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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 studied 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 recognised, 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 have significantly boosted the research of fault sealing behaviour. However, further research is still needed to increase the effectiveness of present fault seal analysis.

Contents

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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 microstructural 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., 1996b; Childs et al., 2009; 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 and Scholz, 1992; Cowie et al., 1993; Cowie et al., 1996; 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, have 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,b, 1994), Fisher and Knipe (1998, 2001), Fisher et al. (2003, 2009) and Jolley et al. (2007a,b) 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 (Fossen and Bale, 2007; Balsamo et al., 2010; Faulkner et al., 2010);
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; Tueckmantel et al., 2010; Fossen et al., 2011).

Although geologists have also realised 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 analyses has still focused on the fault zone architecture and fault seal analysis in siliciclastic reservoirs since the 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, methodologies 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 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., 1999; Walsh et al., 2003; 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