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], the fault rock development [Caine et al., 1996; Childs et al., 2009; Childs et al., 1996b; Walsh et al., 2003], the fault geometry [Fisher and Knipe, 1998; Jolley et al., 2007b; Knipe, 1989; Knipe et al., 1997; Tueckmantel et al., 2010], 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 \textcite{Fisher et al., 2003, Fossen et al., 2007, Jolley et al., 2007b} and the amount/rate of strain \textcite{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 \textcite{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 \textcite{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.

Several quantitative dynamic models have been presented (e.g., Egholm et al., 2008; Welch et al., 2009a; 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.

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.
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; 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. (a) Shows a single high-strain core surrounded by a fractured damage zone and (b) shows multiple cores model, where many strands of high-strain material enclose fractured lenses. 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 (e.g., 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 redistribution 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], 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]. 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 \cite{Fisher_and_Knipe_1998};

(ii). there is a higher potential for clay/phyllosilicate smearing within the sedimentary units with high clay/phyllosilicate contents \cite{Lindsay_et_al._1993}; and (iii). the existence of clay/phyllosilicate materials between framework-silicate grains promotes pressure solution and quartz cementation \cite{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 \cite{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 \cite{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 \cite{modified_from_Ottesen_Ellevset_et_al._1998}. 

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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. \cite{OttesenEllevsetEtAl1998} 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 \cite{Fig3}, 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 \cite{JolleyEtAl2007b, Knipe1997, KnipeEtAl1997, OttesenEllevsetEtAl1998}. In this situation, a continuous clay material zone with low-permeability along fault planes can be produced during the faulting deformation \cite{Fig5}. The factors controlling the clay/phyllosilicate smear continuity are the content and distribution of clay/phyllosilicate-rich units, fault throw \cite{BouvierEtAl1989, FulljamesEtAl1997, LindsayEtAl1993, YieldingEtAl1997}, and the lithification state \cite{EgholmEtAl2008, HeynekampEtAl1999, LovelessEtAl2011}. Based on the studies on the distribution of clay smears in Sleipner Vest of North Sea \cite{Knipe1997, OttesenEllevsetEtAl1998}, 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/phylllosilicate smears, containing >40% clay/phylllosilicate minerals. Clay smears can act as effective seals when continuous clay material zones are produced along fault planes during the faulting deformation.

5.3. Phylllosilicate-framework fault rocks (PFFRs)

As shown in the fault rock classification, phylllosilicate-framework fault rocks (PFFRs) contain 15-40% clay/phylllosilicate minerals. These can develop from impure sandstones containing 15-40% clay/phylllosilicate 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 phylllosilicates 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 (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 phylllosilicates.

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/phylllosilicate 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 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 \cite{Fulljames1997}. 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.

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

\cite{Lindsay1993} introduced Shale Smear Factor (SSF, \cite{fig11b}) 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.

\[
\text{SSF} = \frac{\text{Fault throw}}{\text{Shale layer thickness}}
\]

The Shale Gouge Ratio (SGR, \cite{fig11c}) was proposed \cite{Yielding1997}
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.

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

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

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

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.

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. For 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 [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°C.

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
defformation 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
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 Indrevaer 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., 1993; 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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**Figure 1**

- **Fault Zone Geometry**
- **Fracture Density**
- **Permeability**
Figure 2

A: mudstone
B: sandstone
C: mudstone
Figure 3

Fault Rock

- cemented
  - 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
Figure 5
Figure 6
Figure 7

cataclasites

cataclastic fault rock

grain size reduction
Figure 8
Figure 9
**Figure 11**

Clay Smear Potential

\[ \text{CSP} = \sum \frac{\text{thickness}^2}{\text{distance}} \]

Shale Smear Factor

\[ \text{SSF} = \frac{\text{throw}}{\text{thickness}} \]

Shale Gouge Ratio

\[ \text{SGR} = \frac{\sum \text{thickness}}{\text{throw}} \times 100\% \]

\[ \text{SGR} = \frac{\sum (\text{Vcl.} \, \Delta z)}{\text{throw}} \times 100\% \]
Figure 13

Rotliegendes fault rocks
cataclasites

Middle Jurassic fault rocks
- disaggregation zones
cataclasites
- phyllosilicate-framework fault rocks (PFFR)
clay smears
Figure 14
Figure 15

Clay/Phyllosilicate Content %

Burial Depth (reflecting increasing effective stress & temperature)
Figure 16

Legend

- Fractures (active/sealed fluid pathways)
- Horizontal (across fault) permeability
- Vertical (along fault) permeability
- Host rock permeability

(a) Permeability during faulting deformation
(b) Permeability in periods after faulting
(c) Permeability in periods of extended fault quiescence
(d) Fault reactivation
**Table 1**

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