Reservoir Scale Deformation and Advances in Fault Seal Analysis

Tim Needham
Introduction

• The answer to the question, “Does this fault seal?” is “It depends” …

• This is what “It depends” on:
  – Juxtaposition
  – Fault rocks
  – Geohistory
  – Relative permeability
  – Fluid properties

• How much more do we know now compared with 1997?
Rotliegend fault traps in the main part of the Lauwerszee Trough
Juxtaposition types

Færseth et al. (2007)
Wolfson Multiphase Flow Laboratory, University of Leeds

- Run by Professor Quentin Fisher

- State-of-the-art SCAL facilities for low permeability rocks:
  - Pulse-decay gas and brine permeameters to <10 nD
  - Oil-water or gas-water relative permeabilities
  - Ultrasonics/rock mechanics
  - NMR
  - Access to state-of-the-art electron microscopes
  - Dedicated Hg laboratory - up to 100,000 psi $P_{\text{con}}$
  - Ultracentrifuge for drainage and imbibition experiments
  - Quantitative XRD
Fault rock classification

Fisher & Knipe (1998)
Backscattered electron images

Quartz

K-feldspar

Porosity

Tueuckmantel et al. (2012)
Disaggregation zone

Needham et al. (2008)
Cataclasites: quartz rich - clay poor

Core & outcrop images by Tim Needham

Fossen et al. (2007)
Cataclasites

Backscattered

CL

Tueckmantel et al. (2010)

Lower images by Tim Needham
Cataclasites

Fisher & Knipe (1998)

Fisher & Knipe (2001)

Sperrevik et al. (2002)
Phyllosilicate Framework Fault Rock

Images by Tim Needham

Abbreviated to PFFR!
Phyllosilicate Framework Fault Rock

Knipe et al. (1997)

Image by Tim Needham
Clay smear fault rocks

Knipe et al. (1997)

Fisher & Knipe (2001)

Image by Tim Needham
Permeability & threshold pressure

Fisher & Knipe (2001)

Sperrevik et al. (2002)
Relative permeability: Location, location

Fisher et al. (2001)

Al-Hinai et al. (2008)
Fault rock permeability vs. clay content

Sperrevik et al. (2002)

Also relationships developed by Manzocchi et al. (1999) & Jolley et al. (2007)

Frischbutter et al. (2017)
Fault seal algorithms

Shale Gouge Ratio (SGR)
- Mixing algorithm is a measure of the proportion of shale in the interval that has slipped past any point on the fault surface
- More shale gives greater seal potential

\[
SGR = \frac{\sum (VCI \times Z)}{\text{Throw}}
\]

Shale Smear Factor (SSF)
- Algorithm estimates ratio of throw to thickness of a shale source layer
- Continuous smears required to seal occur at SSF<4 on seismic scale faults

\[
SSF = \frac{\text{Throw}}{\text{Thickness}}
\]

SGR see: http://youtu.be/HMod1bhH-fo
SSF see: http://youtu.be/bhWwdPJbDTQ?list=PL70E44B94AC18E73A
Allan diagrams: Footwall Vshale

Generated by TrapTester
Allan diagrams: SGR

Generated by TrapTester
Shale smear

Færseth et al. (2007)

SSF = Critical SSF

Yielding (2012)
Cross-fault seal calibration

Across-fault pressure difference plotted against clay-content (SGR) with seal ‘envelopes’ corresponding to different depths of burial

AFPD = 10\(^{[(SGR/d)-c]}\)

AFPD = Across fault pressure difference

d = 27

c = 0.5 at <3km
0.25 at 3-3.5km
0 at >3.5km

Bretan et al. (2005)
Comparing calibrations

Yielding et al. (2010)
Published fault seal data for the Brent Province shows that most faults are sealing where the minimum SGR is >20% (0.2). Yellow bars are faults supporting <15m OWC difference.
SSF & CSP calibration

SSF

Outcrop: Childs et al. (2007)

CSP

No horizontal scale on original figure of Fulljames et al. (1997)

Yielding et al. (2010)
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Manzocchi et al. (2002)

Fault seal in exploration & production
Transmissibility multipliers

• Fault-zone properties are conventionally incorporated in production flow simulators using Transmissibility Multipliers.

• Depends on fault-rock thickness and fault-rock permeability at each cell-cell connection on the fault plane.

• In general, the thickness of the fault zone increases with its local displacement.

Islam & Manzocchi (2017)
Fault zone thickness

Çiftçi et al. (2013)

Fault zones & fault rock data from Childs et al. (2009)
Using fault properties

Jolley et al. (2007)
Using realistic TM values

Zijlstra et al. (2007)
Carbonates

- Compactive shear bands
  - Host rock
  - Compactive shear bands with stylolites, localized grain to grain (Zone II). Solved solids precipitate in nearby pores occluding porosity (Zone III).
- Compactive shear bands with discontinuities, pockets of fine grained and residual material and slip surfaces (Zone I). Zone III expands.
- Compactive shear bands with a well-developed zone of fine grained and residual material and slip surfaces (Zone I). Zone III expands.

![Graph](image)
For the future …

Some continuing questions summarised by Dewhurst & Yielding (2017)*:

- Can we predict how faults and fractures work in shaly seals?
- How do we bridge the gap between the fault-zone detail we see at outcrop and the large-scale structures mapped on seismic data?
- Are we any closer to a predictive method of fault seal in carbonate reservoirs?
- How well do we understand uncertainty in our seal predictions?

* Thematic issue of Petroleum Geoscience, February 2017