Integrated Fault Seal Analysis: An Introduction

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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 CO_2 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.

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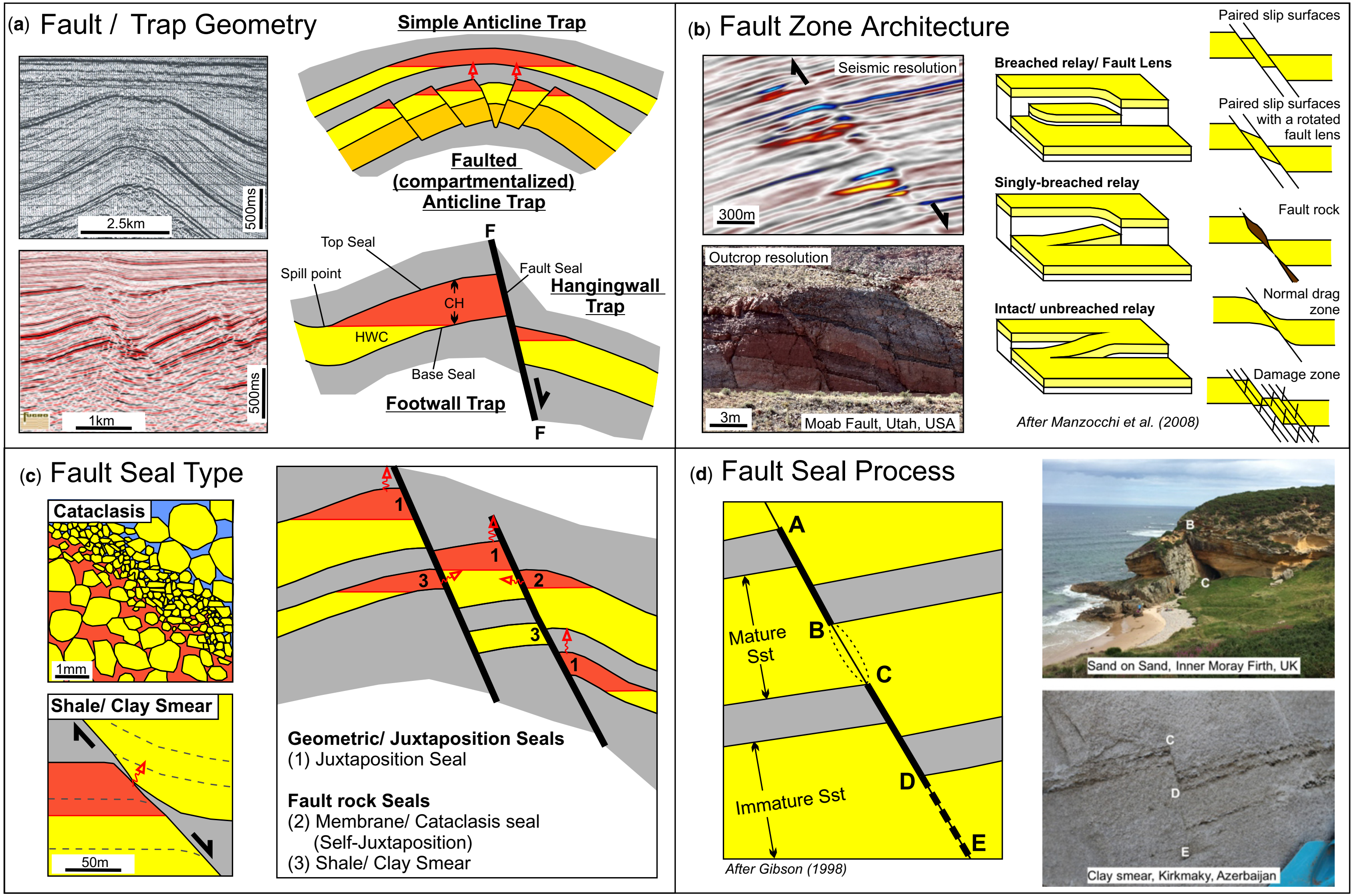
(a) Fault / Trap Geometry
Simple Anticline Trap
2.5km
500ms
1km
500ms
Faulted (compartmentalized) Anticline Trap
Top Seal
Spill point
CH
HWC
Base Seal
Fault Seal
Hangingwall Trap
Footwall Trap
F
F
(b) Fault Zone Architecture
Seismic resolution
300m
Outcrop resolution
3m
Moab Fault, Utah, USA
Breached relay/ Fault Lens
Singly-breached relay
Intact/ unbreached relay
After Manzocchi et al. (2008)
Paired slip surfaces
Paired slip surfaces with a rotated fault lens
Fault rock
Normal drag zone
Damage zone
(c) Fault Seal Type
Cataclasis
1mm
Shale/ Clay Smear
50m
1
1
2
3
3
1
Geometric/ Juxtaposition Seals
(1) Juxtaposition Seal
Fault rock Seals
(2) Membrane/ Cataclasis seal (Self-Juxtaposition)
(3) Shale/ Clay Smear
(d) Fault Seal Process
A
B
C
D
E
Mature Sst
Immature Sst
After Gibson (1998)
B
C
Sand on Sand, Inner Moray Firth, UK
C
D
E
Clay smear, Kirkmaky, Azerbaijan

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, CO_2 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 (cataclasis 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 (e.g. 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**).

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.

van Ojik *et al.* (2019) test the ability of existing empirical SGR functions (Sperrevik *et al.* 2002; Bretan *et al.* 2003; based on data from Brent Province) to predict capillary pressures and across-fault pressure differences in two case studies from Permian Upper Rotliegende reservoirs. They conclude that these functions predict the fault seal potential of faults in these reservoirs with reasonable results within the uncertainty ranges. They stress that, although these functions produce reasonable first estimates in high net-to-gross rocks (low clay content), there are several orders of magnitude of uncertainty.

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.

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, splays. 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 datasets 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 Ojik *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 CO_2 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 depletion 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 CO_2 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.

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

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