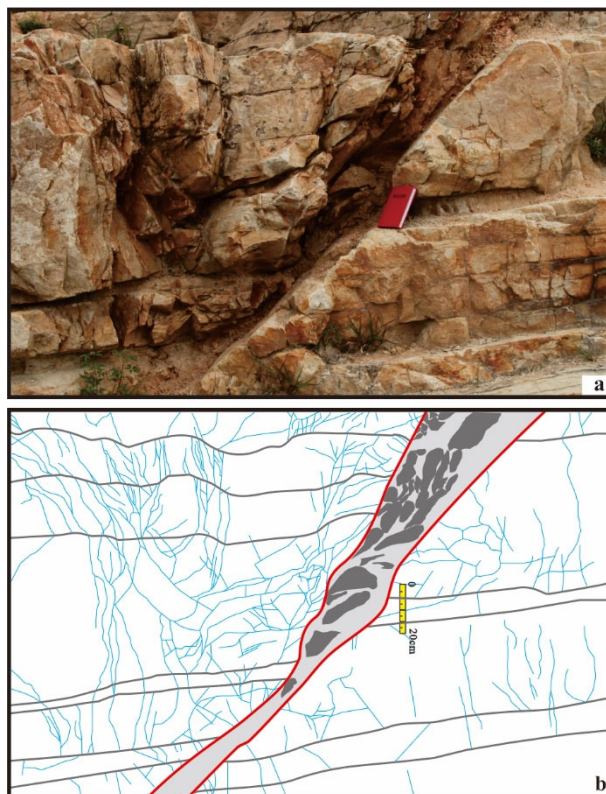


Figure 3. Structure and structural elements of normal fault zones.

a. Photo of the Qinhuangdao Jiguan Mountain normal fault outcrop; b. Sketch of the structural elements of the Jiguan Mountain normal fault (black lines represent strati-graphic boundaries, blue lines indicate structural fractures, the area between the two red lines represents the fault core, the light gray area represents fault gouge, and the dark gray area represents fault breccia and structural lenses).

3. PERMEABILITY AND EVOLUTION OF FAULT ZONES

As a hotspot and challenge in the study of fluid dynamics in fault zones, the current re-search on fault permeability mainly focuses on the characterization of present-day permeability and the reconstruction of ancient permeability and its evolutionary history.

3.1. Permeability Characteristics of Fault Zones

A large number of laboratory and in-situ permeability test results of fault zone rocks indicate that the fault core, which is highly deformed and rich in fault gouge, typically exhibits very low permeability, while the surrounding damage zones dominated by fractures show relatively high permeability (Figure 4). This creates an “M”-shaped permeability distribution across the fault zone, forming a binary structure of fluid flow "path-ways/barriers" (Faulker et al., 2010; Bense et al., 2013; Farrell et al., 2014). The formation of this high-permeability damage zone and low-permeability fault core is attributed to the transition from the damage zone to the fault core, where rock deformation intensity increases, grain size decreases, and clay mineral content increases. Additionally, the permeability of fault zones exhibits significant anisotropy, with permeability parallel to the fault slip direction being markedly higher than in other directions, indicating that fluids are more likely to flow along the direction of fault slip (Farrell et al., 2014).

The lithology of the host rock has a significant impact on the permeability characteristics of fault zones. Research by Laubach et al. (2014) on fault zones developed in Proterozoic sandstones in northwest Scotland indicates that even with the same thermal history and fault

evolution process, the characteristics of fault cores and damage zones can vary greatly among different lithological units, resulting in pronounced spatial heterogeneity in the permeability structure of the same fault zone. Specifically, the fault core of the same fault zone can transition from being a low-permeability barrier to a high-permeability conduit, while the damage zone can change from a high-permeability conduit to a low-permeability barrier. This is primarily reflected in the distribution patterns of fracture lengths and apertures, as well as the locations of quartz precipitation, which differs significantly from the previously mentioned binary “pathway/barrier” permeability structure. This is mainly due to differences in host rock lithology, leading to distinct patterns of fracture length and aperture distribution and cementation characteristics within different structural units of the fault zone, resulting in spatial variations in permeability structure with changes in lithology (Laubach et al., 2014; Haines et al., 2016). Furthermore, the flow-rock interactions occurring within different lithological units in fault zones differ, with local flow-rock interactions in the fault core increasing fault strength, leading to predominantly brittle deformation and enhanced permeability during subsequent fault activity. In contrast, local flow-rock interactions within the damage zone can block fractures, reducing fracture apertures and consequently weakening permeability.

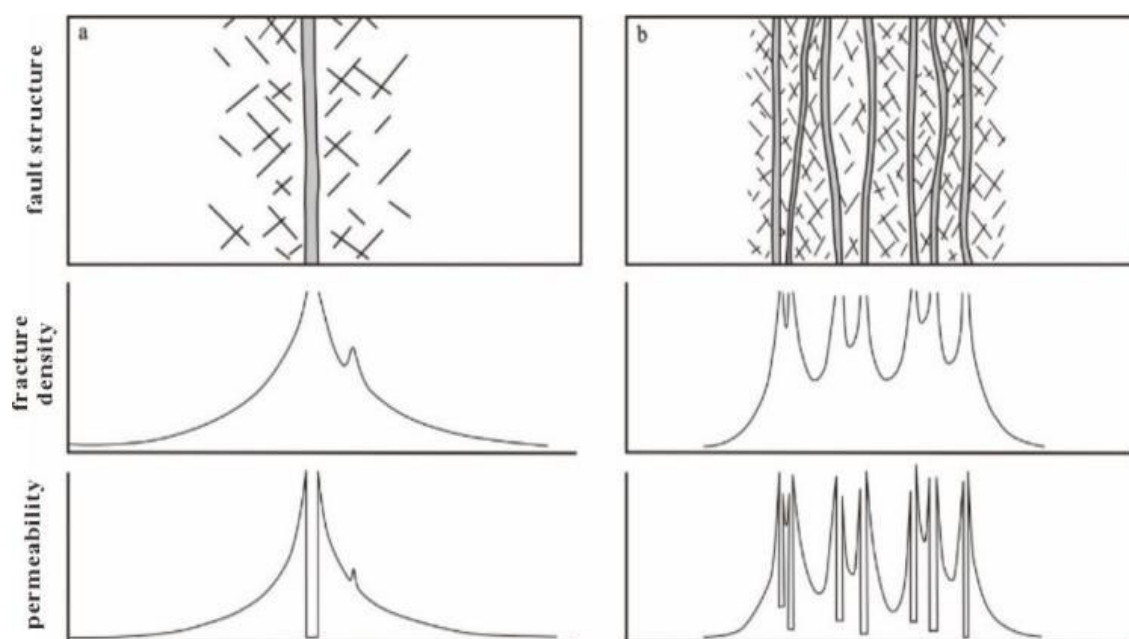


Figure 4. Relationship between fault structure, fracture density, and permeability (Faulkner et al., 2010)

a Single fault core model; b. Multiple fault core model.

3.2. Evolution of Permeability in Fault Zones

During earthquakes, phenomena such as sand eruptions, sudden water influx, and increased production in oil and gas wells commonly occur along fault zones. These anomalies indicate a significant enhancement in fluid activity during fault activity, drawing researchers' attention to the evolution of permeability in fault zones. Micklethwaite et al. (2004) found through numerical simulations that shear forces during earthquakes can create numerous voids in the fault core and open fractures in the surrounding damage zone, transforming the entire fault zone into a transient high-permeability area. As seismic energy is released, the fault core rapidly heals and closes, becoming a low-permeability barrier, while the damage zone heals more slowly, remaining a relatively high-permeability fluid pathway for some time. This permeability

evolution process aligns with results from permeability tests conducted on the fault zone after the Wenchuan earthquake (Xue et al., 2013). Additionally, laboratory simulations of permeability evolution in fault zones (Faulkner et al., 2013; Scuderi et al., 2015) show that permeability slowly increases prior to rupture; as differential stress approaches the rupture limit, rock dilation and opening of fractures lead to a rapid increase in permeability. After maintaining constant confining and differential stress, the permeability of the fault zone decreases, exhibiting an exponential decline over time. These findings suggest that during fault activity, both the fault core and damage zone experience rapid increases in permeability, while in the quiescent phase, the permeability of the fault core decreases rapidly, and that of the damage zone declines more slowly. The structural effects during fault activity can effectively enhance the transient permeability of the fault zone, while fluid-rock interactions during the quiescent phase are a primary factor in reducing porosity and permeability.

Fluid-rock interactions within fault zones and their influence on permeability have become a recent research focus. Based on differing results of permeability alteration, these interactions can be classified into porosity-reducing processes dominated by cementation and recrystallization, and porosity-enhancing processes primarily driven by dissolution (Laubach et al., 2014; Haines et al., 2016). Furthermore, fluid-rock interactions within fault zones are closely linked to the lithology of the surrounding rock; there are significant differences in these interactions across different lithologies, leading to spatial and temporal variations in the permeability structure of the fault zone. For clastic rocks, quartz-rich protolith are generally favorable for the precipitation of quartz cement within fault zones, whereas rock fragments and feldspar-rich protolith hinder quartz cementation (Laubach et al., 2014). In carbonate rocks, particle-supported facies promote recrystallization and obstruct primary porosity, while matrix-supported facies, rich in clay, inhibit recrystallization but facilitate fracturing and subsequent dissolution processes (Haines et al., 2016).

4. OUTSTANDING ISSUES AND RESEARCH OUTLOOK

In light of the current state of research on fault zone structure and permeability, the author believes that addressing the following two aspects will help better understand the fluid dynamics characteristics of fault zones, thereby resolving related issues in energy exploration, disaster forecasting, and management.

Current research on fault structure primarily focuses on normal faults formed in extensional stress fields, while there is less attention paid to faults with other mechanical properties. Therefore, studies should enhance the analysis of different types of fault structures and the quantitative characterization of structural elements, summarizing and comparing their differences. Additionally, since fault structures are not static, it is necessary to analyze the spatiotemporal evolution characteristics of fault structures and their elements using an evolutionary-modification perspective.

Although progress has been made in the quantitative characterization of fault zone permeability, research on ancient permeability structures or permeability structures during mineralization remains lacking. Thus, there should be a stronger emphasis on the quantitative recovery of ancient permeability structures and the study of permeability evolution laws in fault zones. Research on the permeability evolution of fault zones must be conducted from the perspectives of tectonic stress fields, strain rates, displacements, deformation mechanisms, thermal histories, host rock lithologies, and fluid-rock interactions.

Fluid flow in fault zones is a complex process involving multiple physical fields, and thus its study must adopt a multidisciplinary approach. By analyzing the spatiotemporal evolution laws of fault structure and permeability from the coupled perspective of fault structure, dynamic

mechanisms, and fluid flow, we can gain a better understanding of the fluid dynamics characteristics of fault zones.

5. CONCLUSION

In summary, research on the fluid dynamics of fault zones is of great significance for understanding fault structures and their permeability evolution. Current studies indicate that the structural characteristics of fault zones are influenced by multiple factors, including tectonic stress, fluid properties, and host rock lithology, and exhibit notable spatiotemporal variations throughout different stages of fault activity. To gain a deeper understanding of the fluid dynamics characteristics of fault zones, future research should focus on the quantitative characterization of structural elements in various types of faults and the restoration and evolutionary patterns of ancient permeability structures.

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