Workflows for Fault Seal Prediction in Siliciclastics and Carbonates*

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Search and Discovery Article #41821 (2016)**
Posted June 27, 2016

*Adapted from oral presentation given at AAPG/EAGE Hydrocarbon Seals of the Middle East, January 18-20, 2016, Muscat, Oman
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Abstract

Fault-bound traps represent an important class of hydrocarbon-bearing structure. Whether a fault can seal hydrocarbons on a geological timescale may be controlled by one or more of three conditions: (1) whether the fault slip has juxtaposed reservoir against sealing intervals, (2) whether the fault slip has created new fault rock with sealing capability where reservoir is juxtaposed against reservoir, and (3) whether the in situ stress state is conducive to up-fault leakage out of the trap. A key first step in evaluating these conditions is a structurally-robust interpretation of the sub-surface geometry of the reservoir layers and the faults. A three-dimensional framework model should be constructed where fault-fault and horizon-fault intersections are built in a way that honours established structural-geological rules, particularly in regard to fault geometry and displacement patterns. If reservoir-reservoir juxtapositions occur, the fault displacement and stratigraphic profile can be used together to estimate the nature of the fault-rock which might be present.

In reservoir-shale sequences, clay smears provide a mechanism to introduce sealing material between juxtaposed reservoirs. A variety of predictive techniques have been developed for clay smears, all dependent in some way on the number and thickness of clay beds in the faulted section and the amount of fault displacement. In shale-poor sequences, whether siliciclastic or carbonate, the stress and temperature conditions during and after faulting play an important part. In intra-sandstone faults, the processes of cataclasis and diagenetic overprinting are now well understood, but only now is comparable progress being made to determine permeability behaviour in intra-carbonate faults. Routine prediction of fault transmissibilities in carbonate reservoirs is the goal of this research.

References Cited


Lindsay, N.G., F.C. Murphy, J.J. Walsh, and J. Watterson, 1993, Outcrop studies of shale smear on fault surfaces: Spec. Publ. Int. Ass. Sediment, v. 15, p. 113-123.


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Acknowledgements

We are grateful for financial and technical support, recent and present, from the following organisations:
How does a fault seal?

**Sealing units are juxtaposed against the reservoir**
The subsurface structural framework is critical to the first-order control of the potential connections across fault surfaces, visualized in Allan Diagrams.

**OR**

**Fault processes have created a seal**
The fault-zone rock-type depends upon the composition of the faulted sequence, and the burial/temperature history during and after faulting.

**AND**

**Fault has not been reactivated or critically stressed**
Assess the risk of fault reactivation in terms of in-situ stresses and rock properties.
How does a fault seal?

- **Juxtaposition Seal**: (sand against shale)
- **Fault-rock Seal**: (dominated by the properties of the fault zone)
- **Fault Reactivation**: (dominated by stress field & fault orientation)
How does a fault seal?

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Juxtaposition analysis

The basic tool of juxtaposition analysis is the **Allan diagram**, which is a fault-plane section (strike projection) illustrating the stratigraphy brought into contact at the fault plane (after Allan 1989).

The Allan diagram shows reservoir intervals on each side of the fault.

Non-reservoir intervals are typically left blank.
Fault polygons are computed in 3D as the intersection lines between the fault surface and adjacent parts of the horizon surface.
Importance of mapping faults in 3D

Faults form the side-seals to traps – mapping the faults is essential to define the traps.

Reservoir horizon mapped around 2 crossing faults.

What is the age/geometrical relationship of the faults?

Fault-block connectivity?

The E-W fault is continuous, offsetting the N-S fault into two. The NW and SE blocks connect (NE/SW blocks do not)

This relationship is very difficult to see in map or section, but is obvious in 3D.
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Fault rocks

- Interbedded reservoirs and clays/shales
  - Clay smears, shaly gouge

- Sandstone reservoirs
  - Disaggregation zones, cataclasites

- Carbonate reservoirs
  - Breccias, cataclasites, recrystallised
Clay smears

Observations of real and synthetic shale smears suggest that smears become discontinuous (i.e. non-sealing) at Throw/Thickness (Shale Smear Factor SSF) ~4-8.

(e.g. Lindsay et al 1993, Aydin & Eyal 2002, Takahashi 2003, Faerseth 2006).

Data from Takahashi (2003), Childs et al (2007).
Upscaling clay smears

- Shale Smear Factor describes the observed seal/leak potential of *individual* clay or shale beds, but is less easy to apply in a multi-layer sequence.
- A more pragmatic approach is ‘Shale Gouge Ratio’ (SGR) which is notionally the upscaled clay content of the faulted sequence.
- In simple sequences, SGR is the reciprocal of SSF. A seal threshold of SGR~20% is often observed, corresponding to SSF~5.
- Stochastic modelling of more complex sand-shale sequences suggests that SGR approximates the behaviour of multiple breached clay smears.
Fault rocks in clean sands

Fault-rock properties depend on
- fault displacement
- depth of burial during faulting
- burial depth (temp.) after faulting

### Fault seal, static vs dynamic

<table>
<thead>
<tr>
<th>Large Scale Process</th>
<th>Migration and Accumulation</th>
<th>Aquifer Flow</th>
<th>Dynamic Two-Phase Flow</th>
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<tr>
<td>Buoyancy</td>
<td>Capillary Threshold Pressure</td>
<td>Aquifer Production</td>
<td>Artificial or Natural Water Flow</td>
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<td>Capillary Threshold Pressure</td>
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<table>
<thead>
<tr>
<th>Small-Scale Process</th>
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<th>Flow Rate</th>
<th>Oil Flow Rate</th>
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<td>Oil Pressure</td>
<td>Water Pressure</td>
<td>Pressure Difference</td>
<td>Water Pressure Difference</td>
<td>Oil Pressure Difference</td>
</tr>
</tbody>
</table>

| Principal Fault Rock Properties | Capillary Threshold Pressure | Permeability and Thickness | Permeability, Thickness, Relative Permeability and Capillary Pressure Curves |

| Fault modelling parameters | Capillary threshold pressure | Transmissibility multipliers | Relative transmissibility multipliers |

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Workflows for siliciclastic sequences

Trap Analysis for Exploration

Vshale

Throw (max ~150m)

Shale Gouge Ratio (SGR)

Capillary Thr. Pressure (bars)
Column height (m)

geohistory

Shale Gouge Ratio (% clay in fault)
Predicting column heights: Trap Analysis with multiple faults in framework model

With multiple faults, different parts of several faults need to be tested against several different potential spill points defined by the top-reservoir structure.
Predicting column heights: Trap Analysis with multiple faults in framework model

Black arrow = fault leak point (supports a column with **shallower** contact relative to the structural spill points)

**Orange surface** = Extent of accumulation (~trap fill) supported by fault seal

**Dashed line** = predicted hydrocarbon contact

**Predicted contact shallower than spill point. Column in trap is dependent on fault seal**
Workflows for siliciclastic sequences

Fault Transmissibilities for Production

Computation of fault transmissibility multipliers can be performed at all faulted connections in a simulation model, based on geological cell properties such as Vshale and permeability. This workflow is now well established in clastics.
Fault rocks in carbonates

- In principle, fault seal prediction in carbonate-dominated rocks can be approached in the same way as for quartz-rich sandstones.
- However, calcite differs in its rheology and solubility, being much more reactive at low temperatures.
- Cementation is common at shallow burial depths, leading to embrittlement and fracturing.
- This behaviour reduces the chances of long-term static seal, but low-permeability fault rocks are likely to be a key component of carbonate reservoirs.

Carbonate fields review, from Solum (2015)
Carbonate Fault Rock Microstructures

Examples….

- **Grain-dominated carbonates** deform on the grain-scale, breaking down individual fossil clasts creating fault rocks such as protocataclasites and cataclasites.

- **Micrite-dominated carbonates** disperse the deformation such that fractures dominate, to break up the rock into a variety of different breccia types.

Overprinting mechanisms also occur:
- recrystallisation by mechanical e-twinning (micrite-dominated carbonates),
- cementation by aggrading neomorphism (grain-dominated carbonates),
- fracturing (micrite- and grain-dominated carbonates).

from Michie (2015)
Carbonate Fault Rock – Displacement control

Low displacements.

- Limited variety of fault-rock development
- Fault-rock type mainly controlled by self-juxtaposed lithofacies
- However, at juxtapositions of different lithofacies, the stronger lithofacies (grain-dominated carbonate) dominates.
- Low fault-rock permeabilities.

High displacements.

- Wider variety of fault-rock development as higher strain and more facies mixing forms more complex fault rocks.
- Fault-rock types mainly controlled by juxtaposed lithofacies.
- Wider range of fault-rock permeabilities.

Examples from Malta, Michie (2015)
The temporal evolution of fault rocks influences the petrophysical properties of the fault core.

(a) Less lithofacies mixing (at lower displacements) creates fewer fault rock types, all with similar low permeabilities.

(b) The increased complexities in fault rock microstructures at higher displacements create a larger range of permeabilities, with a higher mean.

Evolution of fault rock, therefore, creates a low-perm fault core at lower displacements, evolving to a higher permeability fault core at higher displacements.

This behaviour contrasts with sandstone fault-rock.
Fault transmissibility multipliers, 0-60 m displacement

- Highest fault transmissibility multipliers (red) on large-displacement faults juxtaposing different lithofacies.
- Small multipliers (reduced flow) on self-juxtapositions.

These relationships are the opposite of those seen in sandstone reservoirs.
Ongoing research – Carbonate Fault Rock project

- We have begun a systematic sampling programme of carbonate fault-rocks from a wide variety of lithofacies and a variety of tectonic environments.
- The fault-rock samples are being analyzed in the state-of-the-art Wolfson Multiphase Flow Laboratory, Leeds University.
- Producing carbonate fields will be re-examined to better understand the role of faults.
- The new-found relationships will be used to develop the first software tool for the prediction of fault transmissibilities in carbonate reservoirs.

- Faults in carbonates are often thought to be mainly conduits due to their brittle nature.
- Field work as part of the CFR project suggests however that:
  - Low permeability fault rocks are extremely common.
  - Chemical reactivity of carbonates results in rapid healing even after fault reactivation (unlike siliciclastics).
  - Faults appear to stop fracture propagation so open fractures may not link across the faults.
Conclusions

- Structurally-robust subsurface mapping of faults and reservoirs is an essential first step in fault-seal analysis.
- When clay/shale beds are present, clay smears tend to dominate the seal/leak behaviour of the faults.
- SGR (Shale Gouge Ratio) provides a pragmatic way of predicting the fault seal potential for an assemblage of clay smears on a fault surface.
- Trap Analysis in 3 dimensions is a preferred workflow to determine probable trap fill in a multiply-faulted prospect.
- In both clean sandstones and carbonates, fault-rock properties are strongly controlled by different aspects of geohistory, including lithofacies, stress, temperature and fault displacement.
- Our current work aims to better understand the controls on carbonate fault-rock permeability, in order to populate fault transmissibilities in production models in carbonate reservoirs.