Integrated Fault Seal Analysis: An Introduction

STEVEN R. OGILVIE1*, STEVE J. DEE2, ROBERT W. WILSON2 & WAYNE R. BAILEY3

1Ogilvie Geoscience Ltd, Blenheim Place, Aberdeen, AB25 2DN, UK
2BP Exploration Ltd, Chertsey Road, Sunbury-on-Thames, Middlesex, TW16 7LN, UK
3Woodside Energy Ltd, Mia Yellagonga, Karlak, 11 Mount Street, Perth, WA 6000, Australia

*Correspondence: info@ogilviegeoscience.com

Abstract: Faults commonly trap and impact the flow of fluids such as hydrocarbons and water over a range of timescales and therefore are of economic significance. During hydrocarbon exploration, analysis of the sealing capacity of faults can impact both the assessment of the probability of finding hydrocarbons and also the estimate of the likely resource range. During hydrocarbon field development, smaller faults can provide seals, baffles and/or conduits to flow. There are relatively simple, well-established workflows to carry out a fault seal analysis for siliciclastic rocks based primarily on clay content. There are, however, outstanding challenges related to other rock types, to calibrating fault seal models (with static and dynamic data) and to handling uncertainty. The variety of studies presented here demonstrate the types of data required and workflows followed in today’s environment in order to understand the uncertainties, risks and upsides associated with fault-related fluid flow. These studies span all parts of the hydrocarbon value chain from exploration to production but are also of relevance for other industries such as radioactive waste and CO2 containment.

Faults commonly trap fluids such as hydrocarbons and water and therefore are of economic significance. In the hydrocarbon industry, faults can bound two- or three-way closures which pose riskier exploration prospects than the simpler four-way closures owing to the inherent uncertainties associated with predicting fault seal and column heights. Juxtaposition seal (Fig. 1), where the reservoir is completely set against non-reservoir (such as mudrock – grey colored unit in Fig. 1) across a fault can, at cursory assessment, be a relatively clear-cut case of fault seal, often resulting in pressure and fluid contact differences (e.g. Watts 1987; Yielding et al. 2010). Complications, however, commonly arise from natural geological uncertainty (e.g. spatial variability of the thickness and quality of reservoir and seal units) and mapping (e.g. well calibration, seismic imaging, velocity modelling; Fig. 1b), introducing the chance of across-fault leakage.

Well-established, published algorithms provide a means to estimate fault seal capacity based on the assessment of fault displacement and shale/clay content of the faulted intervals to calculate fault rock shale/clay content (e.g. shale gouge ratio, SGR, Yielding et al. 1997; clay smear potential, CSP, Bouvier et al. 1989). This in turn can be converted into capillary threshold pressures (Smith 1966; Schowalter 1981) that the fault rock could support (Yielding et al. 2010). However, even in these scenarios, the industry remains divided in its assessment that the fault can form a seal over a geological timescale based on the inherent subsurface uncertainty.

Once a field has been discovered, smaller faults can either hinder communication (Hardman & Booth 1991; e.g. between a producer and a supporting injector) or enhance production (e.g. connect stratigraphically offset flow units, or connect to an aquifer to maintain pressure support). In baffling scenarios, fault throw can be less than reservoir thickness, but the content of the fault rock (Fig. 1c, d) itself can create permeability barriers. Conversely, faults are characteristically segmented at a range of scales with relay zones (Fig. 1b) that can allow or retard communication. The key fault properties that need to be considered during a production simulation case are permeability and thickness (Manzocchi et al. 1999). Estimates of fault rock permeability are founded on the same algorithms to estimate fault rock shale/clay content as for exploration-focused seals.

From: OGILVIE, S. R., DEE, S. J., WILSON, R. W. & BAILEY, W. R. (eds) 2020. Integrated Fault Seal Analysis. Geological Society, London, Special Publications, 496, 1–8.

First published online May 7, 2020, https://doi.org/10.1144/SP496-2020-51

© 2020 The Author(s). This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/). Published by The Geological Society of London.

Publishing disclaimer: www.geolsoc.org.uk/pub_ethics
(a) Fault / Trap Geometry

Faulted (compartmentalized) Anticline Trap

Simple Anticline Trap

Fault Seal Type

Geometric/ Juxtaposition Seals
1. Juxtaposition Seal

Fault rock Seals
2. Membrane/ Cataclasis seal
   (Self-Juxtaposition)
3. Shale/ Clay Smear

Fault Seal Process

(b) Fault Zone Architecture

Seismic resolution
Breached relay/ Fault Lens
Singly-breached relay
Intact/ unbreached relay

Outcrop resolution
Fault rock
Normal drag zone
Damage zone

After Manzocchi et al. (2008)

(c) Fault Seal Type

Cataclasis

Shale/ Clay Smear

Geometric/ Juxtaposition Seals
1. Juxtaposition Seal

Fault rock Seals
2. Membrane/ Cataclasis seal
   (Self-Juxtaposition)
3. Shale/ Clay Smear

(d) Fault Seal Process

Mature Sst
Immature Sst

After Gibson (1998)
As the previous paragraphs allude to, the wealth of knowledge that the industry has accumulated pertains mainly to siliciclastic depositional systems, and this has dominantly focused on well-explored extensional rift and passive margin settings. Significant uncertainty remains in different reservoir types (e.g. carbonates, basement, unconventional) and in different tectonic settings (e.g. neo-tectonic, strike-slip).

Characterizing the fluid-flow properties of faults is often seen as a specialist subject, requiring dedicated software, and is often overlooked. However, most aspects of fault-seal analysis draw upon the skills of an integrated geoscientist who can utilize all available data and assess uncertainty in both input data and interpretation. 3D modelling packages allow for the integration of seismic, well and core data. This, for example, allows core-scale structures to be quickly related to seismically resolvable faults and decisions to be efficiently made.

The contributions in this volume, either individually or in combination, showcase the integrated nature of a fault seal study in today’s environment in order to understand the uncertainties, risks and upsides associated with fault-related fluid flow. We start by highlighting the relatively simple and well-established workflows (i.e. juxtaposition analysis, shale gouge calculations) that a geoscientist should follow that help characterize fault seal potential. There are of course certain outstanding challenges related to geological setting (i.e. non-clastic lithologies, burial depth/diagenesis, neo-tectonics), fault geometries and the intrinsic properties of fault rocks (e.g. in clay-free sandstones), which remain part of a future direction. Also, fault seal models need to be ground truthed against fluid chemistry, pressure and field production data. Unfortunately, such studies are quite rare in the literature but our case histories integrate dynamic data as well as in-situ stress data (requirement from the summary section of Knipe et al. 1998). During editing this volume, we became acutely aware that complete and detailed analyses of fault seal, for example those that contain juxtaposition fault maps (Allan diagrams; Allan 1989) and/or description of uncertainty and alternative scenarios, are not common. This may be due in part to confidentiality constraints intrinsic to our business, but is also likely to be due to a cultural bias and the desire to provide a concise answer. Predicting the fault seal potential is also of considerable value to other industries such as radioactive waste containment, CO₂ storage (e.g. Miocic et al. 2014) and the water industry.

**Fault seal processes and workflows**

Juxtaposition or Allan (after Allan 1989) diagrams are used to show the various juxtaposition relationships and leak points that exist across a fault or fault zone (e.g. Bouvier et al. 1989; Clarke et al. 2005). These should be accompanied by relevant maps (depth, seismic attributes etc.), seismic sections (showing spill points, depth contours, structural crest, leak points, etc.), well correlation panels (showing clay and mineral content) and calibration data such as pressures (v. depth).

Fault rock clay content has been correlated with seal capacity and inversely correlated with permeability (e.g. Yielding et al. 2010). Therefore, the result of algorithms that estimate fault rock petrophysical properties are often plotted on Allan diagrams and used to assess the fault sealing potential. These algorithms are all based on the same premise: that the higher the clay content of the faulted sequence is, the higher the clay content of the fault rock and its chance and capacity to seal, either by ‘smearing’ of host mudrocks into the fault rock (Shale Smear Factor, SSF, Lindsay et al. 1993) or by mixing of the host rock into the fault rock (SGR,

---

**Fig. 1.** Fault seal summary montage. (a) Fault/trap geometry: examples of how faults impact trap geometry. Upper – simple anticline trap v. a faulted (compartmentalized) anticline trap with seismic example of a fold above a salt structure in the southern North Sea (source: Simon Stewart, Virtual Seismic Atlas, https://www.seismicatlas.org/); lower – footwall and hanging-wall trap showing top seal, structural spill point, fault seal and base seal, with seismic example from the Moray Firth, UK (source: Robert Butler, Virtual Seismic Atlas, https://www.seismicatlas.org/). (b) Fault zone architecture: a comparison of seismic resolution v. outcrop resolution showing a more detailed sub-seismic fault architecture. Schematic cartoons of fault zone complexity, including relay ramp development through to breached relays, and multiple slip surfaces scenarios which could impact communication across the fault zone; modified from Manzocchi et al. (2008). (c) Fault seal type: showing the difference between juxtaposition and fault rock seals and examples of fault rock processes (cataclasite and shale/clay smear). (d) Fault seal process (in a mature quartzose sandstone and an immature sandstone) illustrated along a single fault plane – schematic modified from Gibson (1998). Shale smear developed at A–B, creating a spill point at B. Unlikely to be a spill point at C (B–C illustrated by outcrop example from Hopeman Sandstone, Inner Moray Firth, UK) as the deformation bands present at this sand-on-sand contact will not have significantly reduced pore throats compared with the host rock. In the lower trap, (immature sandstones), the spill point can be deeper (D–E, illustrated by outcrop example in deltaic sandstones from Kirkmaky, Baku, Azerbaijan) as the clay content of the sandstone itself can be mixed into the fault rock by the clay-mixing processes. The C–D portion of the fault is sealed by clay smear owing to intra-beds being present but the D–E portion across immature, clay rich sandstones is sealed by clay mixing processes.
Yielding et al. 1997) or a combination of both (CSP, Bouvier et al. 1989; effective shale gouge ratio, Knipe et al. 2004). It currently appears that SGR is the most often used algorithm applied to exploration and production challenges. Pressure data is needed to calibrate a fault seal model if it is to be used to justify future wells. To this end, SGR has been plotted against buoyancy pressure to demonstrate the higher sealing capacity of fault rocks with higher shale/clay content (Yielding et al. 2010).

In summary, regardless of which methods are favoured by different companies, well-established, essentiality deterministic workflows exist in the industry revolving around juxtaposition analysis, shale gouge calculations and shale/clay smear calculations. However, key challenges remain outside of these core topics, namely:

- seals in low clay content host rocks (van Ojik et al. 2019);
- non-clastic rocks: carbonates; Ferrill et al. 2019; Nogueira Kiewiet et al. 2019) and geo-history (e.g. burial depth, diagenesis, kinematic history);
- the impact of stress (including neotectonics) on seal/conductivity (Ferrill et al. 2019);
- sub-resolution fault segmentation (relays, damage zones; Shipton et al. 2019; Torabi et al. 2019);
- uncertainty analysis (Grant 2019; Knai & Lescoffit 2020; Murray et al. 2019);
- potential for integrated studies (e.g. Bretan et al. 2019; Osmond & Meckel 2019; Wilkins et al. 2019).

Non-clastic rocks: carbonates
Most of the historical focus in carbonate rocks has been upon the distribution of natural fractures that provide permeability, but recent focus has been upon fault-sealing mechanisms (e.g. Billi et al. 2003; Wennberg et al. 2013; Piane et al. 2017). Nogueira Kiewiet et al. (2019) employ a three-pronged approach in order to characterize the sealing potential of faults in carbonate rocks: (1) direct shear experiments; (2) triaxial experiments to simulate fault reactivation; and (3) the use of smooth particle hydrodynamic models to reproduce the direct shear experiments. They conclude that the sealing capacity of faults in carbonates increases with the amount of slip irrespective of the numerous scenarios tested. The ability of a fault to reactivate is generally considered to depend upon its orientation with respect to the current in-situ stresses and the magnitude of these stresses.

Low clay-content host rocks
Often, faults which juxtapose high-porosity, relatively clay-free (e.g. aeolian) sandstones (e.g. Edwards et al. 1993) create barriers to fluid flow and support different fluid contacts and pressure differentials (e.g. Leveille et al. 1997). The clay content algorithms and tools discussed above cannot be used to predict fault seal potential in these sandstones. Examples are the cataclastic deformation bands studied by Underhill & Woodcock (1987) in high-porosity (Permian) sandstones (Arran, Scotland; cover photograph) and in the relatively clay-free Entrada and Navajo Sandstones of Utah (Aydin 1978). Instead, reliance is placed upon an understanding of the geo-history of the faulted reservoir, in particular, the petrophysical properties of the fault rock, burial depths at the time of faulting and the temperature-experienced post-faulting (classification of Fisher & Knipe 1998; Knai & Lescoffit 2020). For example, the mechanical reduction of grain size (and porosity and permeability) is more likely with increasing confining pressures at depth.

Stress
Ferrill et al. (2019) use established dilation tendency and slip tendency calculations and link them to observations at outcrop to understand past, present and future behaviour of faults and fractures in terms of deformation mode and fluid conductivity. They employ these techniques on mapped outcrop faults in Texas (Canyon Lake Gorge, at Pinto Creek and in the Big Bend National park) to assess past stress history and promote their use to evaluate the fault-sealing potential of faults in modern in-situ stress fields. They point out that different deformation styles can occur along the same fault, which has a large effect upon the ability of the fault to act as a conduit or barrier along and across the fault.

Fault zone architecture and outcrop studies
Outcrops provide the ideal opportunity to study the various fault geometries which are important in fault seal analysis and may not be observed at
seismic, core or log scale (Fig. 1b). For example, relay ramps (Fig. 1b) can provide communication pathways between fault segments (Manzocchi et al. 2017). A reservoir simulation model would predict quite a different result if the segments were considered to be a continuous fault (either mapped on seismic or the resolution of the model, e.g. cell size). Similarly, near-fault folding (e.g. ‘fault drag’) below or close to seismic and simulation grid resolution can impact communication paths across a fault (Hesthammer & Fossen 2000). This relationship may be neglected in a fault framework model when using tolerance limits to ignore seismic data close to faults, again resulting in a different dynamic prediction. There are currently no widely accepted routines to assess this uncertainty in reservoir/simulation models, yet the impact can be significant, e.g. pressure support (injector-producer communication, aquifer support), water breakthrough and compartment sizes.

Faults are associated with sub-seismic deformation (Fig. 1b) immediately adjacent to the fault (e.g. ‘damage zone’ geometries (Caine et al. 1996), normal drag, splay, segmentation), which needs to be considered during a fault study as it will be critical to the dynamic behaviour of the fault zone. However, caution should be exercised when attempting to predict the extent of this deformation from fault displacement: this could result in negative (i.e. ‘damage’) and positive (communication resulting from segmentation) outcomes. Torabi et al. (2019) collected structural data from scanlines across damage zones in three different geological environments: siliciclastics in Utah (USA), carbonates (Majella Mountain, Italy) and metamorphic rocks (western Norway). They were able to constrain damage zone width by identifying the changes in the slope of cumulative plots from frequency data. They show a stepwise power law relationship between damage zone width and displacement.

Some confusion comes from the description of what constitutes the region of associated fractures around a fault or compound zone of deformation bands, i.e. damage zones v. fault zones. Shipton et al. (2019) addresses the key biases that need to be considered when building predictive models of fault architecture. They provide a very useful inventory of the commonly used terminology and the various ambiguities that affect our understanding of the relationship between fault width and displacement. For example, multiple slip surfaces have been interpreted on seismic data bound fault zones (Childs et al. 2009), whereas the fault zones described by Beach et al. (1997) and Knott et al. (1996) are regions of discrete damage around single faults. Given the sub-seismic fault zone complexity, there remains no consensus on how we handle this in a seismic-to-simulation workflow. However, we recommend that at least a consistent terminology is used internally within organizations.

**Modelling approaches and handling uncertainty**

In the authors’ view, a description of subsurface uncertainty is a frequent omission in fault seal analysis publications. The reasons for this are varied (e.g. an industry-wide cultural bias to provide precision and a ‘prediction’, and/or to be concise for publication and/or a need for confidentiality). Further, we note that Allan diagrams (with or without a description of the intrinsic uncertainties associated with seismic data, mapping, stratigraphic variability, rock quality variations, etc.) are a frequent omission in fault seal publications. Murray et al. (2019) outline an approach to handling stratigraphic and structural uncertainty in estimating hydrocarbon column height. In analysing 96 accumulations from 42 fields using their method, the authors concluded that primary juxtaposition alone, without additional contribution of fault rock membrane sealing, most closely predicts hydrocarbon columns. In exploration workflows that use fault rock seal predicting algorithms (such as SGR) the conclusion implies that there may be a systematic bias overpredicting potential column heights. Grant (2019) takes a stochastic modelling approach to handle the complexity of composition of fault rocks. In this approach, a stochastic model of the fault core gouge zone is used to illustrate how variable distribution for fault rock leads to differing seal predictions. Compositional controls on seal potential using this technique are referenced to a case study and compared with other prediction algorithms. A key issue in both Murray et al. (2019) and Grant (2019) is the probability of the continuity of a sealing fault rock (cf. ‘smear’) and the location of resulting leak points along the fault plane (Noorsalehi–Garakani et al. 2013; Vrolijk et al. 2016), particularly in 3D.

Often, reservoir simulators use fault transmissibility multipliers to represent faults during conventional production simulation (Manzocchi et al. 1999), although enhanced fault representations are possible, but not common practice (Ziljstra et al. 2007). Also, it is usually an oversimplification to represent faults as single entities in models as the fault zone usually has more than one slip surface (Childs et al. 2009). Knai & Lescoffit (2020) present an alternative method to generate fault transmissibility multipliers using a matrix or juxtaposition table. It provides a straightforward communication tool with reservoir engineers, allowing geologists to be more easily involved at all stages in the transmissibility multiplier tuning process, handling...
uncertainty and providing an efficient route to history matching.

**Integrated studies**

*Bretan et al. (2019)* compliment footwall trap data-sets with a knowledge database of fault rock properties in hanging-wall traps that are dependent on fault rock seal. Hydrocarbon columns supported by process seals are typically less than 190 m over a range of burial depths whereas those supported by juxtaposition seals can exceed 600 m. The contribution contains cross-plots of buoyancy pressure and SGR, which have a similar data distribution to published calibration plots (e.g. *Yielding et al. 2010*). This is a very useful addition to the global calibration database, enabling evaluation of the sealing potential of hanging-wall traps in the same manner as for footwall traps.

*Wilkins et al. (2019)* use a wide range of static (e.g. core, CT images) and dynamic data (including well tests) to characterize the petrophysical and flow properties of fold-related deformation bands in poorly lithified turbidite sandstones from the Holstein Field in the Gulf of Mexico. These cataclastic deformation bands have only experienced a 1 order magnitude reduction in permeability relative to their host sandstones (shallower burial depths to those reported by *van Oijik et al. 2019*). Deformation band presence does, however, explain the lower than expected well test permeabilities, but it is difficult to explain the apparent mismatch between effective permeabilities calculated from core data and those from well tests.

*Osmond & Meckel (2019)* demonstrate the value of a combined fault seal analyses in the reservoir and the overburden rocks. Traditional fault seal studies of reservoirs in the San Luis Pass area of the Texas inner Shelf suggested sizeable trapped volumes. However, a parallel study of high-definition seismic in the overburden and the results from wildcat wells did not validate this data. They stress the importance of studying high-definition overburden data (in addition to conventional 3D) for reservoir fault seal analysis and for improved interpretation of geological history with application in hydrocarbon prospectivity and CO₂ storage.

**Future trends in fault seal analysis**

Faults that were once a hindrance to reaching (risk of wellbore instability, etc.; Ogilvie et al. 2015) deeper reservoir targets, could, in some geological settings, themselves become targets for production (fractures around faults) and be an integral part of a field deple- tion plan. This will probably coincide with an increasing focus upon unconventional reservoirs (e.g. the faulted, oil-bearing mudstones in the overburden section of the Valhall Field, Central North Sea studied by *Bradley et al. 2019*). Fault seal studies will require close integration with geomechanical studies in these types of reservoirs. It is also expected that the ability of downhole logs to compute rock (and fault) properties will improve in the future. In fact, advances in logging while drilling technology over the last 15 years or so have meant that time (and money) does not need to be spent on wireline and pipe conveyance. Also, decommissioning and abandonment are likely to be focus areas for fault seal analysis in mature basins such as the North Sea, Gulf of Mexico, etc. Operating companies are likely to be interested in whether or not faults that breach cap rocks are likely to be potential pathways for hydrocarbons to the surface. This could impact the overall well abandonment philosophy.

Whether or not a fault forms a seal, baffle or conduit has considerable application to the exploration and production of fluids such as oil, gas and water. Already, the subject is gaining traction in unconventional hydrocarbon reservoirs and in other industries such as radioactive waste and CO₂ containment. However, fault seal analysis is not necessarily the preserve of specialists. Our objective in this volume is to make the subject accessible to all geoscientists, engineers and practitioners with a vested interest in fault seal mechanisms. We do this by presenting a set of integrated studies to demonstrate the types of data required and workflows followed in today’s economic environment.

**Acknowledgements** The authors wish to acknowledge the generous financial support provided in association with this volume to the Geological Society and the Petroleum Group by Saudi Aramco, Badley Geoscience Ltd, Midland Valley Ltd (now part of Petroleum Experts Ltd), BP and Statoil (now Equinor). We are also very grateful for the help and support provided by the team at the geological society and it’s publishing house.

**Funding** This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

**Author contributions** SRO: visualization (equal), writing – original draft (lead), writing – review & editing (lead); SJD: writing – original draft (equal), writing – review & editing (equal); WWW: visualization (equal), writing – original draft (equal), writing – review & editing (equal); WRB: writing – original draft (equal), writing – review & editing (equal).
INTEGRATED FAULT SEAL ANALYSIS: AN INTRODUCTION

Correction notice: The original version was incorrect. There was an error in the author name for R. W. Wilson. The author names for van Oijk and Nogueira Kiewiet in the references have been corrected.

References

Allan, U.S. 1989. Model for hydrocarbon migration and entrapment within faulted structures. AAPG Bulletin, 73, 803–811, https://doi.org/10.1306/44B4A271-170A-11D7-86450000102C1865D

Aydin, A. 1978. Small faults formed as deformation bands in sandstone. Pure and Applied Geophysics, 116, 913–930, https://doi.org/10.1007/BF00876546

Beach, A., Brown, J.L., Welbon, A.I., McCallum, J.E., Brockbank, P., & Knott, S. 1997. Characteristics of fault zones in sandstones from NW England: application to fault transmissibility. Geological Society, London, Special Publications, 124, 315–324, https://doi.org/10.1144/GSL.SP.1997.124.01.19

Belli, A., Salvini, F., & Storti, F. 2003. The damage zone-fault core transition in carbonate rocks: implications for fault growth, structure and permeability. Journal of Structural Geology, 25, 1779–1794, https://doi.org/10.1016/S0191-8141(03)00037-3

Bouvier, J.D., Kaars-Sippestein, C.H., Kluesner, D.F., Onyejeke, C.C. & Van der Pal, R.C. 1989. Three-dimensional seismic interpretation and fault sealing investigations, Nun River field, Nigeria. AAPG Bulletin, 73, 1397–1414, https://doi.org/10.1306/44B4A4A5-170A-11D7-86450000102C1865D

Bradley, T., Field, P.H., Scott, J. & Ogilvie, S. 2019. Overcoming core challenges in a new unconventional play offshore by integration of formation evaluation data. SPE 195866, SPE Annual Technical Conference and Exhibition, Calgary, Alberta, Canada, 30 September to 2 October 2019, 13, https://doi.org/10.2118/195866-MS

Brietan, P., Yielding, G. & Jones, H. 2003. Using calibrated shale gas ratio to estimate column heights. AAPG Bulletin, 87, 397–413, https://doi.org/10.1306/08010201128

Brietan, P.G., Yielding, G. & Sverdrup, E. 2019. A knowledge database of hanging wall traps that are dependent on fault seal. Geological Society, London, Special Publications, 496, https://doi.org/10.1144/GSPP2018-157

Cane, J.S., Evans, J.P. & Forster, C.B. 1996. Fault zone architecture and permeability structure. Geology, 24, 1025–1028, https://doi.org/10.1130/0091-7613(1996)24<1025:TAMPS>2.3.CO;2

Childs, C., Manzocchi, T., Walsh, J.J., Bosson, C.G., Nicol, A. & Schofer, M.P.J. 2009. A geometric model of fault zone and fault rock thickness variations. Journal of Structural Geology, 31, 117–127, https://doi.org/10.1016/j.jsg.2008.08.009

Clarke, S.M., Burley, S.D. & Williams, G.D. 2005. A three-dimensional approach to fault seal analysis: fault-block juxtaposition and argillaceous smear modeling. Basin Research, 17, 269–288, https://doi.org/10.1111/j.1365-2117.2005.00263.x

Edwards, H.E., Becker, A.D. & Howell, J.A. 1993. compartmentalization of an aeolian sandstone by structural heterogeneities: Permo-Triassic Hopeman Sandstone, Moray Firth, Scotland. Geological Society, London, Special Publications, 73, 339–365, https://doi.org/10.1144/GSL.SP.1993.073.01.20

Ferrill, D.A., Smart, K.J. & Morris, A.P. 2019. Fault failure modes, deformation mechanisms, dilation tendency, slip tendency, and conduits v. seals. Geological Society, London, Special Publications, 496, https://doi.org/10.1144/SP496-2019-7

Fisher, Q.J. & Knipe, R.J. 1998. Fault sealing processes in siliciclastic sediments. Geological Society, London, Special Publications, 147, 117–135, https://doi.org/10.1144/GSL.SP.1998.147.01.08

Gibson, R.G. 1998. Physical character and fluid flow properties of sandstone derived fault zones. Geological Society, London, Special Publications, 127, 83–97, https://doi.org/10.1144/GSL.SP.1998.127.01.07

Grant, N.T. 2019. Stochastic modelling of fault gouge zones: implications for fault seal analysis. Geological Society, London, Special Publications, 496, https://doi.org/10.1144/SP496-2018-135

Hardman, R.F.P. & Booth, J.E. 1991. The significance of normal faults in the exploration and production of North Sea hydrocarbons. Geological Society, London, Special Publications, 56, 1–13, https://doi.org/10.1144/GSL.SP.1991.056.01.01

Hesthammer, J. & Fosseen, H. 2000. Uncertainties associated with fault sealing analysis. Petroleum Geoscience, 6, 37–45, https://doi.org/10.1144/pegeo.6.1.37

Kna, T.A. & Lescoffit, G. 2020. Efficient handling of fault properties using the Juxtaposition Table Method. Geological Society, London, Special Publications, 496, https://doi.org/10.1144/SP496-2018-192

Knipe, R.J., Jones, G. & Fisher, Q.J. 1998. Faulting, fault sealing and fluid flow in hydrocarbon reservoirs: an introduction. Geological Society, London, Special Publications, 147, vii–xxi, https://doi.org/10.1144/GSL.SP.1998.147.01.01

Knipe, R.J., Freeman, S., Harris, S.D. & Davies, R.K. 2004. Structural uncertainty and scenario modelling for fault seal analysis. Proceedings of the AAPG Annual Convention Abstracts, Dallas, TX, 18–21 April, 13, A77.

Knott, S.D., Beach, A., Brockbank, P.J., Brown, J.L., McCallum, J.E. & Welbon, A.I. 1996. Spatial and mechanical controls on normal fault populations. Journal of Structural Geology, 18, 359–372, https://doi.org/10.1016/S0191-8141(96)80056-3

Leveille, G.P., Knipe, R. et al. 1997. Compartmentalisation of Rotliegendes gas reservoirs by sealing faults, Jupiter Fields area, southern North Sea. Geological Society, London, Special Publications, 123, 87–104, https://doi.org/10.1144/GSL.SP.1997.123.01.06

Lindsay, N.G., Murray, F.C., Walsh, J.J. & Watterson, J. 1993. Outcrop studies of shale smears on fault surfaces. In: Flint, S.S. & Bryant, I.D. (eds) The Geological Modelling of Hydrocarbon Reservoirs and Outcrop Analogues. International Association of Sedimentologists, Special Publications, 15, 113–123, https://doi.org/10.1144/9781444303957.ch6

Manzocchi, T., Walsh, J.J., Bell, P. & Yielding, G. 1999. Fault transmissibility multipliers for flow simulation models. Petroleum Geoscience, 5, 53–63, https://doi.org/10.1144/pegeo.5.1.53
MANZOCCHI, T., HEATH, A.E., PALANANTHAKUMAR, B., CHILDS, C. & WALSH, J.J. 2008. Faults in conventional flow simulation models: a consideration of representational assumptions and geological uncertainties. *Petroleum Geoscience*, **14**, 91–110, https://doi.org/10.1144/1354-079306-775

MANZOCCHI, T., CHILDS, C., ISLAM, M.S., TELLES, I. & HEATH, A.E. 2017. Representation of small-scale fault partitioning in reservoir modelling. In: *Handling Fault Seals, Baffles, Barriers and Conduits: Cost Effective and Integrated Fault Seal Analysis*, 15–17 November 2017. *Geological Society, London* (abstract).

MOCC, J.M., JOHNSON, G. & GLEIFLAN, S.M.V. 2014. Fault seal analysis of a natural CO₂ reservoir in the Southern North Sea. *Energy Procedia*, **63**, 3364–3370, https://doi.org/10.1016/j.egypro.2014.11.365

MURRAY, T.A., POWER, W.L., JOHNSON, T.J., CHRISTIE, G.J. & RICHARDS, D.R. 2019. Validation and analysis procedures for juxtaposition and membrane fault seals in oil and gas exploration. *Geological Society, London, Special Publications*, **496**, https://doi.org/10.1144/SP496-2018-171

NOGUERA KIEWET, M., LIMA, C. ET AL. 2019. An experimental and numerical investigation of the hydromechanical behavior of carbonate fault zones upon reactivation: the impact of carbonate mud sealing layers and overall research outcomes. *Geological Society, London, Special Publications*, **496**, https://doi.org/10.1144/SP496-2018-153

NOORSALEHI-GARAKANI, S., KLEIN VENNEKATE, G.J., VROLIK, P. & URI, J.L. 2013. Clay-smear continuity and normal fault zone geometry – first results from excavated sandbox models. *Journal of Structural Geology*, **57**, 58–80, https://doi.org/10.1016/j.jsg.2013.09.008

OGILVIE, S.R., BARE, D., ROYLANCE, P. & DORLING, M. 2015. Structural geology and well planning in the Clair Field. In: *Geological Society, London, Special Publications*, **421**, 197–212, https://doi.org/10.1144/SP421.7

OSMOND, J.L. & MECKEL, T.A. 2019. Enhancing trap and fault seal analysis by integrating observations from HR3D seismic data with well logs and conventional 3D seismic data, Texas inner shelf. *Geological Society, London, Special Publications*, **496**, https://doi.org/10.1144/SP496-2018-142

PIANE, C.D., BEN CLENNELL, M., KELLER, J.V.A., GIWELL, A. & LUIZIN, V. 2017. Carbonate hosted fault rocks: a review of structural and microstructural characteristic with implications for seisimicity in the upper crust. *Journal of Structural Geology*, **103**, 17–36, https://doi.org/10.1016/j.jsg.2017.09.003

SCHOWALTER, T.T. 1981. Prediction of caprock seal capacity. *AAPG*, **65**, 987–988

SHIPTON, Z.K., ROBERTS, J.J., COMBRE, E.L., KREMER, Y., LUNN, R.J. & CAIN, J.S. 2019. Fault frictions: systematic biases in the conceptualization of fault zone architecture. *Geological Society, London, Special Publications*, **496**, https://doi.org/10.1144/SP496-2018-161

SMITH, D.A. 1966. Theoretical consideration of sealing and non-sealing faults. *American Association of Petroleum Geologists Bulletin*, **50**, 363–374, https://doi.org/10.1306/5D25B48F-16C1-11D7-8645000102C1865D

SPERREVIK, S., GILLESPIE, P.A., FISHER, Q.J., HALVORSEN, T. & KNIFE, R.J. 2002. Empirical estimation of fault rock properties. *Norwegian Petroleum Society, Special Publications*, **11**, 109–125, https://doi.org/10.1016/S0928-8937(02)80010-8

TAKABI, A., ELLINGSEN, T.S.S., JOHANENSEN, M.U., ALAEI, B., ROHETAT, A. & CHARELLA, D. 2010. Fault zone architecture and its scaling laws: where does the damage zone start and stop? *Geological Society, London, Special Publications*, **496**, https://doi.org/10.1144/SP496-2018-151

UNDERHILL, J.R. & WOODCOCK, N.H. 1987. Faulting mechanisms in high-porosity sandstones; New Red Sandstone, Arran, Scotland. *Geological Society, London, Special Publications*, **29**, 91–105, https://sp.lyellcollection.org/content/29/1/91

VEN OJIK, K., SILVIUS, A., KREMER, Y. & SHIPTON, Z.K. 2019. Fault seal behavior in Permian Rotliegend reservoir sequences: case studies from the Dutch Southern North Sea. *Geological Society, London, Special Publications*, **496**, https://doi.org/10.1144/SP496-2018-189

VROLIK, P.J., URI, J.L. & KETTERMAN, M. 2016. Clay smear review: mechanisms and applications. *Journal of Structural Geology*, **86**, 95–152, https://doi.org/10.1016/j.jsg.2015.09.006

WATT, N.L. 1987. Theoretical aspects of cap-rock and fault seals for single and two-phase hydrocarbon columns. *Marine and Petroleum Geology*, **4**, 274–307, https://doi.org/10.1016/0264-8172(87)90008-0

WENNBerg, O.P., CASINI, G., JAHANPANAH, A., LAPponI, F., INESON, J., WALL, B.G. & GILLESPIE, P. 2013. Deformation bands in chalk, examples from the Shetland Group of the Oseberg field, North Sea, Norway. *Journal of Structural Geology*, **56**, 103–117, https://doi.org/10.1016/j.jsg.2013.09.005

WILKINS, S.J., DAVIES, R.K. & NARUK, S.J. 2019. Subsurface observations of deformation bands and their impact on hydrocarbon production within the Holstein Field, Gulf of Mexico, USA. *Geological Society, London, Special Publications*, **496**, https://doi.org/10.1144/SP496-2018-139

YIELDING, G., FREEMAN, B. & NEEDHAM, T. 1997. Quantitative fault seal prediction. *AAPG Bulletin*, **81**, 897–917, https://doi.org/10.1306/522B498D-1727-11D7-8645000102C1865D

YIELDING, G., BRETT, P. & FREEMAN, B. 2010. Fault Seal Calibration: a brief review. *Geological Society, London, Special Publications*, **347**, 243–255, https://doi.org/10.1144/SP347.14

ZIJLSTRA, E.B., REEMST, P.H.M. & 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, https://doi.org/10.1144/SP292.17