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A review of fault sealing behaviour and its evaluation in siliciclastic rocks

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Abstract

Faults can be either conduits or retarders for fluid flow. As the presence of faults increases the risks for hydrocarbon exploration, the sealing behaviour of a fault zone has been a focus for geological studies in the past 30 years. Due to the widespread occurrence of fault zones, either in extensional or contractional regimes, knowledge about the fault sealing behaviour is of great importance to a wide spectrum of disciplines in geosciences, for instance, structural geology, geochemistry, petroleum geology, etc. Geologists have extensively study the sealing properties of a fault zone over the last decades, ranging from fault zone architecture, fault seal types, fault seal processes, fault rock classification, research methods and controlling factors.

Although there have not been universal agreements reached on the fault seal classifications, two types of fault seals have already been recognized, which are juxtaposition seals and fault rock seals. The early foundation of Allan map and triangle juxtaposition diagram allows the investigation on the effects of stratigraphic juxtaposition between hanging wall and footwall on the sealing properties of a fault zone. The study on the detailed fault zone architecture also implies the importance of fault arrays that increase the complexity of overall stratigraphic juxtaposition between hanging wall and footwall. The fault seal processes and their generated fault rocks play an important control on sealing properties of a fault zone. Temperature and stress history, which are closely related to burial history, are also found to control the sealing capacity of a fault zone to some extent. The methods such as stratigraphic juxtaposition, clay smear indices, microstructural analysis and petrophysical assessment has significantly boosted the research of fault sealing behaviour. However, further research is still needed to increase the effectiveness of present fault seal analysis.

Keywords: fault zone architecture, fault seal process, fault rocks, hydrocarbon sealing behaviour

1. Introduction

In petroleum exploration and production, as faults can behave as i) conduits, ii) barriers or iii) combined barrier-conduit structures for hydrocarbon migration, the presence of faults increases the risks for hydrocarbon drilling, exploration and development. In order to avoid or minimise the risks, the way in which faults and fractures affect the hydrocarbon migration has attracted the interest of geologists. Previous research (e.g., Allan, 1989; Bouvier et al., 1989; Schowalter, 1979; Smith, 1966; Smith, 1980; Watts, 1987) has studied the fault behaviour and proposed many fundamental principles that control the fault sealing properties within oil/gas reservoirs. In the recent 20 years, the abundance of data, including seismic reflection data, structural and micro-structural analysis from both core and field rock samples, wellbore and production data of oil/gas fields, makes it possible to conduct fault seal analysis to predict fault-sealing properties.

The progress in understanding the faulting processes (Balsamo et al., 2010; Caine et al., 1996; Childs et al., 2009; Childs et al., 1996b; Walsh et al., 2003), the fault rock development (Fisher and Knipe, 1998; Jolley et al., 2007b; Knipe, 1989; Knipe et al., 1997; Tueckmantel et al., 2010), the fault geometry (Jolley et al., 2007b; Peacock and Sanderson, 1991; Peacock and Sanderson, 1992; Peacock and Sanderson, 1994; Walsh et al., 2003) and the fault population (Billi et al., 2003; Cowie et al., 1996; Cowie and Scholz, 1992; Cowie et al., 1993; Faulkner et al., 2010; Kolyukhin et al., 2010; Walsh et al., 2003) has provided a platform for improving the accuracy of fault sealing analysis. The studies on the relationship between different fault parameters, e.g., fault length, fault displacement and fault thickness, has significantly promoted the understanding the effect of fault architecture on fault compartmentalization (Faulkner et al., 2003; Fossen et al., 2007; Torabi and Berg, 2011). Knipe et al. (1992a; 1992b; 1994), Fisher and Knipe (1998; 2001), Fisher et. al. (2003; 2009) and Jolley et. al. (2007a; 2007b) also highlighted the importance of the fault zone complexity and the petrophysical properties of the fault rocks in the evaluation of fault-sealing capacity. Firstly, the fault zone development can involve strain being accommodated by a complex array of faults not just a single, through-going fault; secondly, the sealing capacity of the fault zones may vary significantly depending on the composition of the host rocks that are entrained into the fault zones. Given the important control of fault zone complexity and petrophysical properties of the fault rocks, their controlling factors have been considered in recent studies:

i) the changing chemical/physical processes with time, e.g., the burial/temperature history (Fisher et al., 2003; Fossen et al., 2007; Jolley et al., 2007b) and the amount/rate of strain (Balsamo et al., 2010; Faulkner et al., 2010; Fossen and Bale, 2007);

ii) the diagenetic processes that affect the fault sealing capacity, e.g., disaggregation, clay/phyllosilicate smearing, cataclasis, pressure solution and cementation (Faulkner et al., 2010; Fossen et al., 2011; Tueckmantel et al., 2010).

Although geologists have also realized the importance of the fault zone architecture within carbonates and its sealing properties in recent years (Agosta et al., 2012; Brogi and Novellino, 2015; Collettini et al., 2014; Faulkner et al., 2003; Fondriest et al., 2012; Korneva et al., 2014; Rotevatn and Bastesen, 2014), majority of fault sealing analysis has still focused on the fault zone architecture and fault seal analysis in siliciclastic reservoirs since 1980s. Apparently, the studies of fault zone architecture and hydrocarbon sealing behaviour in siliciclastic reservoirs are more thorough and therefore this review paper has focused on siliciclastic reservoirs by integrating the previous studies of different perspectives. In this paper, we firstly review the sealing behaviour of a fault zone in the aspects of fault zone architecture, fault seal types, fault seal processes, fault rock classification, methods and controlling factors; and then discuss the limitations of the current models/methods to give suggestions on the future work on fault zone architecture and its effects on hydrocarbon sealing behaviour.

2. Fault Zone Architecture

Understanding the effects of stress on given rock volumes is of importance to the investigation of rock deformation mechanisms and their effects on hydrocarbon sealing behaviour of a fault zone. The competent rocks (e.g. sandstones or carbonates) are inclined to brittle deformation (e.g., faulting), whereas the incompetent rocks (e.g., mudstones or shales) prefer to ductile deformation (e.g., folding). In previous studies focusing on the deformation mechanisms of the mechanically layered sequence, it has been reported that the faults tend to form first in the brittle beds (e.g. cemented sandstones or carbonates); while the weak/ductile beds (e.g. clay beds) deform by distributed shear to accommodate the overall strain (Childs et al., 1996a; Eisenstadt and De Paor, 1987; McGrath and Davison, 1995; Peacock and Sanderson, 1992; Schöpfer et al., 2006). Several quantitative dynamic models have been presented (e.g., Egholm et al., 2008; Welch et al., 2009a; Welch et al., 2009b; Welch et al., 2015) to analyse the mechanics of clay/shale smearing along faults in layered sand and shale/clay sequences. These models predict that the isolated initial faults formed within the brittle beds will grow until eventually they link up with increasing strain, by propagating across the ductile intervals to create a complex fault zone architecture (Childs et al., 1996a; Peacock and Sanderson, 1991; Walsh et al., 2003; Walsh et al., 1999; Welch et al., 2009a; Welch et al., 2009b). Many natural examples support those previous studies on detailed fault zone architecture, e.g., the deformed interbedded sandstones and shales derived from the Cutler Formation juxtaposed against limestone from the Honaker Trail Formation near the entrance to Arches National Park (Davatzes and

Aydin, 2005); the outcrop studies from a minor normal-fault array exposed within Gulf of Corinth rift sediments, Central Greece (Loveless et al., 2011); and the multilayer systems in the South-Eastern basin, France (Roche et al., 2012). Fault zone models defining the fault zone architecture have also been proposed, e.g., the fault zone model in crystalline rocks (Caine et al., 1996); the fault zone model in poorly lithified sediments (Heynekamp et al., 1999; Rawling and Goodwin, 2003; Rawling and Goodwin, 2006); and the dynamic fault zone models within poorly consolidated sediments by Balsamo et. al. (2010) and Loveless et al. (2011).

As reviewed by Knipe et. al. (1997; 1998), fault zone geometry and fault population play an important control on the fluid flow properties of fault zones. The internal structures of individual fault zones need to be considered because it affects the distribution of fault rocks and stratigraphic juxtaposition (e.g., Faulkner et al., 2010; Rawling et al., 2001; Walsh et al., 1998; Yielding et al., 1996). For example, in the fault core and damage zone model of Caine et. al. (1996), the fault core was taken as a barrier and the damage zone was taken as a conduit for cross-fault fluid flow (Fig.1a); however, Faulkner et. al. (2010; 2003) found that the intricate internal structures of a fault zone can potentially lead to high degree of permeability heterogeneity and anisotropy (Fig.1b). Many case studies have supported these results, e.g., the fault zone structure and slip localization (Choi et al., 2015; Collettini et al., 2014; Fondriest et al., 2012), the fluid flow properties of a relay zones (Fachri et al., 2013a; Qu et al., 2015; Rotevatn et al., 2007), etc.

Fig.1 Typical fault zone structures (Faulkner et al., 2010). (a) Shows a single high-strain core surrounded by a fractured damage zone (Caine et al., 1996) and (b) shows multiple cores model, where many strands of high-strain material enclose fractured lenses (Faulkner et al., 2003). The diagrams of fracture density and permeability indicate that the complexity of fault zone geometry and fault population can play important control on the fluid flow properties.

3. Fault seal types

Although there have not been universal agreements reached on the fault seal classifications, two types of fault seals have already been recognized, which are juxtaposition seals and fault rock seals (e.g., Cerveny et al., 2004; Faulkner et al., 2010; Jolley et al., 2007a; Jones and Hillis, 2003; Knipe, 1992a; Knipe et al., 1997; Knott, 1993).

3.1. Juxtaposition seals

Juxtaposition seals are associated with cases where cross fault juxtaposition with low permeability non-reservoir units occurs and have been well described in previous studies (Allan, 1989; Knipe, 1997). When a sequence of beds is cut by faults, the hanging wall can be considered to move downward for normal faults; upward for thrust faults; and laterally for strike slip faults. The relative movement between the two walls of the faults gives rise to the occurrence of juxtaposition between the rocks with different lithology or petrophysical properties in the hanging wall and the footwall. As rocks with different lithology usually have different petrophysical properties (e.g. different porosity, permeability, capillary entry pressure), there will be a permeability gradient between different rocks juxtaposed between the hanging wall and the footwall. Juxtaposition seals between the hanging wall and the footwall can be produced by this process. For instance, it is possible to form juxtaposition seals when a sandstone bed is juxtaposed with a mudstone/shale bed; in contrast, it may not form a juxtaposition seal when a sandstone bed juxtaposes with a sandstone bed.

Fig.2 is a schematic diagram demonstrating the occurrence of the juxtaposition seals. As the hanging wall moves downward relative to the footwall, different stratigraphic units (A: mudstone; B: sandstone; C: mudstone) from the hanging wall and the footwall juxtapose against each other. For example, the mudstone bed (A) of the hanging wall juxtaposes against the sandstone bed (B) of the footwall (polygon I); B of the hanging wall juxtaposes against B of the footwall (polygon II); and B of the hanging wall juxtaposes against C of the footwall (polygon III). As sandstone presents higher permeability and lower capillary entry pressure than mudstone, the juxtaposition seals can happen in polygon I and polygon III, but do not happen in polygon II. Apart from the lithology of the hanging wall and footwall, the layer thickness and fault throw are also of importance to juxtaposition seals. For a permeable layer (e.g., sandstones) with a certain thickness, the permeable layers can be self-juxtaposed to form conduits for hydrocarbon migration if the fault throw was smaller than the thickness, whereas juxtaposition seals may occur if the fault throw exceeded the thickness. For a certain fault throw, a permeable layer thicker than the fault throw can be self-juxtaposed to form conduits for hydrocarbon migration, whereas a permeable layer thinner than the fault throw can possibly generate juxtaposition seals.

Fig.2 A schematic diagram shows stratigraphic juxtaposition between the hanging wall and footwall (modified from Knipe et al., 1997). Juxtaposition seal can occur when low-permeable rocks in the hanging wall juxtapose against high-permeable rocks in the footwall (e.g., polygon I and III).

3.2. Fault rock seals

According to terminology for structural discontinuities reviewed by Schultz and Fossen (2008), the term 'fault' is defined as a single plane that has been called a slip plane or shear fracture, whereas the term 'fault zone' is a tabular region containing a set of parallel or anastomosing fault surfaces. As shown in natural examples (e.g., Fig.1), many faults are not single-plane faults but composed of a series of fault planes or networks of small fault segments that form fault zones (Caine et al., 1996; Childs et al., 1996a; Childs et al., 1996b; Faulkner et al., 2010; Knipe et al., 1997). Different fault rocks are then generated when different types of host rocks are entrained into the complex fault zones during faulting (Fisher and Knipe, 1998; Fossen et al., 2007; Knipe et al., 1997; Knipe et al., 1998; Manzocchi et al., 2010; Ottesen Ellevset et al., 1998). The study of Watts (1987) highlighted that most faults/fault zones were membranes or flow retarders with different properties of transmissibility or permeability. As the sealing properties of fault rocks can be evaluated by the permeability and the capillary threshold pressure (Fisher and Jolley, 2007; Fisher and Knipe, 2001; Watts, 1987), the fluid flow across the fault zones will not happen unless the capillary threshold pressure is reached. Therefore, the petrophysical properties of the fault rocks, such as the capillary threshold pressure and permeability control the hydrocarbon sealing properties of faults/fault zones.

As pointed out (Fisher and Knipe, 1998; Knipe et al., 1997), the composition of the host sediments at the time of deformation determines the deformation mechanisms, microstructures and petrophysical properties of the fault rocks within the fault zones; and therefore fault rock seals may occur if fault rocks with low permeability and high capillary threshold pressure are generated within the fault zones.

4. Fault Seal Processes

The fundamental fault seal processes that give rise to the occurrence of fault related permeability barriers have been studied in detail in the past 30 years (e.g., Fisher et al., 2003; Fisher and Knipe, 1998; Fisher et al., 2009; Fossen and Bale, 2007; Fossen et al., 2007; Fossen et al., 2011; Knipe, 1989; Knipe, 1992a; Knipe, 1993a; Knipe, 1993b; Knipe et al., 1998; Tueckmantel et al., 2010). Five types of fault seal processes have been identified, which are: (i) clay/phyllosilicate smearing; (ii) cementation; (iii) cataclasis; (iv) diffusive mass transfer by pressure solution or quartz cementation; and (v) porosity reduction by disaggregation or mixing. However, as Knipe (1997) pointed out, these five fault seal processes can either perform individually during deformation or combine interactively with each other.

4.1. Clay/Phyllosilicate Smearing

As continuous clay/phyllosilicate smear has very low porosity and permeability (Smith, 1966; Smith, 1980), it acts as an extremely effective fluid flow barrier and therefore many studies have focused on this fault seal process. For example, deformation induced shearing of clays/phyllosilicates has been discussed in previous studies (e.g., Aydin and Eyal, 2002; Bouvier et al., 1989; Fulljames et al., 1997; Gibson, 1994; Yielding et al., 1997). Three principle means of clay/phyllosilicate smearing are proposed by Lindsay et al. (1993), which are:

a). abrasion of clay/phyllosilicate when it is moving past sandstones;

b). shearing and ductile deformation of beds (with high clay/phyllosilicate content, e.g. shale or mudstone beds) between hanging wall and footwall;

c). injection of clay/phyllosilicate materials during fluidisation.

It is suggested that the continuity of clay/phyllosilicate smearing is determined by a series of parameters including the sedimentary lithification state, the effective stress, the confining pressure, the strain rate and the mineralogy (Fisher and Knipe, 1998).

Several algorithms have been proposed to evaluate the fault sealing properties quantitatively, either based on the continuity of clay/phyllosilicate smears or average clay content within the fault zones, e.g., Clay Smear Potential (CSP) (Bouvier et al., 1989; Fulljames et al., 1997), Shale Smear Factor (SSF) (Lindsay et al., 1993), Shale Gouge Ratio (SGR) (Yielding et al., 1997) and Scaled Shale Gouge Ratio (SSGR) (Ciftci et al., 2013). These algorithms evaluate the fault sealing properties by considering the re-distribution of mudstone/shale beds or the clay/phyllosilicate content of the beds in sheared fractures. Empirically, the stacking sequences with high clay/phyllosilicate content are likely to form fault zones with low permeability. During the deformation of fault rocks, there can be two competing compaction mechanisms which are the mechanical compaction and chemical compaction (Fisher and Knipe, 2001). These two compaction mechanisms affect fault rock properties depending on the clay/phyllosilicate content of the host rocks. For example, faults developed in impure sandstones (clay content of 15-25%) experienced enhanced chemical compaction (e.g., grain-contact quartz dissolution), whereas faults in clay-rich sandstones (clay content of >25%) are dominated by mechanical compaction. The higher clay/phyllosilicate content in host rocks can significantly decrease the effective quartz surface area, which lead to the inhibition of the chemical compaction (e.g., quartz cementation) (Fisher and Knipe, 1998). The competition between the two mechanisms results in the relationship between clay/phyllosilicate content and fault sealing properties (e.g., porosity, permeability, capillary pressure) being highly complicated and can even lack correlation. Therefore, the algorithms, such as CSP (Bouvier et al., 1989; Fulljames et al., 1997), SSF (Lindsay et al., 1993), SGR (Yielding et al., 1997) and SSGR (Ciftci et al., 2013), should be used with caution when evaluating the fluid flow properties of the fault zones.

4.2. Cementation

The most common result of deformation related cementation includes cemented faults or fractures (Fisher and Knipe, 1998; Fisher and Knipe, 2001; Fisher et al., 2009; Fossen and Bale, 2007; Fossen et al., 2011; Tueckmantel et al., 2010). The microstructures of these features provide important evidence for studying the mechanisms and timing of the cementation processes. As faults/fractures may perform as conduits for fluid flow, the flow behaviour of faults/fractures is sensitive to quartz precipitation because within the fault zones there are both quartz sources (from dissolution) and nucleation sites for potential cementation. The source for cementation can be internal or external, but Fisher and Knipe (1998) pointed out that natural oil/gas field examples do not always require that an external fluid source controls the sealing properties of the fault zones, especially at a large scale where the external fluids may not promote continuous cementation for extensive sealing.

As there may be impure sandstones containing clay minerals, it is important to understand the effects of clay minerals on the quartz cementation, which has been well established in previous studies (e.g., Bjorkum, 1996; Dewers and Ortoleva, 1991; Fisher and Knipe, 1998; Fisher and Knipe, 2001; Fossen and Bale, 2007; Fossen et al., 2011; Heald, 1955; Oelkers et al., 1996). It is suggested that small concentrations of clay/phyllosilicate minerals in sandstones increase the potential of cementation as the clay/phyllosilicate minerals can act as a local source for cementation (Dewers and Ortoleva, 1991; Fisher et al., 2003; Fisher et al., 2009; Heald, 1955; Knipe, 1993a; Oelkers et al., 1996). However, high clay/phyllosilicate contents can lead to the clay/phyllosilicate-coating on the quartz grains, which decreases the effective quartz grain surface area available for cementation (Cecil and Heald, 1971; Fisher et al., 2003; Fossen and Bale, 2007; Fossen et al., 2011; Tada and Siever, 1989; Walderhaug, 1996).

4.3. Cataclasis

Cataclasis involves grain fracturing and can reduce the porosity and the permeability as well as increase the capillary threshold pressure of rocks within fault zones (e.g., Antonellini and Aydin, 1994; Antonellini and Aydin, 1995; Borg et al., 1960; Engelder, 1974; Knipe, 1989). During the process of cataclasis, the porosity and permeability are reduced because the cataclasis results in the collapse of porosity and the reduction of grain size (Fisher and Knipe, 1998). Rawling and Goodwin (2003) also suggests that cataclasis presents different micro-deformation mechanisms depending on the burial depth, i.e., cataclasis in sediments at shallow depths is dominated by grain spalling and flaking whereas cataclasis at deeper depths is primarily characterized by transgranular fracturing and grain crushing. The grain-sorting within cataclasites is becoming poorer by grain fracturing and chipping at early stage, and the following predominant chipping and crushing then enhance the grain sorting. As an effective tool to study the cataclasis processes of fault rocks, micro-structural analysis has been utilized in many case studies (Antonellini et al., 1994; Blenkinsop, 1991; Fisher and Knipe, 1998; Jolley et al., 2007b; Tueckmantel et al., 2010), suggesting that the concentration of clay/phyllosilicate materials in host rocks can inhibit the probability of occurrence of cataclasis. Therefore, the sandstones with high clay/phyllosilicate content are likely to be resistant to the cataclasis during faulting deformation, as the clay/phyllosilicate-rich sandstones tend to deform more easily by grain sliding and rotation rather than by grain fracturing. However, different textures of impure sandstones (e.g., the distribution of clay/phyllosilicate minerals) also affect the modalities of cataclastic deformation.

4.4. Diffusive Mass Transfer by Pressure Solution and Quartz Cementation

Diffusive mass transfer, a process of mass transfer from high-pressure sites to low-pressure sites, happens when materials are dissolved at the grain contacts and then transported by diffusion to free pore spaces where the dissolved materials reprecipitate (Fisher and Knipe, 1998; Fisher et al., 2009; Fossen et al., 2007; Knipe et al., 1997; Rutter, 1983; Spiers and Schutjens, 1990). Diffusive mass transfer is actually a redistribution of soluble materials from their original sites with high pressure, by means of dissolution, transport and reprecipitation (Dewers and Ortoleva, 1990; Fisher et al., 2009; Knipe et al., 1997; Tueckmantel et al., 2010); and can alter the porosity and permeability of fault rocks.

Based on the micro-structural analysis, it is found that the extent of diffusive mass transfer is dominated by the clay/phyllosilicate content and its distribution at the time of deformation (Fisher and Knipe (1998); Fisher and Knipe, 2001; Fossen et al., 2007; Tueckmantel et al., 2010). For example: (i). for clean sandstones with clay/phyllosilicate contents of <5%, the fault zones experience enhanced quartz cementation within fault zones but can occur with no enhanced pressure solution (i.e. an external source is involved); (ii). for clean sandstones with higher clay/phyllosilicate content of 5-15%, there is evidence for both enhanced pressure solution and quartz cementation (i.e. an internal source is involved); (iii). for impure sandstones with clay/phyllosilicate contents of 15-25%, the fault zones can experience enhanced pressure solution but no extensive enhanced quartz cementation; (iv). for impure sandstones with clay/phyllosilicate content of >25%, the porosity and permeability of the fault zones may not be significantly affected by either pressure solution or quartz cementation. The reason for these observations is that diffusive mass transfer needs a catalyst (clay/phyllosilicate) for pressure solution as well as nucleation sites for quartz cementation. The rate of diffusive mass transfer is especially determined by the presence and distribution of clay/phyllosilicate. For example, the presence of small concentration of clay/phyllosilicate minerals at the grain-contact points promotes the occurrence of pressure solution (e.g. Odling et al., 2004); while clay/phyllosilicate-coating on the quartz grains inhibits the quartz cementation (e.g. Tada and Siever, 1989), because the coating clay/phyllosilicate minerals reduce the effective surface area of quartz grains available for precipitation.

4.5. Porosity Reduction by Disaggregation and Mixing

In this fault seal process, there is no extensive grain fracturing but just disaggregation and mixing of grains by means of particulate flow (Rawling and Goodwin, 2003; Rawling and Goodwin, 2006), e.g., grain rolling and grain sliding, which means this process results in the reorganisation of distribution of detrital grains and clay/phyllosilicate minerals without a universal reduction of grain size (Fisher and Knipe, 1998; Fossen et al., 2007; Knipe et al., 1997; Ottesen Ellevset et al., 1998). This fault process is common in sedimentary units that are unconsolidated or unlithified, as in this situation there is enough space for grains and clay/phyllosilicate minerals to be redistributed during faulting deformation (Bense et al., 2003; Fisher and Knipe, 1998; Fossen et al., 2007; Knipe et al., 1997; Ottesen Ellevset et al., 1998). The sedimentary units that are buried at shallow depths tend to experience disaggregation and mixing to reduce the rock porosity. The distribution of both detrital grains and clay/phyllosilicate minerals can be heterogeneous when initially deposited and then becomes more homogeneous after the disaggregation and mixing during faulting deformation, thus altering permeability pathways.

The permeability of fault rocks produced by disaggregation and mixing varies within a big range, depending on the clay/phyllosilicate content of the host rocks (Fisher and Knipe, 1998; Knipe et al., 1997). Furthermore, it is suggested that disaggregation can result in either an enhancement or a reduction of porosity, which depends on whether the disaggregation zone has a dilational or compactional component (Fossen and Bale, 2007; Fossen et al., 2007; Fossen et al., 2011). For clean sandstones, because the grain size and grain sorting of the fault rock do not change considerably after the reorganization of detrital grains, the fault rock porosity and permeability are not changed significantly. In contrast, for impure sandstones, as well as the reorganization of detrital grains, the fine-grained clay/phyllosilicate minerals are also mixed with these detrital grains, resulting in the occupation of micro-porosity between the detrital grains by the fine-grained clay/phyllosilicate minerals. In this scenario, barriers for fluid flow can be produced and the sealing capacity is effectively increased. Although Fisher and Knipe observed a permeability reduction of up to one order of magnitude in phyllosilicate-bearing disaggregation zones (Fisher and Knipe, 2001), disaggregation zones generally have very limited effects on the permeability of sandstone reservoirs as the permeability contrast is relatively low (Fossen et al., 2007).

5. Fault rock classification

Fisher and Knipe (2001) suggested that fluid flow properties of faults are significantly influenced by the presence of clay/phyllosilicate in three ways: (i). the high concentrations of clay/phyllosilicate can produce fault rocks within which most of the original porosity is occupied by the fine grained clay/phyllosilicate minerals and the micro-porosity (Fisher and Knipe, 1998); (ii). there is a higher potential for clay/phyllosilicate smearing within the sedimentary units with high clay/phyllosilicate contents (Lindsay et al., 1993); and (iii). the existence of clay/phyllosilicate materials between framework-silicate grains promotes pressure solution and quartz cementation (Fisher and Knipe, 1998). Therefore, if the faults maintain self-juxtaposition of these units, the fault rock types related to the fault rock seals can be classified according to the composition (especially the clay/phyllosilicate content) of the host rocks from which the fault rocks are produced. Where faulting exceeds the thickness of the host units, the resulting clay content of the fault rock (from smearing and mixing of the host rocks involved in the faulting), grain size reduction processes and the potential for cementation can impact on the fault rock flow properties.

Fault rocks can therefore be classified into the following groups (Fisher et al., 2003; Fisher and Knipe, 1998; Fisher et al., 2009; Knipe et al., 1997; Ottesen Ellevset et al., 1998): the cemented faults/fractures; the clay/phyllosilicate smears; the phyllosilicate-framework fault rocks (PFFRs); the cataclasites; and the disaggregation zones (Fig.3). This classification is based on the relationship between the clay/phyllosilicate content and fault rock types.

Fig.3 Illustration of typical fault rocks and their clay/phyllosilicate contents, showing the important control of the clay/phyllosilicate content on the fault rock development (modified from Ottesen Ellevset et al., 1998).

5.1. Cemented faults/fractures

Fault seal analysis based on the prediction of fault rock clay contents can be invalidated if cemented fault zones are extensively developed (Fig.4) (Jolley et al., 2007b; Knipe, 1993a; Knipe et al., 1997). However, in most cases, the cementation is not extensive enough to influence the sealing properties of the fault zones (Ottesen Ellevset et al., 1998), as the cementation can rarely form continuous seals but is often restricted to limited areas of the fault zone or between the footwall and the hanging wall cut offs of units prone to cementation.

Fig.4 A schematic cartoon (modified from Jolley et al., 2007b) and a typical micro-graph (Pei, 2013) of cemented faults/fractures. The cement seals can occur when minerals' dissolution-reprecipitation process or new minerals' precipitation dominate the sealing properties of faults/fractures.

Generally, cement seals only happen in fault zones where the sealing properties are dominated by the minerals' dissolution-reprecipitation process or where new minerals' precipitation is promoted (Knipe, 1997). Therefore, the cement seals are mostly associated with the sites where local dissolution and reprecipitation happen during deformation or along the invasion paths of fluids in the faults. For cemented faults and fractures, Knipe et al. (1997) found that cementation is the dominant mechanism of porosity reduction within the fault zones. There are probably two main sources of cements: the local soluble minerals within the fault zones; and the invaded fluids along the fault planes. Because of the high density of nucleation sites on the fault planes, both the local soluble minerals and invaded fluids can be easily precipitated along or adjacent to the fault planes. Ottesen Ellevset et al. (1998) suggested that the cementation extent along the fault planes may be limited to three times the thickness of the unit that acts as a source unit for the cementation.

5.2. Clay/Phyllosilicate Smears

As shown in the fault rock classification (Fig.3), fault rocks with clay/phyllosilicate contents >40% are defined as clay smears. These can develop from the deformation of a host shale rock with >40% clay/phyllosilicate content at the time of deformation (Jolley et al., 2007b; Knipe, 1997; Knipe et al., 1997; Ottesen Ellevset et al., 1998). In this situation, a continuous clay material zone with low-permeability along fault planes can be produced during the faulting deformation (Fig.5). The factors controlling the clay/phyllosilicate smear continuity are the content and distribution of clay/phyllosilicate-rich units, fault throw (Bouvier et al., 1989; Fulljames et al., 1997; Lindsay et al., 1993; Yielding et al., 1997), and the lithification state (Egholm et al., 2008; Heynekamp et al., 1999; Loveless et al., 2011). Based on the studies on the distribution of clay smears in Sleipner Vest of North Sea (Knipe, 1997; Ottesen Ellevset et al., 1998), it was suggested that the clay/phyllosilicate smears often become discontinuous once the fault throw is larger than three times the thickness of clay/phyllosilicate-rich stratigraphic units.

Fig.5 A schematic cartoon (modified from Jolley et al., 2007b) and a typical micro-graph (Pei, 2013) of clay/phyllosilicate smears, containing >40% clay/phyllosilicate minerals. Clay smears can act as effective seals when continuous clay material zones are produced along fault planes during the faulting deformation.

5.3. Phyllosilicate-framework fault rocks (PFFRs)

As shown in the fault rock classification (Fig.3), phyllosilicate-framework fault rocks (PFFRs) contain 15-40% clay/phyllosilicate minerals. These can develop from impure sandstones containing 15-40% clay/phyllosilicate at the time of deformation or from the mixing of high and low clay content units (Fisher and Knipe, 1998; Jolley et al., 2007b; Knipe, 1992a; Knipe et al., 1997). An impure sandstone, with a mixture of phyllosilicates and framework silicates, can produce PFFRs where the petrophysical properties are dominated by the generation of anastomosing networks of the micro-smears around the framework fragments or clasts (Fig.6) (Knipe, 1997). These micro-smears may have similar properties to the clay smears; thus, as pointed out by Knipe (1992a), it is not necessary to have clay units for creating PFFRs if the sealing properties are determined by the continuity and the structure of deformed phyllosilicates.

Ottesen Ellevset et al. (1998) pointed out that the occurrence of PFFRs has great effects on the sealing behaviour in two areas, which are the area where the impure sandstones directly juxtapose against the fault zones; and the area along fault planes between the hanging wall and footwall cut-offs of impure sandstone units. The latter scenario is to some extent similar to the behaviour of clay/phyllosilicate smears. The continuity of the PFFRs determines the effectiveness of PFFRs to form effective retarders for fluid flow (Fisher and Knipe, 1998; Knipe et al., 1997; Ottesen Ellevset et al., 1998).

Fig.6 A schematic cartoon (modified from Jolley et al., 2007b) and a typical micro-graph (Pei, 2013) of phyllosilicate-framework fault rocks (PFFRs), containing 15-40% clay/phyllosilicate minerals. The petrophysical properties of phyllosilicate-framework fault rocks are dominated by the generation of anastomosing networks of the micro-smears around the framework fragments or clasts.

5.4. Cataclasites

Cataclasites dominate seal development in clean sandstones containing <15% clay content at the time of deformation (Fisher and Knipe, 1998; Jolley et al., 2007b; Knipe et al., 1997; Ottesen Ellevset et al., 1998). Because of the low clay content within such host rocks, the main mechanisms of porosity and permeability reduction are the cataclasis and the post-deformation quartz cementation (Fisher and Knipe, 1998). During the process of cataclasis, the grain size decreases by means of grain fracturing and frictional grain rolling, resulting in the porosity reduction and potential cementation (Fig.7). The frictional grain rolling lead to the irregular grains sub-parallelly aligned to the shearing direction, which makes the compaction more easily to reduce the fault rock porosity. The granulation seams or deformation bands, which are discussed in many studies (Antonellini and Aydin, 1994; Knipe, 1992a; Knipe, 1993a; Knipe, 1993b), are examples of cataclasites.

Fig.7 A schematic cartoon (modified from Jolley et al., 2007b) and a typical micro-graph (Pei, 2013) of cataclasites, containing <15% clay/phyllosilicate minerals. The grain size reduction of cataclasites is dominated by grain fracturing and frictional grain sliding, resulting in the porosity reduction and potential cementation.

Previous research has pointed out that the permeability of cataclasites varies over a large range; this depends on the lithification state of the host rocks (Fisher and Knipe, 1998; Knipe et al., 1997). According to the lithification state, the cataclasites can be divided into three types: (i). poorly lithified cataclasites, which show little or even no compaction or cementation (post-deformation) and point contacts are maintained between grains; (ii). partially lithified cataclasites, which have some compaction and cementation; and (iii). lithified cataclasites, which comprise grains interlocked by post-deformation dissolution and/or cementation (Knipe, 1992a; Knipe, 1993b; Knipe et al., 1997).

5.5. Disaggregation Zones

The disaggregation zones are fault rocks generated by deformation without fracturing. They can also be produced from pure, low clay-content (<15%) sandstones (Fig.3), similar to the generation of the cataclasites (Fisher and Knipe, 1998; Fossen et al., 2007; Jolley et al., 2007b; Knipe et al., 1997; Loveless et al., 2011; Ottesen Ellevset et al., 1998; Rawling and Goodwin, 2003). However, the host rocks of disaggregation zones are normally sands or poorly consolidated sandstones (Bense et al., 2003; Rawling and Goodwin, 2006). In the process of disaggregation, the grains move by way of particulate flow (Rawling and Goodwin, 2003) to accommodate the strain during faulting deformation, with no extensive grain fracturing (Fisher and Knipe, 1998; Knipe et al., 1997). The permeability of disaggregation zones is usually higher than that of the other types of fault rocks. It is difficult for disaggregation to form effective seals to prevent fluid flow, because there are not sufficient clays/phyllosilicates within the disaggregation zones to act as a source for either the cementation or the clay/phyllosilicate smears (Fisher and Knipe, 2001; Fossen et al., 2007) (Fig.8).

Fig.8 A schematic cartoon (modified from Jolley et al., 2007b) and a typical micro-graph (Knipe et al., 1997) of disaggregation zones. Disaggregation zones are developed in poorly lithified rocks containing <40% clay/phyllosilicate minerals. As there is not sufficient clays/phyllosilicates, disaggregation zones cannot form effective seals for fluid flow under normal conditions.

Based on this fundamental fault rock classification, Fisher and Knipe (1998) constructed the relationship between a wide spectrum of fault rocks with different geological settings, including clay content, degree of fragmentation and lithification state (Fig.9). This detailed fault rock classification allows geologists to make basic prediction of fault rock types (siliciclastic rocks, e.g., sandstones, siltstones, mudstones and shales) and properties by considering clay content, degree of fragmentation and lithification state.

Fig.9 Diagram showing different types of fault rocks developed in the North Sea and their relationship to the composition of the host sediment and the extent of grain-size reduction and post-deformation lithification experienced (Fisher and Knipe, 1998).

6. Methods to evaluate fault sealing properties

In the recent 20 years, geologists have developed and used several methods to evaluate the fault sealing properties. The i) Allan map, ii) triangle juxtaposition diagram and iii) clay smear indices can be employed to evaluate the fluids flow properties for juxtaposition sealing faults, while the micro-structural analysis and petrophysical assessment can be used to investigate the fluids flow properties for fault rock sealing faults (Table 1). The production simulation modelling also has been employed to predict the petroleum migration and accumulation features, including consideration of fault zone compartmentalization and its hydrocarbon sealing behaviour (e.g., Fachri et al., 2013b; Fisher and Jolley, 2007; Manzocchi et al., 2002; Manzocchi et al., 1999; Ottesen Ellevset et al., 1998; Zijlstra et al., 2007). Although all these methods have their own shortcomings, the methods have been improved to become more and more effective and useful for evaluation of the fault sealing properties.

Table 1 A summary of the methods to evaluate fault sealing properties for different fault seal classifications.

6.1. Stratigraphic juxtaposition methods

Allan (1989) introduced a model to relate faults to hydrocarbon migration and entrapment, suggesting the influence of faults on the hydrocarbon migration and the entrapment is determined by the lithology of juxtaposed stratigraphic units on different sides of fault and the fault throws between the hanging wall and the footwall cut-offs. The model provides a 3D overview and understanding on the architecture of the fault juxtapositions, the stratigraphic units and the fault throws, which can help to understand the stratigraphic contacts, the fault geometry and the structure/closure style.

Knipe (1997) presented an effective technique of triangle juxtaposition diagram, which can be used to quickly judge what types of fault seals can be formed based on the resultant stratigraphic juxtapositions between the hanging wall and footwall (Fig.10). The Fig.10 illustrates the use of sidewall charts to review the key host rock characteristics. These variables control the development of fault rocks and seals. This example shows depth plots of the host rock properties, porosity, permeability, percentage of phyllosilicate (abbreviated “Phyllo” in the key) laminations present, and the net/gross ratios.

It is known that reservoir stratigraphic units (e.g., permeable sandstones) juxtaposing against impermeable stratigraphic units (with high concentration of clay/phyllosilicate materials, e.g., shales/mudstones) probably form fault seals; while leaking windows are more likely if reservoir sand stratigraphic units are juxtaposed against each other. By using the triangle juxtaposition diagram, it is possible to make an initial judgement and prediction of fault sealing properties, particularly when seeking possible leaking windows. Moreover, in the triangle juxtaposition diagram, the sidewall charts can also be attached to provide more details of the stratigraphy, such as the sand net/gross ratio, the clay/phyllosilicate content, the host rock lithology and the host rock permeability (e.g., Cerveny et al., 2004; Knipe, 1997; Knipe et al., 1997). These details contribute to allow a more reliable assessment and prediction of sealing properties on the faults. Different types of juxtapositions between different stratigraphic units can be identified on this diagram; and these different juxtaposition types provide important clues for estimating the fault sealing properties of different places on the fault plane with various fault throws.

Fig.10 The triangle juxtaposition diagram uses sidewall chart input to identify the leaking windows and the fault seals resulting from the stratigraphic juxtapositions between the hanging wall and the footwall (Knipe, 1997). The juxtaposition diagram key lists the different types of important juxtapositions that occur on different parts of the fault plane and contribute to the fluid flow behavior of faults with different throw magnitudes. Note that the throws associated with the development of an area of high-permeability sand juxtaposed against high-permeability sand (red area) can be rapidly identified.

A 3D numerical model of fault displacement, proposed by Clarke et. al. (2005), enables the building of geological models to represent the complex 3D geometry and geological properties of a fault, which can be employed to predict the cross-fault juxtaposition relationships in 3D space. The further forward modelling of fault development allows a 4D prediction of fault juxtaposition (with time). The successful application in the Artemis Field (Southern North Sea, UK) and the Moab Fault (Utah, USA) demonstrates significant improvements in the 3D and 4D prediction of fault juxtaposition seals for both a single fault and multiple faults.

6.2. Clay smear indices

Bouvier et al. (1989) employed Clay Smear Potential (CSP) to estimate the potential of occurrence of clay smearing based on studies of three-dimensional seismic interpretation and fault sealing investigations in Nun

River field in Nigeria. The CSP represents the relative amount of clay (e.g., mudstones, shales, etc.) that has been smeared from individual shale source beds at a certain point along a fault plane during faulting deformation. The CSP was then expressed more explicitly by Fulljames et al. (1997) (Fig.11a). The CSP represents the total amount of clay/phyllosilicate that has been smeared from every stratigraphic unit with high clay/phyllosilicate content along the fault planes. The value of CSP increases with increasing thickness of shale/mudstone beds and the number of stratigraphic units with high concentrations of clay/phyllosilicate, and the CSP decreases with increasing fault throw.

$$\mathrm{CSP} = \sum \frac{(\text{Shale bed thickness})^2}{\text{Distance from source bed}}$$

Lindsay et al. (1993) introduced Shale Smear Factor (SSF, Fig.11b) to estimate the magnitude of fault seals formed by smearing of clay/phyllosilicate-rich units, e.g., shales and mudstones. The SSF value is proportional to the fault throws and inversely proportional to the thickness and the number of source units of clay/phyllosilicate. Using the SSF algorithm to estimate the extent of clay/phyllosilicate smears, there is increasing potential to form a continuous clay/phyllosilicate smears with increasing thickness and number of source unites of clay/phyllosilicate and decreasing fault throws, and vice versa.

$$\mathrm{SSF} = \frac{\text{Fault throw}}{\text{Shale layer thickness}}$$

The Shale Gouge Ratio (SGR, Fig.11c) was proposed (Yielding et al., 1997) to estimate the clay content in faults from the mixing of units with different clay contents in the throw interval. This helps evaluate fault seals in more complex stacking sequences. The SGR is proportional to cumulative thickness of shale beds within a scale of a distance equal to fault throw and inversely proportional to fault throw.

$$\mathrm{SGR} = \frac{\sum(\text{Shale bed thickness})}{\text{Fault throw}} \times 100\%$$

Furthermore, the definition of SGR was extended for a package of sediments (Fig.11d). In this situation, SGR is considered to be the percentage of clay present in all units in the throw interval.

$$\mathrm{SGR} = \frac{\sum[(\text{Zone thickness}) \times (\text{Zone clay fraction})]}{\text{Fault throw}} \times 100\%$$

The CSP and SSF estimate the fault sealing properties by considering the continuity of smearing of shale/mudstone beds; while the SGR calculates the average mixture of clays likely to be present at different point on a fault.

Fig.11 Diagram and calculation of methods for estimation of fault seals (especially fault seals formed by clay/phyllosilicate smearing): (a) Clay Smear Potential (CSP) (Bouvier et al., 1989; Fulljames et al., 1997); (b) Shale Smear Factor (SSF) (Lindsay et al., 1993); (c, d) Shale Gouge Ratio (SGR) (Yielding et al., 1997).

6.3. Microstructural analysis

As introduced above, the fault rocks are generated when the sedimentary units are entrained into the fault zones. The detailed evaluation of different types of fault rocks can be achieved by integrating micro-structural analysis on the deformation mechanisms and the porosity and permeability data. The Scanning Electron Microscope (SEM) was employed in Knipe (1992a) to investigate the micro-structures of fault rocks. The following studies (e.g., Fisher et al., 2003; Fisher and Knipe, 1998; Fisher and Knipe, 2001; Fisher et al., 2009; Ottesen Ellevset et al., 1998; Rawling and Goodwin, 2003; Tueckmantel et al., 2010) integrated the fault rock petrophysical sealing properties with the micro-structural analysis on the fault rocks developed within the fault zones.

Fig.12 The sample photo and BSE micrographs showing the PFFRs developed in impure sandstones (Pei, 2013).

The micro-structural analyses undertaken are laboratory based that aim to characterise the microstructures and the petrophysical properties of fault rocks and compare these to their host rocks, in order to estimate the deformation mechanisms and the fault seal processes that the fault rocks experienced, and to identify the relative timing of deformation during diagenesis. Fox example, Fig.12 presents the BSE micrographs of a fault rock sample from northern Qaidam basin in China (Pei, 2013). The sample is located within the fault zone of the fault outcrop, comprising fine-grained impure sandstone (7-13% clay content) as the dominated lithology. A series of PFFRs (20-35% clay content) are formed in the shear zones or deformation bands. The grain size experiences small reduction in the fault rocks. The BSE micrographs demonstrate the relative high content of fine-grained phyllosilicates, strong pressure solution and low porosity in the fault rocks when compared to the surrounding host rocks.

6.4. Petrophysical assessment

The petrophysical properties of the fault rocks have been measured to evaluate the sealing capacity of the fault rocks quantitatively in many previous studies (e.g., Fisher and Knipe, 1998; Fisher and Knipe, 2001;

Jolley et al., 2007b; Ottesen Ellevset et al., 1998; Tueckmantel et al., 2010). A case study in the North Sea and Norwegian Continental Shelf plotted the permeability of fault rocks against the clay content of the host rocks for various fault rock types (Fig.13) (Fisher and Knipe, 2001). The case study suggests that for low throw faults with self-juxtaposition, the clean sandstones (clay content <15%) tend to form cataclasites that do not always represent effective fluid flow barriers; the impure sandstones (clay content 15%-40%) experience significant porosity and permeability reduction; while the mudstones or shales form continuous clay smears with very low permeability that can be effective barriers for fluid flow across the fault zones. It also highlights that the permeability of the fault rocks is not only determined by the clay content of host rocks, but also related to their burial history (Fig.13). Different burial history implies that fault rocks have experienced different stress and temperature during fault deformation, which results in variable range of permeability of fault rocks. Therefore, the petrophysical assessment of fault rocks becomes an effective method to provide reliable poroperm results for the evaluation of fault sealing capacity.

Fig.13 Summary of the fault rock permeability from the North Sea and Norwegian Continental Shelf (modified from Fisher and Knipe, 2001). The permeability of various fault rocks is plotted against the clay content of the host rocks. The chart also describes the control of the burial depth at the time of faulting and maximum post-deformation burial depth on the fault rock permeability.

6.5. Production simulation modelling

Production simulation modelling is an effective tool to predict the petroleum migration and accumulation characteristics in petroleum industry in the last decades. The accurate input of geologic data into the simulation model, particularly the data of fault zone architecture and fault rock properties, is vital to increase the confidence in the reliability of its predictive capability. Based on a series of case studies (Fisher and Jolley, 2007; Harris et al., 2007; Jolley et al., 2007b; Zijlstra et al., 2007), Fisher and Jolley (2007) proposed several advices for those who would like to incorporate the effects of fault architecture on fluid flow in a production simulation model.

i) A geometrically accurate structural interpretation should not get compromised during transfer and incorporation into the production simulation model, particularly the fault zone geometry and fault compartmentalization.

ii) The transmissibility multipliers should be calculated based on realistic fluid flow properties of the fault rocks obtained within the field.

iii) Apart from single-phase permeability of the fault rocks, it is also of importance to consider the capillary pressure and relative permeability in some situation, particularly for high net: gross reservoirs with cataclastic fault rocks developed within the fault zone (Al-Busafi et al., 2005; Manzocchi et al., 2002).

iv) As the interpretation of the data is often non-unique, caution must be given when concluding what the data actually reveal about fault-related fluid flow, in order to decrease the uncertainties being introduced into the production-related fault seal analysis.

The concept of ‘fault facies’ has also been proposed to define any features deriving its present properties from tectonic deformation, which can improve the understanding the impact of fault zone architecture on hydrocarbon sealing behaviour (Tveranger et al., 2004; Tveranger et al., 2005). Originally, the concept of 'facies' is normally used to describe sedimentary rocks or metamorphic rocks. The introduction of fault facies allows the natural extension of the facies concept into the realm of both fault zone architecture and its fault rock properties (Braathen et al., 2009). As fault facies are associated to the fault geometry, internal structure, petrophysical properties and fault spatial distribution, it provides a novel approach to incorporate fault zone architecture and its impact on fluid flow properties into a three-dimensional production simulation model (Braathen et al., 2009; Fachri et al., 2013b; Fachri et al., 2011; Manzocchi et al., 2010).

7. Factors affecting petrophysical properties of fault rocks

The petrophysical properties of fault rocks are mainly determined by the clay/phyllosilicate content, the level of cataclasis and the amount of cementation (Fig.9) (Fisher and Knipe, 2001). However, in some natural oil/gas fields, the fault rocks, generated from sandstones with identical clay/phyllosilicate contents, can have different porosity and permeability characteristics (e.g. Fisher et al., 2003; Fisher and Knipe, 2001; Fossen et al., 2007). Based on a case study on the cataclastic faults from the Rotliegendes of the Southern North Sea, this can be attributed to the burial history that leads to interaction between the temperature history and the stress history (Fig.14), which can alter the petrophysical properties of fault rocks within the fault zones (Fisher and Knipe, 2001). For example, faults within the Rotliegendes formed at deeper depths than that in the Middle Jurassic reservoirs and therefore are closer to the temperature at which quartz precipitates rapidly (Fig.14). Apart from temperature and stress history, geological time is a third factor influencing the permeability evolution of a fault zone, which means a same fault zone can present different sealing properties through geological time (Indrevær et al., 2014).

Fig.14 Data of cataclastic faults from the Rotliegendes of the Southern North Sea. The plots show (a) permeability against their maximum burial depth and (b) permeability contrast against their maximum burial depth (Fisher and Knipe, 2001).

7.1. Temperature history

It has been commonly accepted that the temperature history of fault rocks has a significant effect on the rate of meso-diagenesis, e.g., quartz cementation and pressure solution (Walderhaug, 1996). The rate usually increases as a function of temperature (Fisher et al., 2003; Fisher and Knipe, 2001; Fisher et al., 2009), e.g., the quartz cementation and pressure solution occurs at rapid rate when the temperature exceeds ~90℃.

7.2. Stress History

Many studies tried to identify the effects of confining pressure on the deformation behaviour of faults/fault zones in sandstones. These studies suggest that: the sandstones at low confining pressures are likely to experience brittle faulting (failure occurs along single slip planes), while the sandstones at high confining pressures prefer more distributed ductile deformation without the generation of discrete slip planes (e.g. Handin et al., 1963; Scott and Nielsen, 1991). The experimental studies indicate that the grain size and the permeability of faults/fault zones decrease with increasing confining pressure and temperature (e.g. Crawford, 1998; Engelder, 1974; Fisher and Knipe, 2001; Zhu and Wong, 1997).

Therefore, as well as the clay/phyllosilicate content of host rocks, the effects of temperature history and stress history need to be taken into account when evaluating the fault sealing properties (Fisher et al., 2003; Fisher and Knipe, 2001; Fossen et al., 2007; Jolley et al., 2007b). The schematic cartoons in Fig.15 demonstrate the potential effects of burial depth (increasing effective stress and temperature) on micro-structural deformation mechanisms (Jolley et al., 2007b). Firstly, the different fault seal processes do not always occur independently, and it is common to observe multiple fault seal processes in a same fault zone. Secondly, the occurrence of combinations of fault seal processes is determined by both the clay/phyllosilicate content and the burial depth, as these two factors control the clay/phyllosilicate content of the generated fault rocks and its deformation environment (stress & temperature).

Fig.15 Schematic cartoons of micro-structural deformation mechanisms with various fault rocks generated in different geological settings, e.g., clay content of the host rocks and burial depth (reflecting increasing effective stress and temperature) (modified from Jolley et al., 2007b).

7.3. Cyclic evolution of permeability through geological time

As a same fault zone can present different hydrocarbon sealing behaviour through geological time, it is of importance to understand the control of geological time on the permeability evolution of a fault zone (both cross and along a fault zone). Many studies, particularly on production simulation modelling, have investigated the role of geological time on fault zone permeability evolution (Fisher and Knipe, 2001; Indrevær et al., 2014; Jolley et al., 2007b; Knipe et al., 1997; Manzocchi et al., 2010; Manzocchi et al., 2002). Indrevær et. al. (2014) proposed a model to demonstrate the cyclic permeability evolution of fault zones through geological time (Fig.16), describing faults as (i) conduits, (ii) barriers or (iii) conduits and barriers under different circumstances. At stage (a), the fault zone acts as fluid conduits as the porosity and permeability are increased by fracturing and cataclasis during faulting deformation. At stage (b), after the faulting deformation, the fault core zone acts as barriers whereas the damage zone acts as conduits for fluid flow, as the following precipitation of minerals and grain growth within the fault core zone inhibit the fluid flow. At stage (c), the entire fault zone is sealed by further grain growth and precipitation processes through time, and therefore acts as barriers for fluid flow, both along and across fault zone. At stage (d), a new permeability evolution cycle of the fault zone is restarted when the fault zone is reactivated in a later faulting deformation. Although this schematic permeability evolution model oversimplified many details associated with fault zone architecture and fault sealing properties, it reveals a basic cyclic changes of leakage and sealing across or along a fault zone through geological time.

Fig.16 Schematic illustration of a model showing the cyclic permeability evolution of fault zones through geological time (modified from Indrevær et al., 2014). (a) With faulting deformation, movement along a fault causes fracturing and cataclasis within the core zone and increases permeability. The core zone thereby acts as a fluid conduit. (b) Precipitation of minerals and grain growth within the core zone decreases permeability within the core zone and forces fluid flow into the damage zone. (c) Further grain growth and precipitation processes through time decrease porosity and permeability to gradually seal the entire fault zone. (d) Fault reactivation will initiate a new fluid flow evolution cycle.

8. Limitations and future of fault seal analysis

Fault seal analysis has been evolved since the concept of 'sealing' and 'non-sealing' was proposed by Smith in 1966 (Smith, 1966). In the past 50 years, by understanding the fault zone architecture, fault seal types, fault seal processes and generated fault rocks, geologists have proposed a bunch of models and methods to evaluate the hydrocarbon sealing behaviour of a fault zone. The initial application of Allan map (Allan, 1989) and triangle juxtaposition diagram (Knipe, 1997) makes it possible to investigate the effects of stratigraphic juxtaposition on the fluid flow properties of a fault zone. The later utilization of clay smear indices allows the quantitative evaluation of fault sealing capacity (Bouvier et al., 1989; Fulljames et al., 1997; Lindsay et al., 1993; Yielding et al., 1997). The recent employment of SEM photography and petrophysical assessment enables the investigation of deformation mechanisms of fault rocks and their effects on grain size reduction, porosity collapse and permeability decrease (e.g., Fisher et al., 2003; Fisher and Knipe, 1998; Fisher and Knipe, 2001; Fisher et al., 2009; Ottesen Ellevset et al., 1998). These methods have significantly boosted the fault seal related analysis in the past decades; however, there is still great potential for further progress in fault seal related research. The apparent limitations of the present-day models/methods have significantly constrained the effectiveness of fault seal analysis, such as:

a). Each individual model/method in present-day mostly focuses on a certain scale, which inhibits the ‘extrapolation’ of the results to a larger or smaller scale. A scale-dependent model/method may overlook the characteristics at its own scale while neglect that at other scales.

b). Further investigation and case studies are still necessary, as the present models/methods have not been sufficiently validated by physical simulation. The stratigraphic/mechanical heterogeneity contributes to high degree of fault zone complexity; therefore, the physical simulation is of great importance to validate the effectiveness of fault seal evaluation using present models/methods.

c). The present methods of fault seal analysis are mostly used to study the fault zone architecture and fault sealing properties in extensional regimes. Many case studies have realized that faults/fractures can play important control on the hydrocarbon migration in contractional regimes, e.g., the study in Kentucky, USA (Lewis et al., 2002), the New Guinea Fold Belt (Hill et al., 2004), the North West Borneo (Ingram et al., 2004), the Qaidam basin (Pang et al., 2004), etc. However, the detailed thrust fault architecture (particularly the meso- to micro-scale deformation features) and its effect on the fault sealing behaviour have not been well studied in contractional systems.

d). The concept of 'fault facies', associated to the fault geometry, internal structure, petrophysical properties and fault spatial distribution, is apparently an effective approach for incorporating both fault zone architecture and its impact on fluid flow properties into a three-dimensional production simulation model. However, further studies on fault facies are necessary to find how to apply this concept in different geological settings.

Considering the limitations of present fault seal analysis methods, there are a number of general paths to improve the fault seal analysis, for instance:

a). Multi-approach/scale investigation should be the direction for further fault seal analysis. The results from an individual model/method, however good, is of much less value if it was highly scale-dependent. The multi-approach/scale fault seal analysis can avoid the scale-limitation of the results.

b). Further fluid flow physical simulation of fault zones could be employed to validate the fault seal analysis using the existing models/methods. Fluid flow physical simulation can be an effective 'ground-truthing' tool to discriminate these models/methods as to their accuracy of prediction in particular natural fault zones. A model/method can be an effective model/method only if it was sufficiently tested by 'ground-truthing' tools.

c). Fault seal analysis in contractional systems should be taken into account. It is of great value to understand the differences of fault sealing properties between contractional and extensional regimes, particularly in the aspects of fault architecture, fault seal processes and their effects on fluid flow properties.

d).Fault facies should be integrated into the production simulation model to predict the impact of fault architecture on hydrocarbon sealing behaviour within a fault zone.

9. Conclusions

Fault sealing properties is one of the most important aspects of fault zone associated research. By understanding the fault zone architecture, fault seal types, fault seal processes and generated fault rocks, geologists have proposed different models and methods to evaluate the hydrocarbon sealing behaviour of a fault zone in the past decades. The proposal of these models/methods has significantly promoted the application of fault seal analysis to natural fault zones.

The present models/methods have clearly enhanced the understanding of fault zone sealing behaviour; however, further fault seal analysis should consider multi-approach/scale and physical simulation, in both extensional and contractional regimes.

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References

Agosta, F., Ruano, P., Rustichelli, A., Tondi, E., Galindo-Zaldívar, J. and Sanz de Galdeano, C., 2012. Inner structure and deformation mechanisms of normal faults in conglomerates and carbonate grainstones (Granada Basin, Betic Cordillera, Spain): Inferences on fault permeability. Journal of Structural Geology, 45(0): 4-20.

Al-Busafi, B., Fisher, Q.J. and Harris, S.D., 2005. The importance of incorporating the multi-phase flow properties of fault rocks into production simulation models. Marine and Petroleum Geology, 22(3): 365-374.

Allan, U.S., 1989. Model for Hydrocarbon Migration and Entrapment within Faulted Structures. American Association of Petroleum Geologists Bulletin, 73(7): 803-811.

Antonellini, M. and Aydin, A., 1994. Effect of Faulting on Fluid-Flow in Porous Sandstones - Petrophysical Properties. American Association of Petroleum Geologists Bulletin, 78(3): 355-377.

Antonellini, M. and Aydin, A., 1995. Effect of Faulting on Fluid-Flow Geometry and Spatial-Distribution. American Association of Petroleum Geologists Bulletin, 79(5): 642-671.

Antonellini, M.A., Aydin, A. and Pollard, D.D., 1994. Microstructure of deformation bands in porous sandstones at Arches National Park, Utah. Journal of Structural Geology, 16(7): 941-959.

Aydin, A. and Eyal, Y., 2002. Anatomy of a normal fault with shale smear: Implications for fault seal. Aapg Bulletin-American Association of Petroleum Geologists, 86(8): 1367-1381.

Balsamo, F., Storti, F., Salvini, F., Silva, A.T. and Lima, C.C., 2010. Structural and petrophysical evolution of extensional fault zones in low-porosity, poorly lithified sandstones of the Barreiras Formation, NE Brazil. Journal of Structural Geology, 32(11): 1806-1826.

Bense, V., Van den Berg, E. and Van Balen, R., 2003. Deformation mechanisms and hydraulic properties of fault zones in unconsolidated sediments; the Roer Valley Rift System, The Netherlands. Hydrogeology Journal, 11(3): 319-332.

Billi, A., Salvini, F. and Storti, F., 2003. The damage zone-fault core transition in carbonate rocks: implications for fault growth, structure and permeability. Journal of Structural Geology, 25(11): 1779-1794.

Bjorkum, P.A., 1996. How important is pressure in causing dissolution of quartz in sandstones? Journal of Sedimentary Research, 66(1): 147-154.

Blenkinsop, T.G., 1991. Cataclasis and processes of particle size reduction. Pure and Applied Geophysics, 136(1): 59-86.

Borg, I., Friedman, M., Handin, J. and Higgs, D.V., 1960. Chapter 6: Experimental Deformation of St. Peter Sand: A Study of Cataclastic Flow. Geological Society of America Memoirs, 79: 133-192.

Bouvier, J.D., Kaarssijpesteijn, C.H., Kluesner, D.F., Onyejekwe, C.C. and Vanderpal, R.C., 1989. Three-Dimensional Seismic Interpretation and Fault Sealing Investigations, Nun River Field, Nigeria. American Association of Petroleum Geologists Bulletin, 73(11): 1397-1414.

Braathen, A., Tveranger, J., Fossen, H., Skar, T., Cardozo, N., Semshaug, S., Bastesen, E. and Sverdrup, E., 2009. Fault facies and its application to sandstone reservoirs. AAPG bulletin, 93(7): 891-917.

Brogi, A. and Novellino, R., 2015. Low Angle Normal Fault (LANF)-zone architecture and permeability features in bedded carbonate from inner Northern Apennines (Rapolano Terme, Central Italy). Tectonophysics, 638(0): 126-146.

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

Cecil, C.B. and Heald, M.T., 1971. Experimental investigation of the effects of grain coatings on quartz growth. Journal of Sedimentary Petrology, 41: 582-584.

Cerveny, K., Davies, R., Dudley, G., Fox, R., Kaufman, P., Knipe, R.J. and Krantz, B., 2004. Reducing Uncertainty with Fault-Seal Analysis. Oilfield Review, 16(4): 38-51.

Childs, C., Manzocchi, T., Walsh, J.J., Bonson, C.G., Nicol, A. and Schöpfer, M.P.J., 2009. A geometric model of fault zone and fault rock thickness variations. Journal of Structural Geology, 31(2): 117-127.

Childs, C., Nicol, A., Walsh, J.J. and Watterson, J., 1996a. Growth of vertically segmented normal faults. Journal of Structural Geology, 18(12): 1389-1397.

Childs, C., Watterson, J. and Walsh, J.J., 1996b. A model for the structure and development of fault zones. Journal of the Geological Society, 153(3): 337-340.

Choi, J.H., Yang, S.J., Han, S.R. and Kim, Y.S., 2015. Fault zone evolution during Cenozoic tectonic inversion in SE Korea. Journal of Asian Earth Sciences, 98: 167–177.

Ciftci, N.B., Giger, S.B. and Clennell, M.B., 2013. Three-dimensional structure of experimentally produced clay smears: Implications for fault seal analysis. American Association of Petroleum Geologists Bulletin, 97(5): 733-757.

Clarke, S.M., Burley, S.D. and Williams, G.D., 2005. A three-dimensional approach to fault seal analysis: fault-block juxtaposition & argillaceous smear modelling. Basin Research, 17(2): 269-288.

Collettini, C., Carpenter, B.M., Viti, C., Cruciani, F., Mollo, S., Tesei, T., Trippetta, F., Valoroso, L. and Chiaraluce, L., 2014. Fault structure and slip localization in carbonate-bearing normal faults: An example from the Northern Apennines of Italy. Journal of Structural Geology, 67, Part A(0): 154-166.

Cowie, P.A., Knipe, R.J. and Main, I.G., 1996. Introduction to the Special Issue: Scaling Laws for fault and fracture populations - analyses and applications. Journal of Structural Geology, 18(2-3): v-xi.

Cowie, P.A. and Scholz, C.H., 1992. Displacement-length scaling relationship for faults: data synthesis and discussion. Journal of Structural Geology, 14(10): 1149-1156.

Cowie, P.A., Vanneste, C. and Sornette, D., 1993. Statistical physics model for the spatiotemporal evolution of faults. Journal of Geophysical Research, 98(B12): 21809-21821.

Crawford, B.R., 1998. Experimental fault sealing: shear band permeability dependency on cataclastic fault gouge characteristics. Geological Society, London, Special Publications, 127(1): 27-47.

Davatzes, N. and Aydin, A., 2005. Distribution and nature of fault architecture in a layered sandstone and shale sequence: An example from the Moab fault, Utah. in R. Sorkhabi and Y. Tsuji, eds., Faults, fluid flow, and petroleum traps: American Association of Petroleum Geologists Memoir, 85: 153-180.

Dewers, T. and Ortoleva, P., 1991. Influences of clay minerals on sandstone cementation and pressure solution. Geology, 19(10): 1045-1048.

Dewers, T. and Ortoleva, P.J., 1990. Interaction of reaction, mass transport, and rock deformation during diagenesis: mathematical modelling of integranular pressure solution, stylolites, and differential compaction/cementation. in I. D. Meshri and P. J. Ortoleva, eds., Prediction of Reservoir Quality through Chemical Modelling: American Association of Petroleum Geologists Memoir, 49: 147-160.

Egholm, D.L., Clausen, O.R., Sandiford, M., Kristensen, M.B. and Korstgård, J.A., 2008. The mechanics of clay smearing along faults. Geology, 36(10): 787-790.

Eisenstadt, G. and De Paor, D.G., 1987. Alternative model of thrust-fault propagation. Geology, 15(7): 630-633.

Engelder, J.T., 1974. Cataclasis and the Generation of Fault Gouge. Geological Society of America Bulletin, 85(10): 1515-1522.

Fachri, M., Rotevatn, A. and Tveranger, J., 2013a. Fluid flow in relay zones revisited: Towards an improved representation of small-scale structural heterogeneities in flow models. Marine and Petroleum Geology, 46(0): 144-164.

Fachri, M., Tveranger, J., Braathen, A. and Schueller, S., 2013b. Sensitivity of fluid flow to deformation-band damage zone heterogeneities: A study using fault facies and truncated Gaussian simulation. Journal of Structural Geology, 52: 60-79.

Fachri, M., Tveranger, J., Cardozo, N. and Pettersen, O., 2011. The impact of fault envelope structure on fluid flow: A screening study using fault facies. AAPG bulletin, 95(4): 619-648.

Faulkner, D.R., Jackson, C.A.L., Lunn, R.J., Schlische, R.W., Shipton, Z.K., Wibberley, C.A.J. and Withjack, M.O., 2010. A review of recent developments concerning the structure, mechanics and fluid flow properties of fault zones. Journal of Structural Geology, 32(11): 1557-1575.

Faulkner, D.R., Lewis, A.C. and Rutter, E.H., 2003. On the internal structure and mechanics of large strike-slip fault zones: field observations of the Carboneras fault in southeastern Spain. Tectonophysics, 367(3): 235–251.

Fisher, Q.J., Casey, M., Harris, S.D. and Knipe, R.J., 2003. Fluid-flow properties of faults in sandstone: The importance of temperature history. Geology, 31(11): 965-968.

Fisher, Q.J. and Jolley, S.J., 2007. Treatment of faults in production simulation models. Geological Society, London, Special Publications, 292: 219-233.

Fisher, Q.J. and Knipe, R.J., 1998. Fault sealing processes in siliciclastic sediments. Geological Society, London, Special Publications, 147: 117-134.

Fisher, Q.J. and Knipe, R.J., 2001. The permeability of faults within siliciclastic petroleum reservoirs of the North Sea and Norwegian

Continental Shelf. Marine and Petroleum Geology, 18(10): 1063-1081.

Fisher, Q.J., Knipe, R.J. and Worden, R.H., 2009. Microstructures of Deformed and Non-Deformed Sandstones from the North Sea: Implications for the Origins of Quartz Cement in Sandstones. in R. H. Worden and S. Morad, eds., Quartz Cementation in Sandstones, Blackwell Publishing Ltd., Oxford, UK, 14: 129-146.

Fondriest, M., Smith, S.A.F., Toro, G.D., Zampieri, D. and Mittempergher, S., 2012. Fault zone structure and seismic slip localization in dolostones, an example from the Southern Alps, Italy. Journal of Structural Geology, 45: 52–67.

Fossen, H. and Bale, A., 2007. Deformation bands and their influence on fluid flow. Aapg Bulletin, 91(12): 1685-1700.

Fossen, H., Schultz, R.A., Shipton, Z.K. and Mair, K., 2007. Deformation bands in sandstone: a review. Journal of the Geological Society, 164(4): 755-769.

Fossen, H., Schultz, R.A. and Torabi, A., 2011. Conditions and implications for compaction band formation in the Navajo Sandstone, Utah. Journal of Structural Geology, 33(10): 1477-1490.

Fulljames, J.R., Zijerveld, L.J.J. and Franssen, R.C.M.W., 1997. Fault seal processes: systematic analysis of fault seals over geological and production time scales. In: P. Møller-Pedersen and A.G. Koestler (Editors), Norwegian Petroleum Society Special Publications, pp. 51-59.

Gibson, R.G., 1994. Fault-Zone Seals in Siliciclastic Strata of the Columbus Basin, Offshore Trinidad. American Association of Petroleum Geologists Bulletin, 78(9): 1372-1385.

Handin, J., Hager Jr, R.V., Friedman, M. and Feather, J.N., 1963. Experimental deformation of sedimentary rocks under confining pressure: pore pressure tests. American Association of Petroleum Geologists Bulletin, 47(5): 717-755.

Harris, S.D., Vaszi, A.Z. and Knipe, R.J., 2007. Three-dimensional upscaling of fault damage zones for reservoir simulation. Geological Society, London, Special Publications, 292: 353-374.

Heald, M.T., 1955. Stylolites in Sandstones. The Journal of Geology, 63(2): 101-114.

Heynekamp, M.R., Goodwin, L.B., Mozley, P.S. and Haneberg, W.C., 1999. Controls on fault-zone architecture in poorly lithified sediments, Rio Grande Rift, New Mexico: Implications for fault-zone permeability and fluid flow, Faults and Subsurface Fluid Flow in the Shallow Crust. Washington, DC, AGU. Geophys. Monogr. Ser., pp. 27-49.

Hill, K.C., Keetley, J.T., Kendrick, R.D. and Sutriyono, E., 2004. Structure and hydrocarbon potential of the New Guinea Fold Belt. in K. R. McClay, eds., Thrust tectonics and hydrocarbon systems: American Association of Petroleum Geologists Memoir, 82: 494-514.

Indrevær, K., Stunitz, H. and Bergh, S.G., 2014. On Palaeozoic–Mesozoic brittle normal faults along the SW Barents Sea margin: fault processes and implications for basement permeability and margin evolution. Journal of the Geological Society, 171(6): 831-846.

Ingram, G.M., Chisholm, T.J., Grant, C.J., Hedlund, C.A., Stuart-Smith, P. and Teasdale, J., 2004. Deepwater North West Borneo: hydrocarbon accumulation in an active fold and thrust belt. Marine and Petroleum Geology, 21(7): 879-887.

Jolley, S.J., Barr, D., Walsh, J.J. and Knipe, R.J., 2007a. Structurally complex reservoirs: an introduction. Geological Society, London, Special Publications, 292: 1-24.

Jolley, S.J., Dijk, H., Lamens, J.H., Fisher, Q.J., Manzocchi, T., Eikmans, H. and Huang, Y., 2007b. Faulting and fault sealing in production simulation models: Brent Province, northern North Sea. Petroleum Geoscience, 13(4): 321-340.

Jones, R.M. and Hillis, R.R., 2003. An integrated, quantitative approach to assessing fault-seal risk. AAPG bulletin, 87(3): 507-524.

Knipe, R.J., 1989. Deformation Mechanisms - Recognition from Natural Tectonites. Journal of Structural Geology, 11(1-2): 127-146.

Knipe, R.J., 1992a. Faulting processes and fault seal. In: R.M. Larsen, H. Brekke, B.T. Larsen and E. Talleraas (Editors), Norwegian Petroleum Society Special Publications, pp. 325-342.

Knipe, R.J., 1992b. Faulting processes, seal evolution, and reservoir discontinuities: An integrated analysis of the ULA Field, Central Graben, North Sea, Abstracts of the Petroleum Group meeting on collaborative research programme in petroleum geoscience between UK Higher Education Institutes and the Petroleum Industry, Geological Society, London.

Knipe, R.J., 1993a. The Influence of Fault Zone Processes and Diagenesis on Fluid Flow. Diagenesis and Basin Development(36): 135-154.

Knipe, R.J., 1993b. Micromechanisms of deformation and fluid flow behaviour during faulting. The mechanical behavior of fluids in fault zones: USGS Open-File Report: 94-228.

Knipe, R.J., 1994. Fault zone geometry and behaviour: the importance of damage zone evolution. Abstracts of Meetings Modern Developments in Structural Interpretation, Geological Society, London.

Knipe, R.J., 1997. Juxtaposition and seal diagrams to help analyze fault seals in hydrocarbon reservoirs. American Association of Petroleum Geologists Bulletin, 81(2): 187-195.

Knipe, R.J., Fisher, R.J., Jones, G., Clennell, M.R., Farmer, A.B., Harrison, a., Kidd, B., McAllister, E., R., P.J. and White, E.A., 1997. Fault seal analysis: successful methodologies, application and future directions. Norwegian Petroleum Society Special Publications, 7: 15-40.

Knipe, R.J., Jones, G. and Fisher, Q.J., 1998. Faulting, fault sealing and fluid flow in hydrocarbon reservoirs: an introduction. Geological Society, London, Special Publications, 147(1): vii-xxi.

Knott, S.D., 1993. Fault Seal Analysis in the North-Sea. American Association of Petroleum Geologists Bulletin, 77(5): 778-792.

Kolyukhin, D., Schueller, S., Espedal, M. and Fossen, H., 2010. Deformation band populations in fault damage zone—impact on fluid flow. Computational Geosciences, 14(2): 231-248.

Korneva, I., Tondi, E., Agosta, F., Rustichelli, A., Spina, V., Bitonte, R. and Di Cuia, R., 2014. Structural properties of fractured and faulted Cretaceous platform carbonates, Murge Plateau (southern Italy). Marine and Petroleum Geology, 57: 312-326.

Lewis, G., Knipe, R.J. and Li, A., 2002. Fault seal analysis in unconsolidated sediments: a field study from kentucky, USA. In: G.K. Andreas and H.

Robert (Editors), Norwegian Petroleum Society Special Publications, pp. 243-253.

Lindsay, N.G., Murphy, F.C., Walsh, J.J. and Watterson, J., 1993. Outcrop Studies of Shale Smears on Fault Surface, The Geological Modelling of Hydrocarbon Reservoirs and Outcrop Analogues. Blackwell Publishing Ltd., pp. 113-123.

Loveless, S., Bense, V. and Turner, J., 2011. Fault architecture and deformation processes within poorly lithified rift sediments, Central Greece. Journal of Structural Geology, 33(11): 1554-1568.

Manzocchi, T., Childs, C. and Walsh, J.J., 2010. Faults and fault properties in hydrocarbon flow models. Geofluids, 10(1-2): 94-113.

Manzocchi, T., Heath, A.E., Walsh, J.J. and Childs, C., 2002. The representation of two phase fault-rock properties in flow simulation models. Petroleum Geoscience, 8(2): 119-132.

Manzocchi, T., Walsh, J.J., Nell, P. and Yielding, G., 1999. Fault transmissibility multipliers for flow simulation models. Petroleum Geoscience, 5(1): 53-63.

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

Odling, N.E., Harris, S.D. and Knipe, R., 2004. Permeability scaling properties of fault damage zones in siliclastic rocks. Journal of Structural Geology, 26(9): 1727-1747.

Oelkers, E.H., Bjorkum, P.A. and Murphy, W.M., 1996. A petrographic and computational investigation of quartz cementation and porosity reduction in North Sea sandstones. American Journal of Science, 296(4): 420-452.

Ottesen Ellevset, S., Knipe, R.J., Svava Olsen, T., Fisher, Q.J. and Jones, G., 1998. Fault controlled communication in the Sleipner Vest Field, Norwegian Continental Shelf; detailed, quantitative input for reservoir simulation and well planning. Geological Society, London, Special Publications, 147(1): 283-297.

Pang, X.Q., Li, Y.X. and Jiang, Z.X., 2004. Key geological controls on migration and accumulation for hydrocarbons derived from mature source rocks in Qaidam Basin. Journal of Petroleum Science and Engineering, 41(1-3): 79-95.

Peacock, D.C.P. and Sanderson, D.J., 1991. Displacements, segment linkage and relay ramps in normal fault zones. Journal of Structural Geology, 13(6): 721-733.

Peacock, D.C.P. and Sanderson, D.J., 1992. Effects of layering and anisotropy on fault geometry. Journal of the Geological Society, 149(5): 793-802.

Peacock, D.C.P. and Sanderson, D.J., 1994. Geometry and development of relay ramps in normal fault systems. American Association of Petroleum Geologists Bulletin, 78(2): 147-165.

Pei, Y.W., 2013. Thrust fault evolution and hydrocarbon sealing behaviour, Qaidam basin, China. PhD Thesis, University of Leeds.

Qu, D., Røe, P. and Tveranger, J., 2015. A method for generating volumetric fault zone grids for pillar gridded reservoir models. Computers & Geosciences, 81: 28-37.

Rawling, G.C. and Goodwin, L.B., 2003. Cataclasis and particulate flow in faulted, poorly lithified sediments. Journal of Structural Geology, 25(3): 317-331.

Rawling, G.C. and Goodwin, L.B., 2006. Structural record of the mechanical evolution of mixed zones in faulted poorly lithified sediments, Rio Grande rift, New Mexico, USA. Journal of Structural Geology, 28(9): 1623-1639.

Rawling, G.C., Goodwin, L.B. and Wilson, J.L., 2001. Internal architecture, permeability structure, and hydrologic significance of contrasting fault-zone types. Geology, 29(1): 43-46.

Roche, V., Homberg, C. and Rocher, M., 2012. Architecture and growth of normal fault zones in multilayer systems: A 3D field analysis in the South-Eastern Basin, France. Journal of Structural Geology, 37(0): 19-35.

Rotevatn, A. and Bastesen, E., 2014. Fault linkage and damage zone architecture in tight carbonate rocks in the Suez Rift (Egypt): implications for permeability structure along segmented normal faults. Geological Society, London, Special Publications, 374(1): 79-95.

Rotevatn, A., Fossen, H., Hesthammer, J., Aas, T.E. and Howell, J.A., 2007. Are relay ramps conduits for fluid flow? Structural analysis of a relay ramp in Arches National Park, Utah: in. Geological Society of London, 270(1).

Rutter, E.H., 1983. Pressure solution in nature, theory and experiment. Journal of the Geological Society, 140(5): 725-740.

Schöpfer, M.P.J., Childs, C. and Walsh, J.J., 2006. Localisation of normal faults in multilayer sequences. Journal of Structural Geology, 28(5): 816-833.

Schowalter, T.T., 1979. Mechanics of secondary hydrocarbon migration and entrapment. American Association of Petroleum Geologists Bulletin, 63(5): 723-760.

Schultz, R.A. and Fossen, H., 2008. Terminology for structural discontinuities. Aapg Bulletin, 92(7): 853-867.

Scott, T.E. and Nielsen, K.C., 1991. The Effects of Porosity on the Brittle-Ductile Transition in Sandstones. Journal of Geophysical Research, 96(B1): 405-414.

Smith, D.A., 1966. Theoretical considerations of sealing and non-sealing faults. American Association of Petroleum Geologists Bulletin, 50(2): 363-374.

Smith, D.A., 1980. Sealing and nonsealing faults in Louisiana Gulf Coast salt basin. American Association of Petroleum Geologists Bulletin, 64(2): 145-172.

Spiers, C.J. and Schutjens, P.M.T.M., 1990. Densification of crystalline aggregates by fluid-phase diffusional creep, Deformation Processes in Minerals, Ceramics and Rocks. The Mineralogical Society Series. Springer Netherlands, pp. 334-353.

Tada, R. and Siever, R., 1989. Pressure Solution during Diagenesis. Annual Review of Earth and Planetary Sciences, 17: 89-118.

Torabi, A. and Berg, S.S., 2011. Scaling of fault attributes: A review. Marine and Petroleum Geology, 28(8): 1444-1460.

Tueckmantel, C., Fisher, Q.J., Knipe, R.J., Lickorish, H. and Khalil, S.M., 2010. Fault seal prediction of seismic-scale normal faults in porous sandstone: A case study from the eastern Gulf of Suez rift, Egypt. Marine and Petroleum Geology, 27(2): 334-350.

Tveranger, J., Skar, T. and Braathen, A., 2004. Incorporation of fault zones as volumes in reservoir models. Bolletino di Geofisica Teoretica et Applicata, 45: 316-318.

Tveranger, J., Skauge, A., Braathen, A. and Skar, T., 2005. Centre for integrated petroleum research: Research activities with emphasis on fluid flow in fault zones. Norsk Geologisk Tidsskrift, 85(1-2): 63-71.

Walderhaug, O., 1996. Kinetic modeling of quartz cementation and porosity loss in deeply buried sandstone reservoirs. American Association of Petroleum Geologists Bulletin, 80(5): 731-745.

Walsh, J.J., Bailey, W.R., Childs, C., Nicol, A. and Bonson, C.G., 2003. Formation of segmented normal faults: a 3-D perspective. Journal of Structural Geology, 25(8): 1251-1262.

Walsh, J.J., Watterson, J., Bailey, W.R. and Childs, C., 1999. Fault relays, bends and branch-lines. Journal of Structural Geology, 21(8–9): 1019-1026.

Walsh, J.J., Watterson, J., Heath, A.E. and Childs, C., 1998. Representation and scaling of faults in fluid flow models. Petroleum Geoscience, 4(3): 241-251.

Watts, N.L., 1987. Theoretical aspects of cap-rock and fault seals for single- and two-phase hydrocarbon columns. Marine and Petroleum Geology, 4(4): 274-307.

Welch, M.J., Davies, R.K., Knipe, R.J. and Tueckmantel, C., 2009a. A dynamic model for fault nucleation and propagation in a mechanically layered section. Tectonophysics, 474(3–4): 473-492.

Welch, M.J., Knipe, R.J., Souque, C. and Davies, R.K., 2009b. A Quadshear kinematic model for folding and clay smear development in fault zones. Tectonophysics, 471(3–4): 186-202.

Welch, M.J., Souque, C., Davies, R.K. and Knipe, R.J., 2015. Using mechanical models to investigate the controls on fracture geometry and distribution in chalk. Geological Society, London, Special Publications, 406(1): 281-309.

Yielding, G., Freeman, B. and Needham, D.T., 1997. Quantitative fault seal prediction. American Association of Petroleum Geologists Bulletin, 81(6): 897-917.

Yielding, G., Needham, T. and Jones, H., 1996. Sampling of fault populations using sub-surface data: a review. Journal of Structural Geology, 18(2): 135-146.

Zhu, W.L. and Wong, T.F., 1997. The transition from brittle faulting to cataclastic flow: Permeability evolution. Journal of Geophysical Research, 102(B2): 3027-3041.

Zijlstra, E.B., Reemst, P.H.M. and Fisher, Q.J., 2007. Incorporation of fault properties into production simulation models of Permian reservoirs from the southern North Sea. Geological Society, London, Special Publications, 292: 295-308.

Figure 1

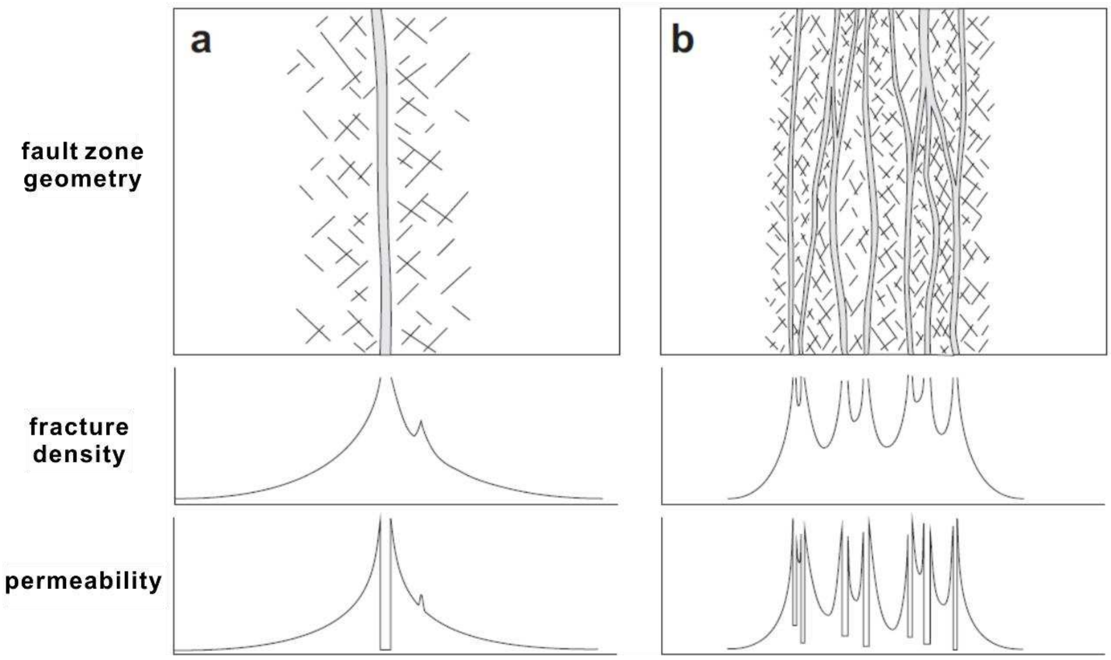


Figure 2

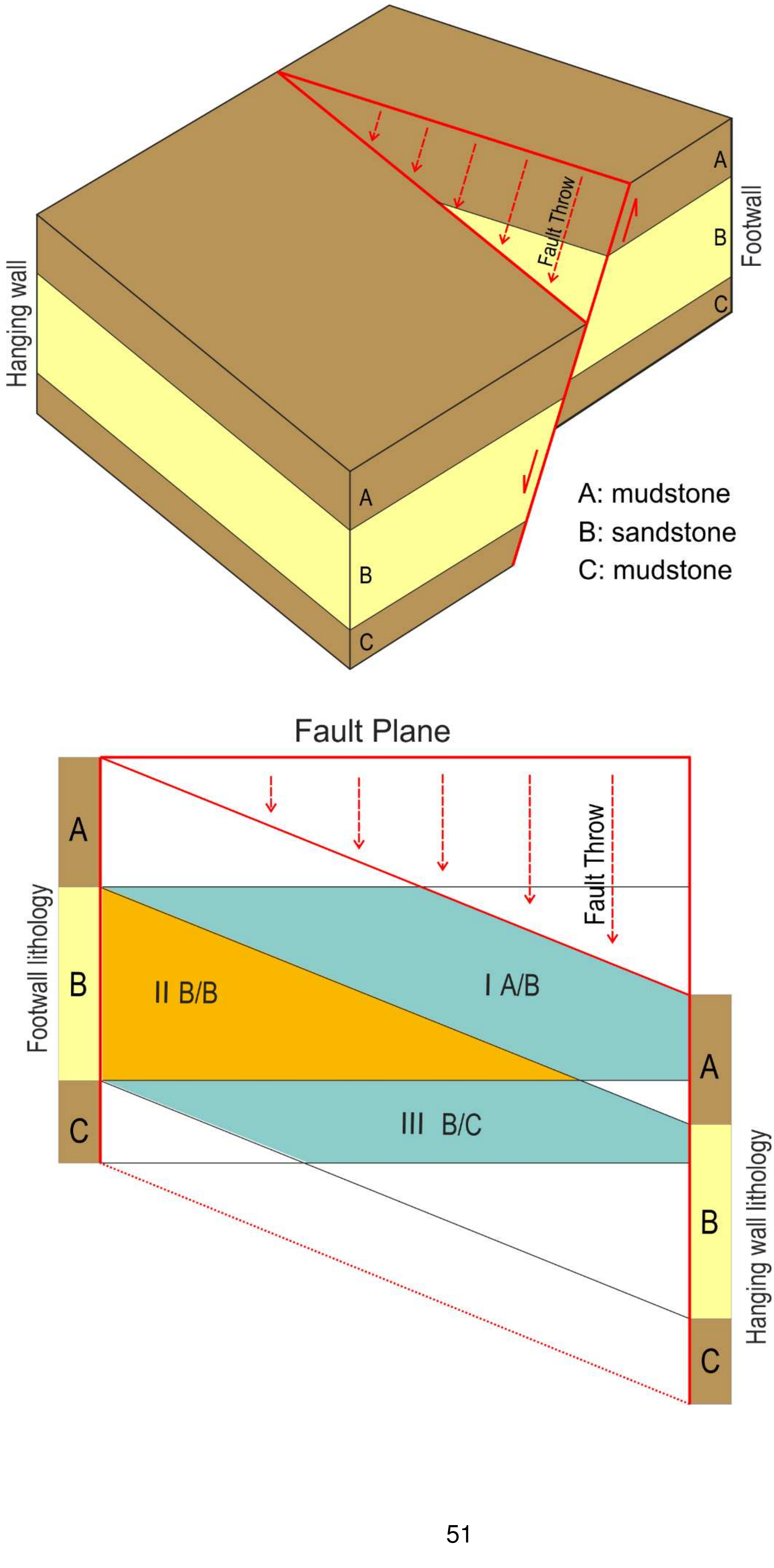
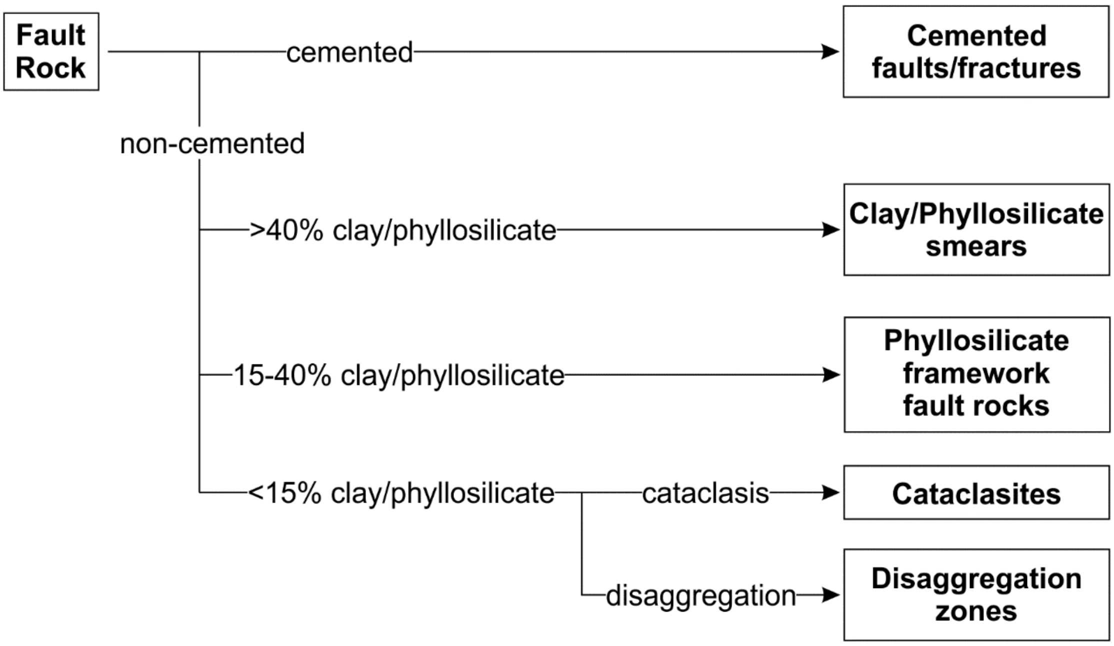

Hanging wall
Footwall
A
B
C
Fault Throw
A: mudstone
B: sandstone
C: mudstone
A
B
C
Fault Plane
Fault Throw
Footwall lithology
A
B
C
II B/B
I A/B
III B/C
Hanging wall lithology
A
B
C

Figure 3



Fault Rock
cemented
Cemented faults/fractures
non-cemented
>40% clay/phyllosilicate
Clay/Phyllosilicate smears
15-40% clay/phyllosilicate
Phyllosilicate framework fault rocks
<15% clay/phyllosilicate
cataclasis
Cataclasites
disaggregation
Disaggregation zones

Figure 4

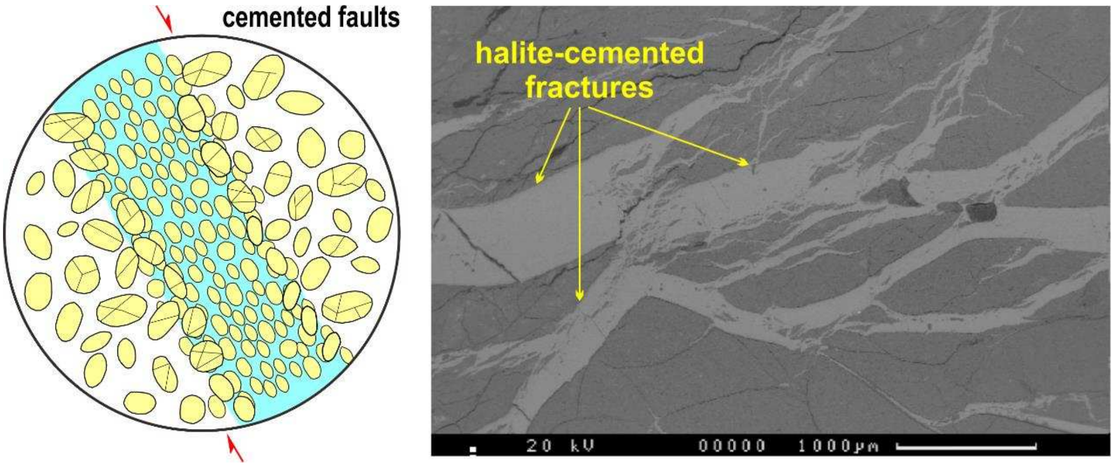

cemented faults
halite-cemented fractures
20 kV 00000 1000µm

Figure 5

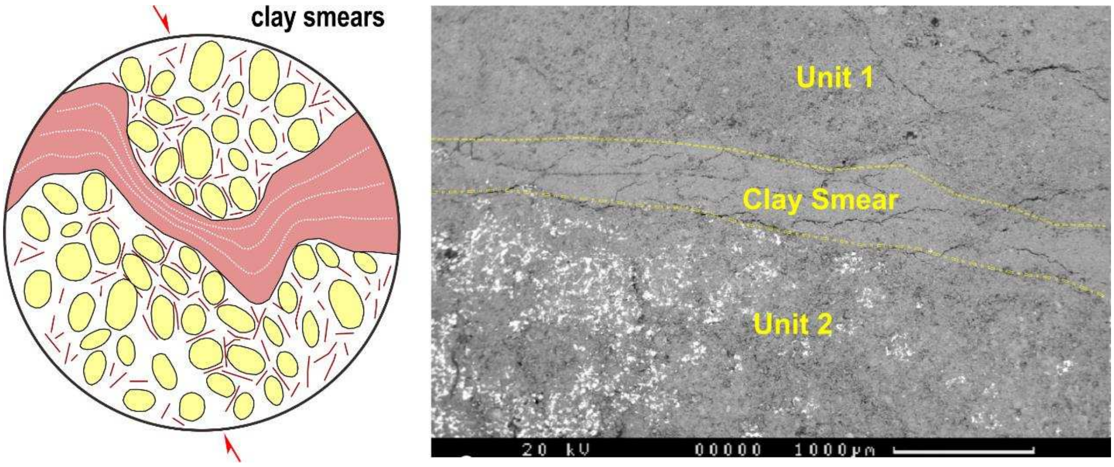


Figure 6

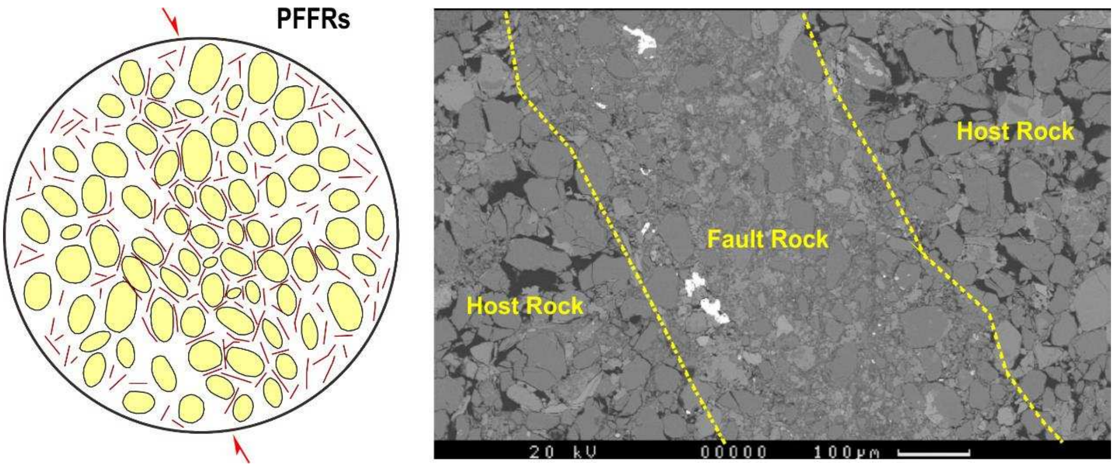


Figure 7

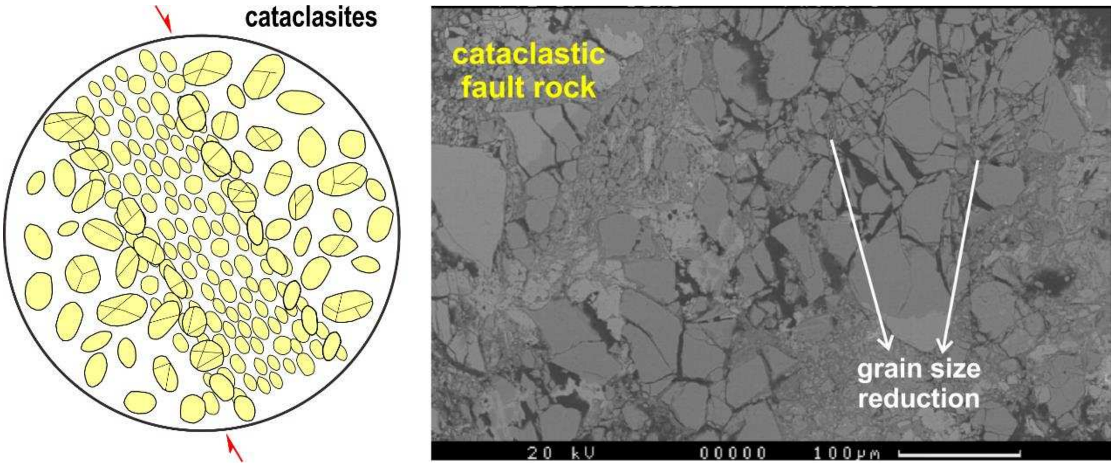
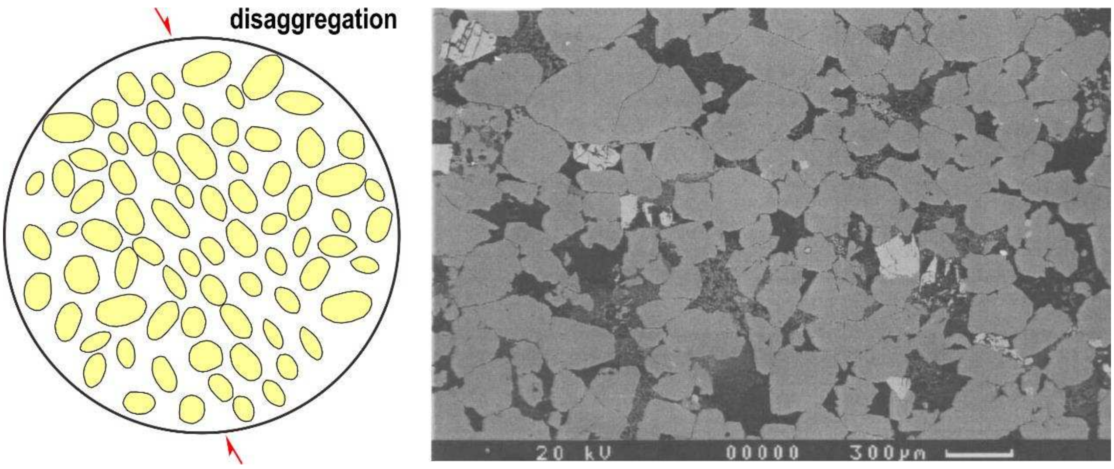

cataclasites
cataclastic
fault rock
grain size
reduction
20 kV
00000
100µm

Figure 8



1403 **Figure 9**

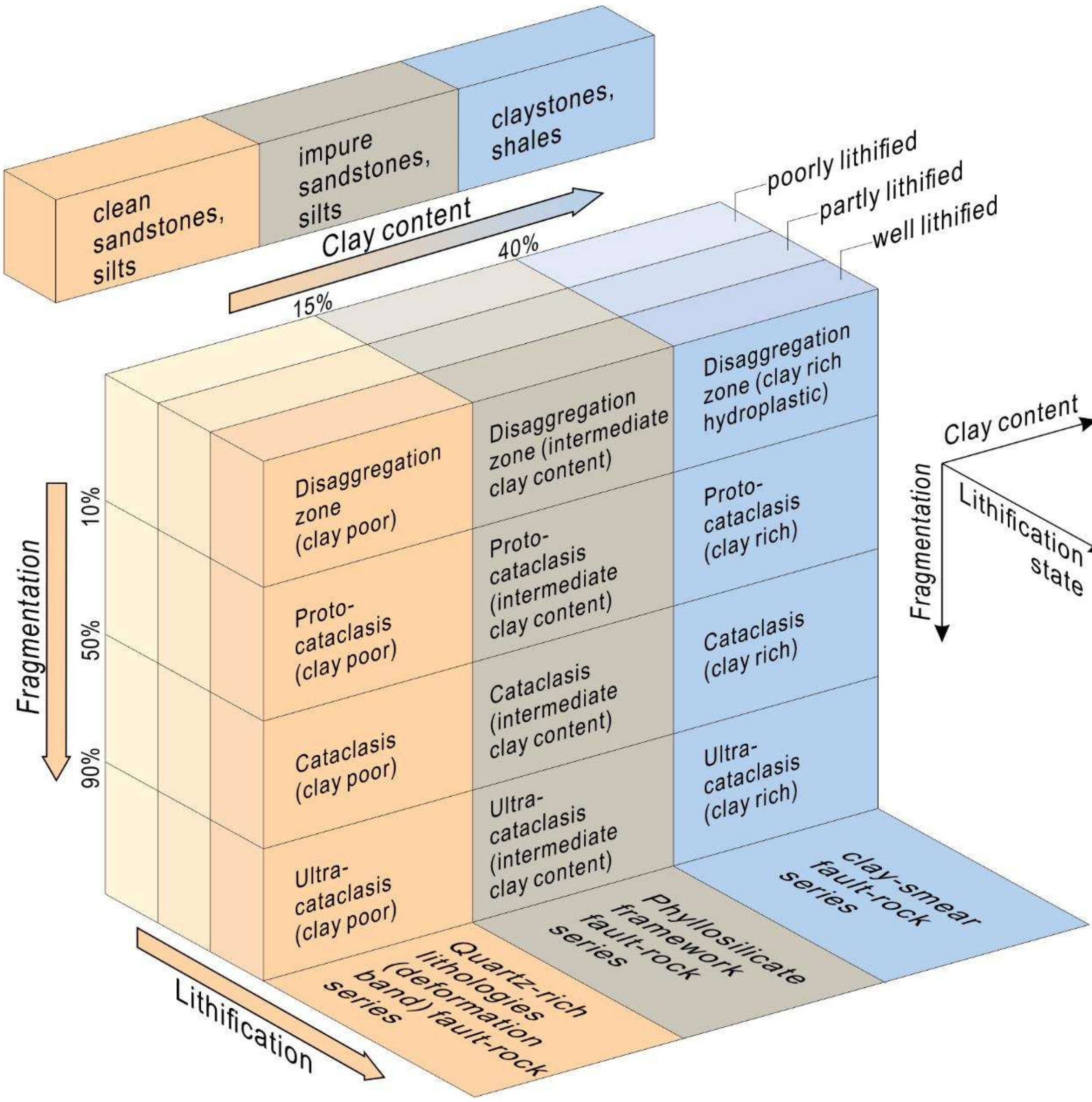


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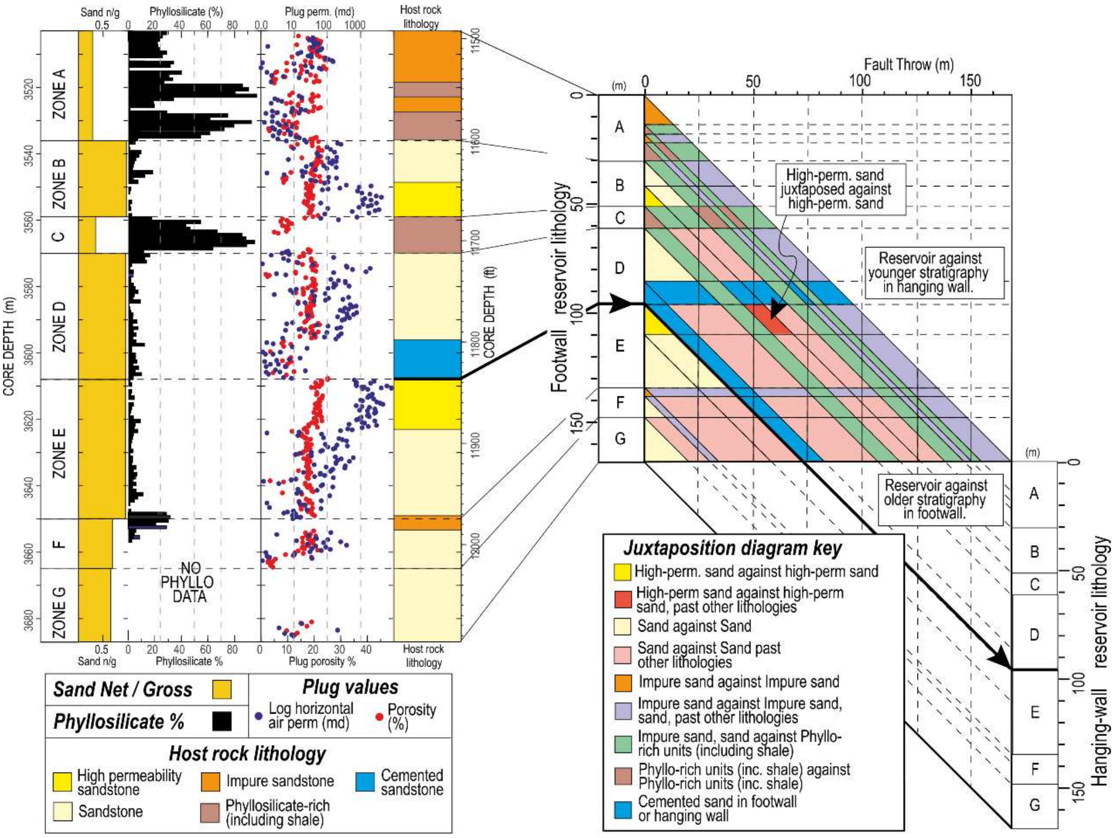
Figure 10



Sand n/g
Phyllosilicate (%)
Plug perm. (md)
Host rock lithology
CORE DEPTH (m)
CORE DEPTH (ft)
ZONE A
ZONE B
C
ZONE D
ZONE E
F
ZONE G
NO PHYLLO DATA
Sand n/g
Phyllosilicate %
Plug porosity %
Host rock lithology
Sand Net / Gross
Phyllosilicate %
Plug values
Log horizontal air perm (md)
Porosity (%)
Host rock lithology
High permeability sandstone
Impure sandstone
Cemented sandstone
Sandstone
Phyllosilicate-rich (including shale)
Fault Throw (m)
Footwall reservoir lithology
Hanging-wall reservoir lithology
High-perm. sand juxtaposed against high-perm. sand
Reservoir against younger stratigraphy in hanging wall.
Reservoir against older stratigraphy in footwall.
Juxtaposition diagram key
High-perm. sand against high-perm sand
High-perm sand against high-perm sand, past other lithologies
Sand against Sand
Sand against Sand past other lithologies
Impure sand against Impure sand
Impure sand against Impure sand, sand, past other lithologies
Impure sand, sand against Phyllo-rich units (including shale)
Phyllo-rich units (inc. shale) against Phyllo-rich units (inc. shale)
Cemented sand in footwall or hanging wall

Figure 11

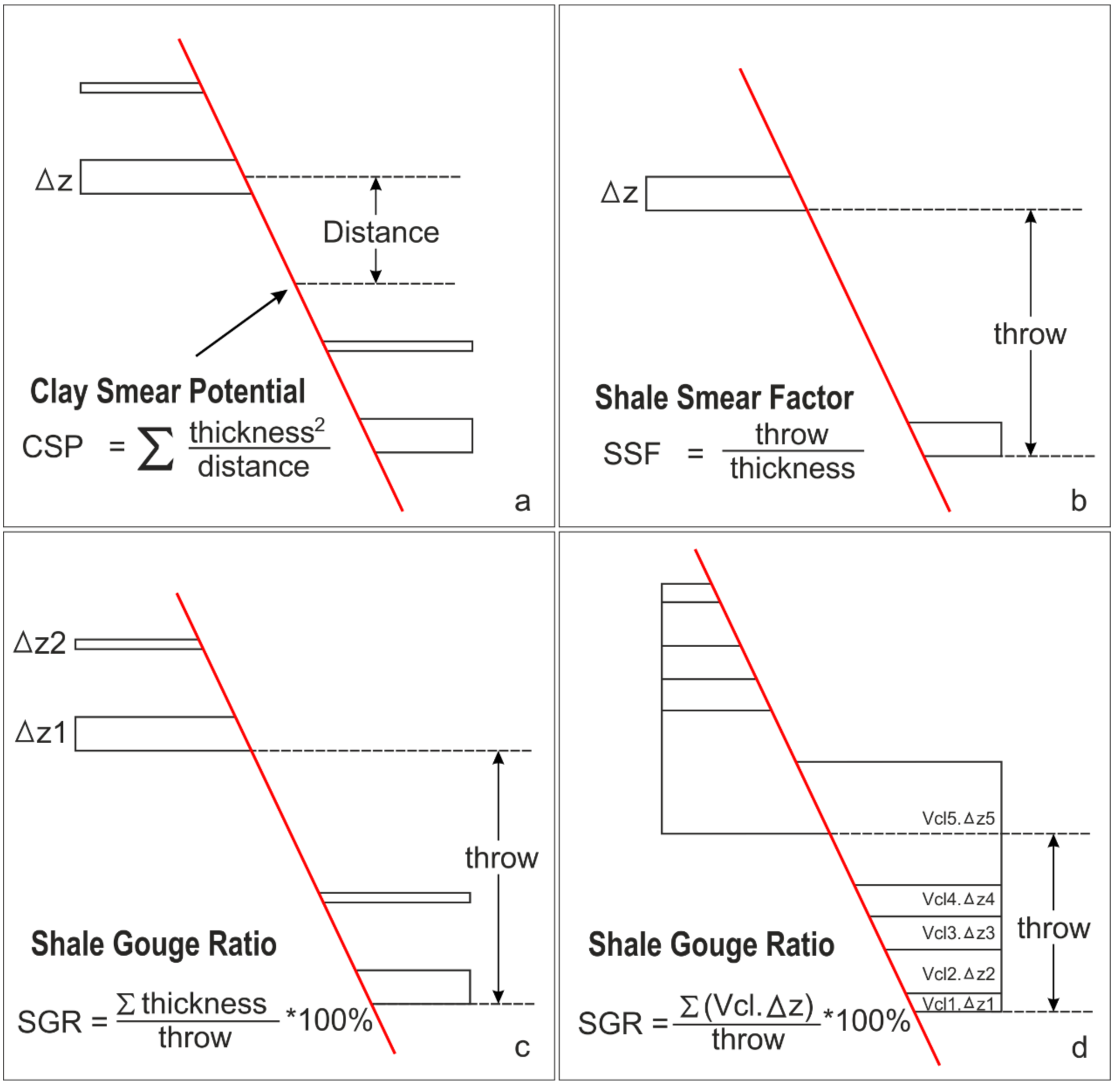
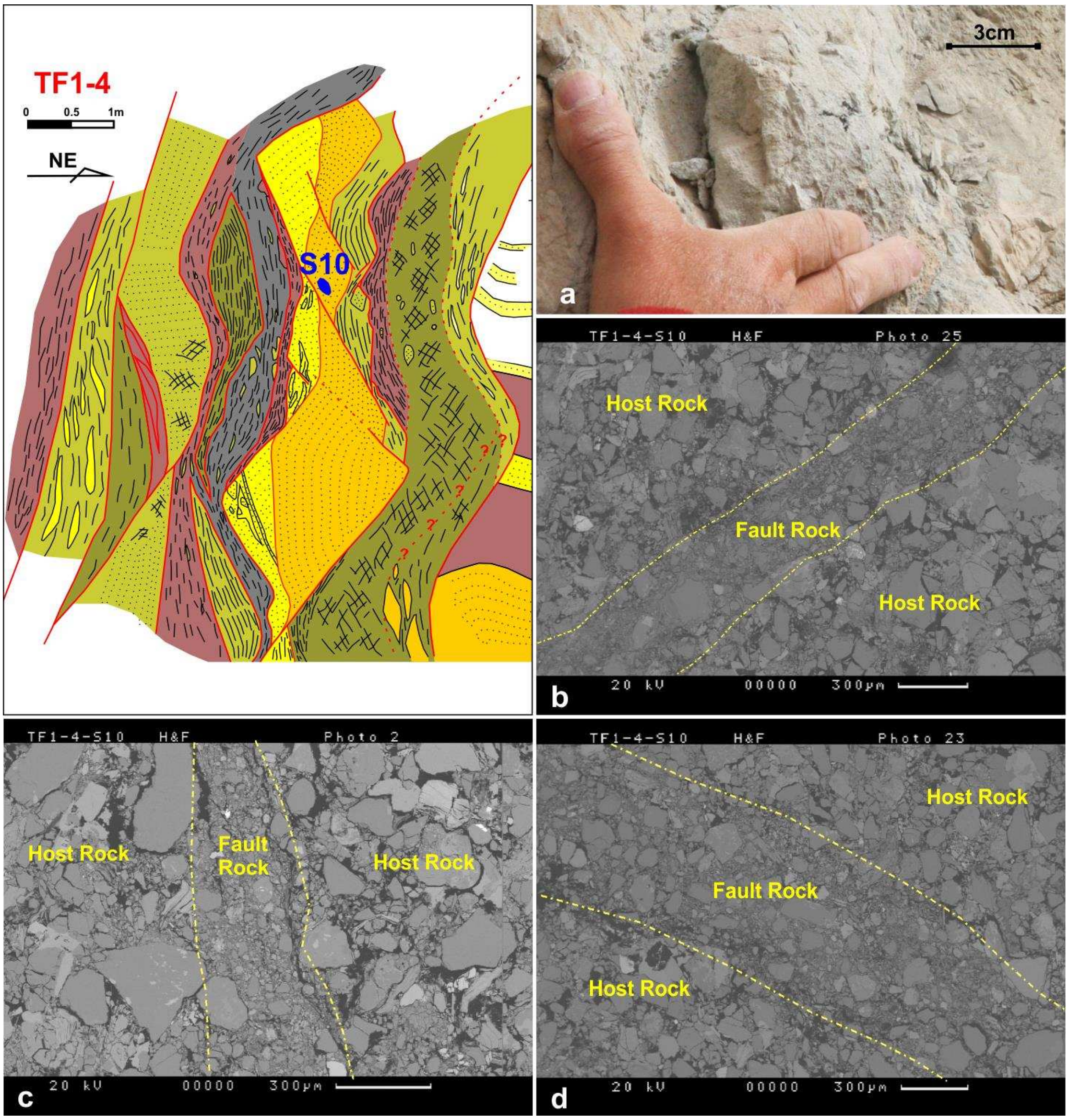

Δz
Distance
Clay Smear Potential
CSP = Σ thickness² / distance
a
Δz
throw
Shale Smear Factor
SSF = throw / thickness
b
Δz2
Δz1
throw
Shale Gouge Ratio
SGR = Σ thickness / throw *100%
c
Vcl5.Δz5
Vcl4.Δz4
Vcl3.Δz3
Vcl2.Δz2
Vcl1.Δz1
throw
Shale Gouge Ratio
SGR = Σ (Vcl.Δz) / throw *100%
d

Figure 12



TF1-4
0
0.5
1m
NE
S10
3cm
a
TF1-4-S10 H&F Photo 25
Host Rock
Fault Rock
Host Rock
20 kV 00000 300μm
b
TF1-4-S10 H&F Photo 2
Host Rock
Fault Rock
Host Rock
20 kV 00000 300μm
c
TF1-4-S10 H&F Photo 23
Host Rock
Fault Rock
Host Rock
20 kV 00000 300μm
d

Figure 13

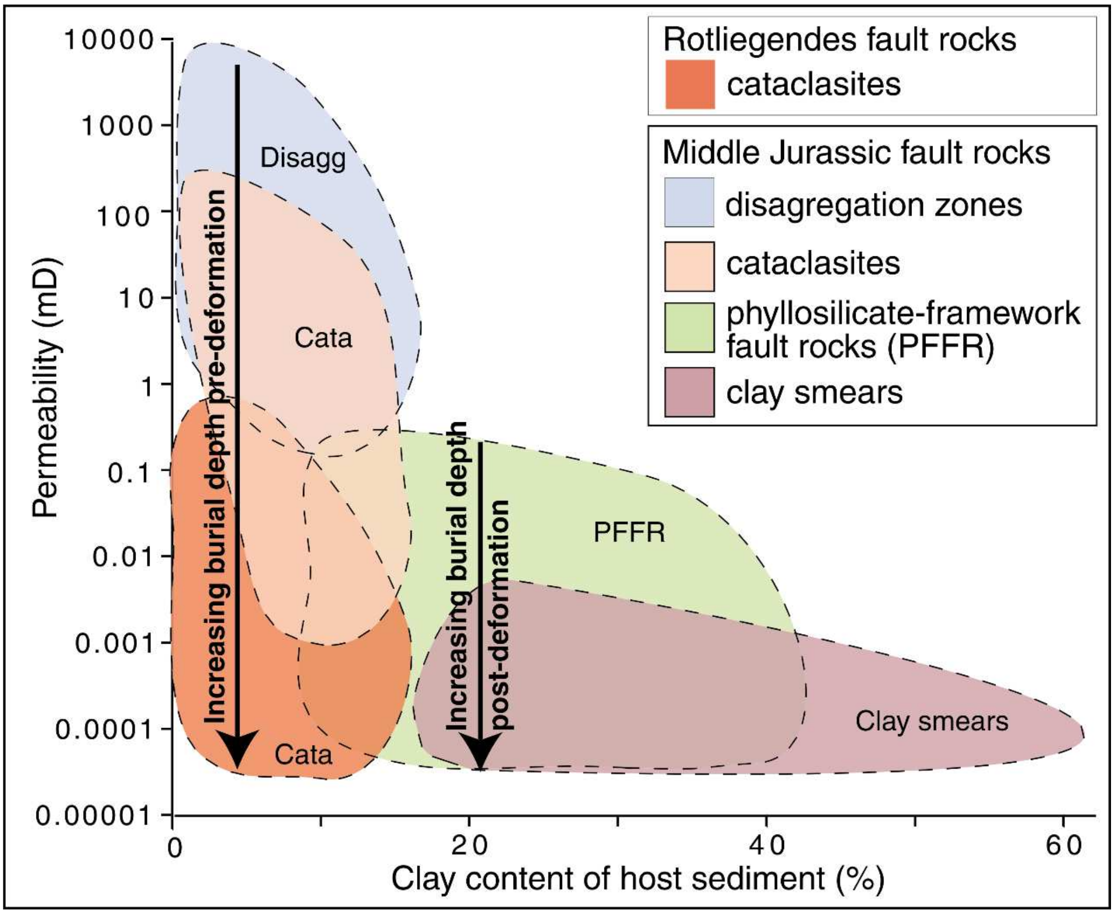
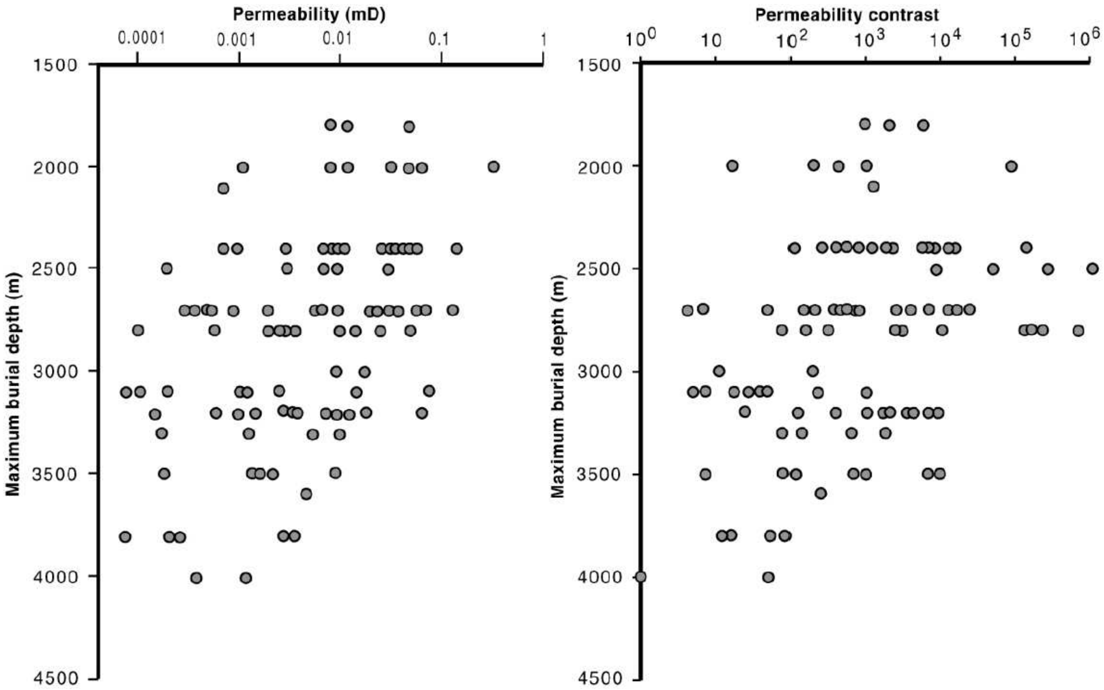

Rotliegendes fault rocks
cataclasites
Middle Jurassic fault rocks
disagregation zones
cataclasites
phyllosilicate-framework fault rocks (PFFR)
clay smears
Disagg
Cata
Cata
PFFR
Clay smears
Increasing burial depth pre-deformation
Increasing burial depth post-deformation
Permeability (mD)
10000
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0
20
40
60
Clay content of host sediment (%)

Figure 14



Permeability (mD)
0.0001
0.001
0.01
0.1
1
1500
2000
2500
3000
3500
4000
4500
Maximum burial depth (m)
Permeability contrast
10^0
10
10^2
10^3
10^4
10^5
10^6
1500
2000
2500
3000
3500
4000
4500
Maximum burial depth (m)

Figure 15

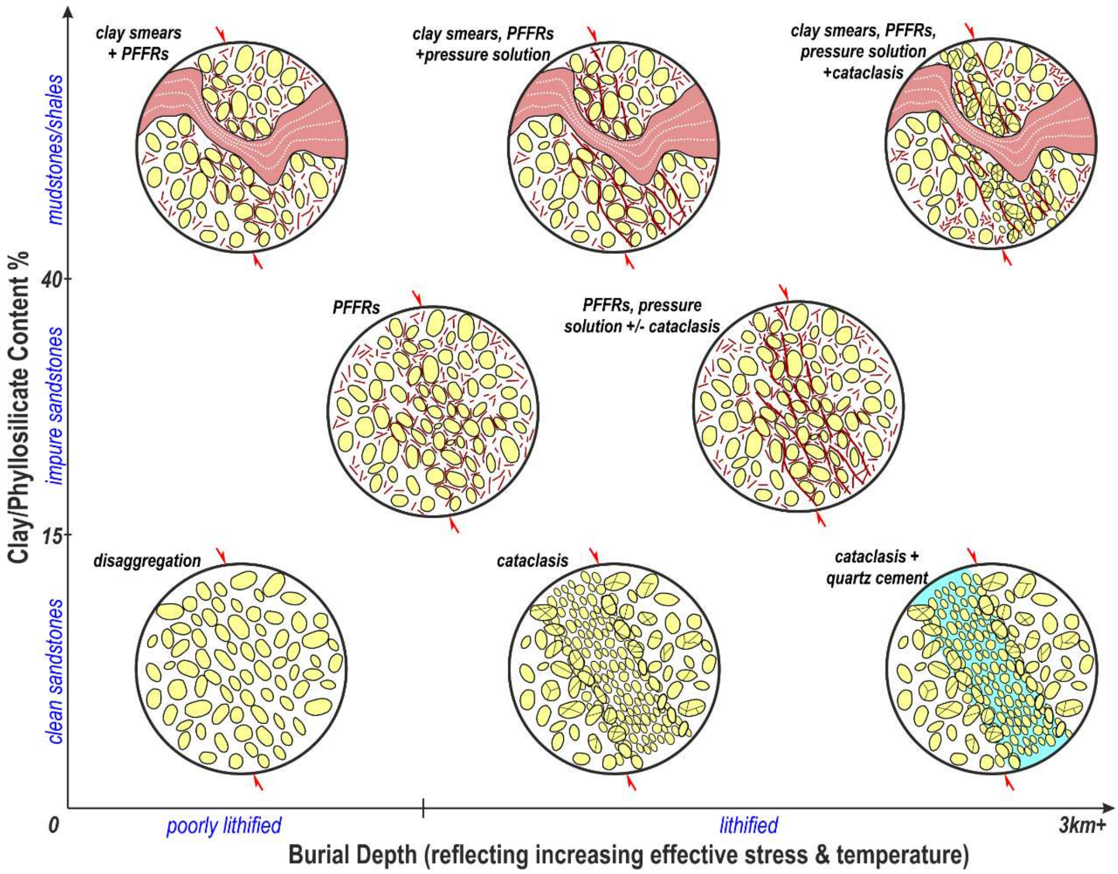
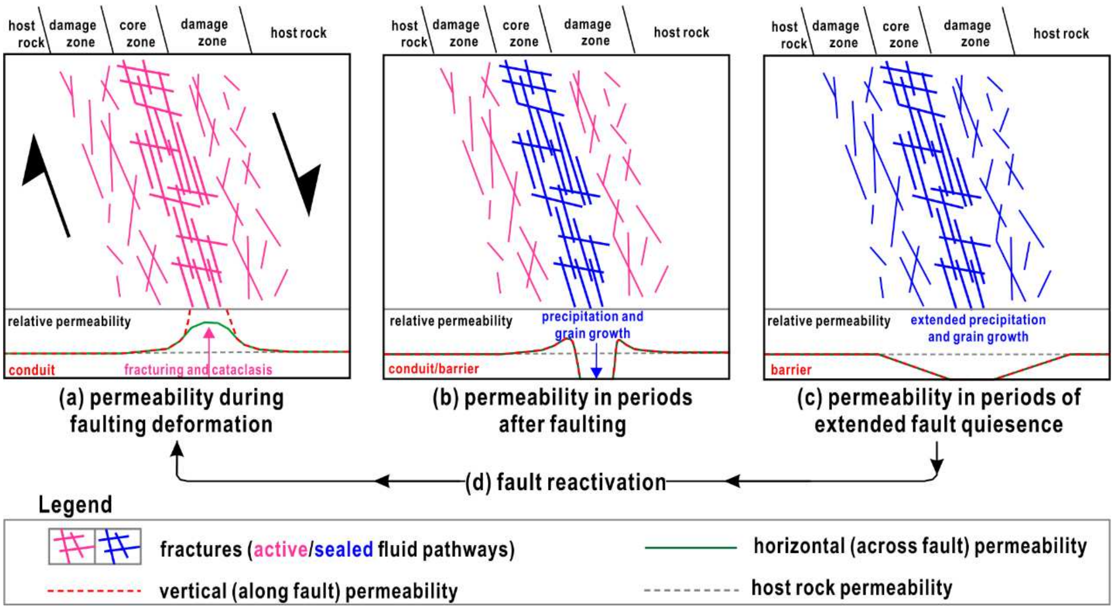

clay smears
+ PFFRs
clay smears, PFFRs
+pressure solution
clay smears, PFFRs,
pressure solution
+cataclasis
PFFRs
PFFRs, pressure
solution +/- cataclasis
disaggregation
cataclasis
cataclasis +
quartz cement
mudstones/shales
impure sandstones
clean sandstones
Clay/Phyllosilicate Content %
40
15
0
poorly lithified
lithified
3km+
Burial Depth (reflecting increasing effective stress & temperature)

Figure 16



host rock
damage zone
core zone
damage zone
host rock
relative permeability
conduit
fracturing and cataclasis
(a) permeability during faulting deformation
precipitation and grain growth
conduit/barrier
(b) permeability in periods after faulting
extended precipitation and grain growth
barrier
(c) permeability in periods of extended fault quiesence
(d) fault reactivation
Legend
fractures (active/sealed fluid pathways)
horizontal (across fault) permeability
vertical (along fault) permeability
host rock permeability

Table 1

fault seal classifications	methods	references
juxtaposition seals	Allan map	Allan (1989)
	triangle juxtaposition diagram	Knipe (1997)
	clay smear indices	Bouvier et. al., (1989)
		Fulljames et al., (1997)
		Lindsay et al., (1993)
		Yielding et al., (1997)
fault rock seals	micro-structural analysis	e.g., Knipe, (1992)
		Fisher and Knipe, (1998)
		Ottesen Ellevset et al., (1998)
	petrophysical assessment	Fisher and Knipe (2001)
		Tueckmantel et. al., (2010)