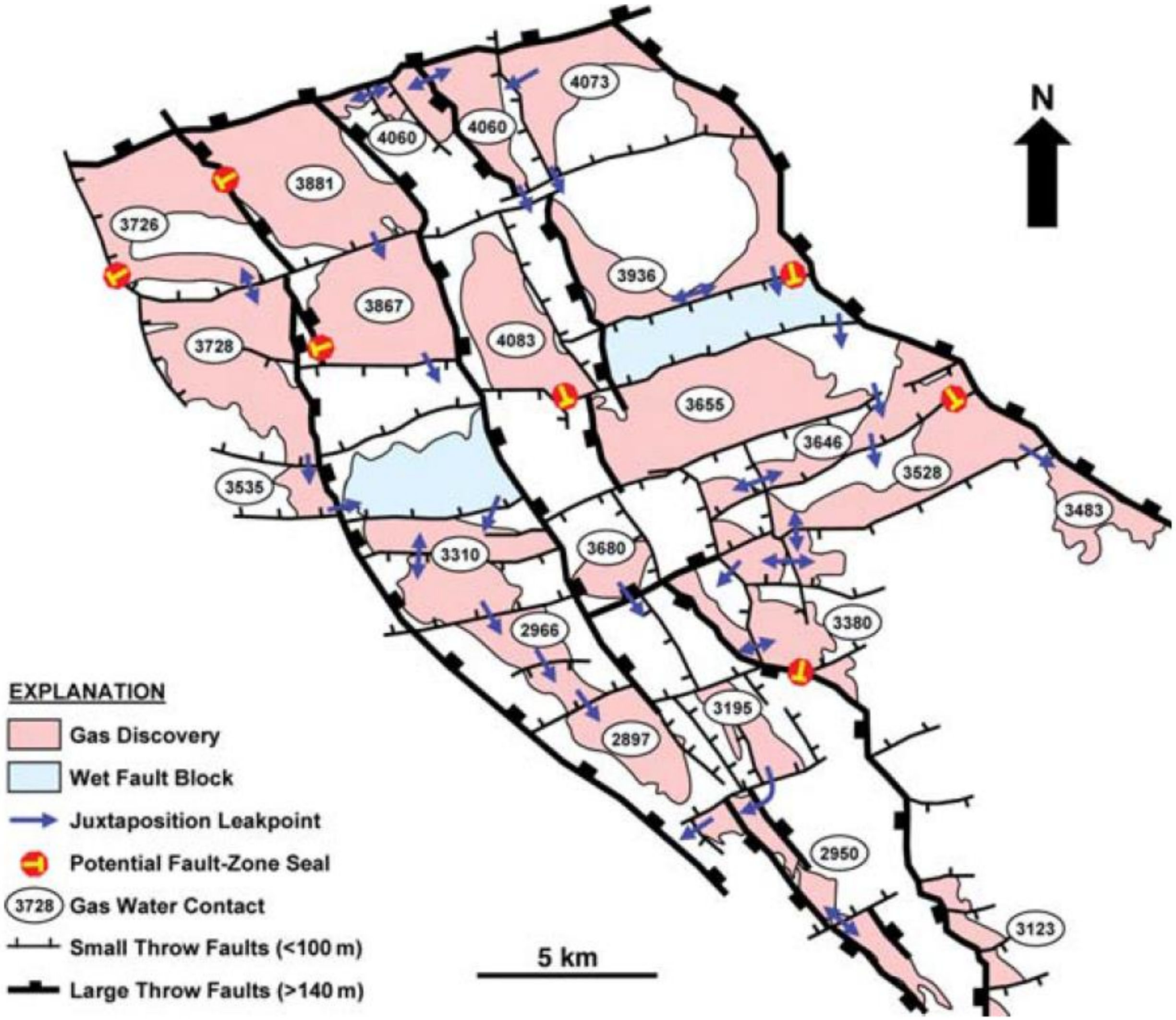
Reservoir Scale Deformation and Advances in Fault Seal Analysis

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



Corona *et al.* (2010)

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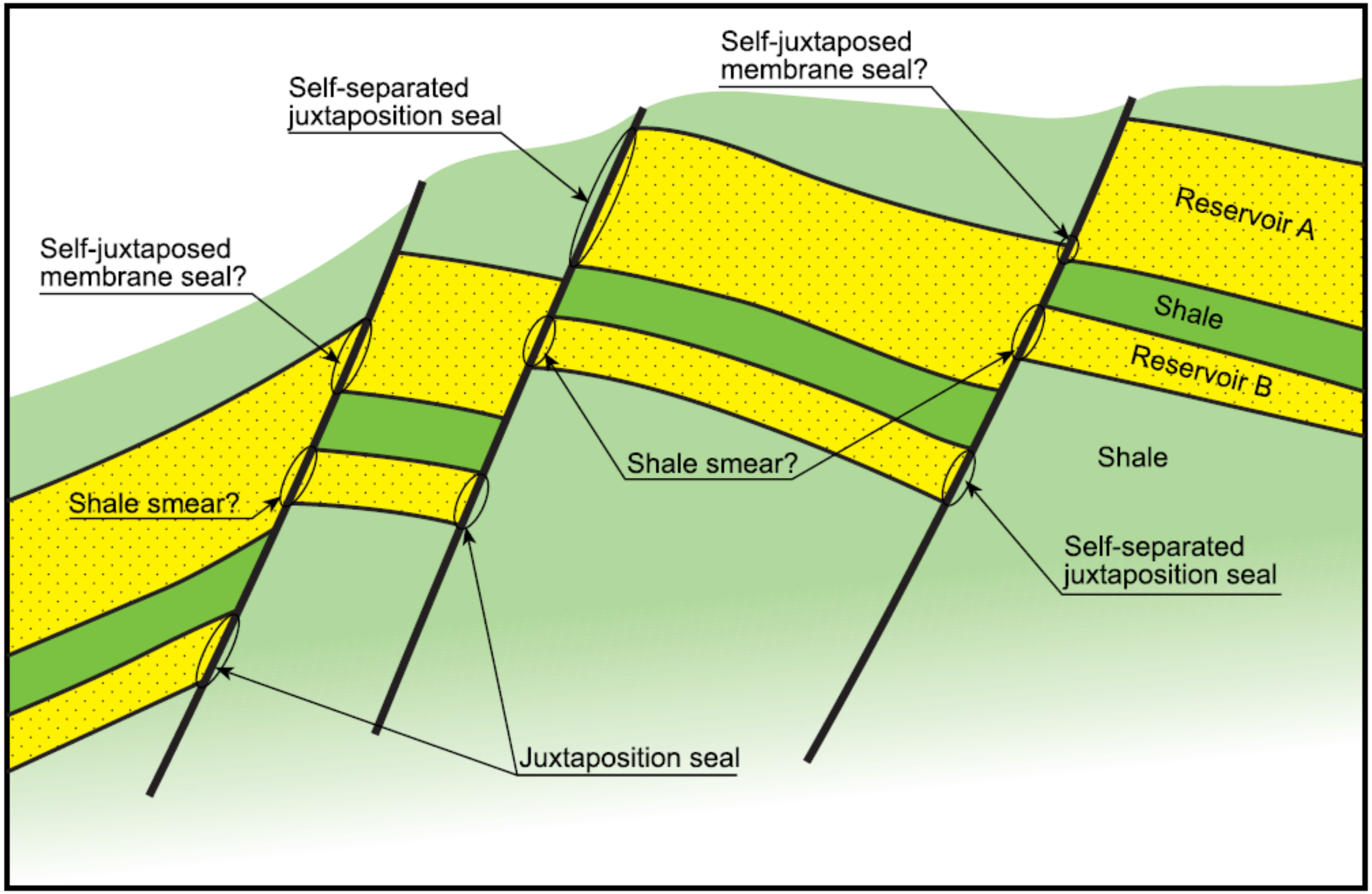
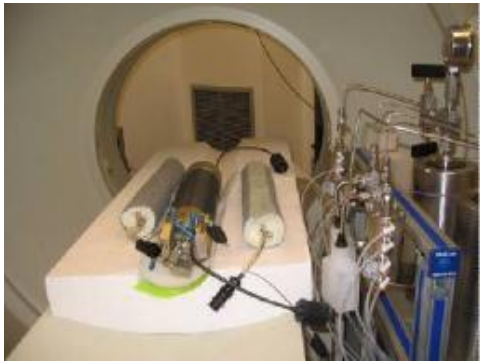
Juxtaposition types



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_{con}
  - Ultracentrifuge for drainage and imbibition experiments
  - Quantitative XRD



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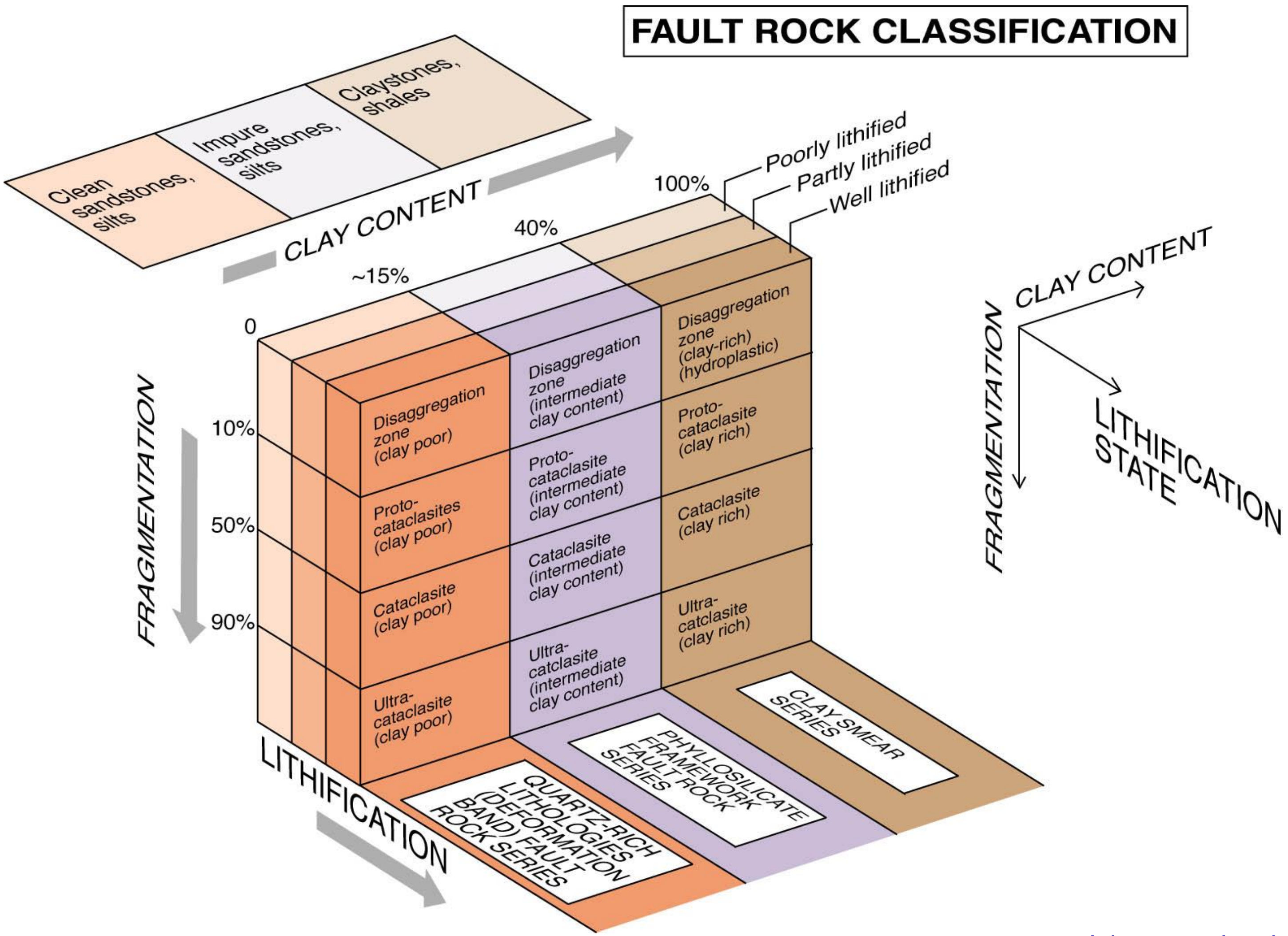
Fault rock classification



Fisher & Knipe (1998)

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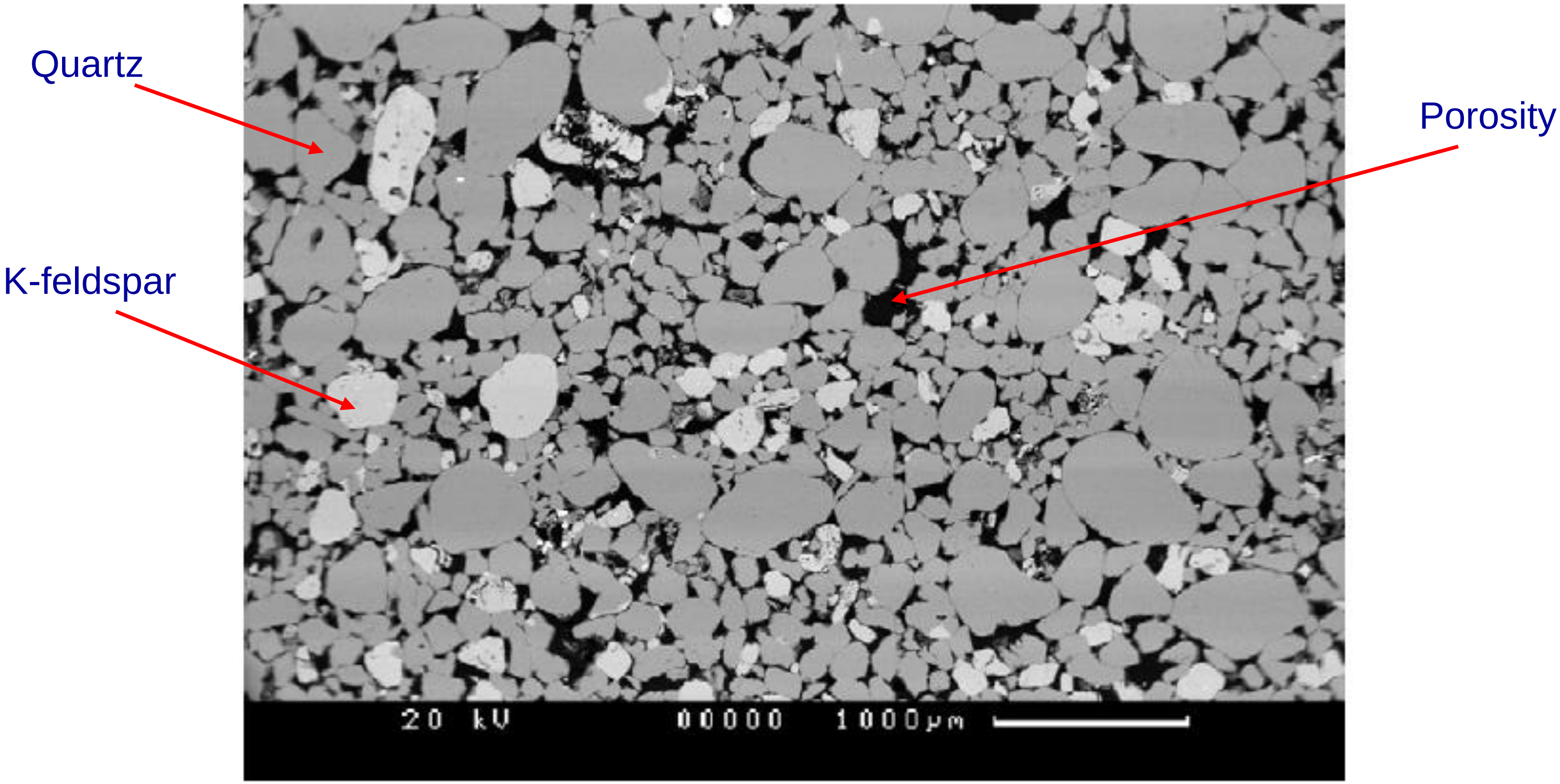
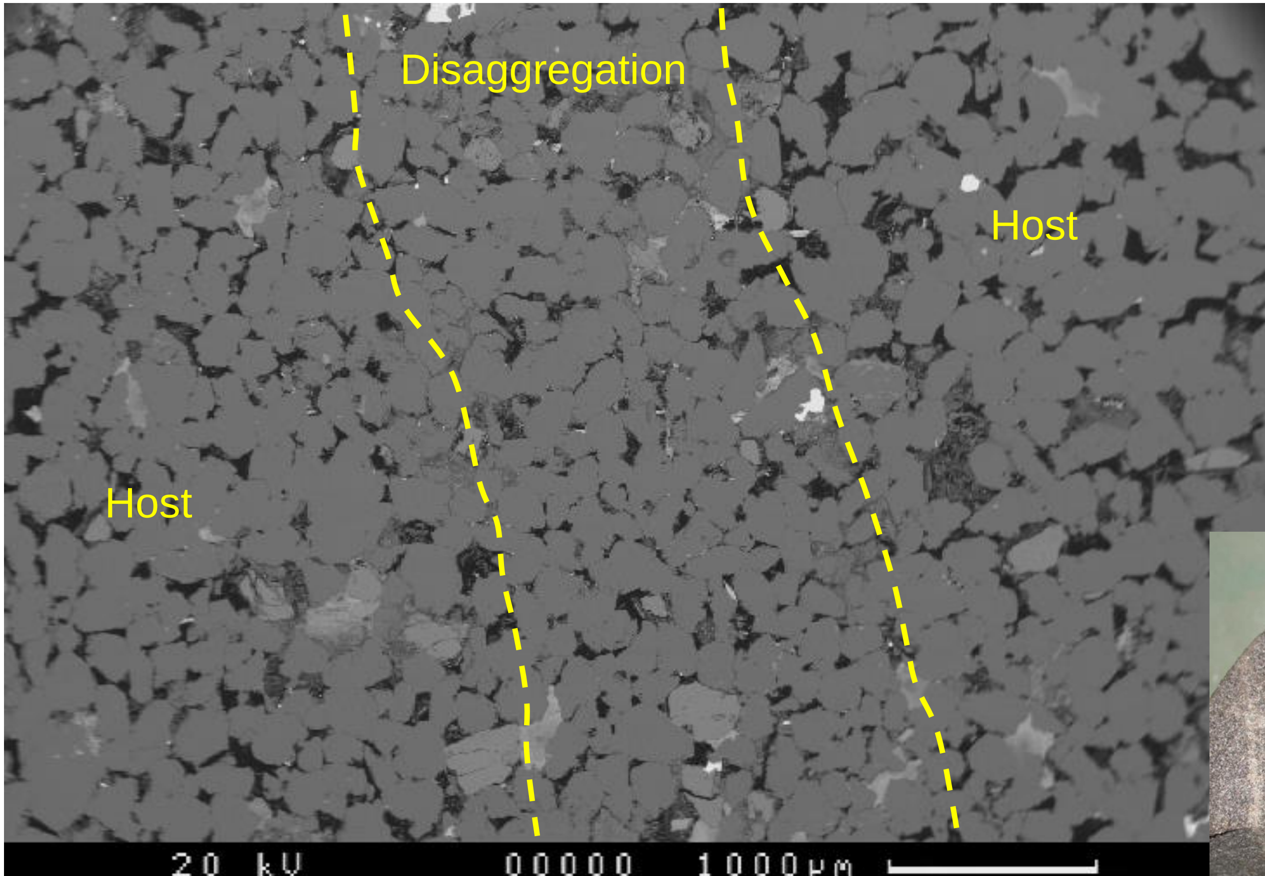
Backscattered electron images

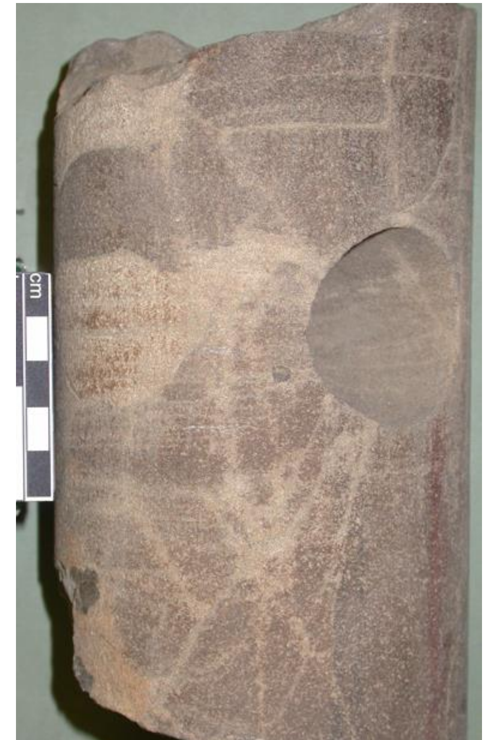


Tueuckmantel *et al. (2012)*

Disaggregation zone



Needham *et al. (2008)*



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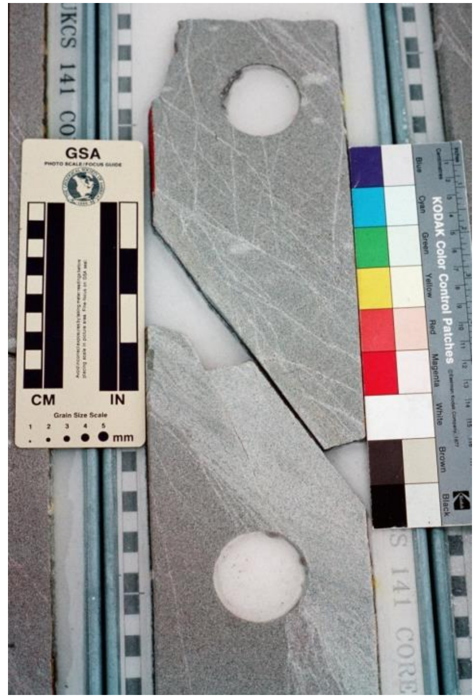
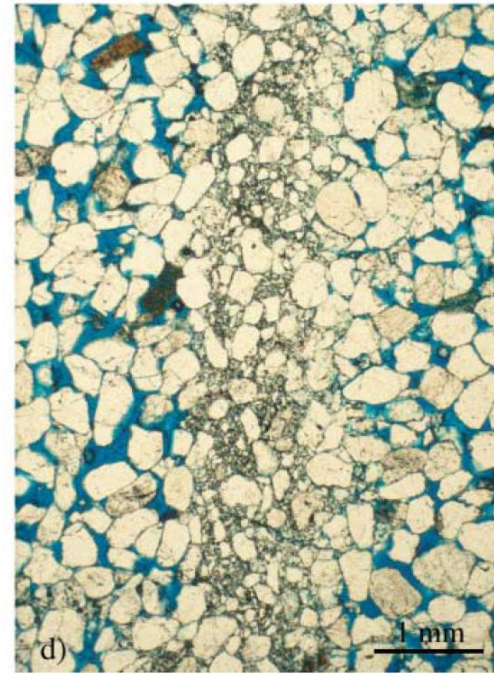
Cataclasites:quartz rich -clay poor

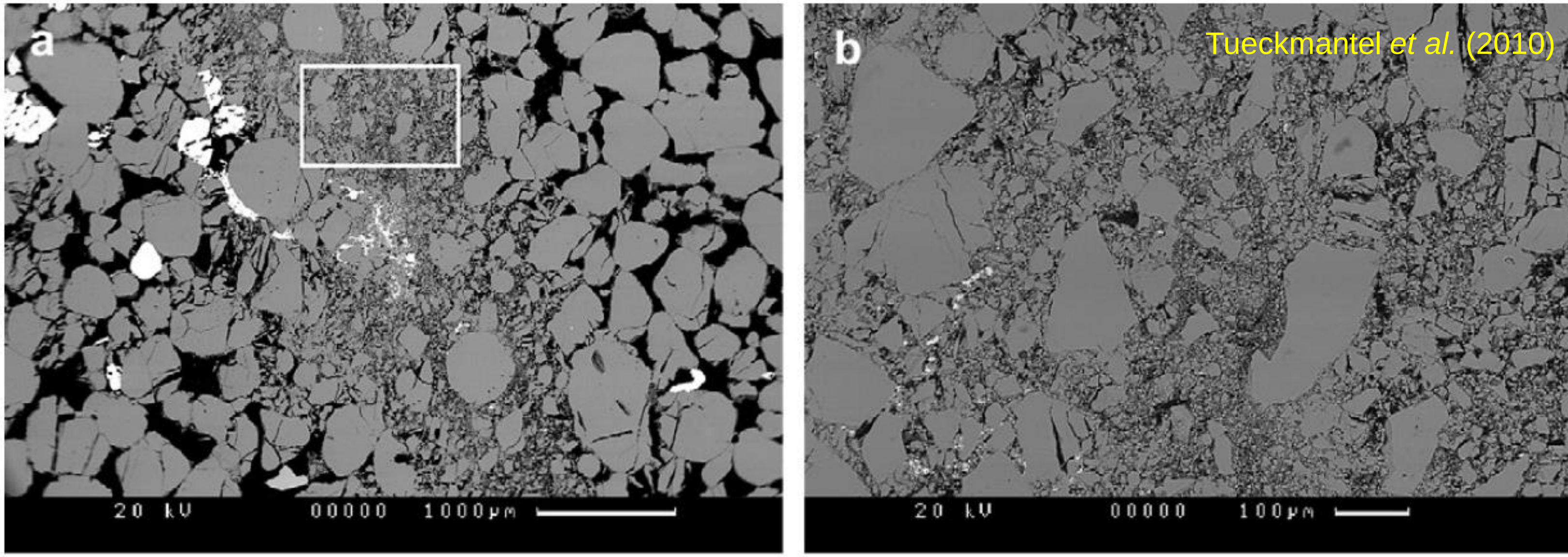


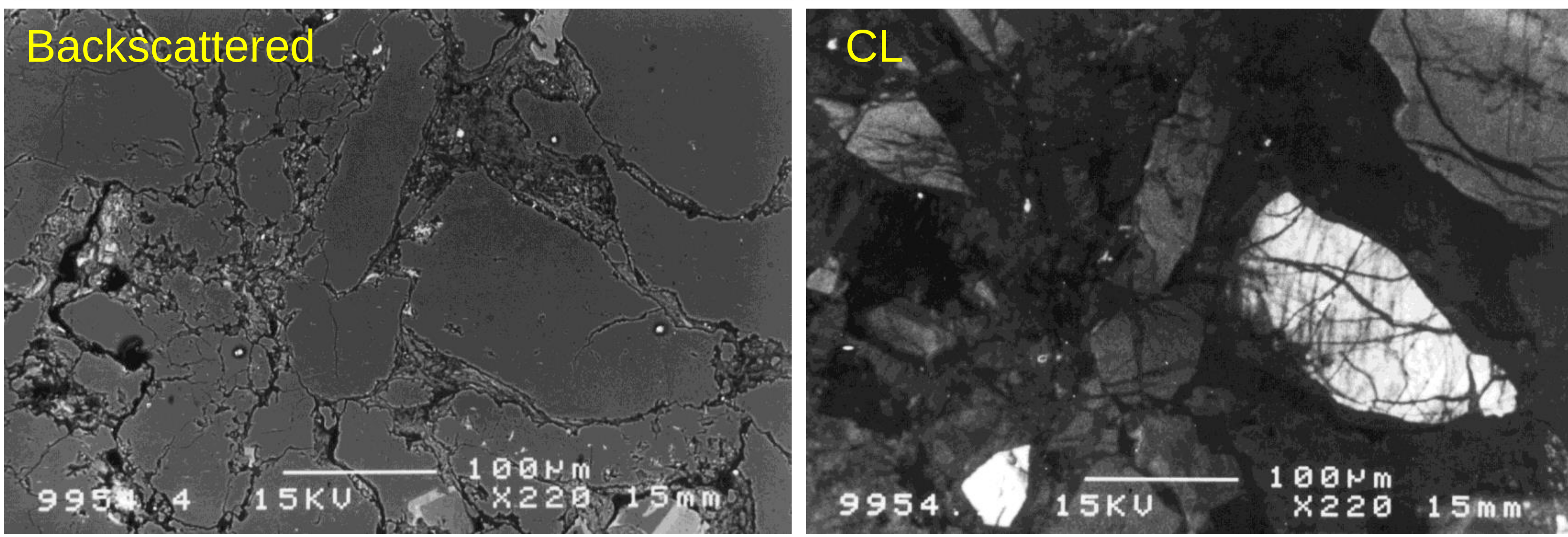


Fossen *et al*. (2007)

Core & outcrop images
by Tim Needham

Cataclasites





Lower images by Tim Needham

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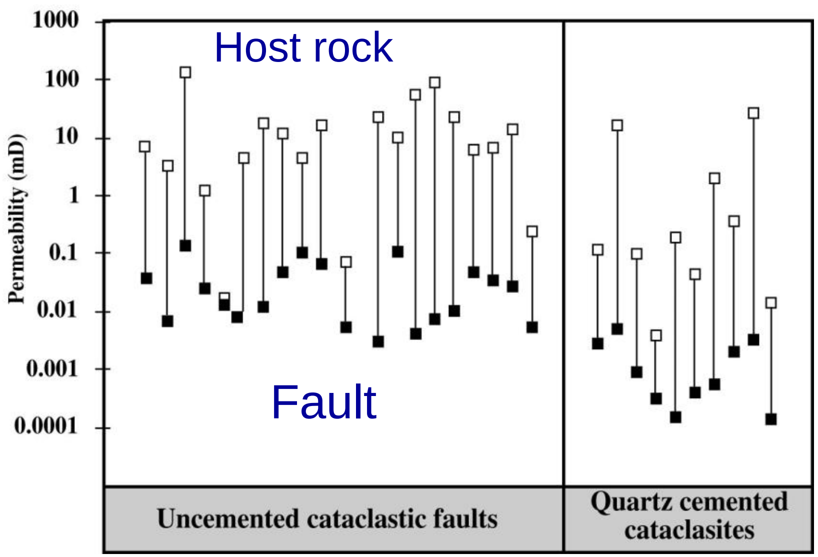
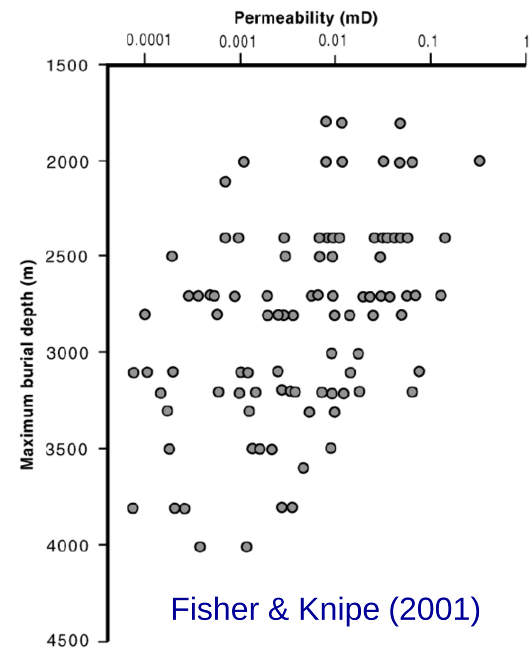
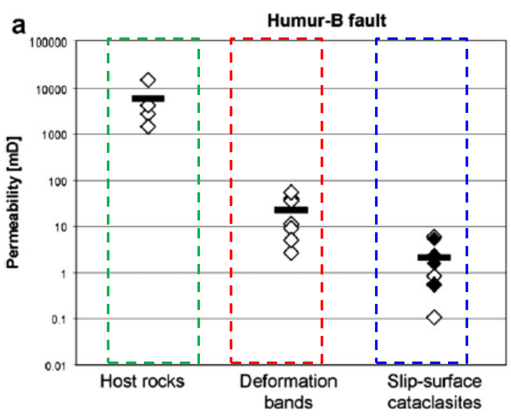
Cataclasites

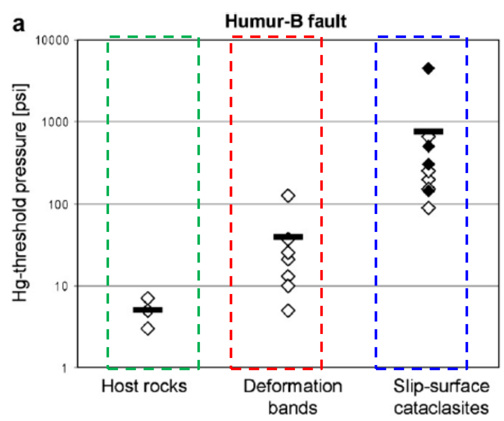


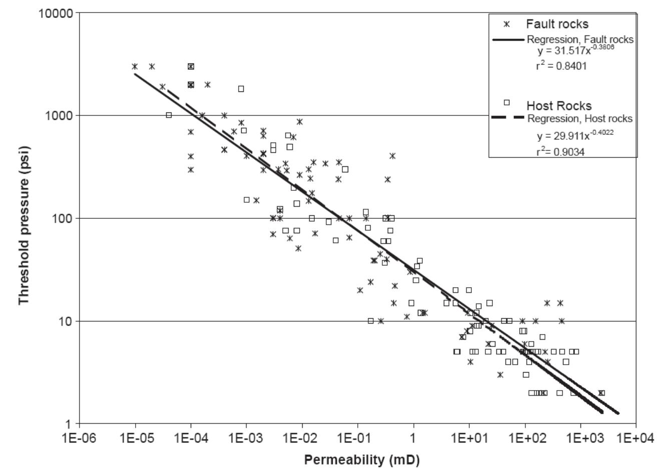
Fisher & Knipe (1998)



Fisher & Knipe (2001)







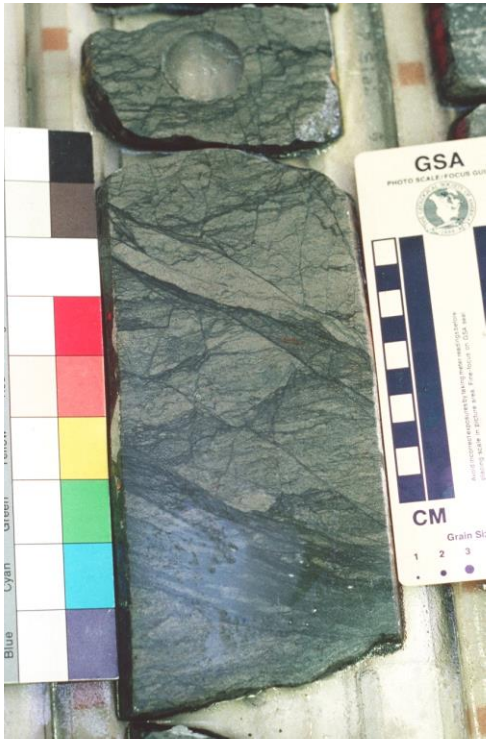
Host

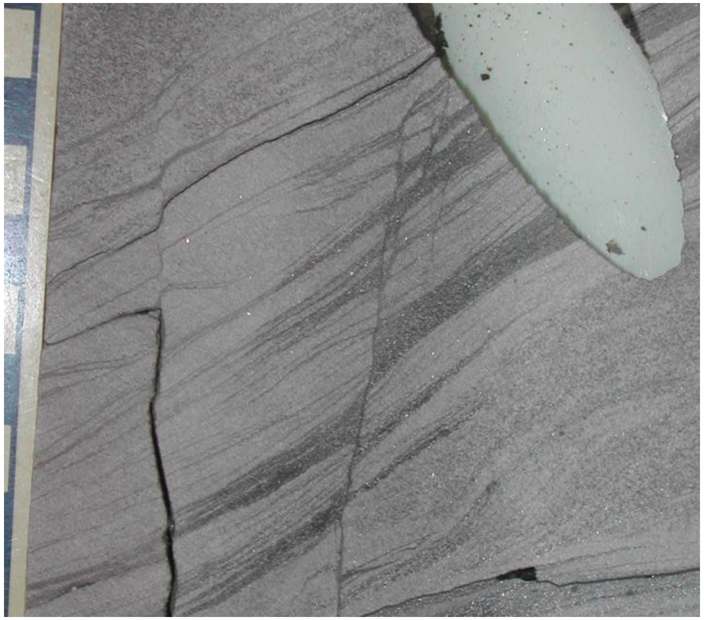
Deformation band

Slip surface

Sperrevik *et al.* (2002)

Phyllosilicate Framework Fault Rock

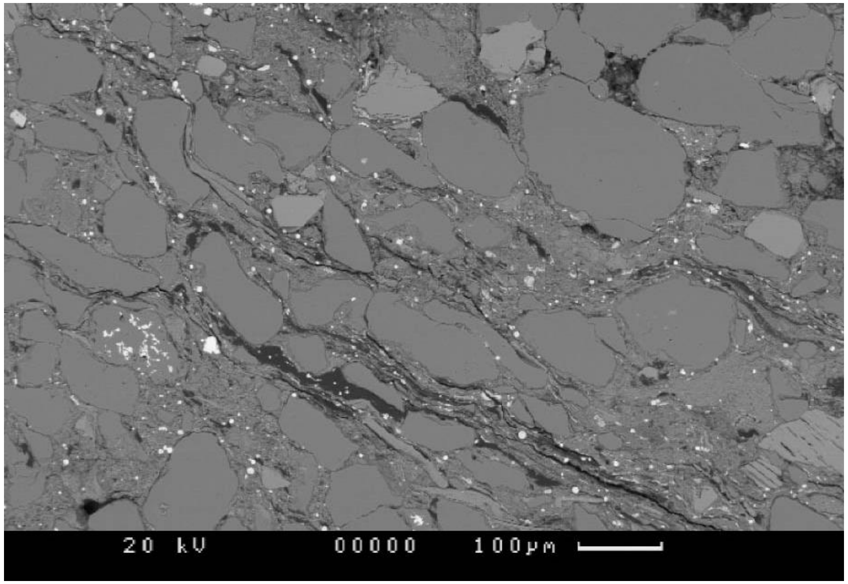


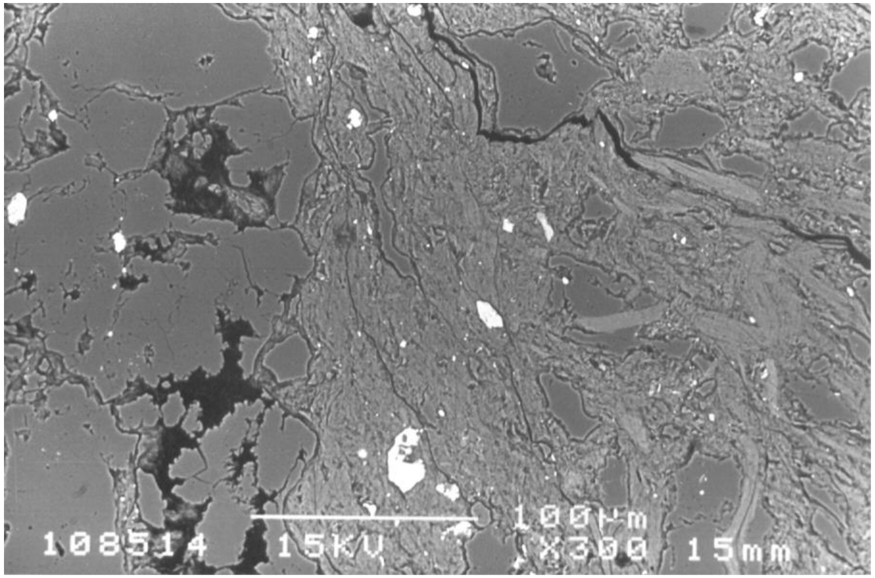


Images by Tim Needham

Abbreviated to PFFR!

Phyllosilicate Framework Fault Rock

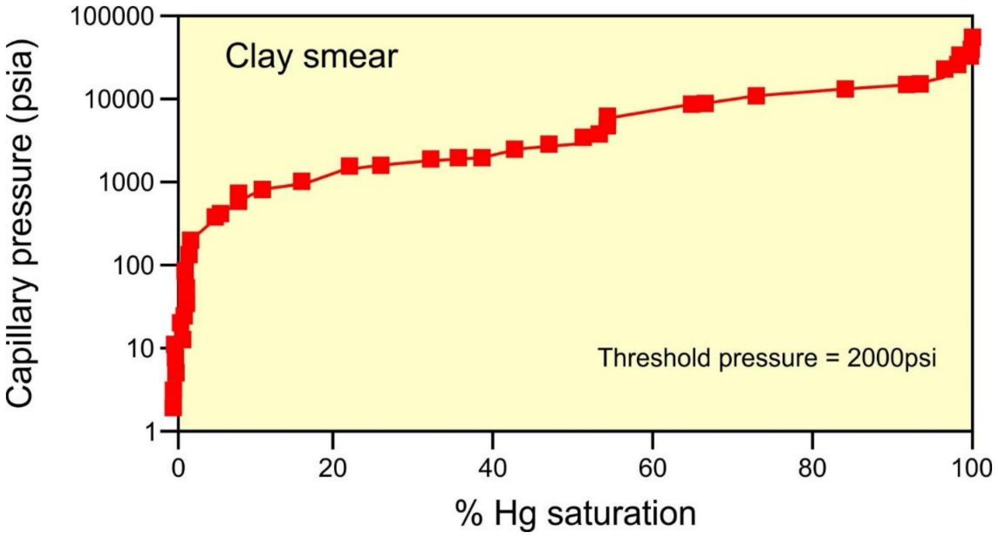




Knipe *et al.* (1997)

Image by Tim Needham

Clay smear fault rocks



Knipe *et al.* (1997)

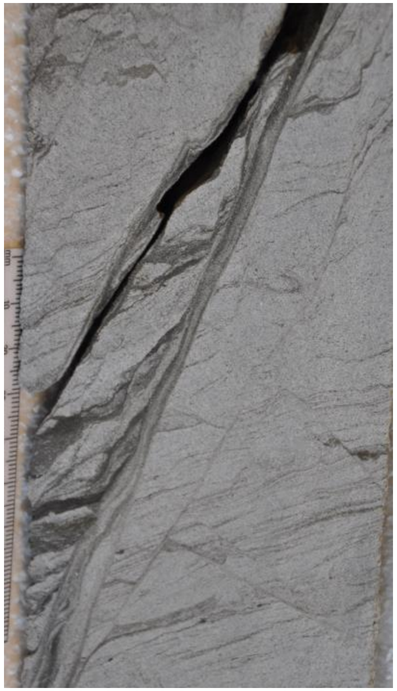
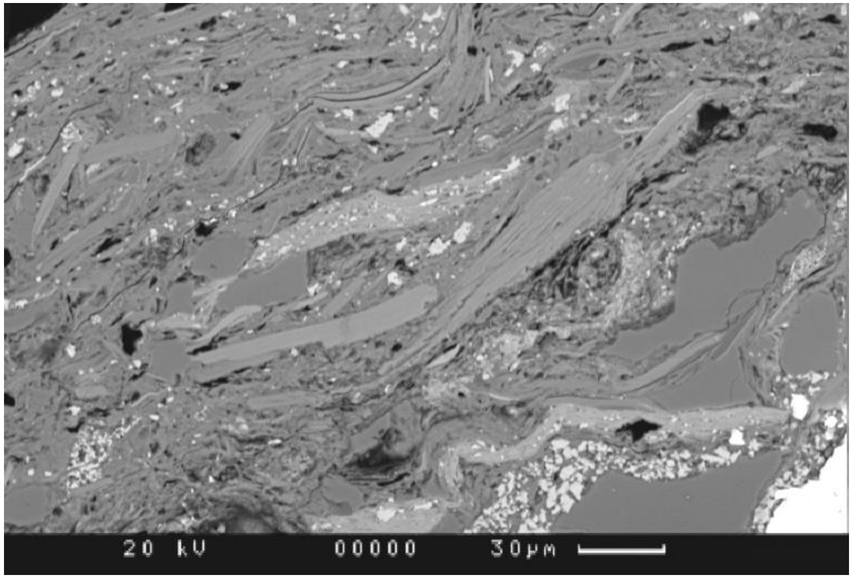
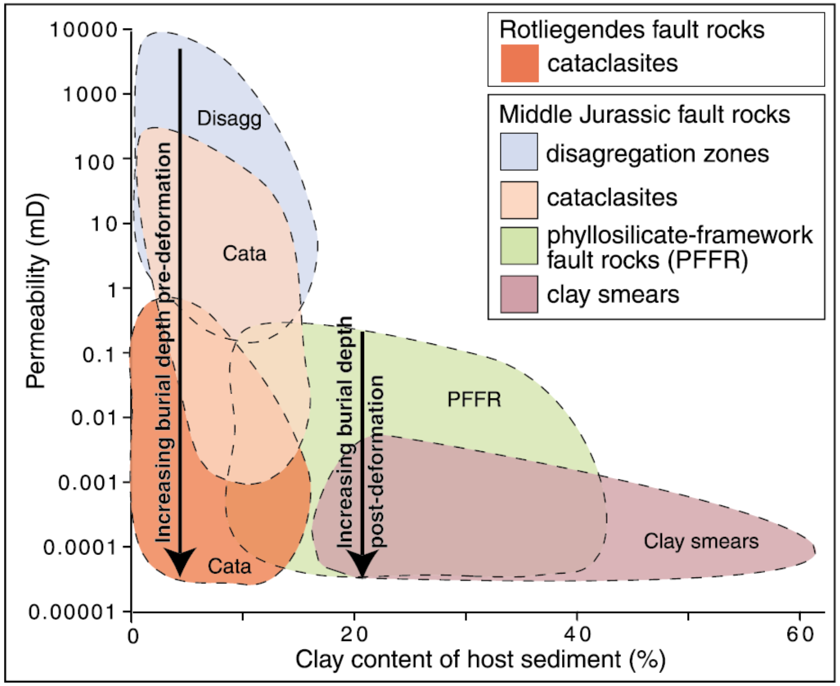


Image by Tim Needham

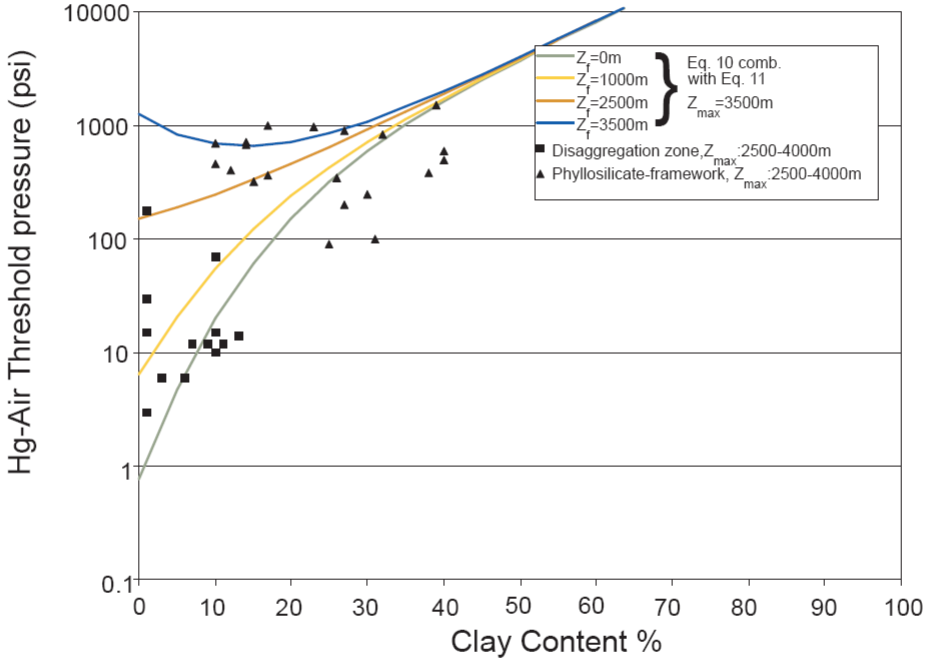


Fisher & Knipe (2001)

Permeability & threshold pressure

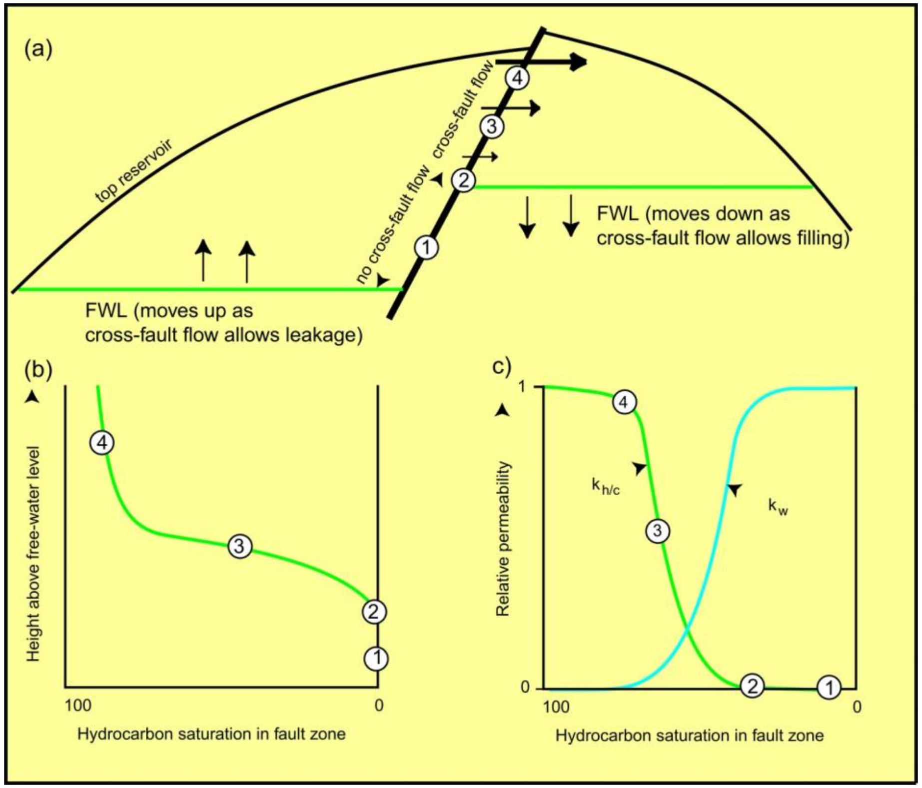


Fisher & Knipe (2001)

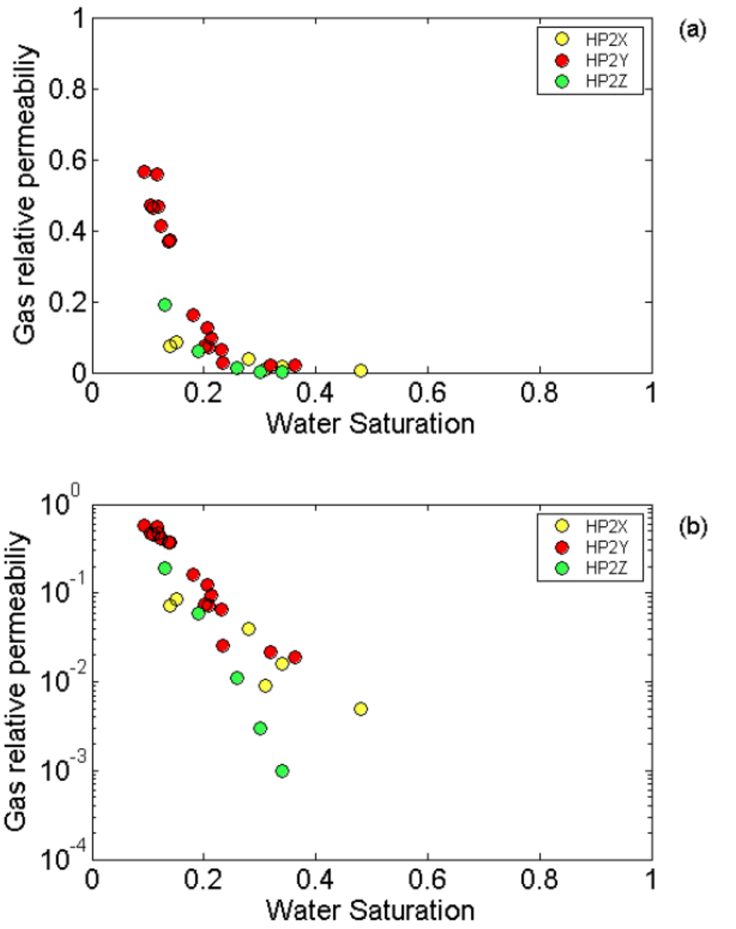


Sperrevik *et al.* (2002)

Relative permeability: Location, location

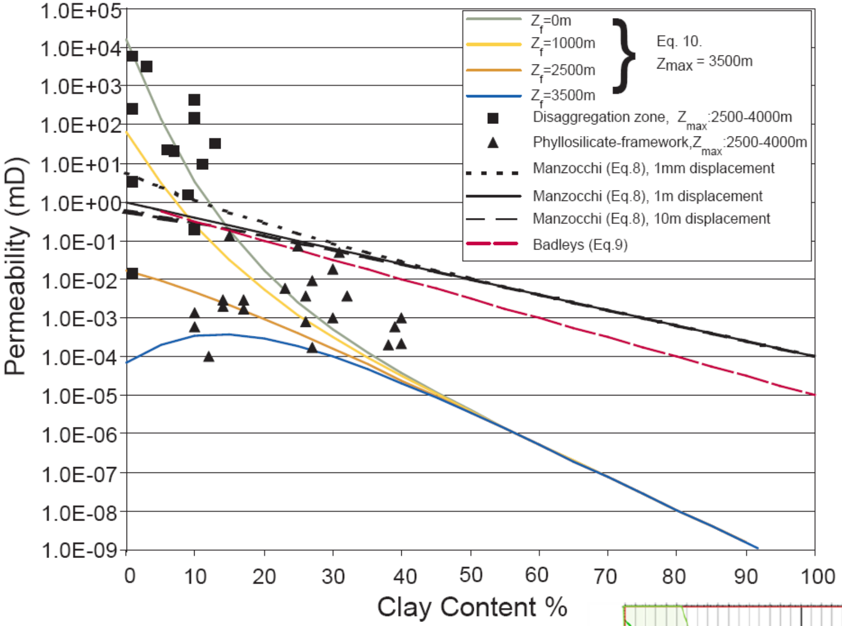


Fisher *et al.* (2001)



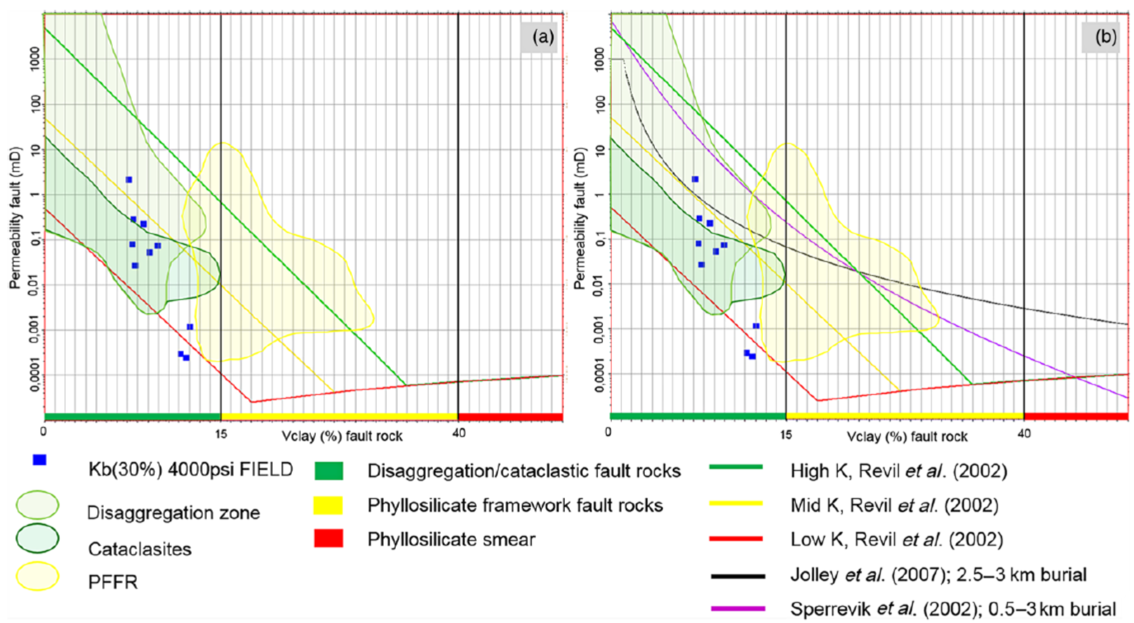
Al-Hinai *et al.* (2008)

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)

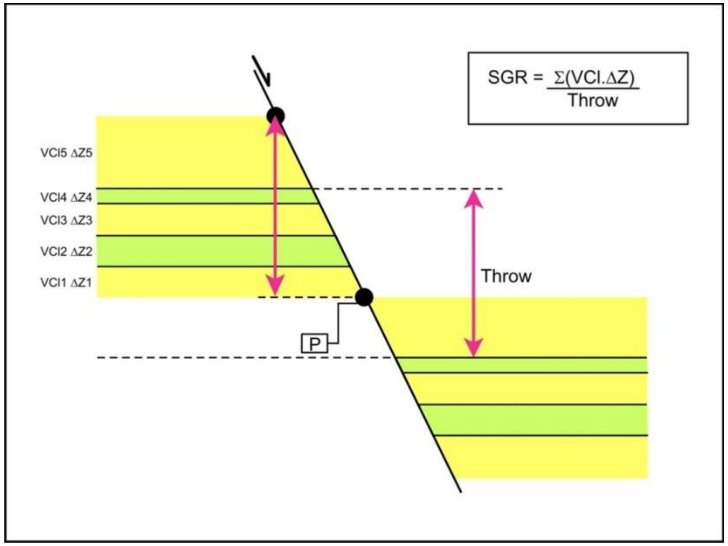
Fault seal algorithms

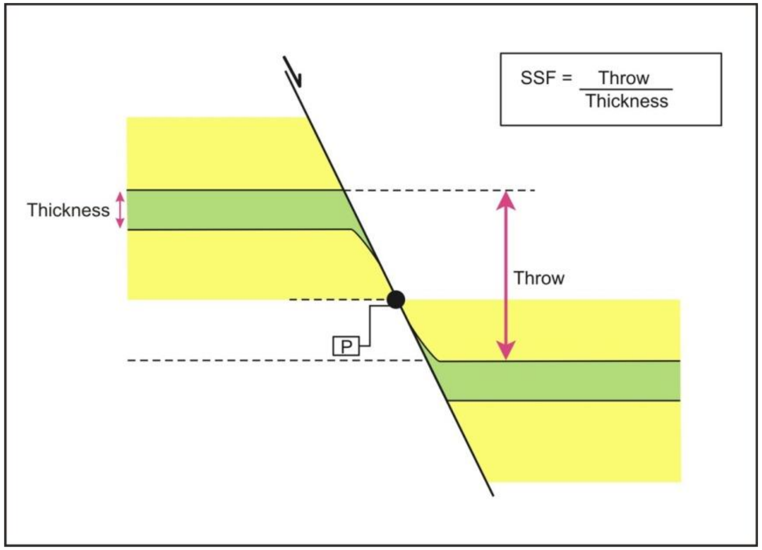
Shale Gouge Ratio (SGR)

- 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

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





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

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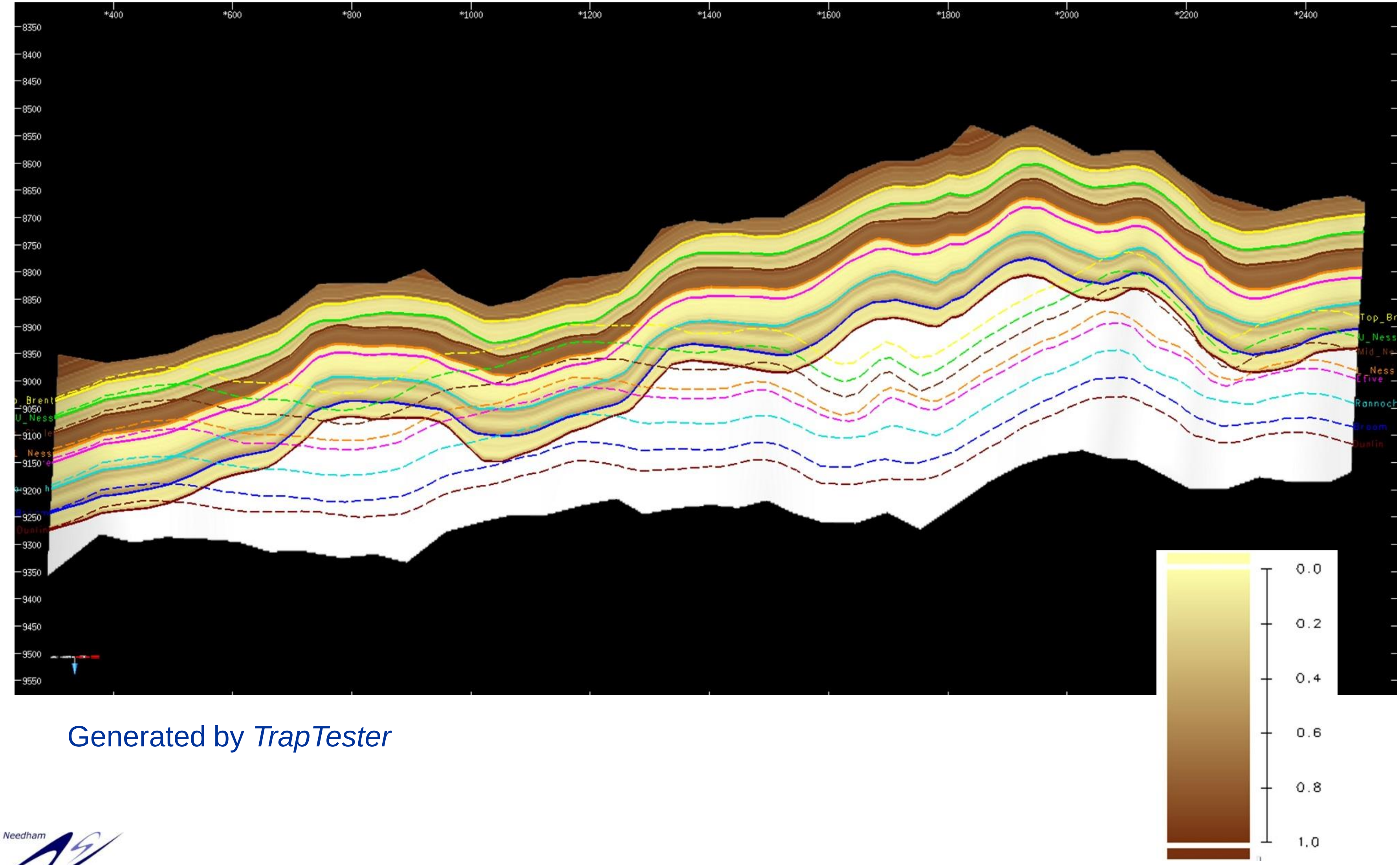
Allan diagrams: Footwall Vshale



Generated by *TrapTester*

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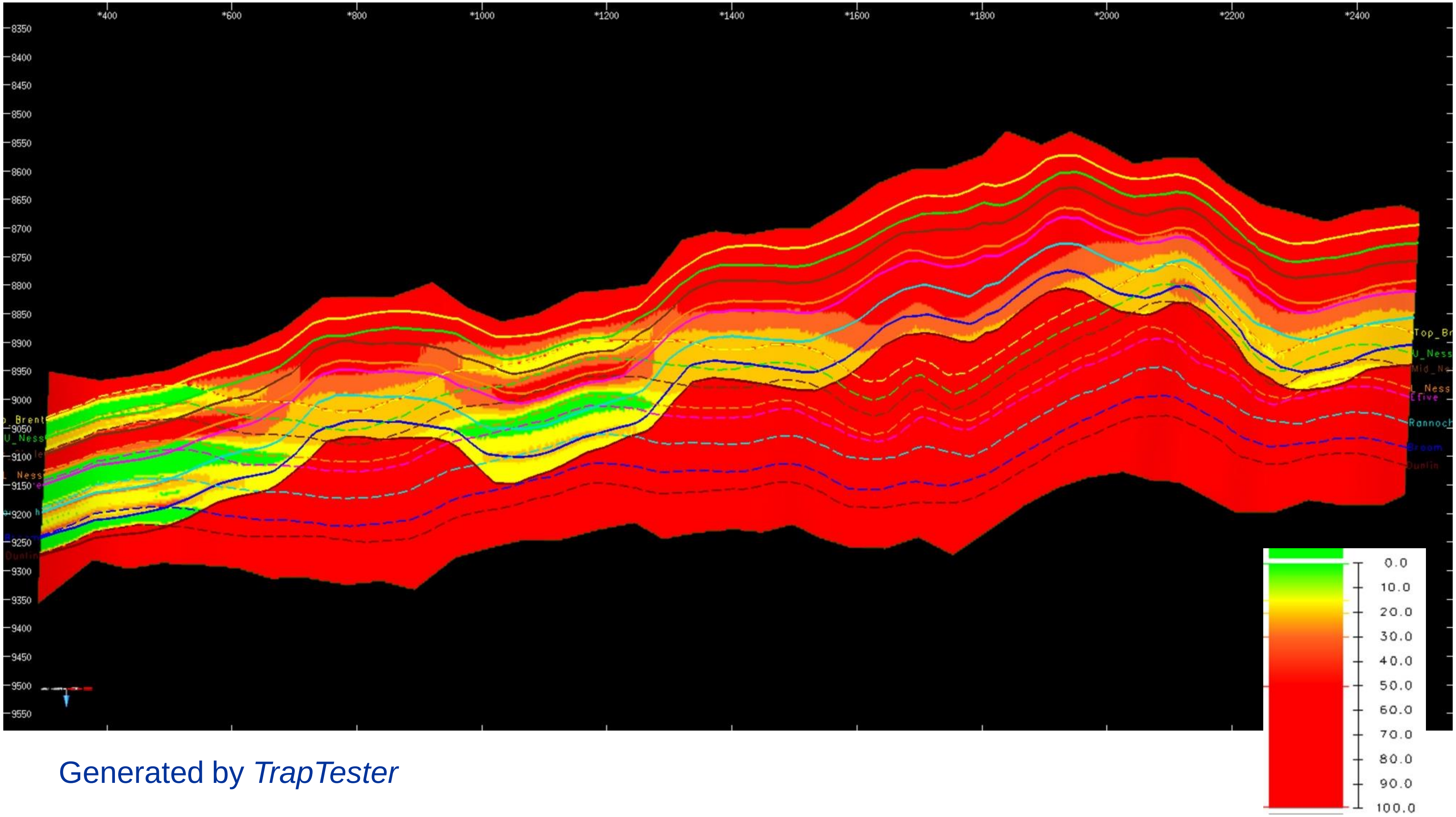
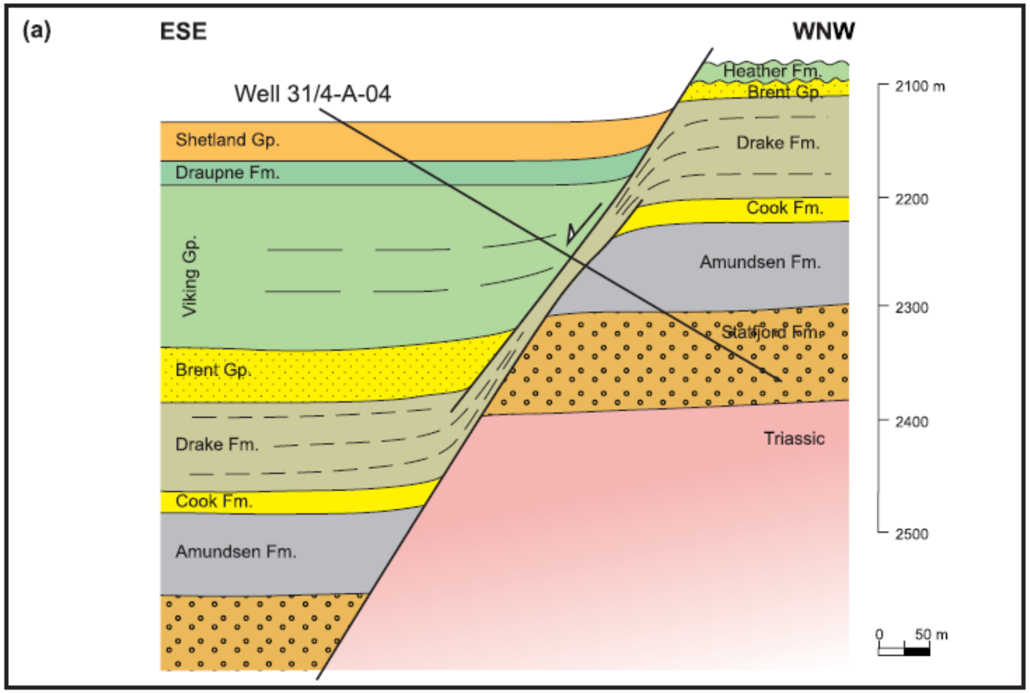
Allan diagrams: SGR

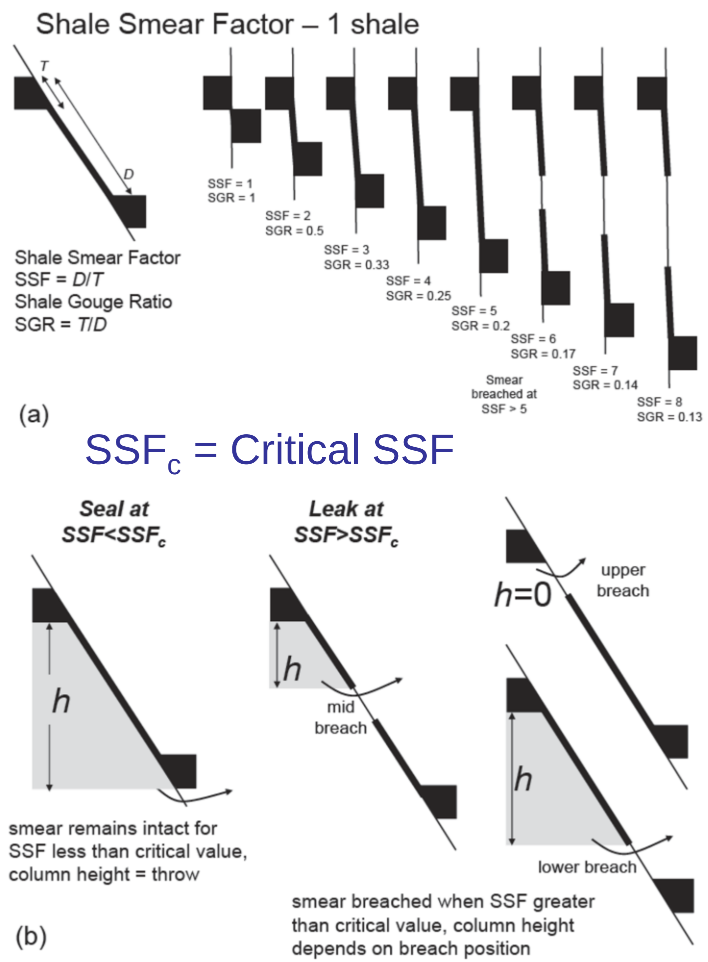


Generated by *TrapTester*

Shale smear



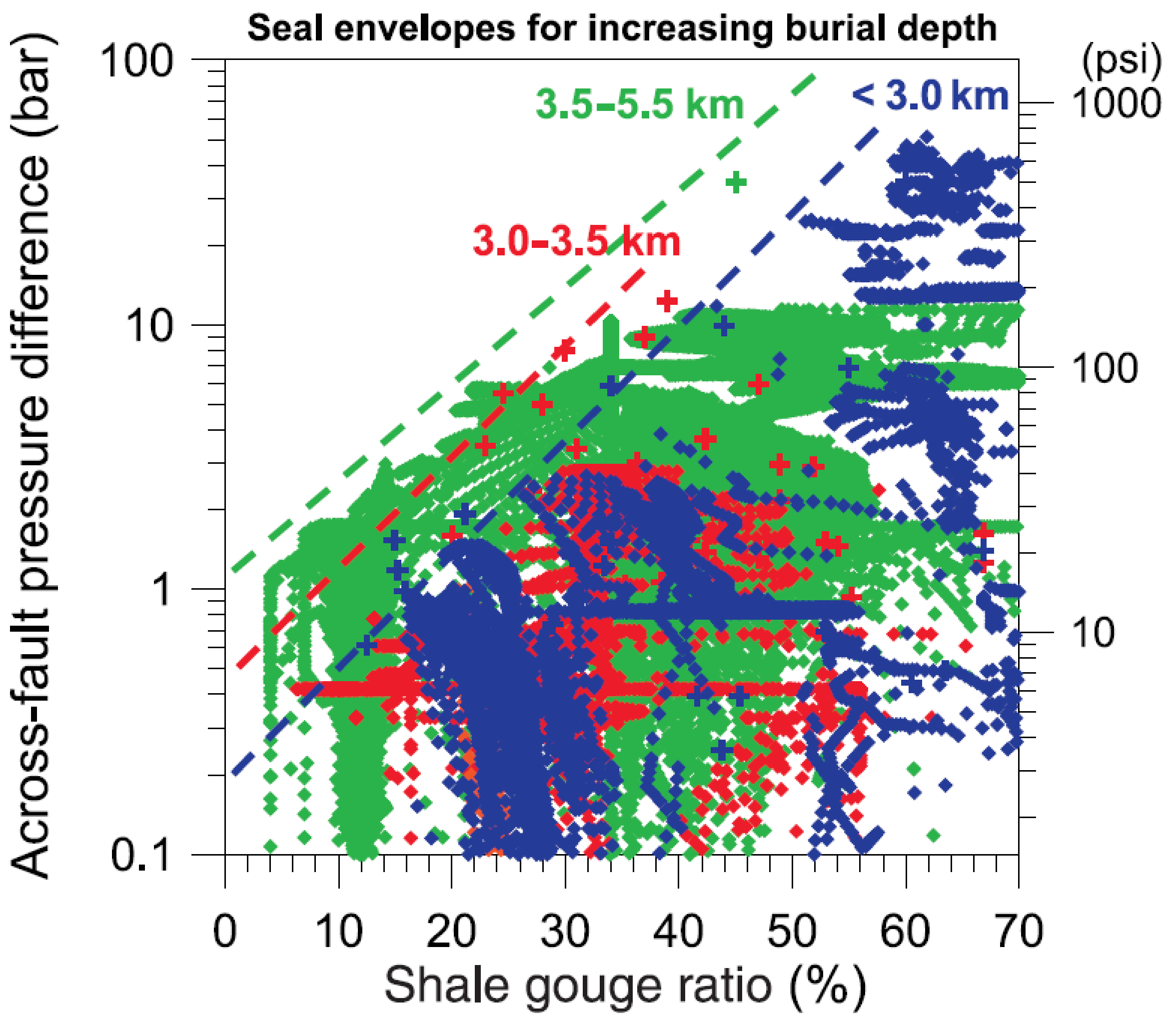
Færseth *et al.* (2007)



SSF_c = Critical SSF

Yielding (2012)

Cross-fault seal calibration



Clay Content %

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

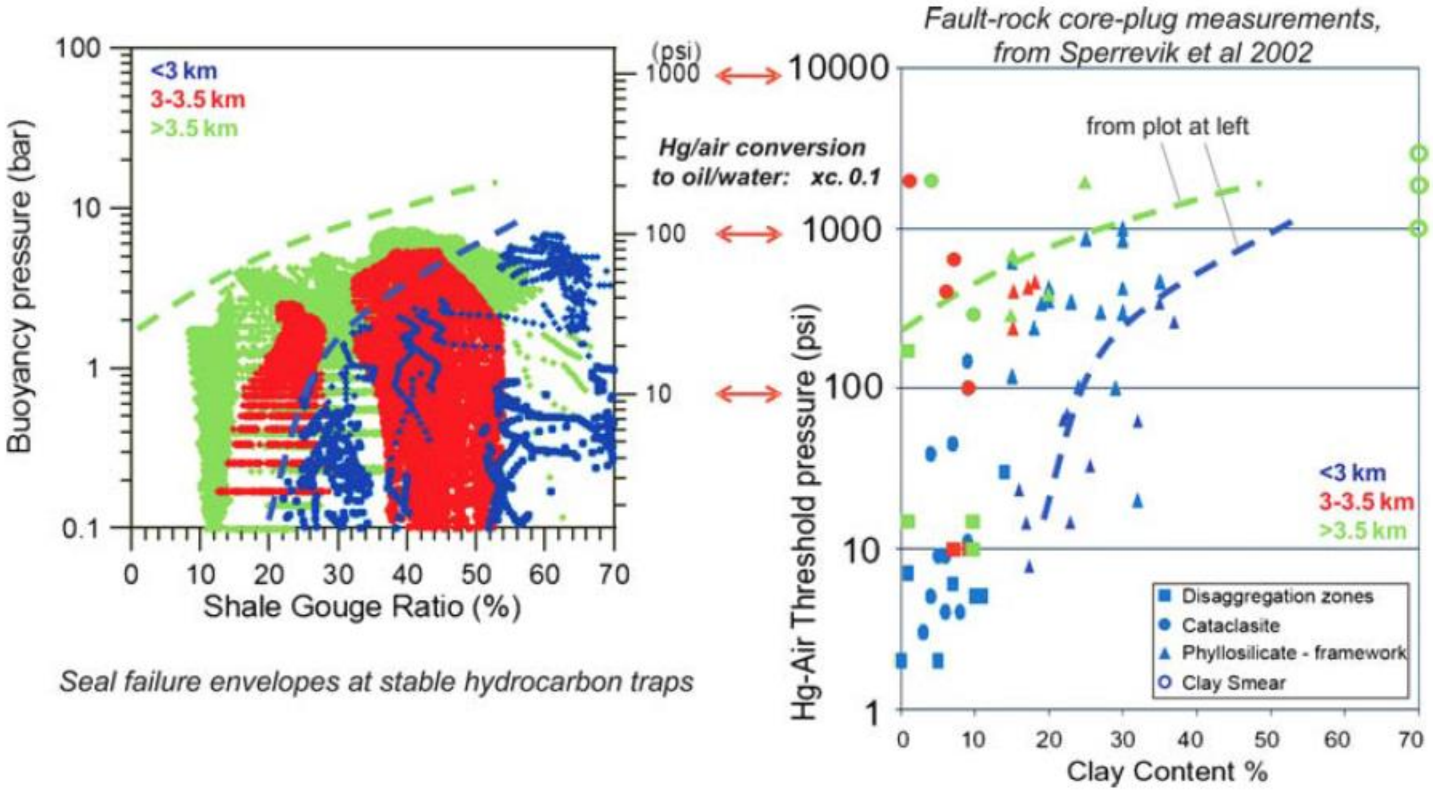
c = 0.5 at <3km

0.25 at 3-3.5km

0 at >3.5km

Bretan *et al.* (2005)

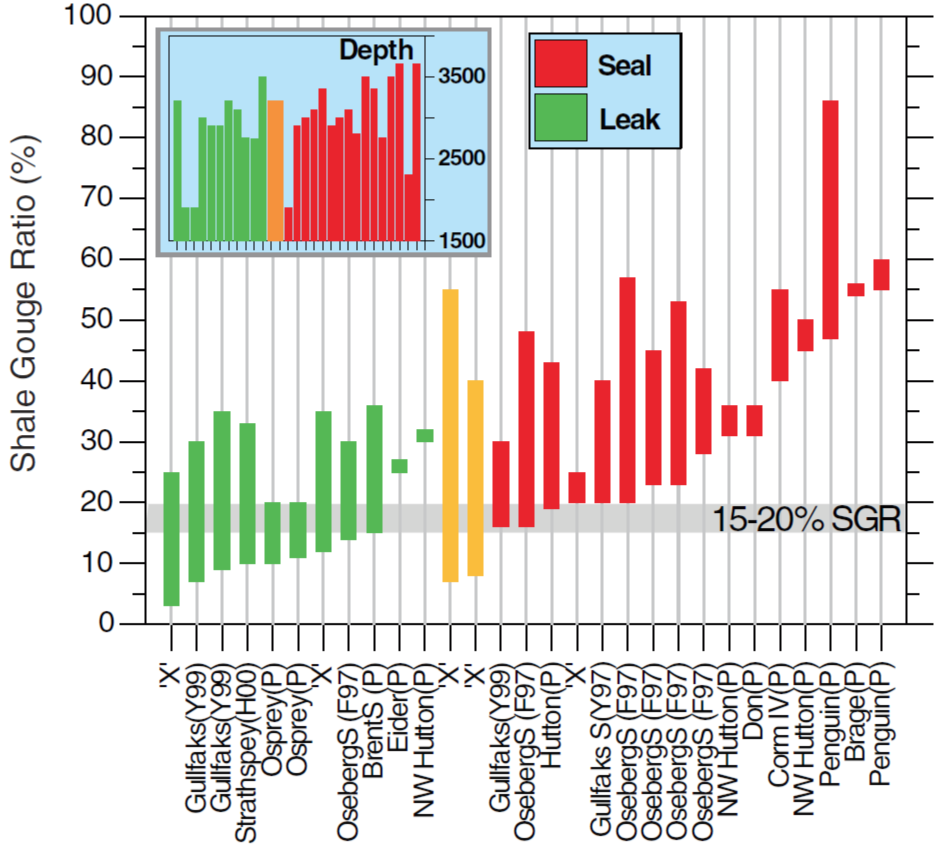
Comparing calibrations



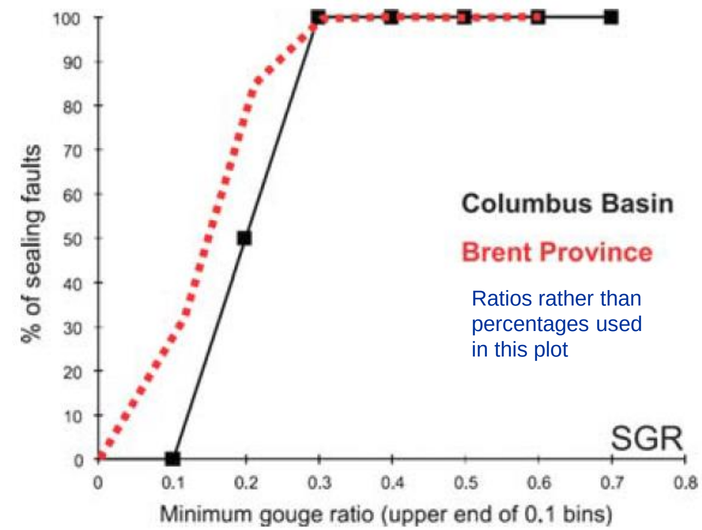
Yielding *et al.* (2010)

Seal/leak: Brent Province

Range of SGR for sealing and leaking faults



29 faults in 15 Brent fields



Yielding (2010)

Yellow bars are faults supporting <15m OWC difference

Yielding (2002)

Published fault seal data for the Brent Province shows that most faults are sealing where the minimum SGR is >20% (0.2)

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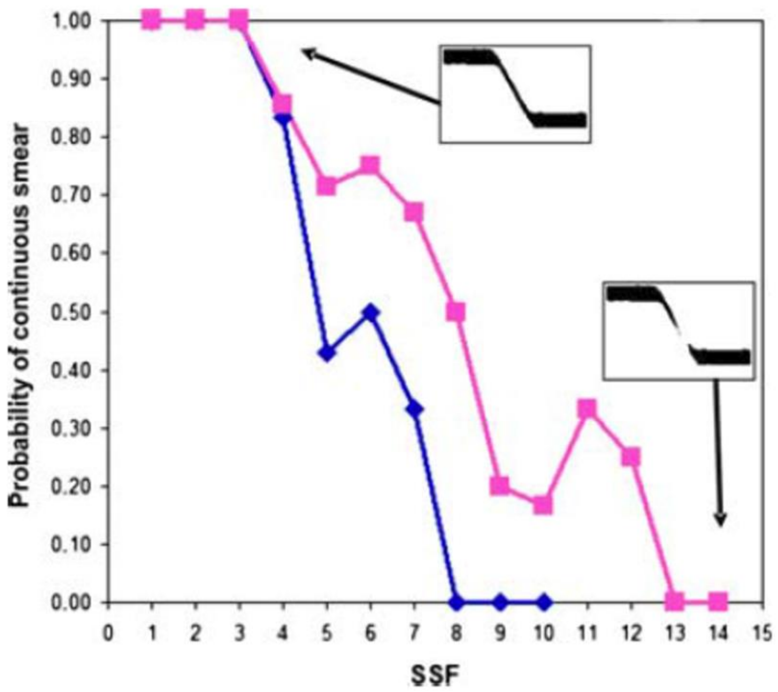
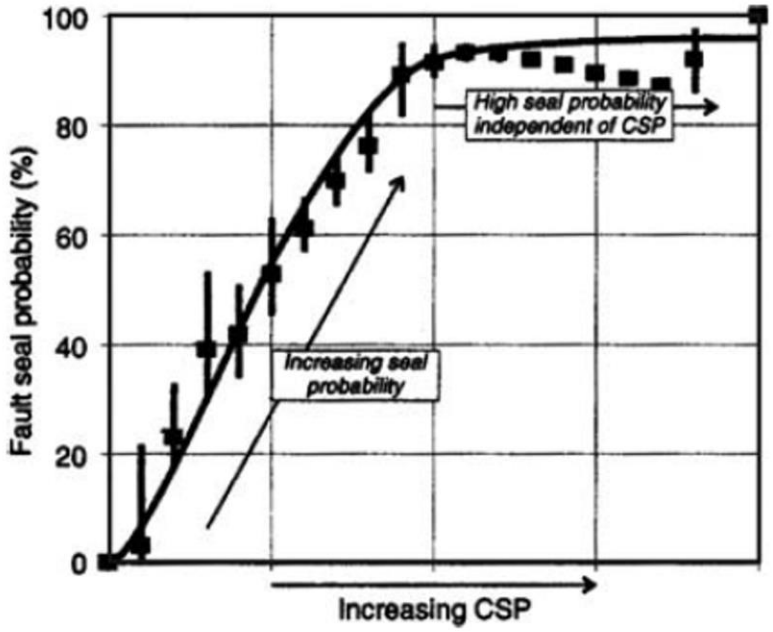
SSF & CSP calibration

SSF



Outcrop: Childs *et al.* (2007)
Experimental: Takahashi (2003)

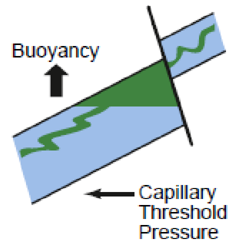
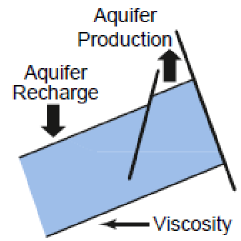
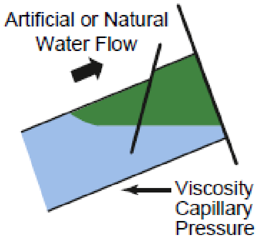
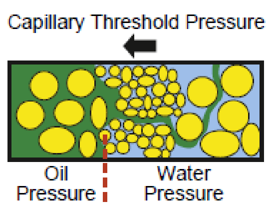
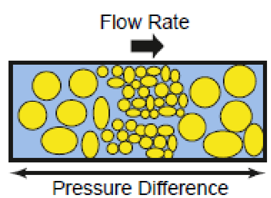
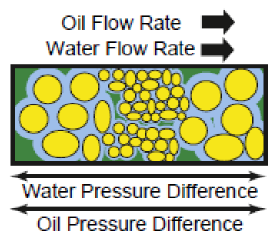
CSP



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

Yielding *et al.* (2010)

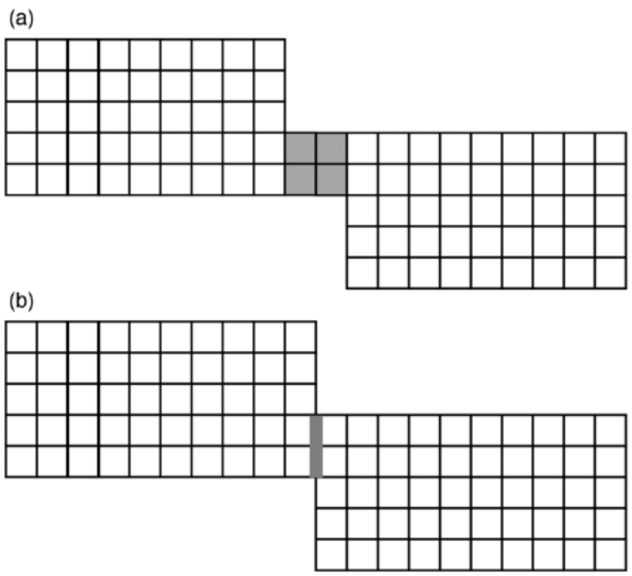
Fault seal in exploration & production

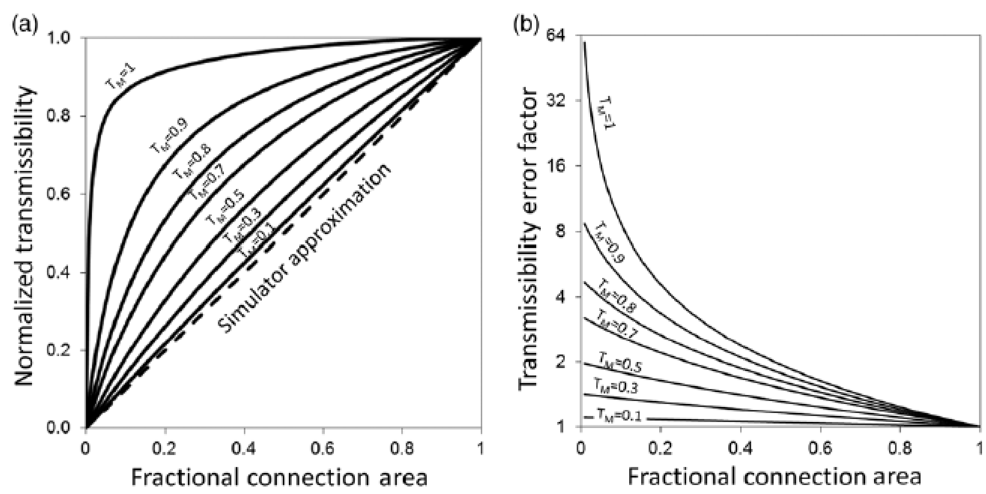
	Migration and Accumulation	Aquifer Flow	Dynamic Two-Phase Flow
Large Scale Process			
Implicit Treatment	Two Phase Static	Single Phase Dynamic	Two Phase Dynamic
Resistance	Capillary Threshold Pressure	Fluid Viscosity	Fluid Viscosities and Capillary Pressure
Small-Scale Process			
Principal Fault Rock Properties	Capillary Threshold Pressure	Permeability and Thickness	Permeability, Thickness, Relative Permeability and Capillary Pressure Curves
Governing Equations	Capillary Pressure Leakage Criterion	Darcy's Law	Two Phase Darcy's Law, Capillary Pressure
Flow-Rate (Time) Dependence	Independent	Dependent	Dependent

Manzocchi *et al.* (2002)

Transmissibility multipliers

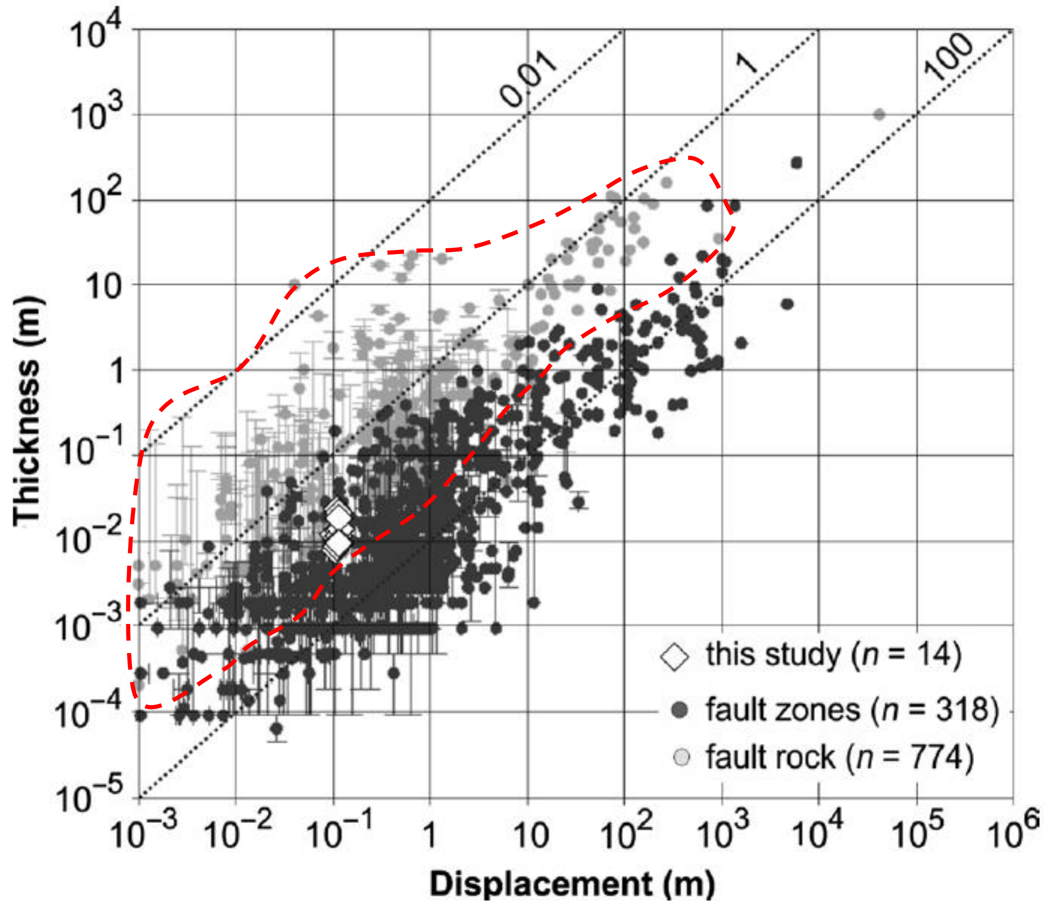
- Fault-zone properties are conventionally incorporated in production flow simulators using Transmissibility Multipliers
- Depends on fault-rock thickness and fault-rock permeability at each cell-cell connection on the fault plane
- In general, the thickness of the fault zone increases with its local displacement





Islam & Manzocchi (2017)

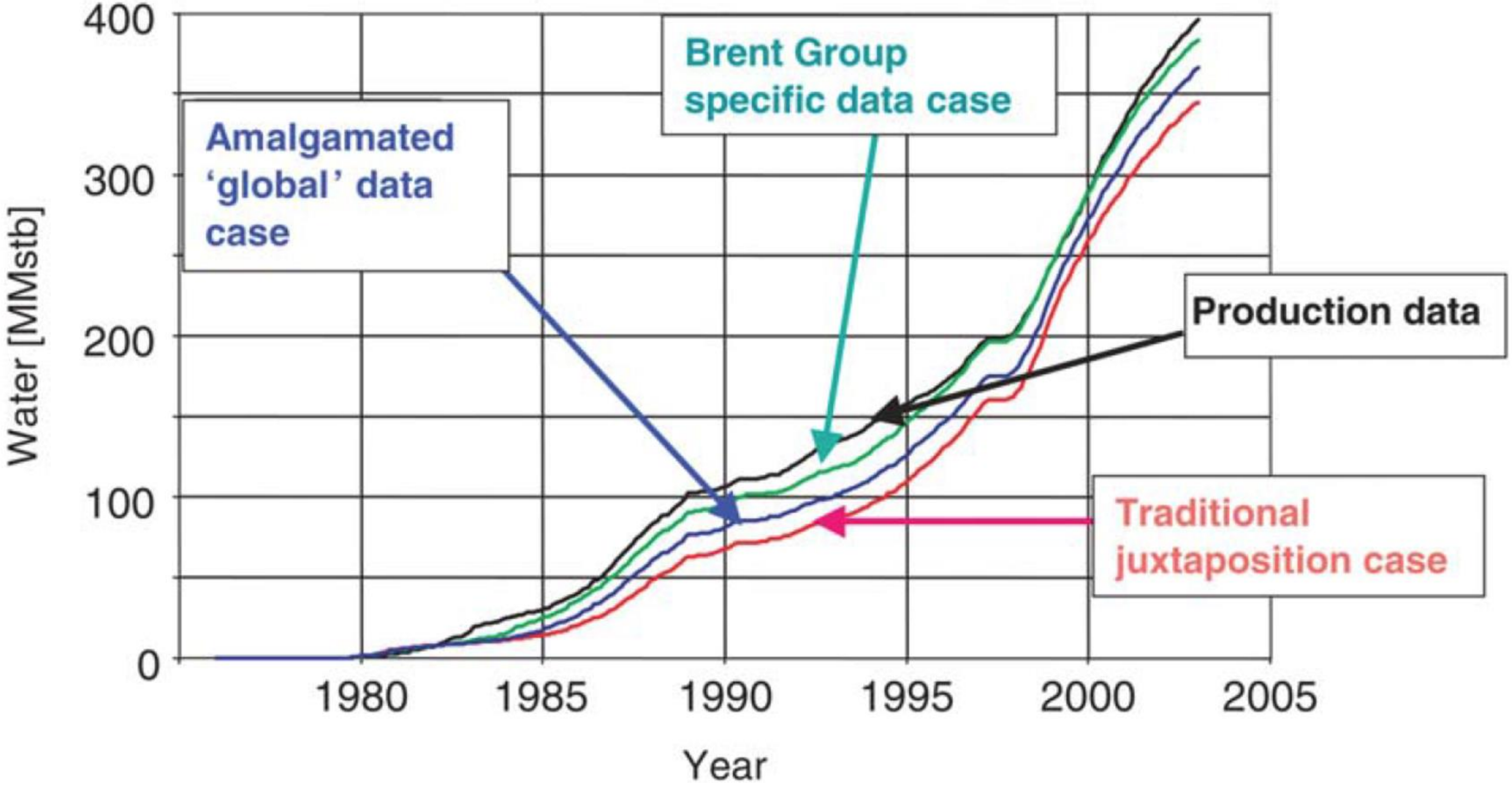
Fault zone thickness



Çiftçi *et al.* (2013)

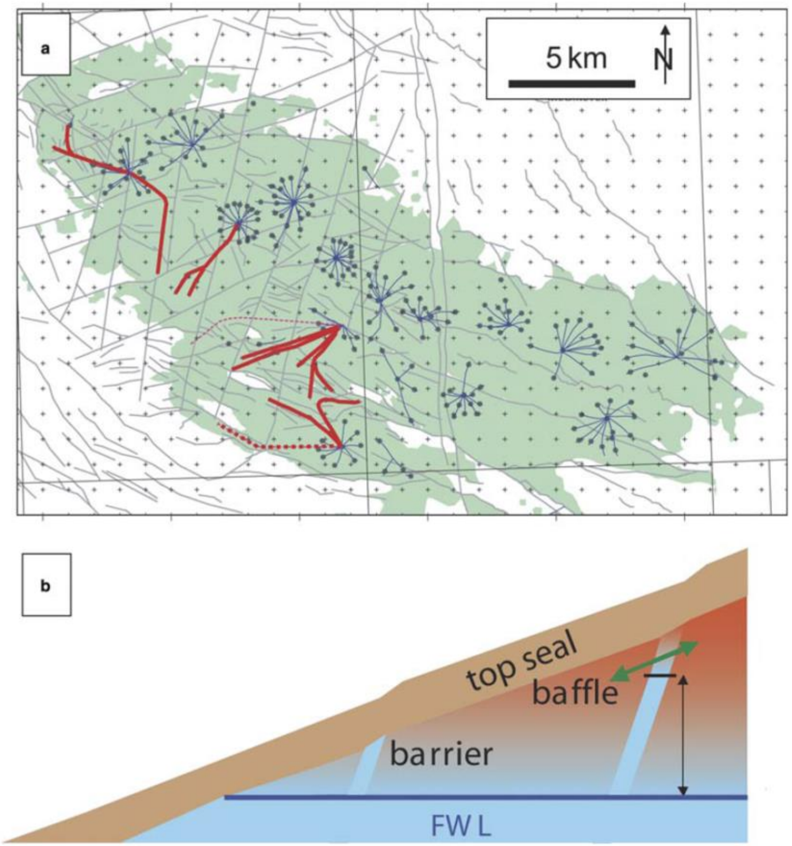
Fault zones & fault rock data from Childs *et al.* (2009)

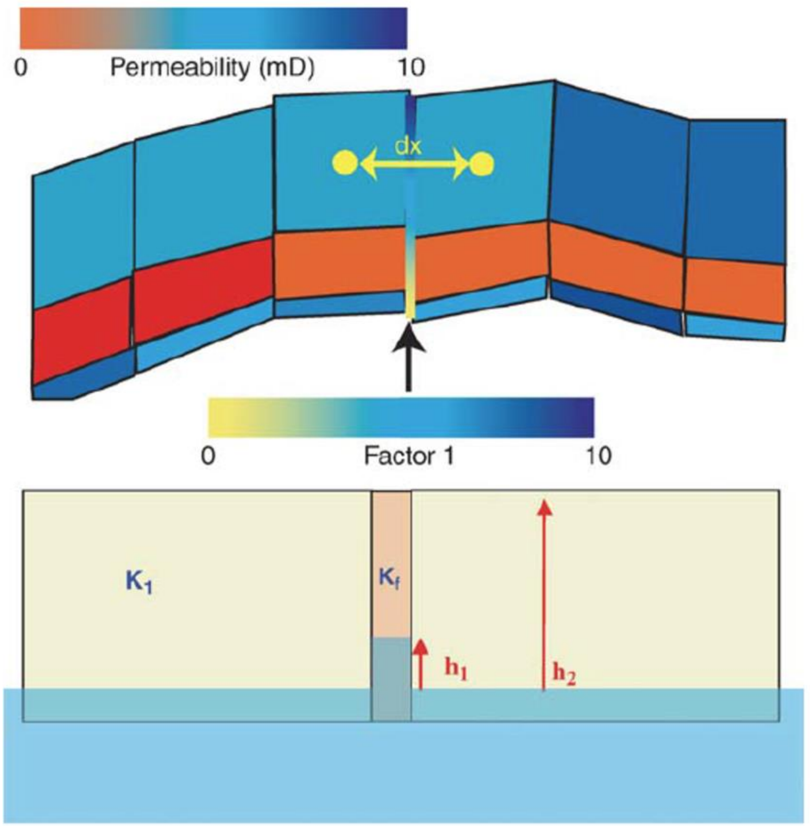
Using fault properties



Jolley *et al.* (2007)

Using realistic TM values



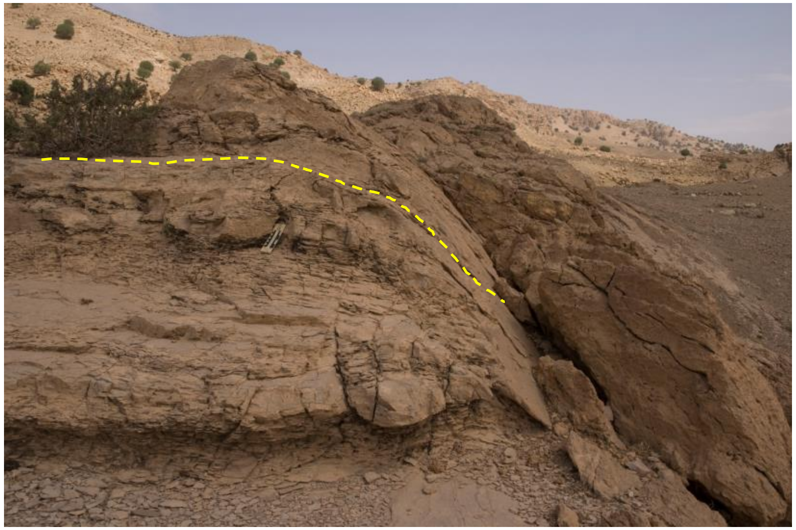


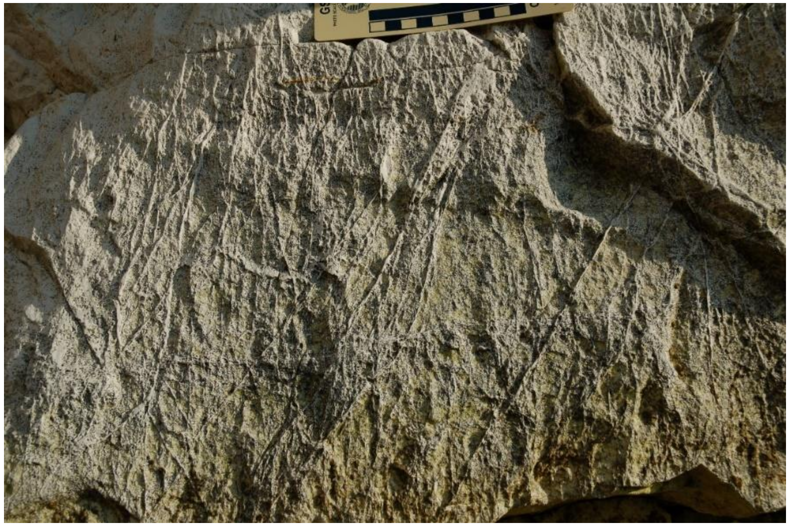
Fault Transmissibility Multiplier = $TM_r \times H_c$

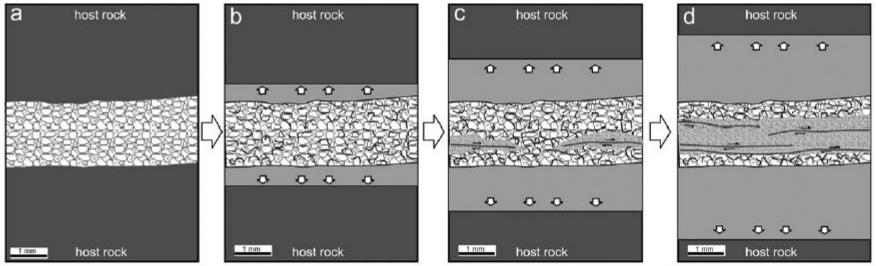
$$= \frac{K_{harm}}{K_1} \times \frac{h_2 - h_1}{h_2}$$

Zijlstra *et al.* (2007)

Carbonates





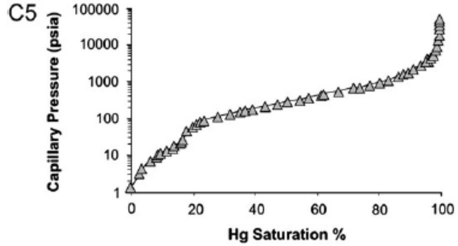


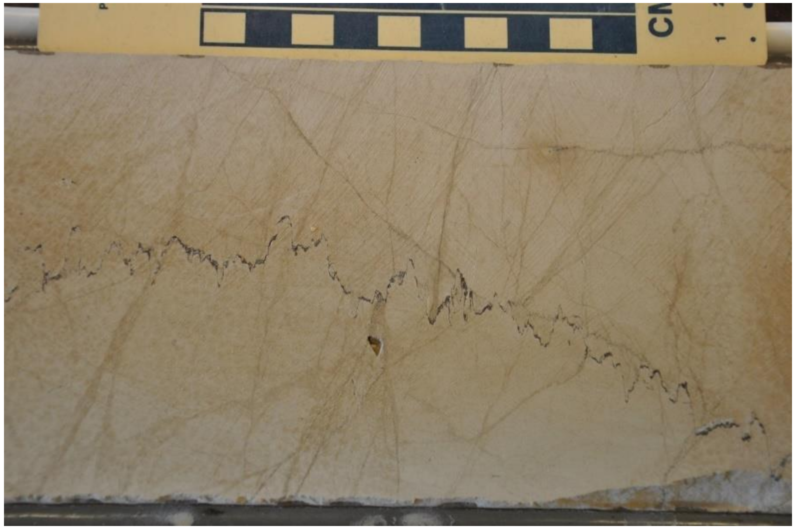
Compactive shear bands

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 discontinues
pockets of fine grained and
residual material and slip surfaces
(Zone I).
Zone III expand.

Compactive shear bands
with a vell developed
zone of fine grained and
residual material and
slip surfaces
(Zone I).
Zone III expand.





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

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