Effect of Hydrodynamics and Fault Zone Heterogeneity on Membrane Seal Capacity*

Julian Strand[1], Jim Underschultz[1], Karsten Michael[1], Brett Freeman[2], and Graham Yielding[2]

Search and Discovery Article #40404 (2009)
Posted April 21, 2009

*Adapted from oral presentation at AAPG International Conference and Exhibition, Cape Town, South Africa, October 26-29, 2008.

[1]Petroleum Resources, CSIRO, Bentley, WA, Australia (karsten.michael@csiro.au)
[2]Badleys Geosciences Ltd, Spilsby, United Kingdom

Abstract

The use of Shale-Gouge-Ratio (SGR) methods to predict across-fault seal capacity relies on a calibration of the methodology against field examples. Existing calibrations have plotted across-fault pressure difference or buoyancy pressure against in situ SGR to define a fault-seal failure envelope. Recent work on hydrodynamics and seal capacity has provided insight on fine-tuning the calibration methodologies that should in turn lead to improved fault seal capacity predictions. A situation not fully addressed, however, is the impact of fault zone heterogeneity on the hydrodynamic characteristics of a fault and thus the membrane seal capacity.

For a fault that defines a hydraulic head discontinuity at the reservoir scale, there exists a hydraulic head gradient or distribution within the fault-zone that is determined by the detailed permeability distribution within the fault zone. As a result, the capillary threshold pressure varies across the fault. When compared with the hydraulic head, the fault zone seal capacity can be estimated at various locations within the fault zone. Theoretical examination of membrane seal capacity for various permeability distributions can be used to understand parameters that control the location of the critical leak point for a membrane fault seal. This can also be extended to examine possible up-fault leakage.

A range of permeability distributions are examined for a theoretical fault zone. Assuming a given across fault pressure difference in the aquifer, the internal fault zone seal capacity is determined to demonstrate the various controls on a faults critical leak point.

www.csiro.au

Effect of Hydrodynamics and Fault Zone Heterogeneity on Membrane and Seal Capacity

Julian Strand, Jim Underschultz, Karsten Michael* (CSIRO Petroleum)
Brett Freeman & Graham Yielding (Badleys Geosciences Ltd.)

CSIRO

AAPG Int'l Conference and Exhibition, 26-29 October 2008 in Cape Town

IPETS Research Consortium on Seals

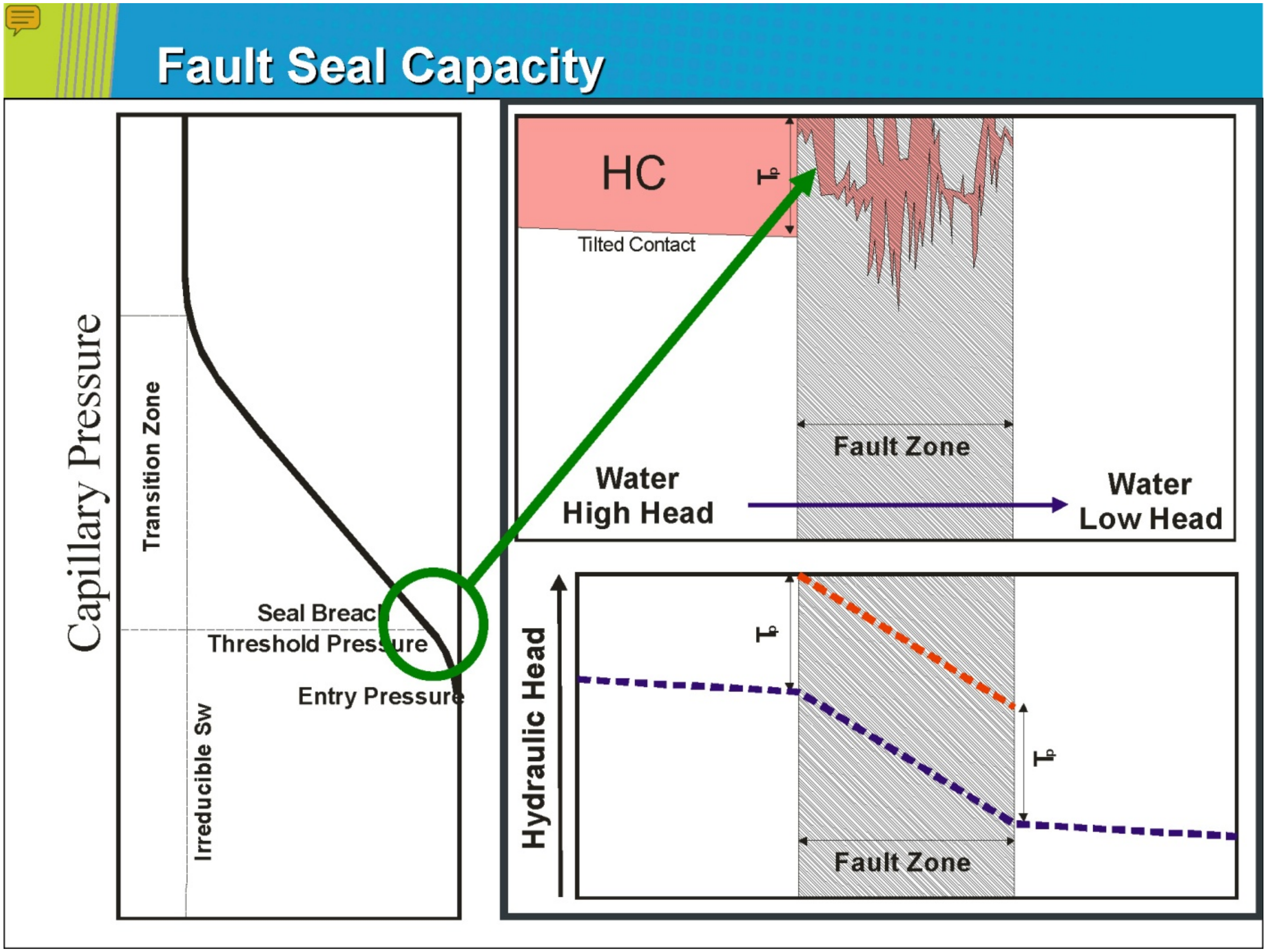
- Formation water fluid gradients and membrane seal capacity
- SGR-AFPD calibration methodologies
- Case studies of fault bound hydrocarbon accumulations
- Up-fault leakage
- Across-fault leakage
- Fault zone architecture
- In-situ stress

Sponsored by: Chevron, Origin, Anadarko, Santos, Schlumberger and Woodside

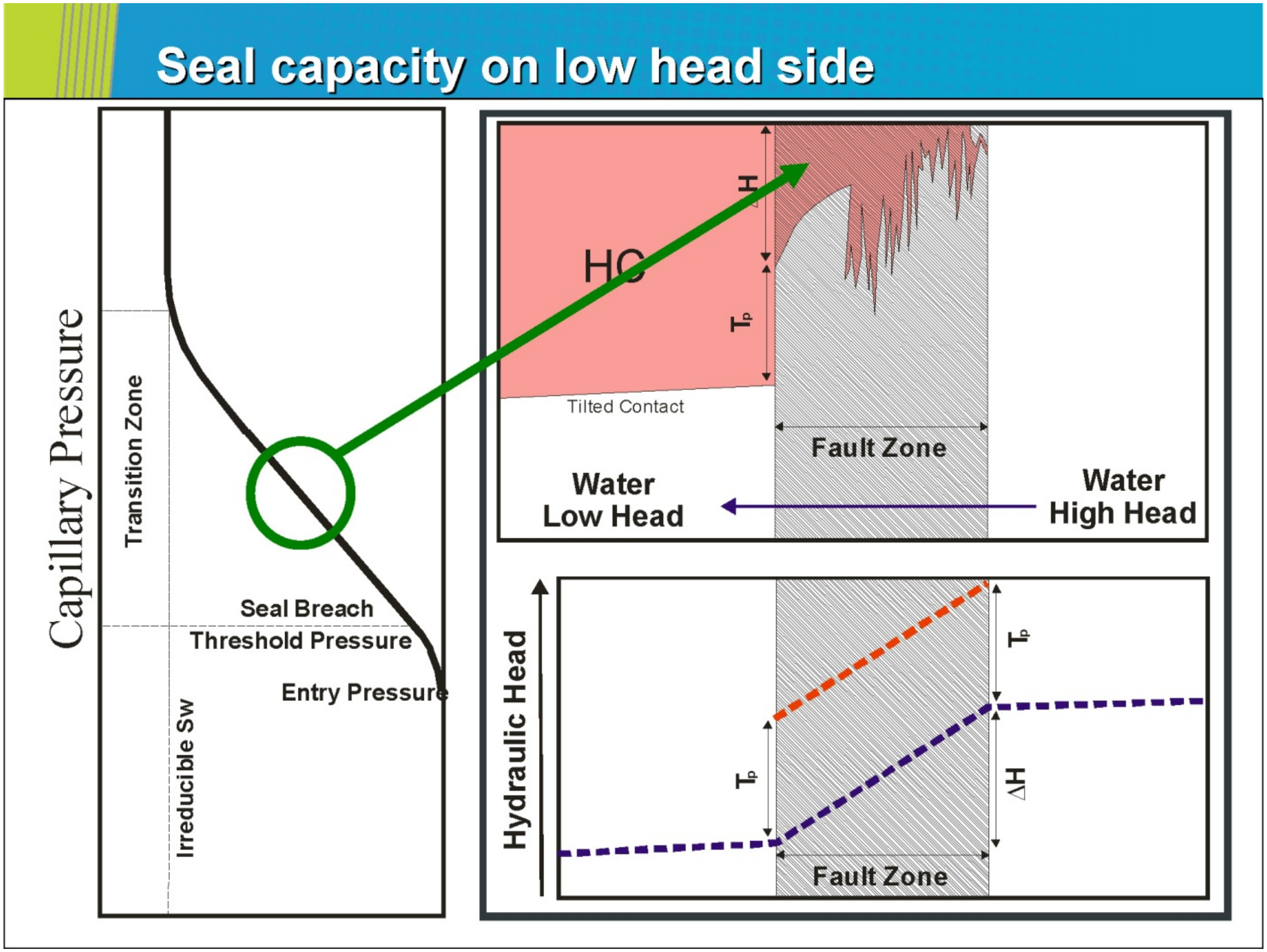
Outline

1. Review of Hydrodynamic Effects on Fault Seal Capacity
2. Implications for SGR-Buoyancy Pressure Calibration
3. “Modelling” of Lateral Fault Heterogeneity
4. Vertical versus Lateral Fault Leakage
5. Conclusions

CSIRO



Notes by Presenter:
Slide shows the case of a homogeneous fault seal with hydraulic head in the aquifer on the right less than that on the left side; i.e., excess pressure on the right hand side of the fault. As a hydrocarbon column accumulates on the left side, the hydrocarbon buoyancy pressure increases until it equals the capillary threshold. At this point, hydrocarbon enters the leftmost pores of the fault seal. The next lateral increment in the seal will have infinitesimally less excess pressure than the leftmost pores as the formation water pressure laterally through the seal is following the pressure profile shown in the lower right. This suggests that the first pores on the left of the seal are the critical part of the seals capacity and once overcome, a filament of the hydrocarbon will percolate freely and migrate across the seal. Put simply, seal thickness has no effect on seal capacity in this case. The fault seal, previously a membrane seal, becomes a hydraulic resistance seal as soon as hydrocarbon invasion commences. If we assume that any additional hydrocarbon charge is at a similar rate as leakage, the implication is that the seal will have low hydrocarbon saturation even after breach, as the hydrocarbon buoyancy pressure will never much exceed the capillary threshold pressure.



Notes by Presenter:
Slide shows the opposite case to previous slide with higher hydraulic head on the right hand side of the fault seal. As a hydrocarbon column accumulates against the seal, the hydrocarbon buoyancy pressure increases until it equals the capillary threshold. At this point hydrocarbon enters the leftmost pores of the seal. The next pores laterally within the seal will have slightly higher excess pressure than the pores to the left as the formation water pressure through the seal is following the pressure profile according to graph in lower right. This suggests that the pores at the right boundary of the fault form the critical part of the seal defining its total membrane seal capacity. In the case where excess pressure occurs on the side opposite of the hydrocarbon accumulation, a larger hydrocarbon column can be held prior to complete seal breach than that expected from the threshold pressure at the left edge of the fault.

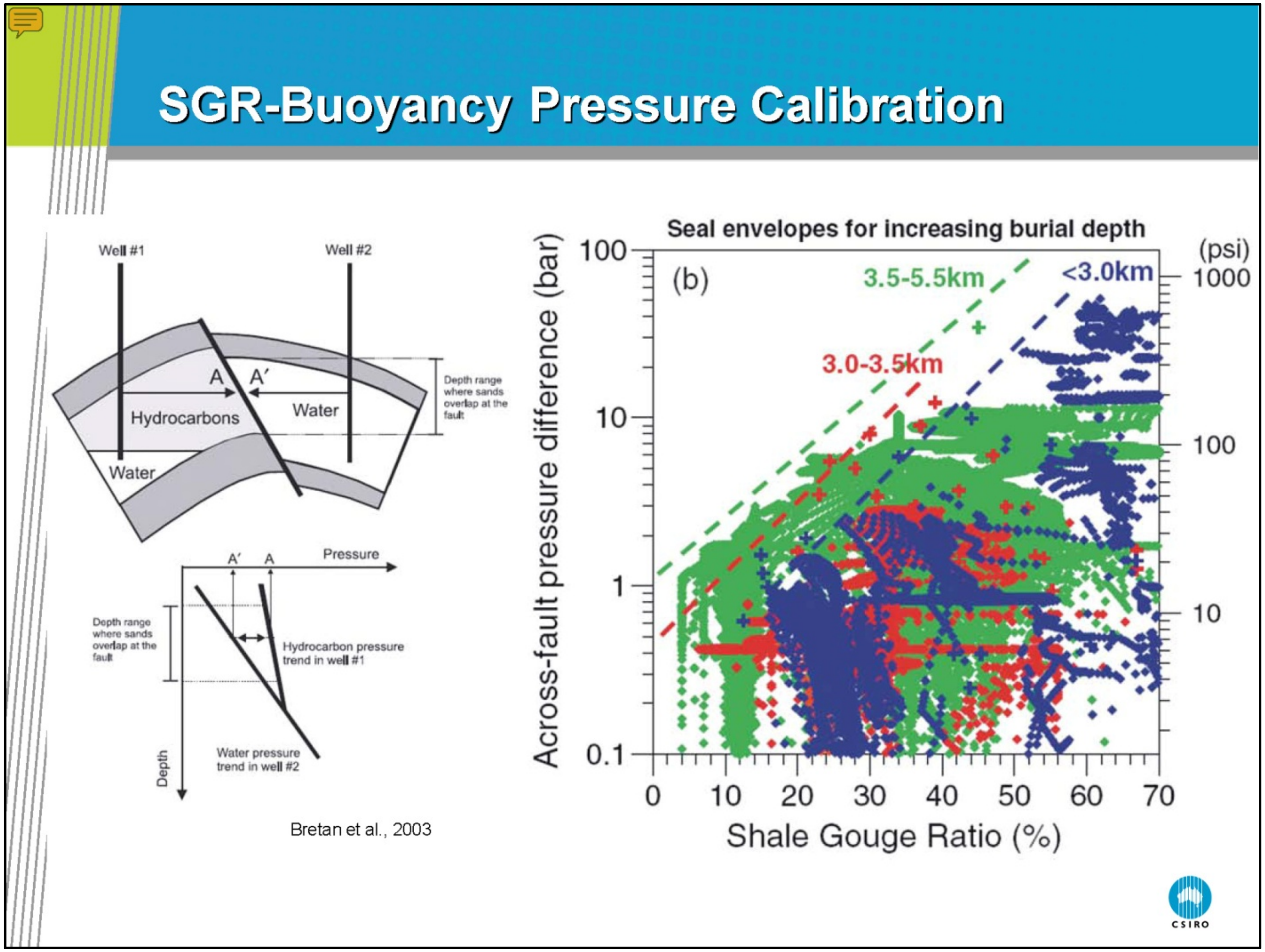
We expect a higher total seal capacity and a larger hydrocarbon column on the low hydraulic head side of a fault.

$$\Delta h = \Delta\rho \, D \,/\, \rho_w$$

Condition beyond which total membrane seal capacity increases

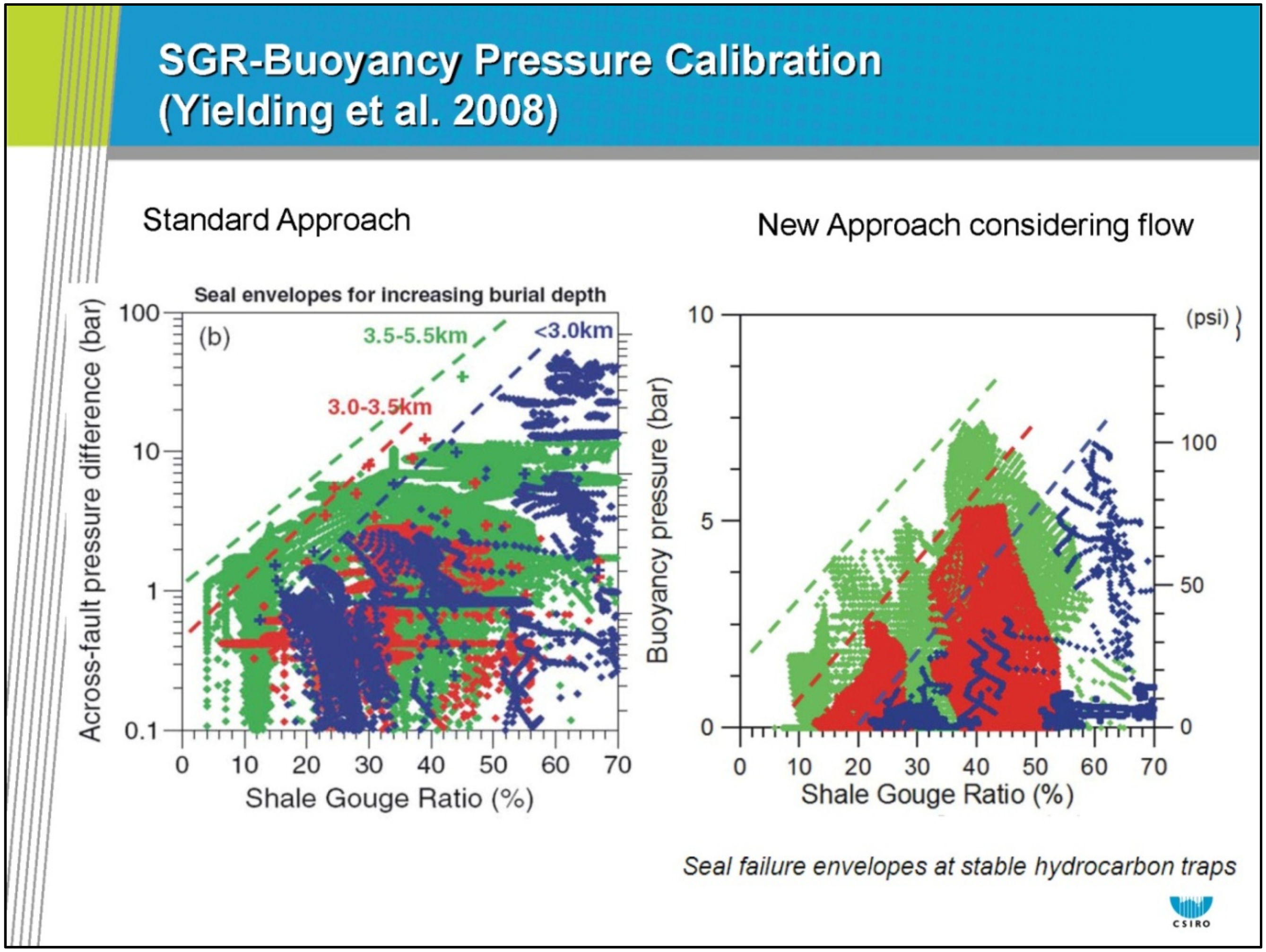
CSIRO

Notes by Presenter:
The critical hydraulic head contrast across the seal (Dh) required to match this condition can be calculated where Dq is the density contrast between the formation water and the hydrocarbon, D is the fault seal thickness and qw is the formation water density. Knowing this condition has application for exploration as excess pressure conditions exceeding that of Eqn (4) will enhance seal capacity. The Dh value is also important for seal capacity calibrations as situations with seal excess pressure less than Dh have seal capacity controlled by aquifer pressure at the FWL, while situations with seal excess pressure greater than Dh have seal capacity controlled by aquifer pressure on the high pressure side of the seal. Note that the seals most affected by the head gradient effects will be the thinnest seals (small D value in Eqn 4), where the analysis of top seal risk is most critical.



Notes by Presenter:

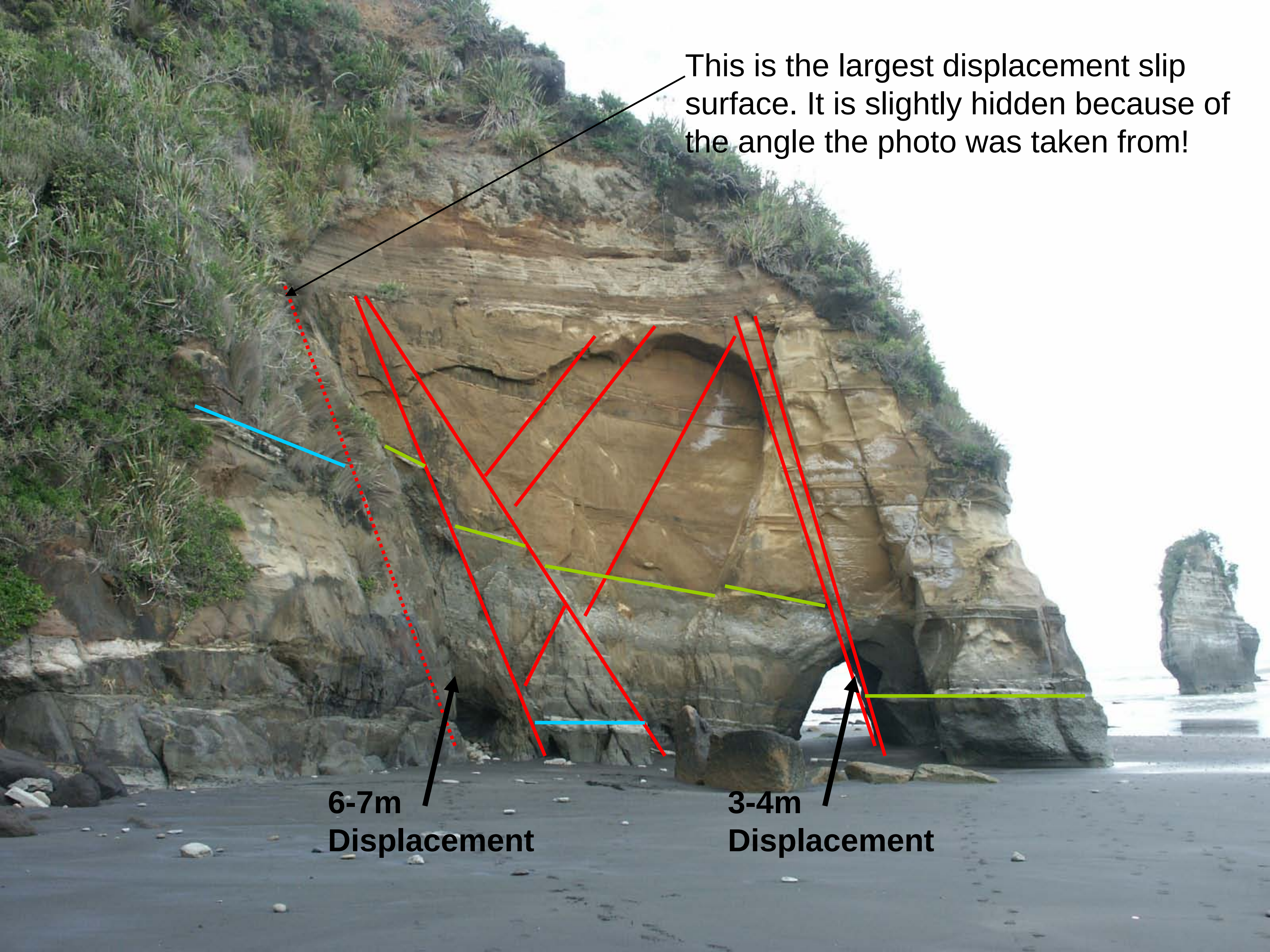
The empirical approach to faul-seal calibration (from Bretan et al 2003). The insets at left show how the across-fault pressure difference can be defined at reservoir-reservoir overlaps from data at adjacent wells. The plot at right shows a global compilation of across-fault pressure differences and their relationship to SGR at the same point on the fault surface. Data points are coloured by maximum burial depth, blue <3km, red 3-3.5km, green >3.5km. The dashed lines indicate suggested log-linear fault-seal failure envelopes for the different depth ranges.

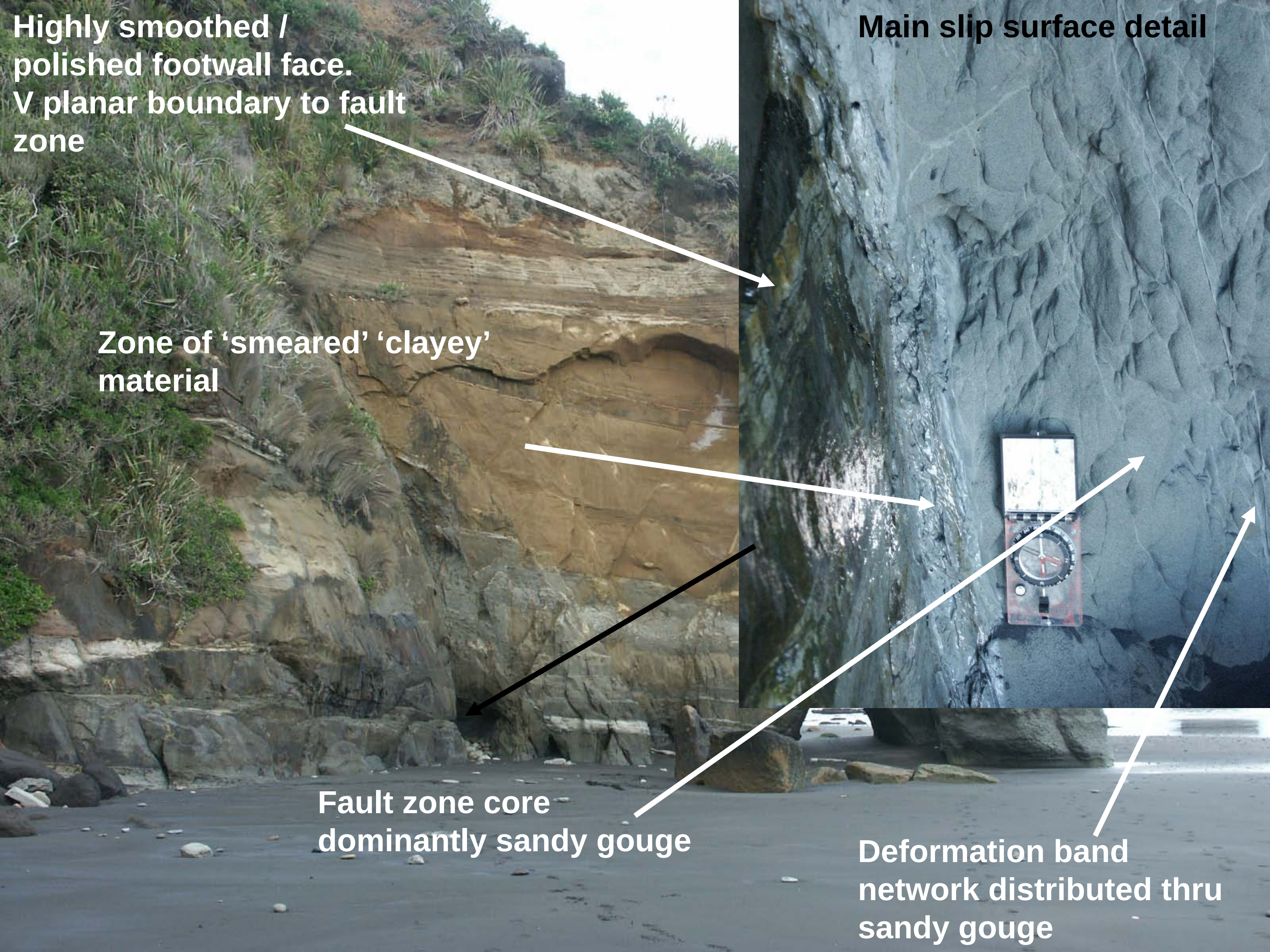


Notes by Presenter:
The cross-plot at right is subset of the subsurface data presented in right Figure, filtered to retain only true measurements of hydrocarbon buoyancy pressure (Bretan & Yielding 2005, Underschultz 2007). Data points are coloured by maximum burial depth,blue <3km, red 3-3.5km, green >3.5km. The curved lines are possible fault-seal failure envelopes.

Linear plot of the same data. Data points are coloured by maximum burial depth, blue <3km, red 3-3.5km, green >3.5km. Note that linear seal failure envelopes are consistent with the data distribution.


~5m
~12m


This is the largest displacement slip surface. It is slightly hidden because of the angle the photo was taken from!
6-7m Displacement
3-4m Displacement


Highly smoothed / polished footwall face. V planar boundary to fault zone
Main slip surface detail
Zone of 'smeared' 'clayey' material
Fault zone core dominantly sandy gouge
Deformation band network distributed thru sandy gouge

Model assumptions

What would be the impact of a heterogeneous fault zone?

Capillary entry pressure:

$$P_{ce} = 2\gamma\cos\Theta/rt$$

where γ is the interfacial tension, Θ is the contact angle of hydrocarbon and water against the solid and rt is the radii of pore throats in the cap rock.

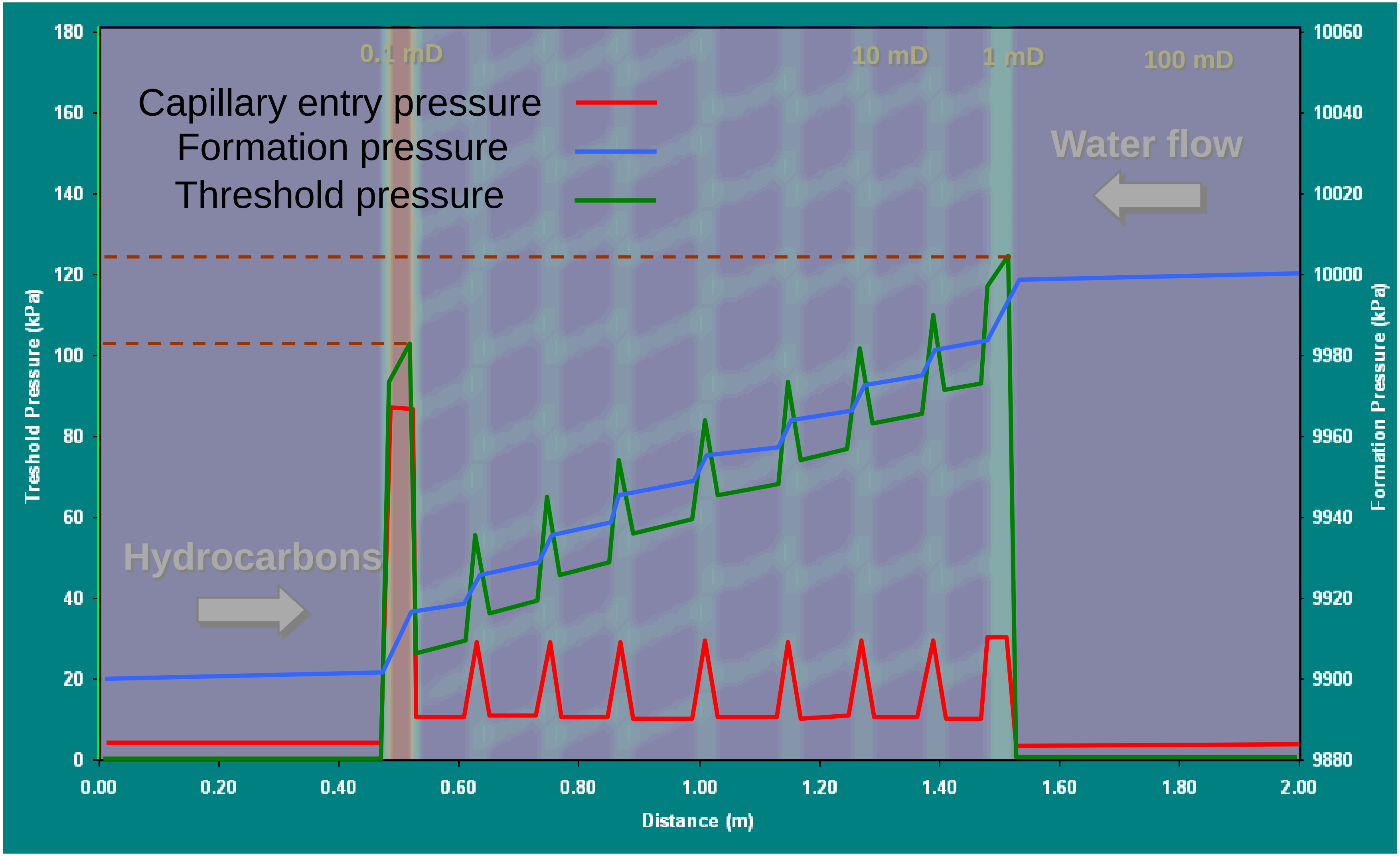
P_{ce} is dependant on permeability:

$$P_{ce} \sim 4.37 * k^{-0.4625}$$

Effective threshold pressure:

$$T_p = \Delta P + P_{ce}$$

Fault zone heterogeneity



Vertical versus lateral fault leakage

Under which conditions is vertical leakage along faults possible?

- Fault permeability is less than seal permeability;
- Favourable stress regime;
- Layered sedimentary sequences where vertical displacement is larger than seal thickness;

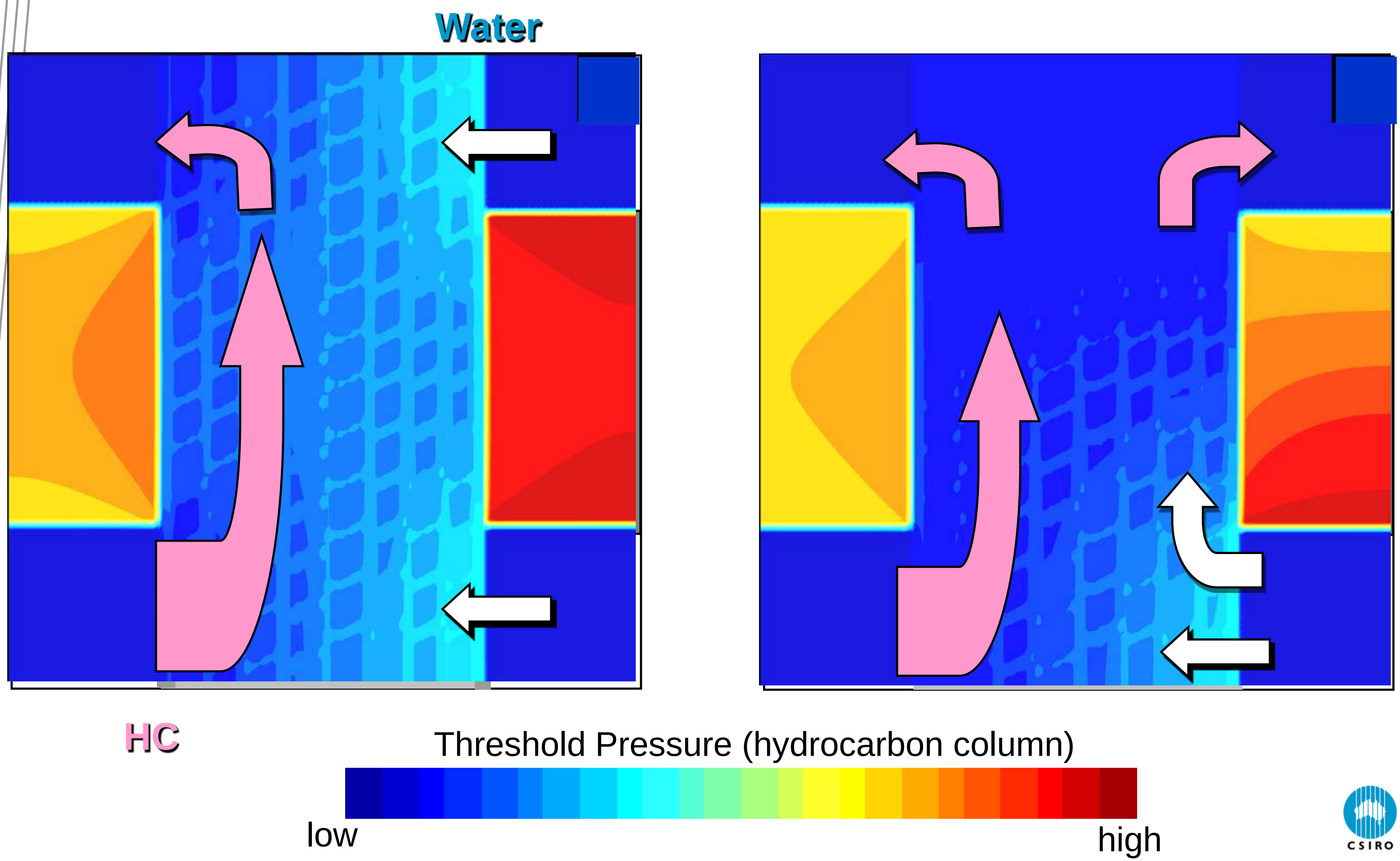
Warning:

Not all faults are leakage pathways!

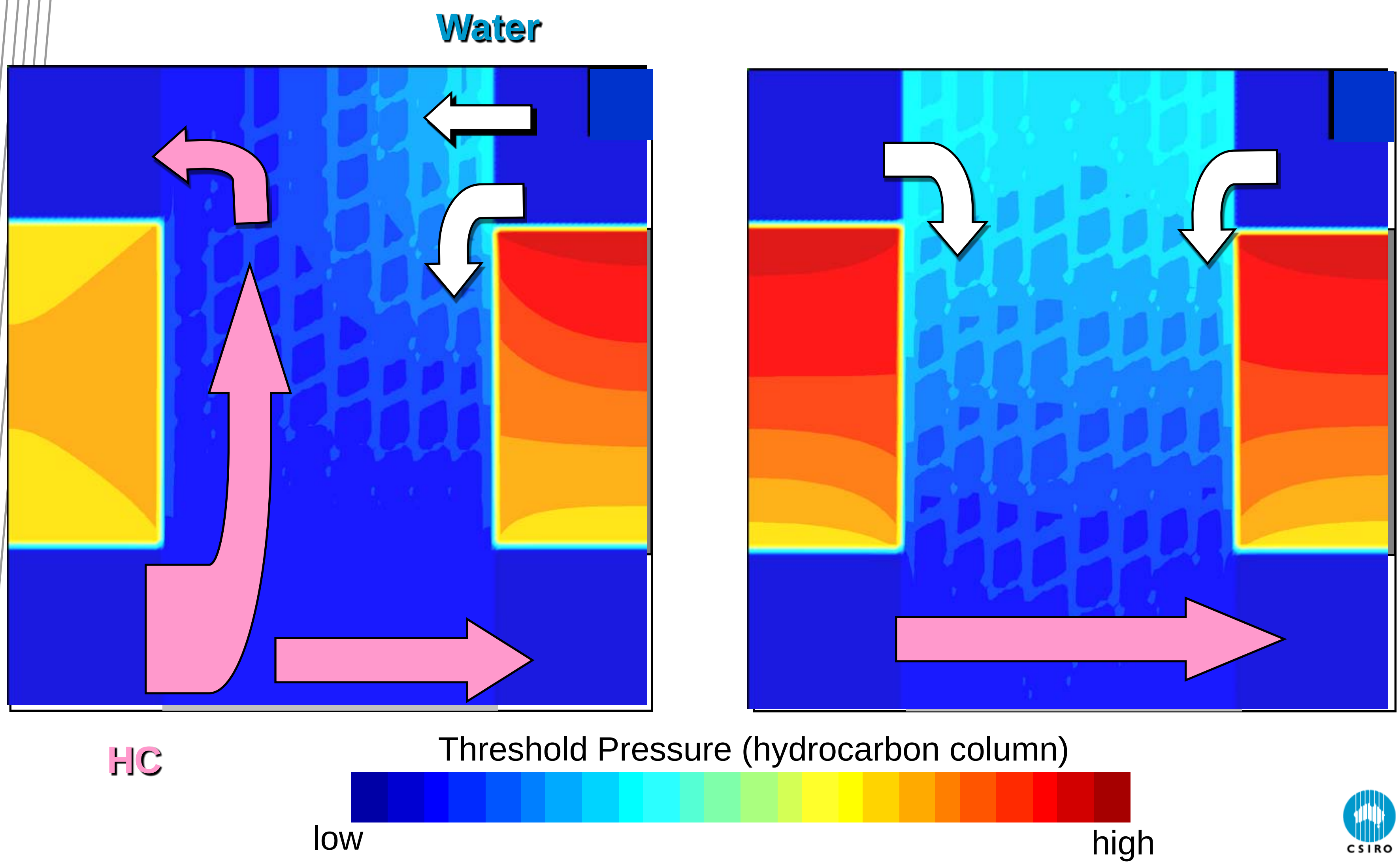
Please consult your structural geologist before making any assumptions regarding fault hydraulic properties.

CSIRO

Vertical versus lateral fault leakage



Vertical versus lateral fault leakage



Conclusions

- Lowest permeability part of the fault is not necessarily the weakest point;
- Consider fault zone thickness;
- Hydrodynamic conditions may favour vertical versus lateral leakage and vice versa, depending on the flow direction;
- Not all faults are vertical leakage pathways.

CSIRO

Thank you

Contact Us

Phone: 1300 363 400 or +61 3 9545 2176

Email: enquiries@csiro.au Web: www.csiro.au

CSIRO

References

Bretan, P. and G. Yielding, 2005, Using buoyancy pressure profiles to assess uncertainty in fault seal calibration, *in* Evaluating fault and cap rock seals: AAPG Hedberg Series, no. 2, p. 151-162.

Bretan, P., G. Yielding, and H. Jones, 2003, Using calibrated shale gouge ratio to estimate hydrocarbon column heights: APPG Bulletin, v. 87/3, p. 397-413.

Underschultz, J., 2007, Hydrodynamics and membrane seal capacity: Geofluids, v. 7/2, p. 148-158.

Yielding, G., A. Roberts, P. Bretan, B. Freeman, D. Quinn, and M. van Noorden, 2008, A review of fault seal calibration methods: AAPG International Conference and Exhibition, Cape Town, South Africa, AAPG Search and Discovery. Web Accessed 27 March, 2009
http://searchanddiscovery.net/abstracts/html/2008/intl_capetown/abstracts/468859.htm