Practical Fault Seal Modelling in HPHT Reservoirs

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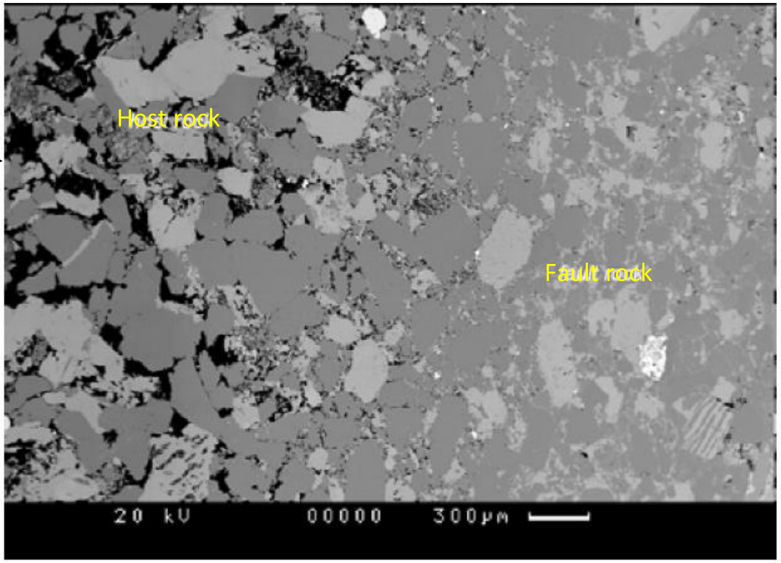
Acknowledgements

- ConocoPhillips UK Ltd & its J-block partners: Chrysaor, ENI, Chevron & Siccar Point are thanked for giving permission to give this talk
- Seismic section from Jade Field courtesy of CGG Veritas

Black=porosity



Low-clay cataclastic fault rock from a HPHT Skagerrak Field, Central Graben

The HPHT Fault Seal "Problem"

- **Paradigm**: HPHT Faults rocks have low permeability and are more sealing
  - Result of high temperature diagenetic enhancement (cementation)
- Industry standard fault seal models: calibrated to core and well data from shallower buried, cooler and often normally pressured fields/wells:
  - Northern North Sea data (e.g Sperrevik et al., 2002) – RDR dataset
  - Global data of cross-fault pressure differences (e.g. Yielding, 2002) – Badley's dataset
- Q: Should we extrapolate the published models into the HPHT realm to make seal predictions or try to derive a more local calibration?

- **Aim of Talk**:

Describe a "practical" way of estimating the permeability of HPHT faults using local well calibration

For fault seal prediction, calibration is key

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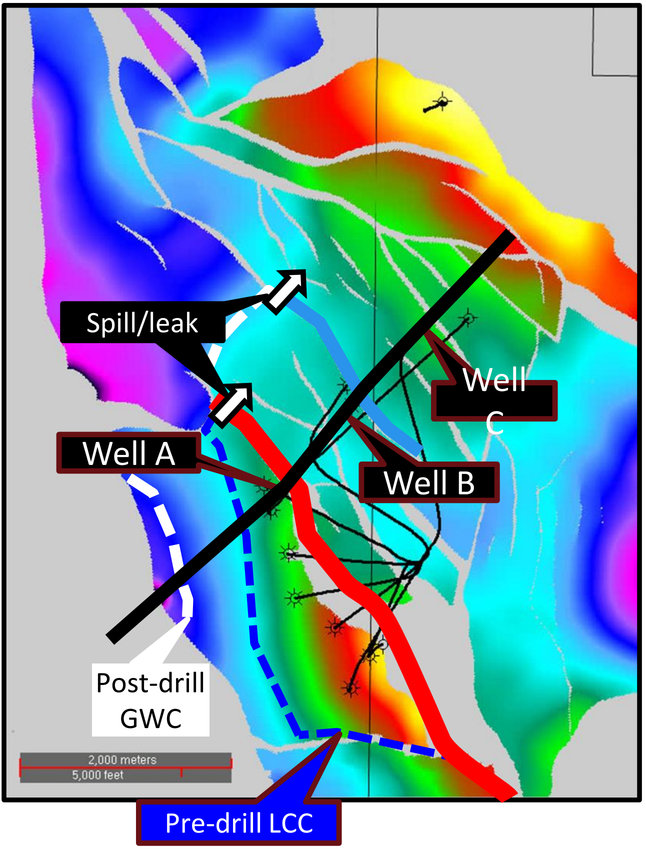
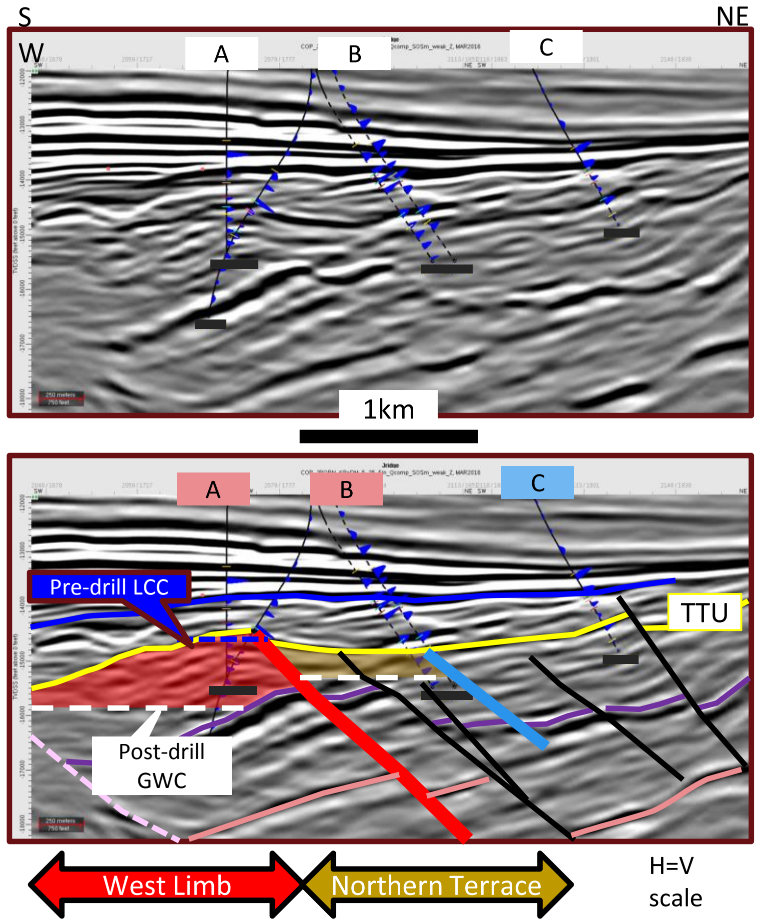
The Problem: HPHT Fault Seal, Jasmine Field, Block 30/6

Depth Map: Top Triassic Unconformity (TTU)

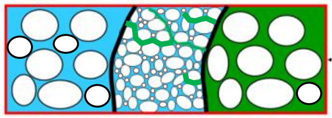




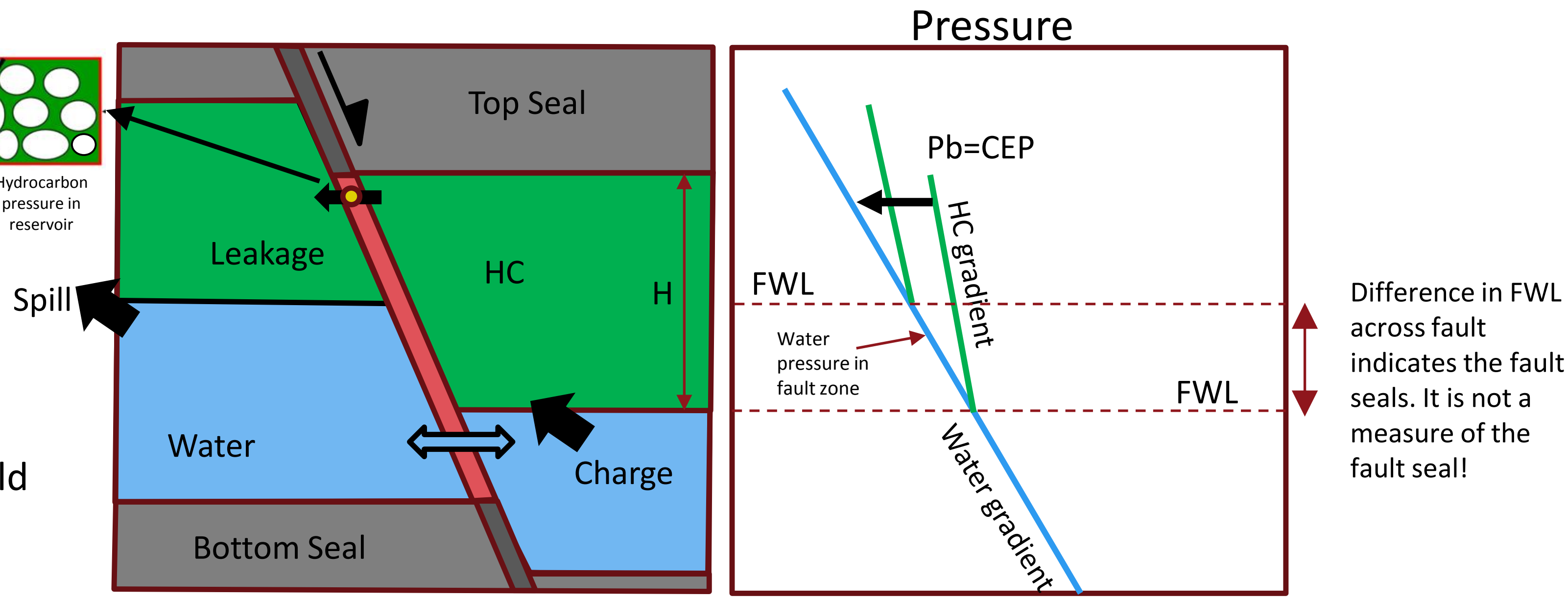
- **Jasmine Field**
- Pre-drill Expectation: No significant fault seal (eroded Red Fault)
- Pre-drill predicted column -1300ft (structure filled to unconformity spill depth)
- Well result: Column~2500ft
- Red Fault holds a column of at least 1200ft of HC by membrane seal
- Later development well C is a dry hole up-dip of well B
- Small Blue fault is sealing (holds 450ft HC column)

HPHT Fault Seal: Sometimes you win and sometimes you lose!

Fault Capillary Seal (Common aquifer)

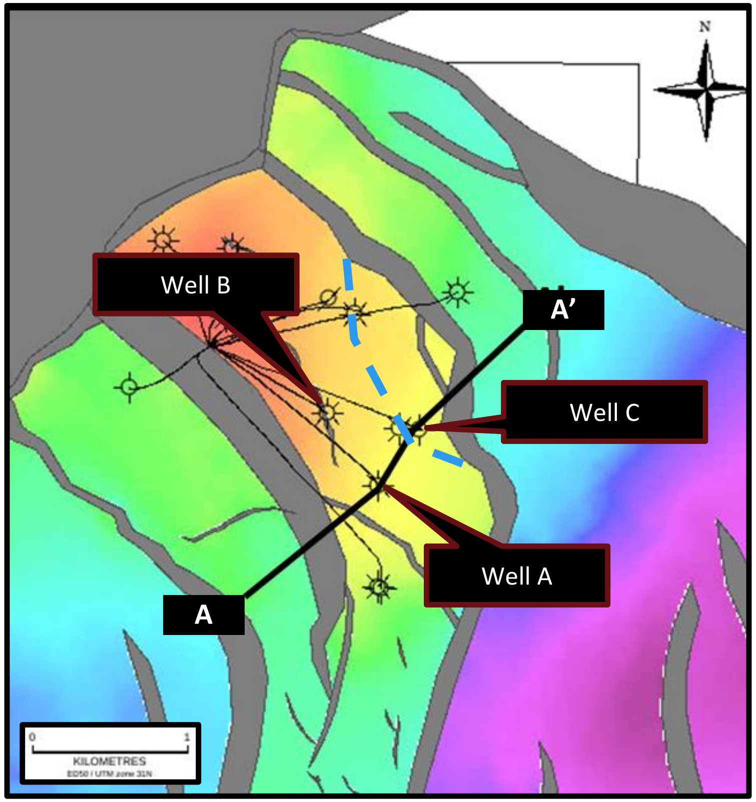


Example:
Jasmine Field

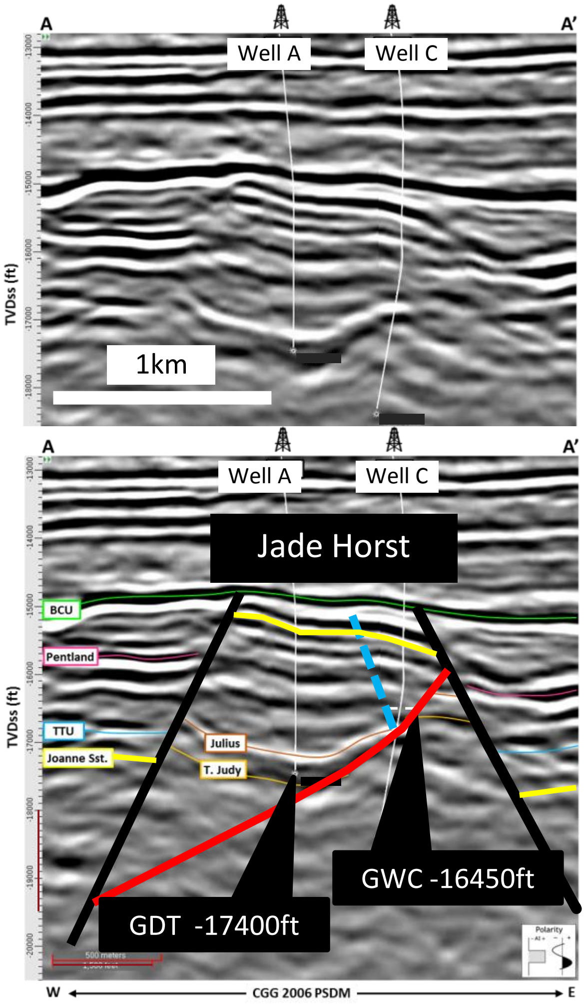


- **Capillary (Membrane) Seal:**
- A seal that holds back hydrocarbons
- Mechanism: Resistance to non-wetting fluid movement through narrow capillary pores within fault rock
- Fault leaks when the hydrocarbon buoyancy pressure (Pb) equals the **Capillary Entry Pressure (CEP)**
- Water moves freely across the fault
- The fault rock is considered part of the aquifer system (drainage occurs via capillary displacement)
- Fault block column height (H) = measure of fault seal capacity

Example 2: HPHT Fault Seal, Jade Field, Block 30/2c



Depth Map of Top Joanne Sst



H=V scale

- **Jade Field**
  - Horst with small footprint (900 acres)
- Traps a condensate column in excess of 3500ft
  - Excellent seals (top and side-seal)
- Drilled an internal well C into structure 500m from neighbouring high performance producers A & B
- Result: Encountered unexpected shallow HWC

- Poorly imaged sealing fault (dashed blue line) holding ~1450ft HC column
- Well C has been poor producer and shows no direct connection to either well A or B

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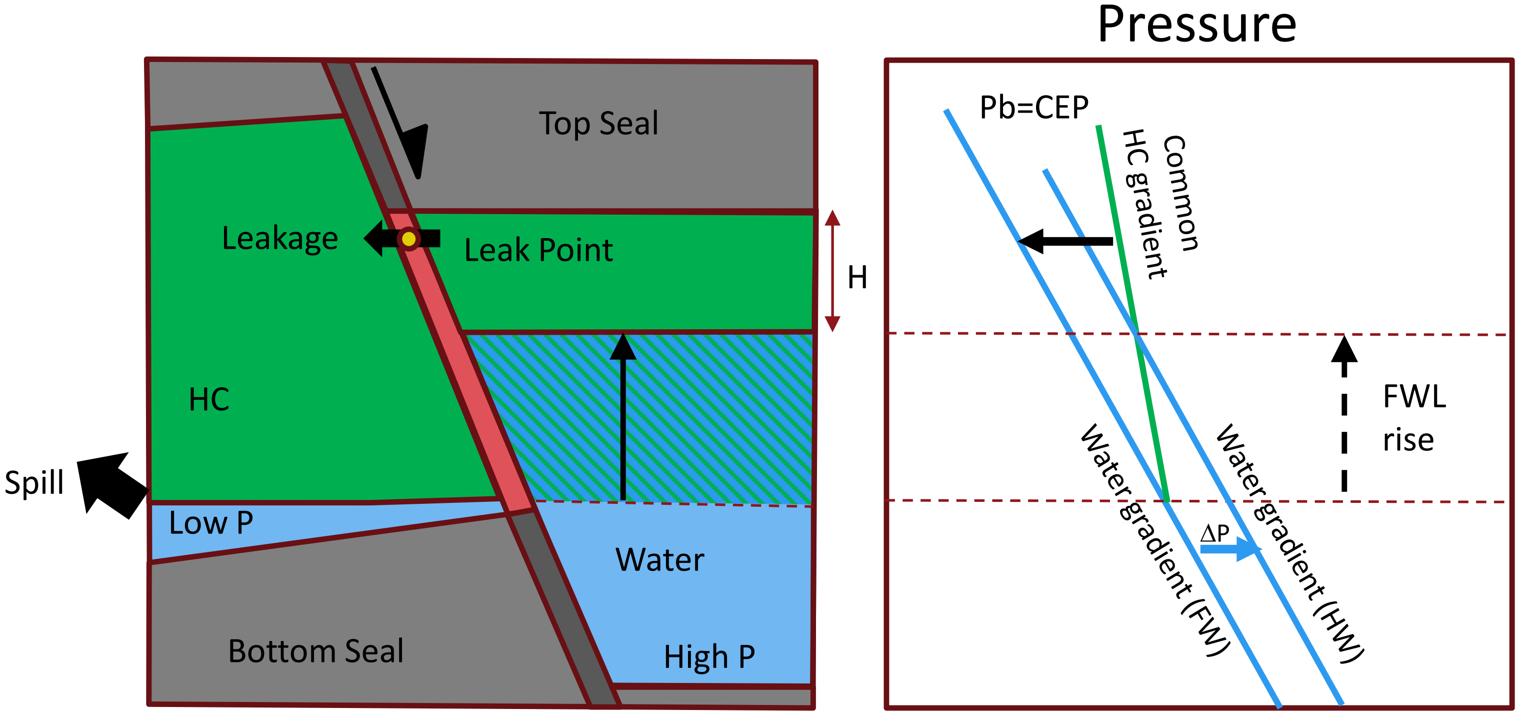
Hydraulic (Permeability) Seal



- Overpressure develops after charge
- Results in water-drive leakage (Heum, 1996)

Explanation for Jade Field

- Low permeability in fault rock prevents aquifer pressure equalisation (yields hydraulic seal)
- The fault seal capacity remains Pb (referenced to the FW)
- A rise in aquifer pressure reduces the fault-trapped column height in the higher pressure fault block (by cross-fault leakage (i.e. U-tubing))
- CEP hung off lower pressure aquifer
- Fault block column height (H) =measure of fault seal capacity

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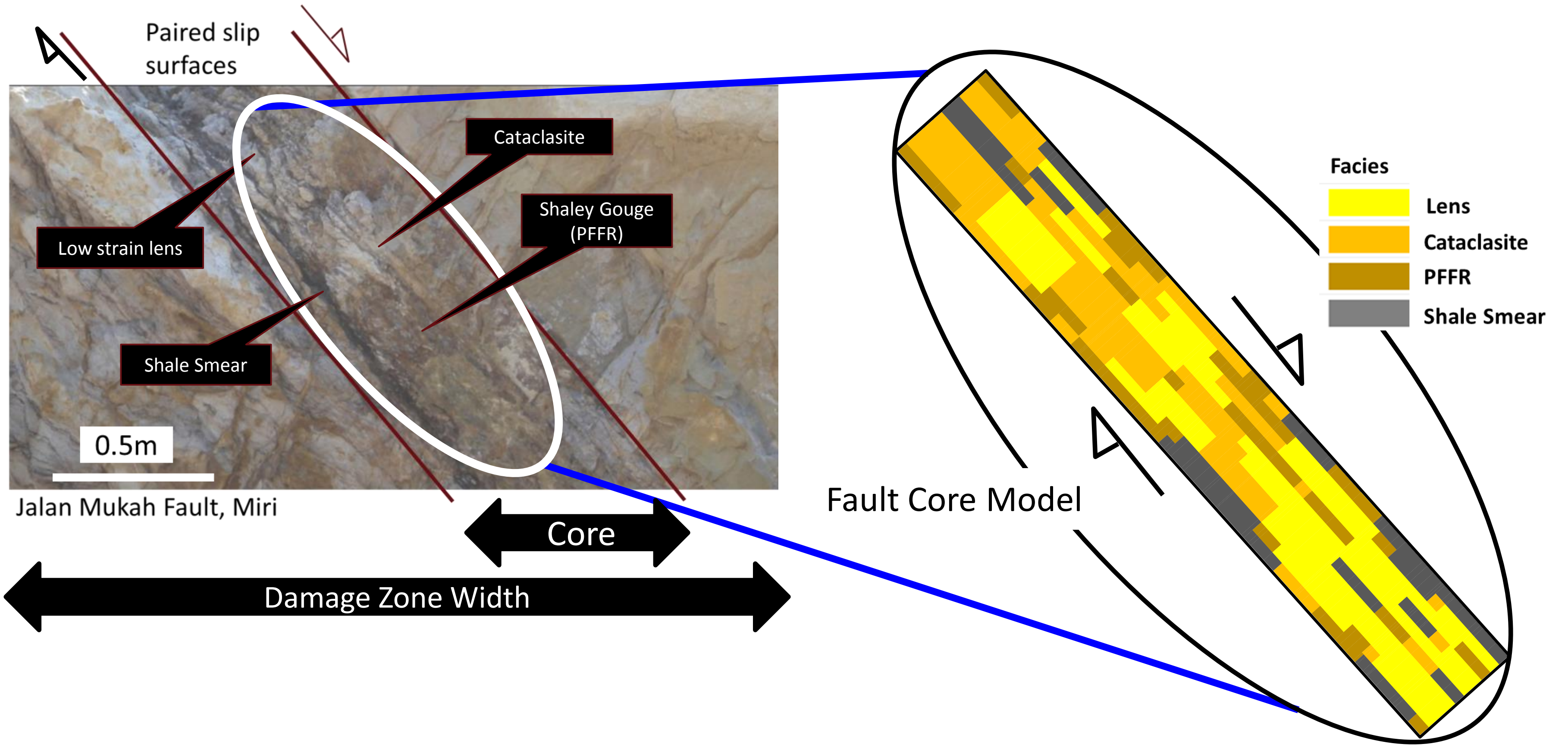
A Stochastic Model Representation of a Fault Core

Fault core: The localised zone of intense deformation that accommodates most of the fault displacement



"The Stochastic Model"

- Represent fault core with a **fault rock object model**
- Fault Facies objects are randomly distributed
- Properties assigned to objects: length, permeability, thickness, Vshale

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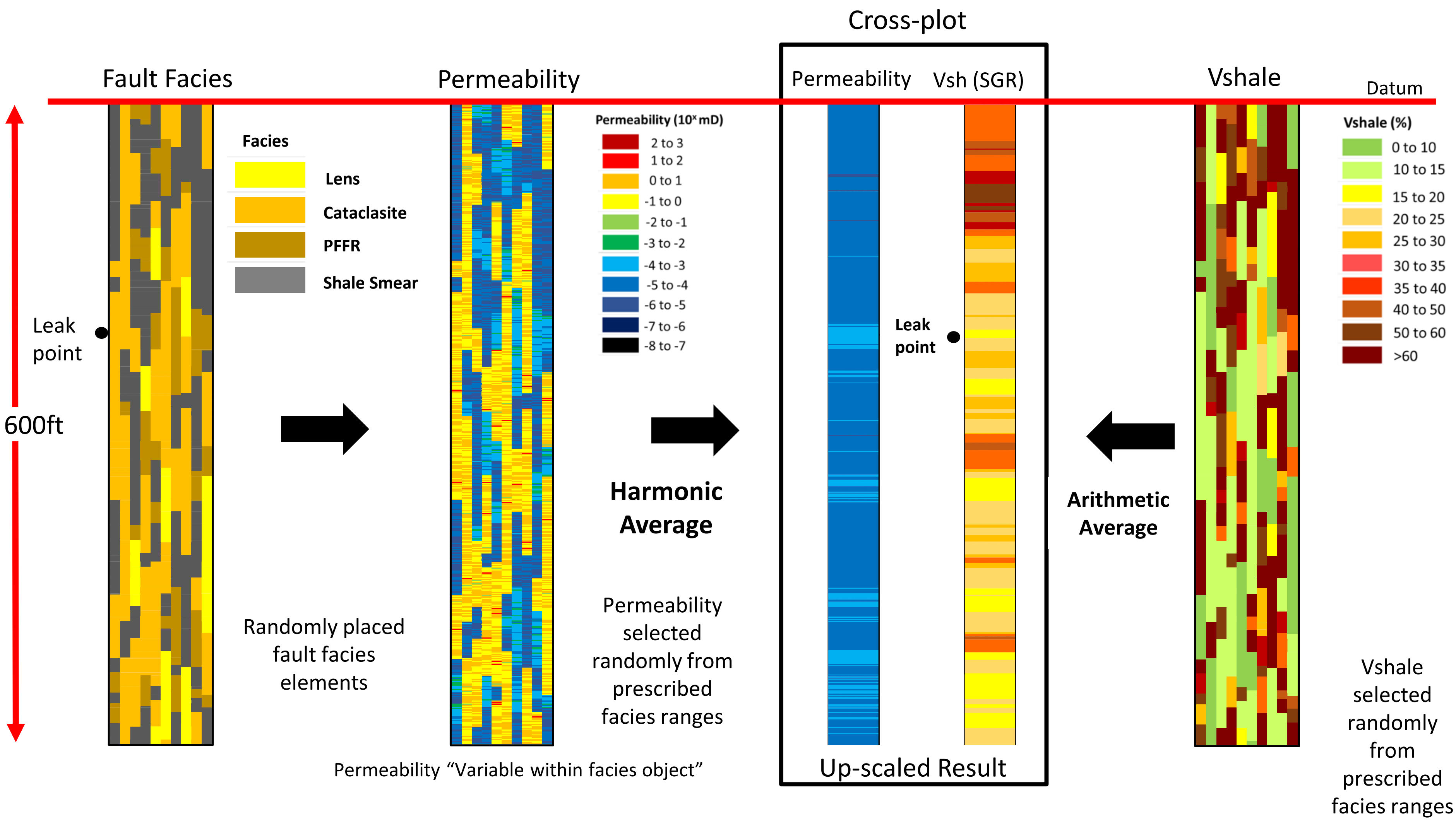
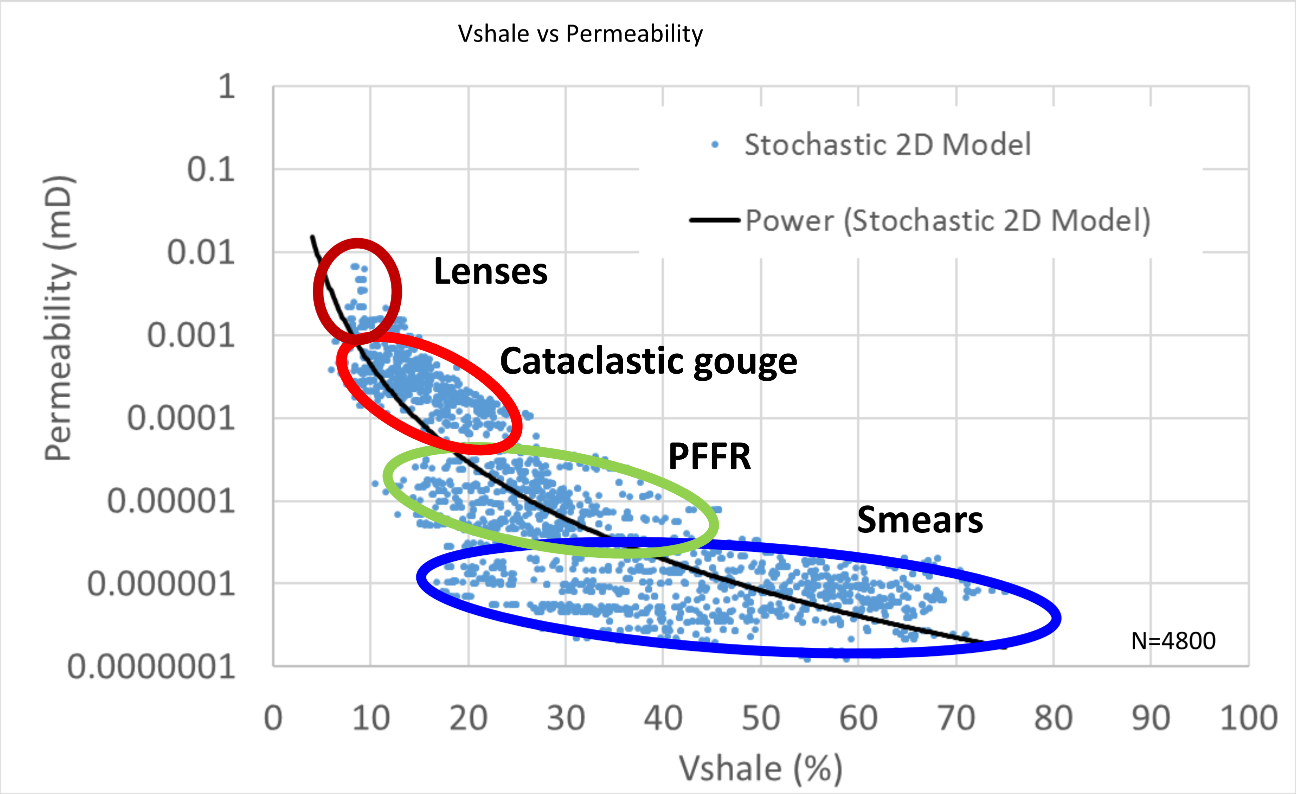
Simple 2D Stochastic Fault Facies Model: Outputs



2D Stochastic Fault Facies Model Results



- Multiple models with variable fault facies proportions.
- Clustering shows **dominant** component affecting up-scaled permeability in fault model
- Approximate power law relationship between Vsh and k

Can this scattered trend be simplified?

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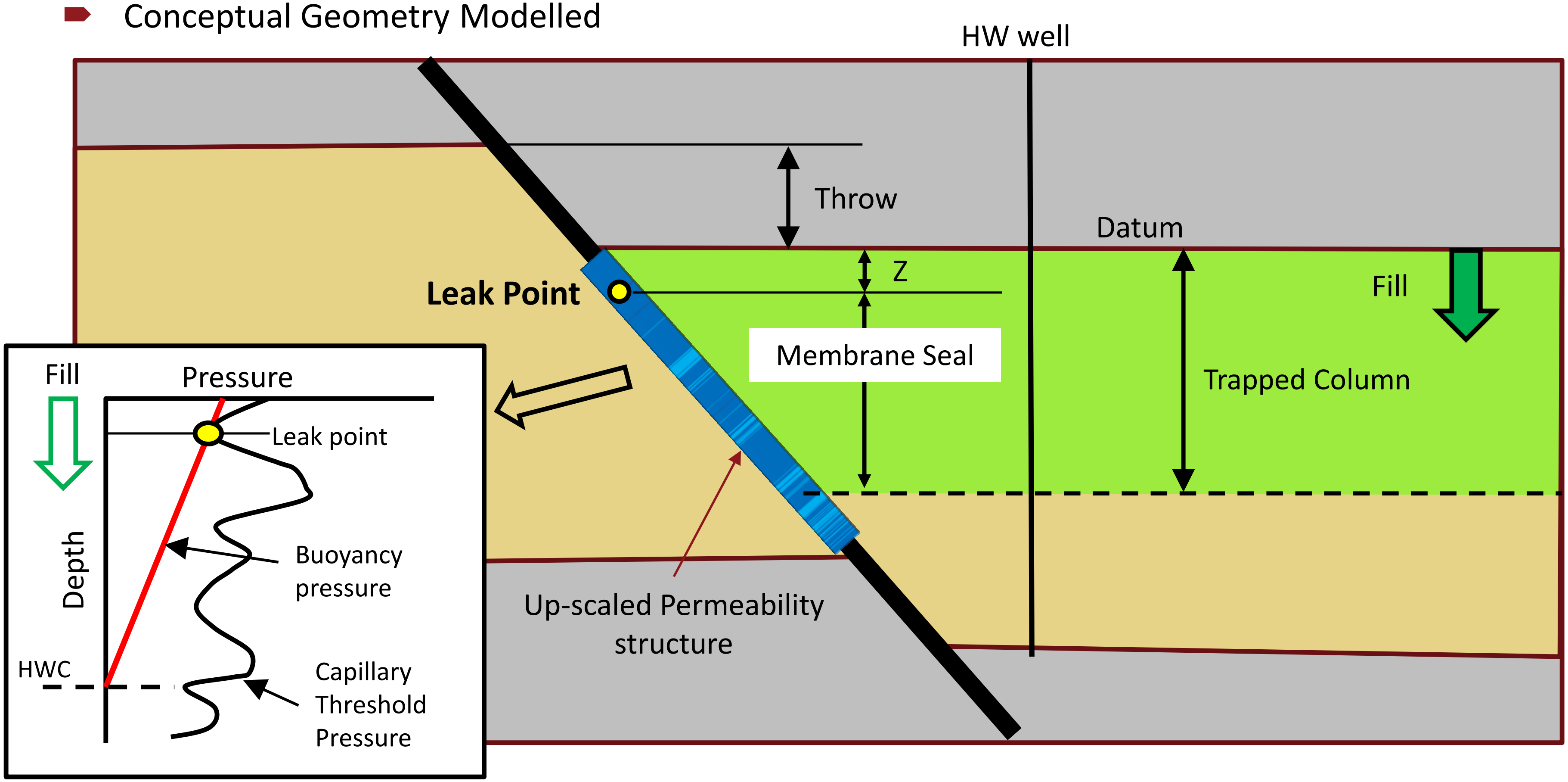
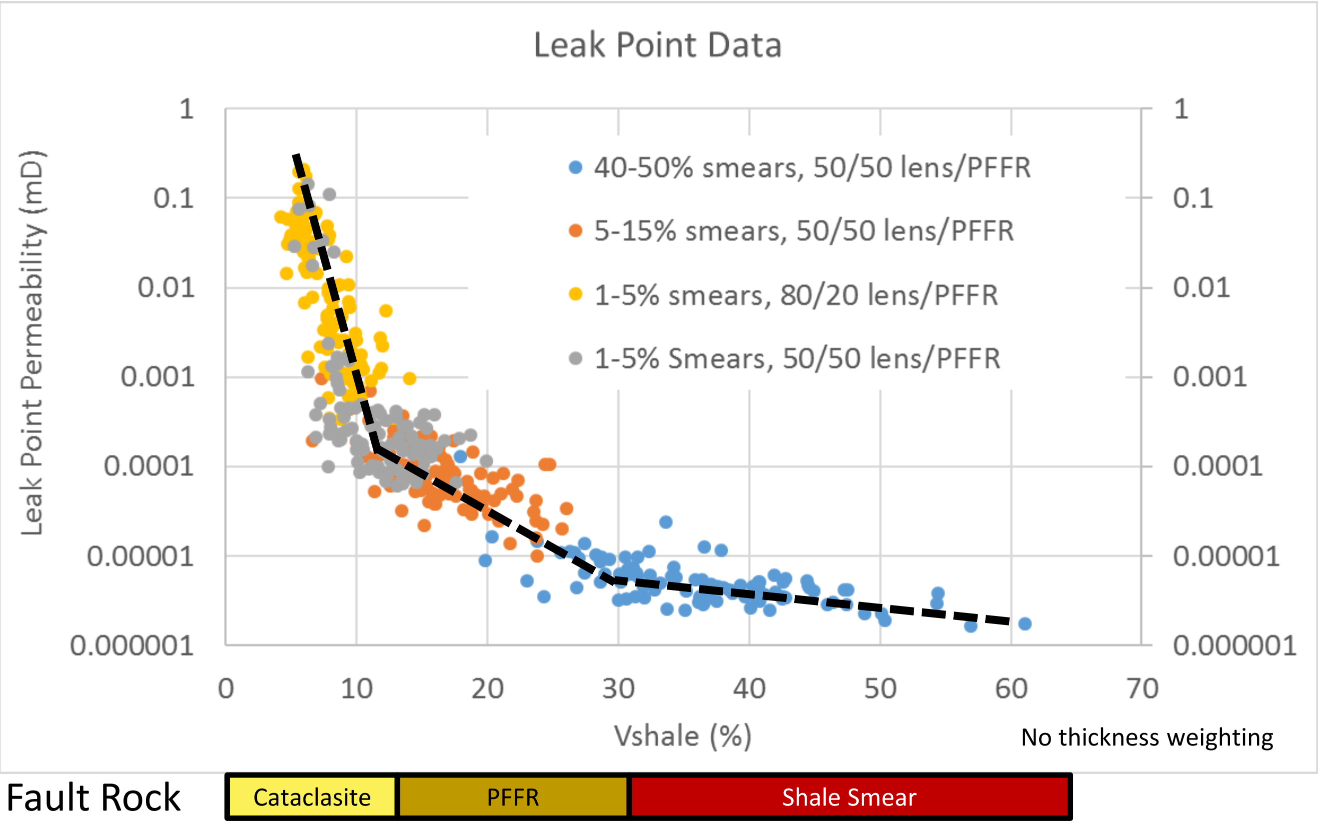
Application to calculating Fault Seal: The leak point

- Conceptual Geometry Modelled



- Column is assumed to be trapped in HW (no juxtaposition seal contribution)
- Downward filling from datum
- Trapped column = Membrane Seal + Leak point Depth (Z)
- Membrane Seal calculated from fault permeability
- Leak point = depth that traps minimum column below the datum

Leak point results from multiple stochastic model realisations



- Leak points define a Log-linear “tripartite dog-leg model” between Vshale and permeability
- Trends reflect the discrete control imposed by different fault rock facies on the permeability as Vshale increases
- Shale smear permeability values calculated from Yang & Aplin (2010)

Yang, Y. & Aplin, A.C., 2010. A permeability-porosity relationship for mudstones. Marine and Petroleum Geology, **27**, 1692-1697.

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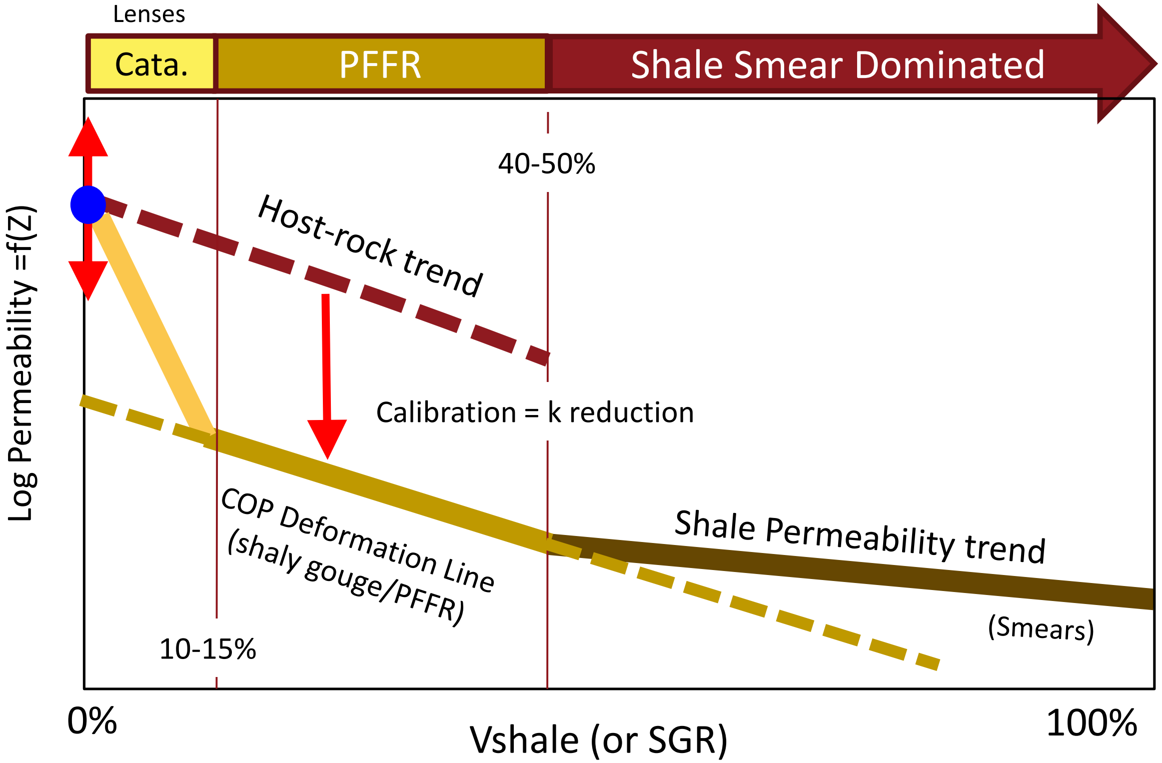
Summary Model for Fault Zone Permeability for clastic faults



- **Tripartite "dog-leg" permeability-Vshale model**:
  - Low Vshale (0-15%): Cataclasites.
    - Large uncertainty range in permeability between host rock and fault gouge
  - Vshale (SGR) 15-40%: Shaley Gouge (PFFR).
    - Log-linear trend linking to shale permeability. Permeability magnitude reduced from host rock by reduction factor (~-4)
  - Vshale>40%, shale permeability dominant (smears)

Fault Permeability Calibration = Deformation adjustment (PFFR reduction factor)
Cataclasis trend adjusted according to depth burial for fault movement

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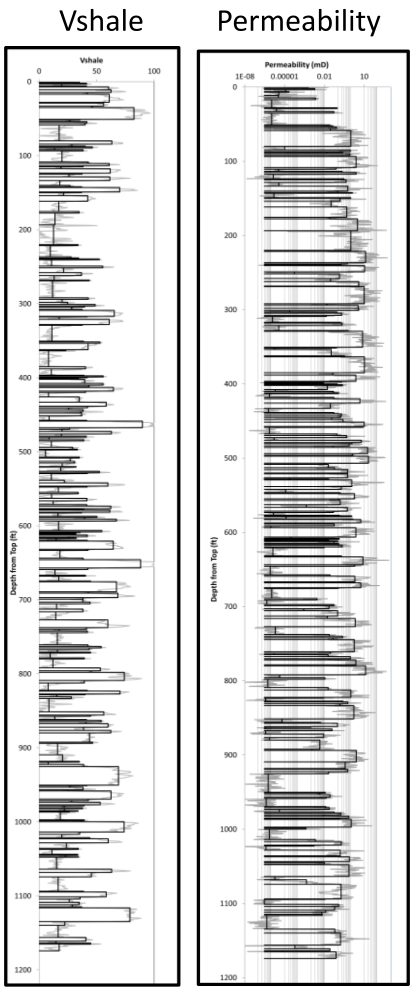
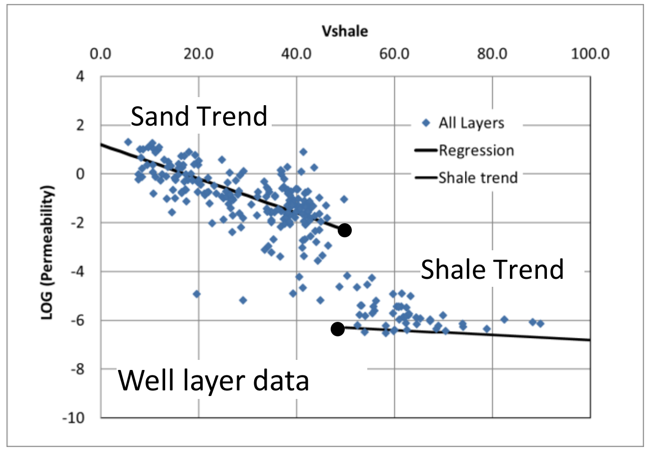
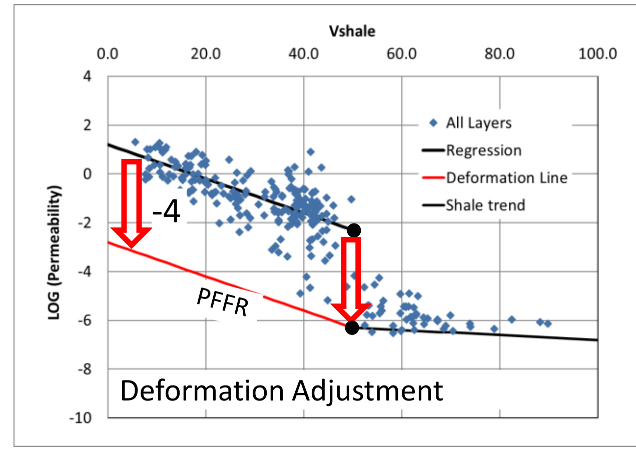
How to link the model to well data: The "COP Local Deformation Line (LDL) Model"

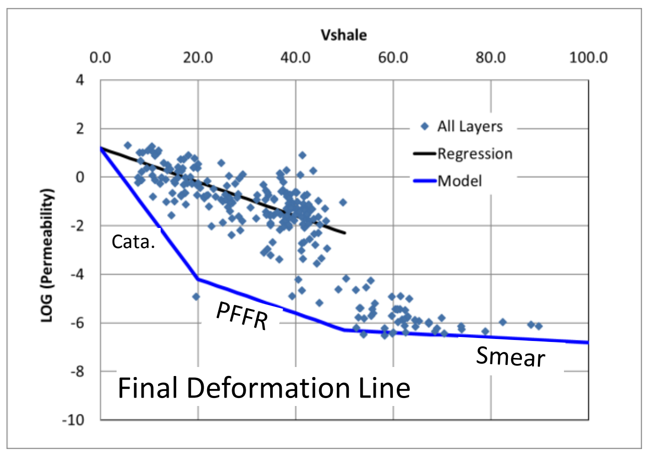
- Fault permeability model anchored directly by well data

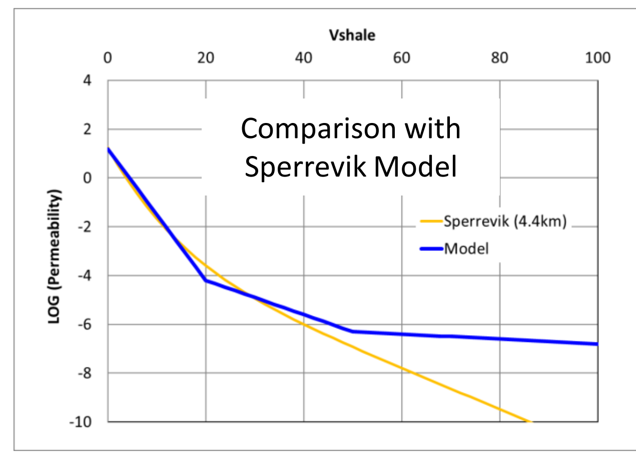


Layer models based on facies discriminators

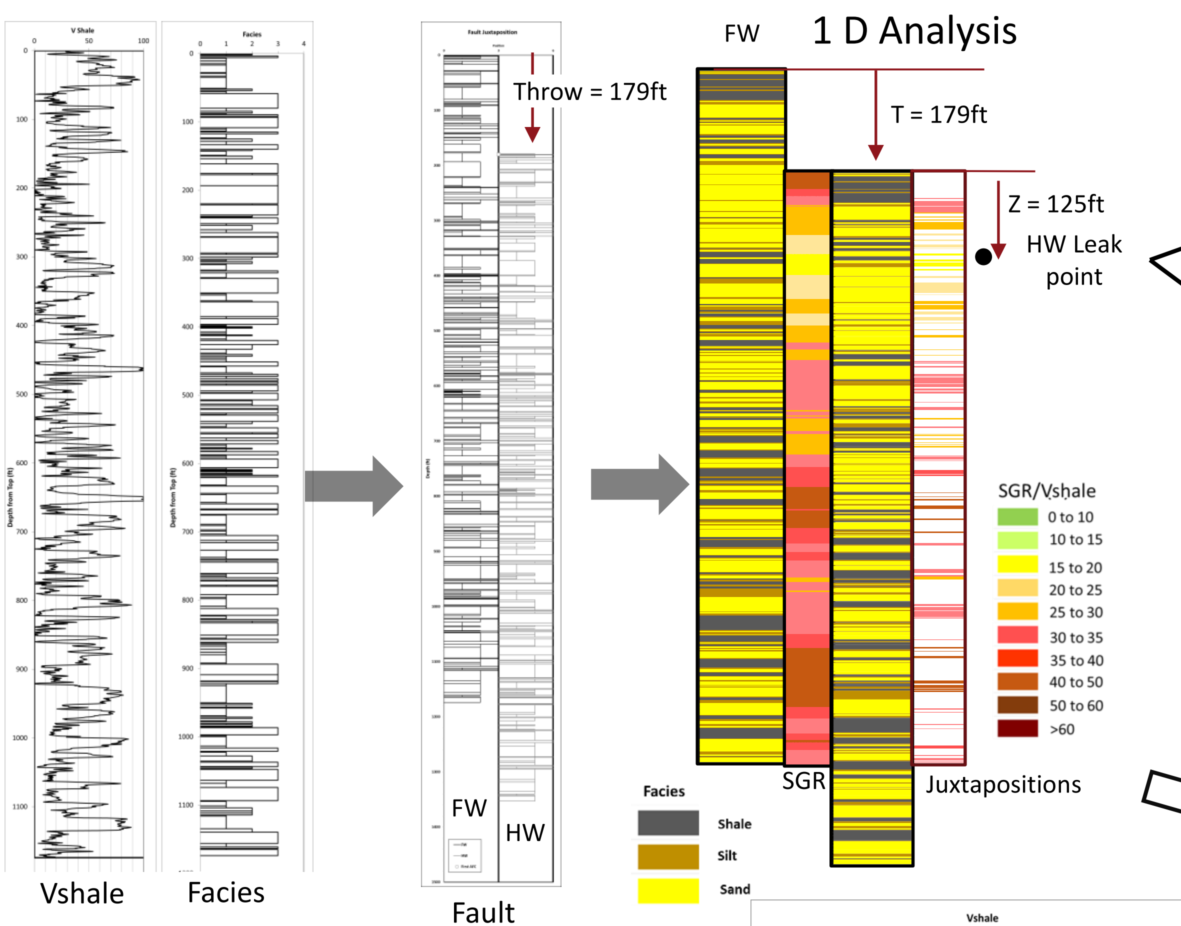


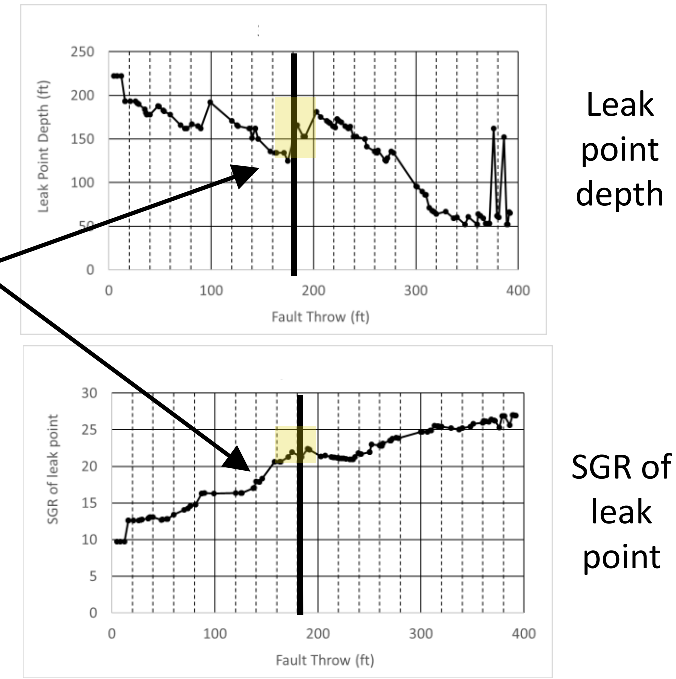


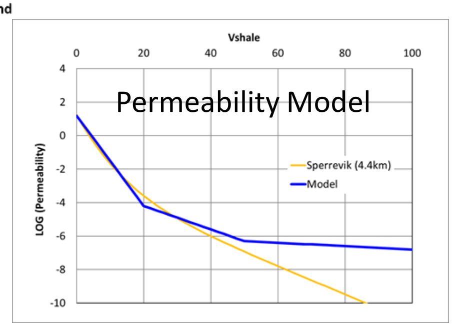


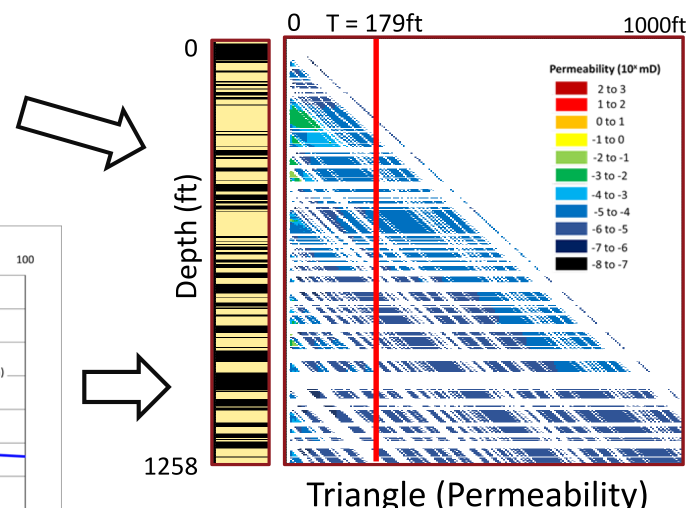


Using the model: Results for Jasmine "Type Well"









Results are input into a Monte Carlo Model to predict fault controlled column height

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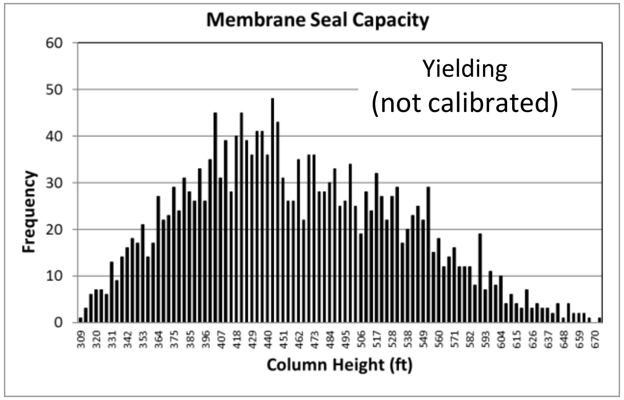
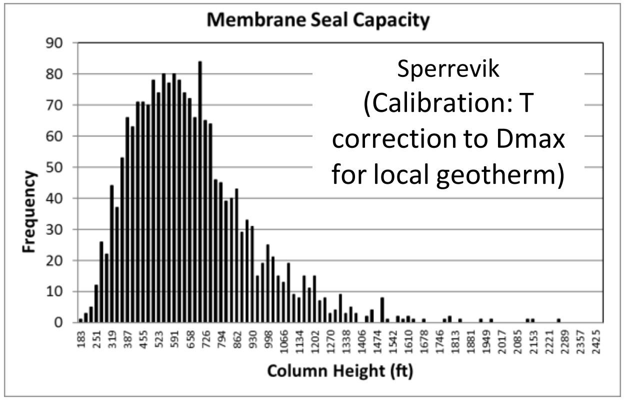
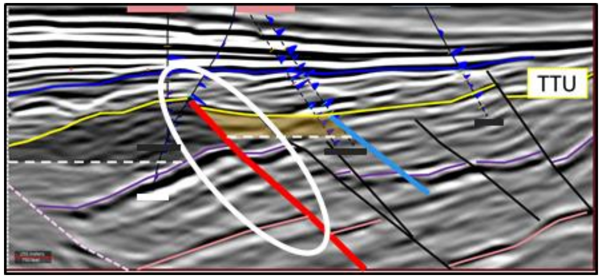
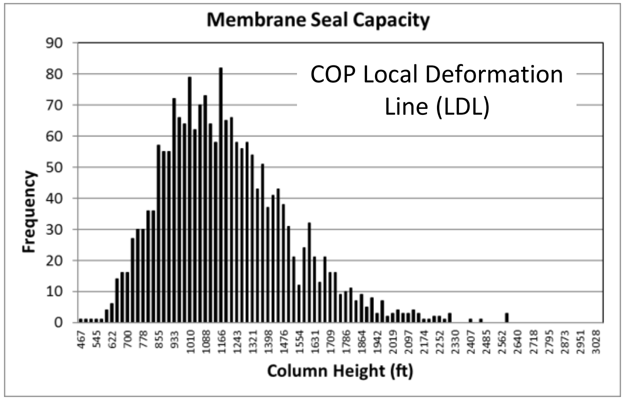
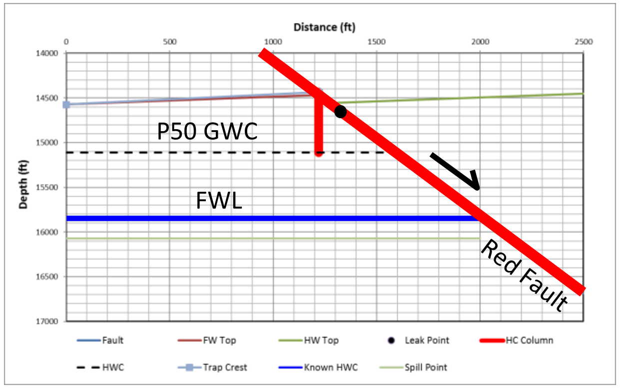
Jasmine Red Fault Seal: Monte Carlo Model Predictions

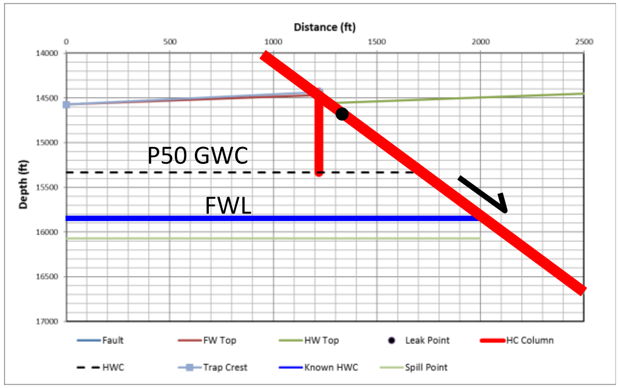


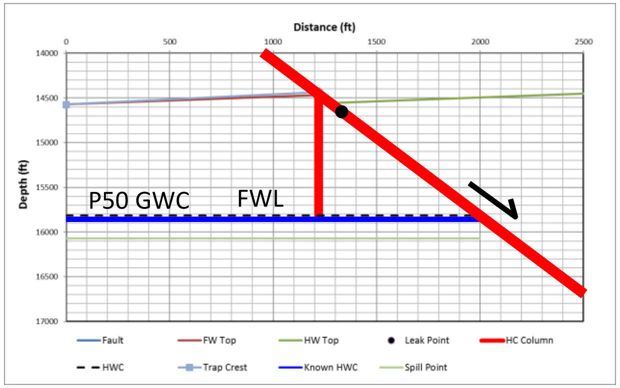












Fault SGR range (PFFR) 0.2-0.25-0.3 (Normally distributed)

LDL yields best P50 result

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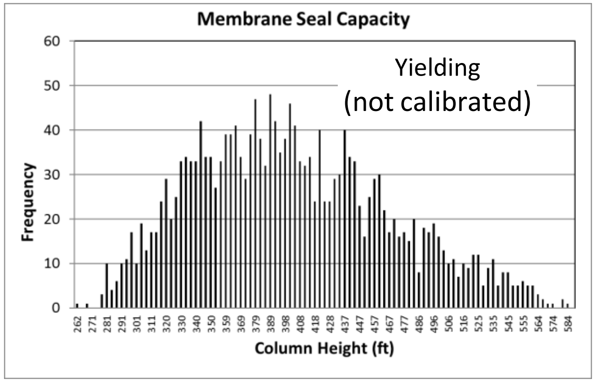
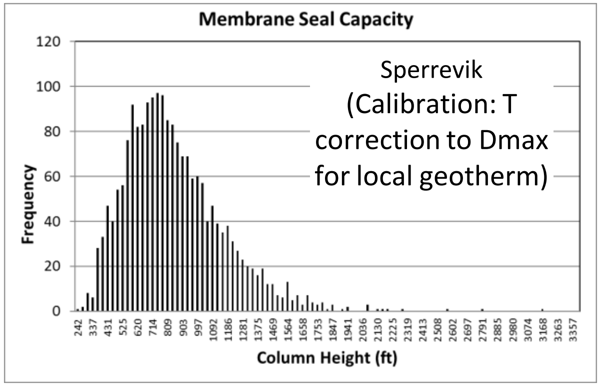
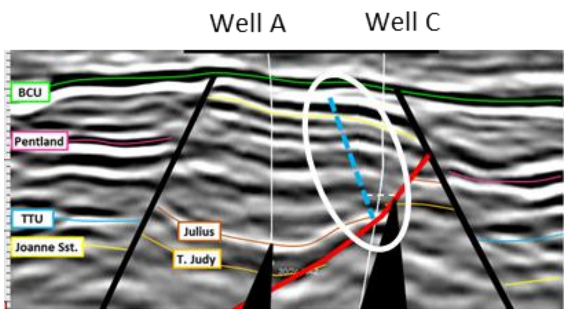
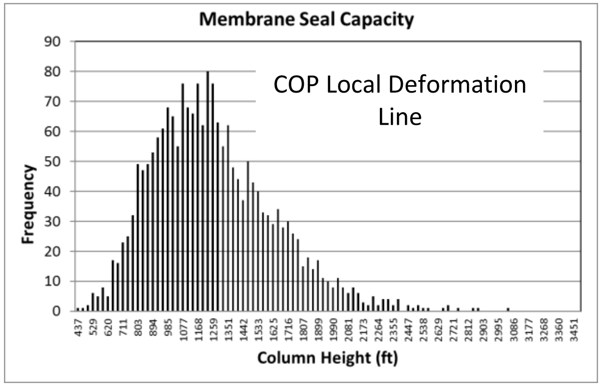
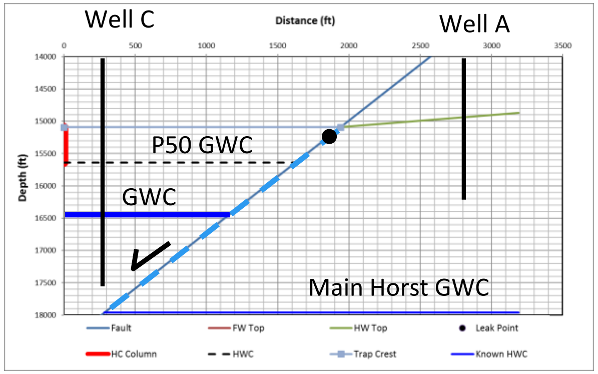
Jade Field, Blue Fault Seal: Monte Carlo Model Predictions

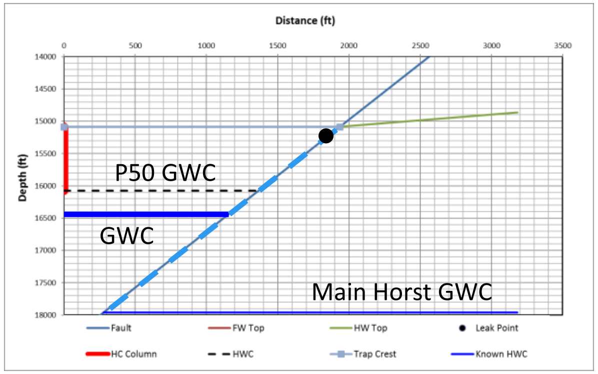


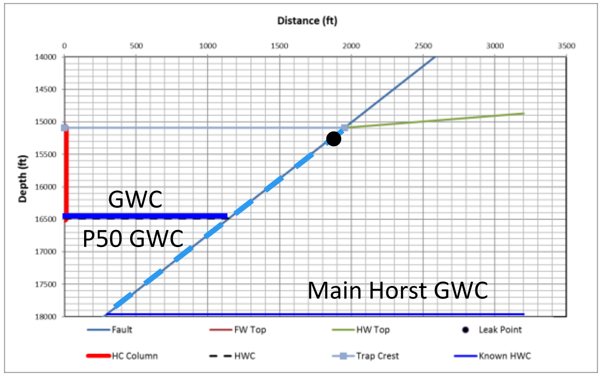












Fault SGR range (PFFR) 0.2-0.25-0.3 (Normally distributed)

LDL yields best P50 result

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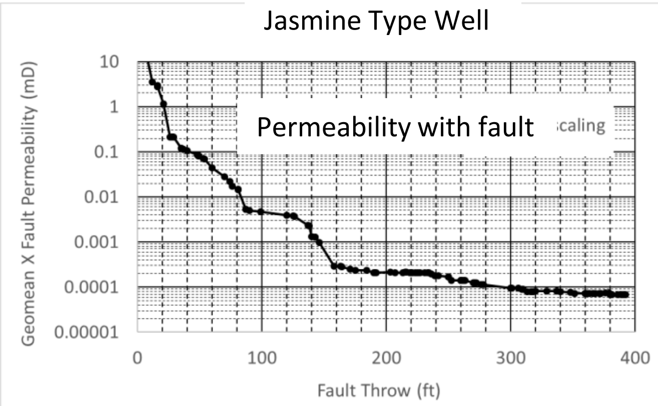
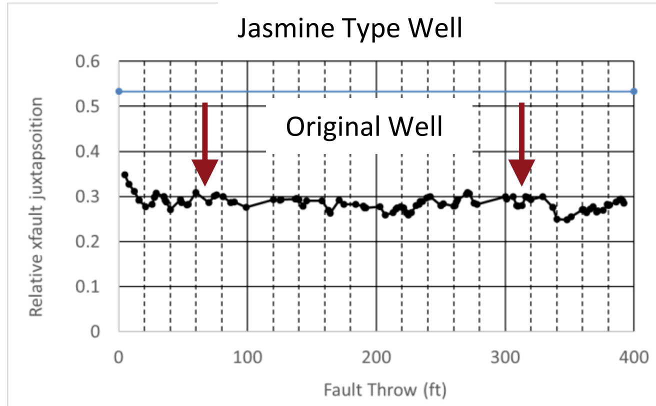
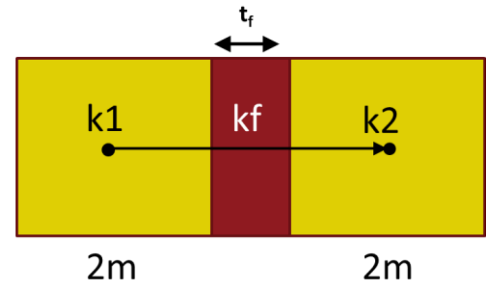
Implications for Production: Modelling Fault Transmissibility Multipliers

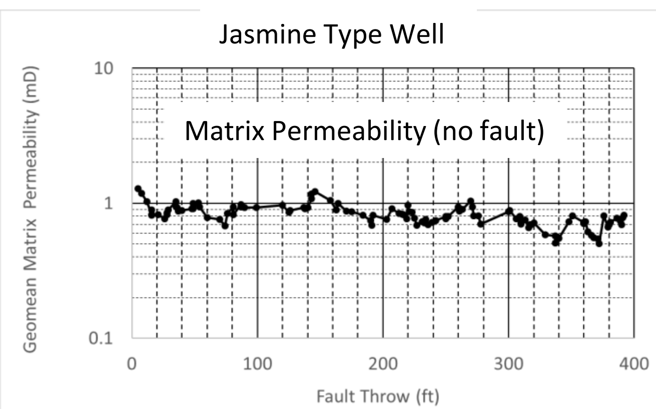


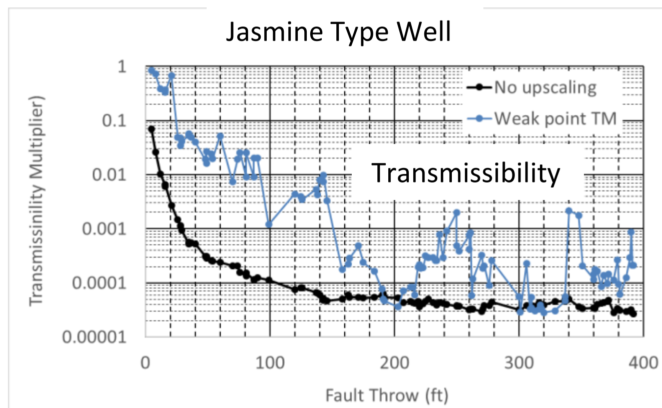


Reduced X-fault sand-sand connectivity



Generic TM calculated using 2m cell widths





TM = harmonic X-fault perm/harmonic matrix perm

- TMs are only calculated at sand-sand juxtapositions
- Fault core thickness (tf) = 0.01 * Throw
- Low proportion of x-fault juxtapositions
- Small throw faults (~100ft) can act as significant barriers/baffles to production in HPHT Skagerrak reservoirs

Conclusions

- Stochastic modelling shows that a "tripartite dog-leg model" describes fault permeability as a function of clay content
  - Cataclasite, PFFR and Shale smear fields form separate linear k-Vshale trends
- An empirical relationship exists between host rock permeability and fault rock permeability as a function of Vshale
  - Shaley gouge fault rock (PFFR) is 4 orders of magnitude less permeable than the host reservoir rock (supported by stochastic modelling)
  - Enables PFFR fault rock properties to be anchored directly to well-based reservoir properties (local calibration)
- The "COP Local Deformation Line (LDL)" method is simple to generate and use
- Low permeability HPHT fault zones act as significant production baffles
  - TM's are typically between 0.00001 - 0.0001 (even for small fault throws ~50-100ft)

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