DETECT

INTEGRATED GEOLOGICAL CO_2
LEAKAGE RISK ASSESSMENT

DETECT

Determining the risk of CO_2 leakage along fractures of the primary caprock using an integrated monitoring and hydro-mechanical-chemical approach

Single Fracture Scale Modeling

Summary & Key Insights

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Accelerating CCS Technologies

The project has been subsidized through the ERANET Cofund ACT (Project no. 271497), the European Commission, the Research Council of Norway, the Rijksdienst voor Ondernemend Nederland, the Bundesministerium für Wirtschaft und Energie, and the Department for Business, Energy & Industrial Strategy, UK.

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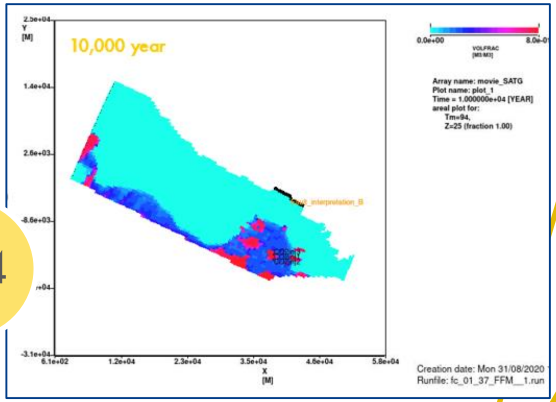
DETECT workflow

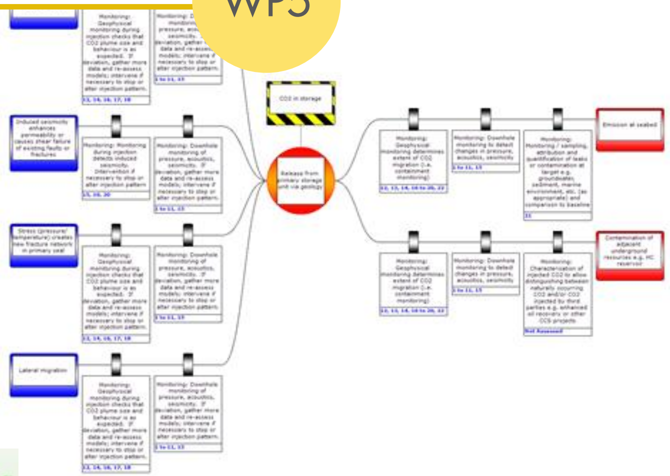
The goal of DETECT is to assess geological leakage risks related to fault and fractures in caprocks



WP5

Geological Leakage Risk Assessment

Incorporate all modelling and monitoring barriers in a qualitative bowtie risk assessment framework with associated quantitative scenario modelling tool



WP4

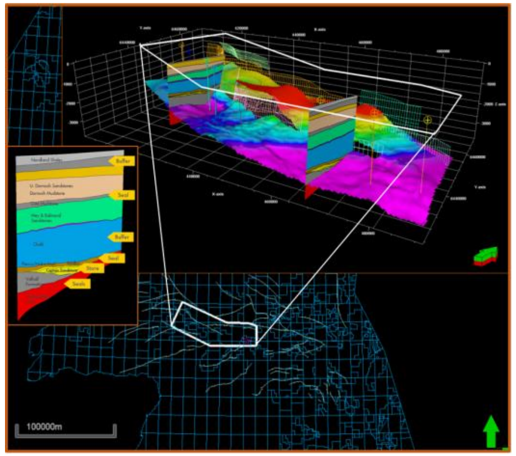
Identify active monitoring barriers relevant for site and expected leakage rates

Modelling results inform effectiveness of passive barriers (in seals and secondary storage units)

WP3

Probabilistic dynamic simulation using uncertainty ranges on all (parametrized) controls

Estimation of leakage rate distribution and likelihood at each caprock in CO_2 storage complex



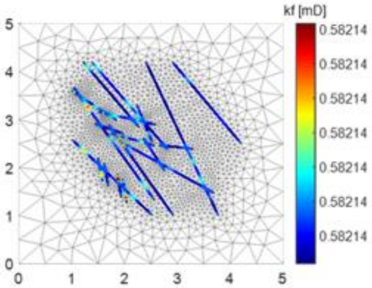
Hydromechanical coupling using lab-derived stress-permeability relations and analytical stress-state model

Effective fracture + matrix vertical permeability, RLP, CPR for each cell in seal derived from numerical up-scaling

Simulate flow in fracture networks in caprocks

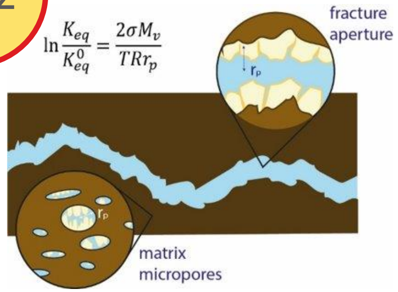
Scaling relations based on meso/fine-scale modelling & analogues

Characterise background stresses and log-derived rock transport and geomechanical properties

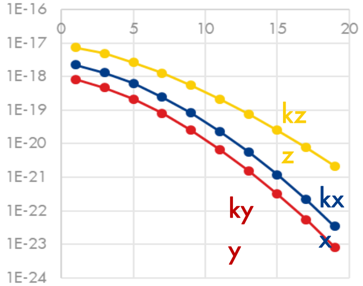


WP2

Experimentation and numerical modeling to characterise single fracture processes



Quantifying the impact of small-scale physics on CO_2-brine flow at fine-scale



Characterise fault-fracture networks using analogue derived scaling relations: fault throw-length-frequency

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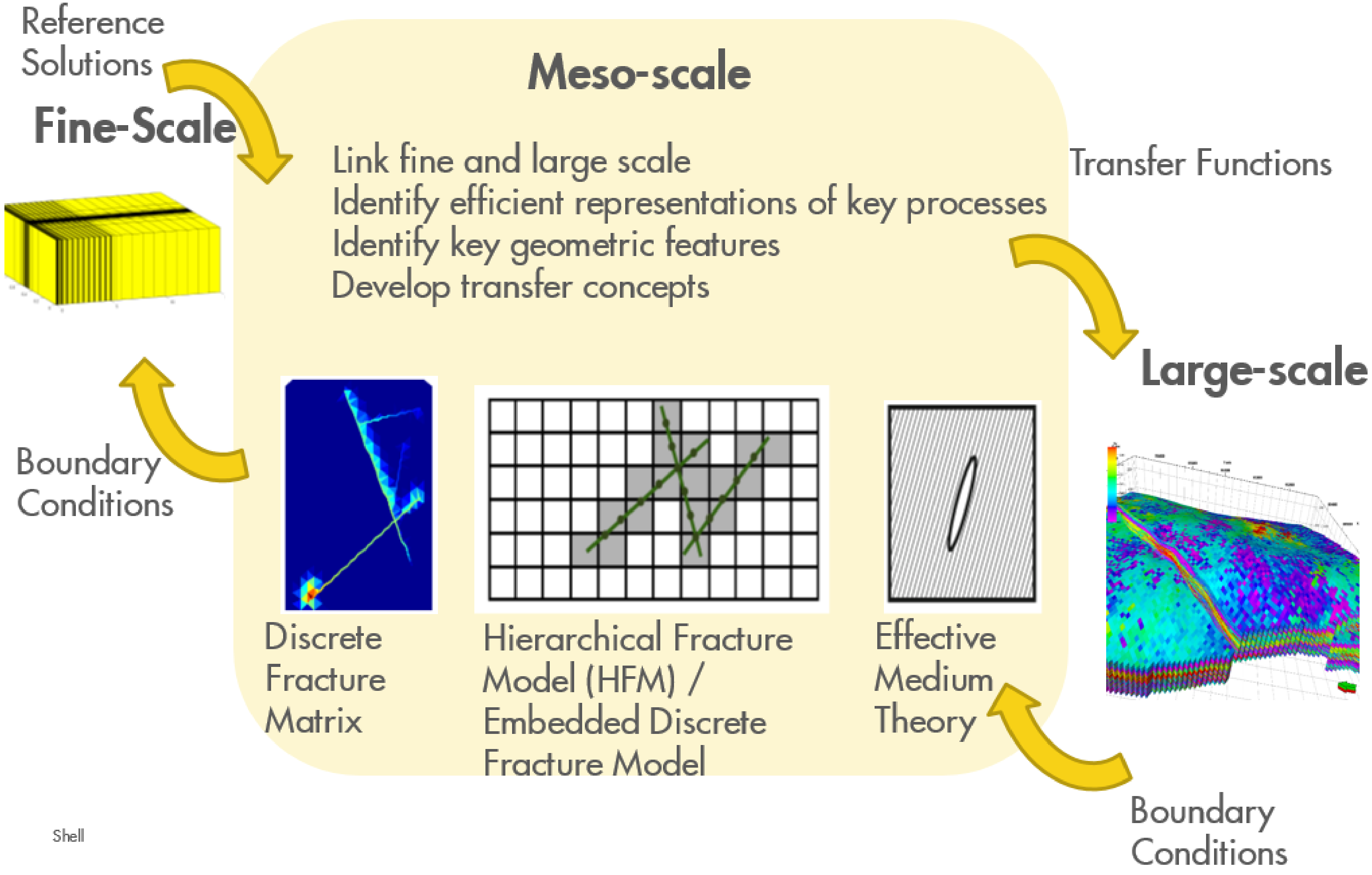
Single fracture modeling and link to meso-scale

Numerical Up-scaling



Reference Solutions

Fine-Scale

Boundary Conditions

Meso-scale

Link fine and large scale
Identify efficient representations of key processes
Identify key geometric features
Develop transfer concepts

Discrete Fracture Matrix

Hierarchical Fracture Model (HFM) / Embedded Discrete Fracture Model

Effective Medium Theory

Transfer Functions

Large-scale

Boundary Conditions

Shell

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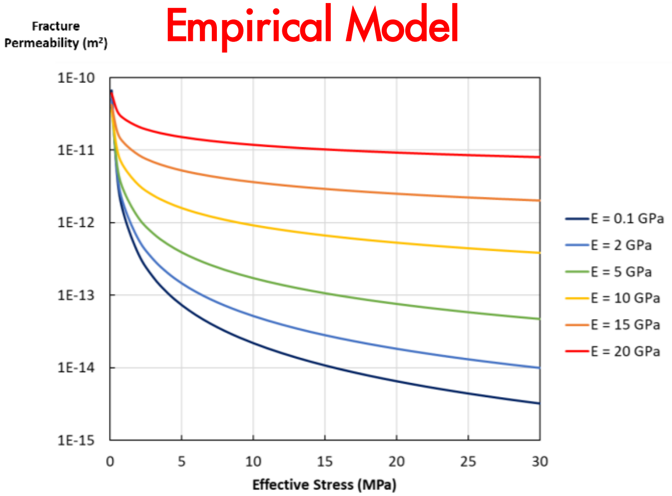
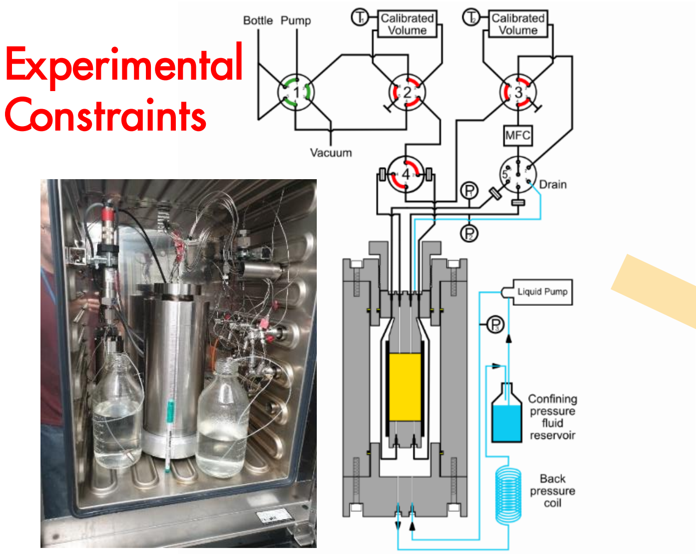
Predicting Mudrock Fracture Permeability

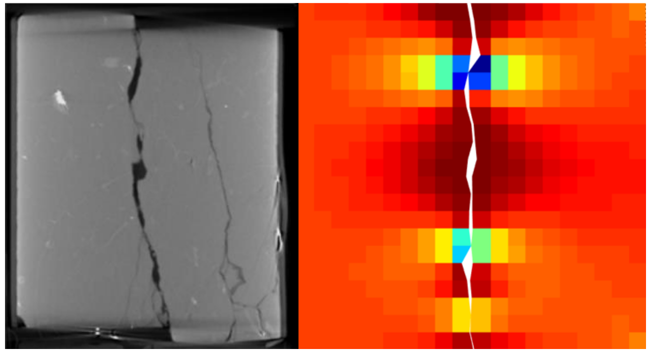
Empirical Model



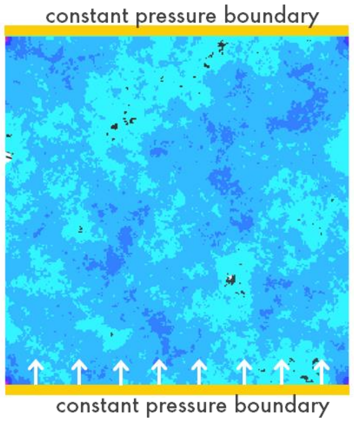
Experimental Constraints

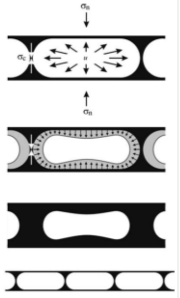


Navier-stokes + numerical elastic contact mechanics

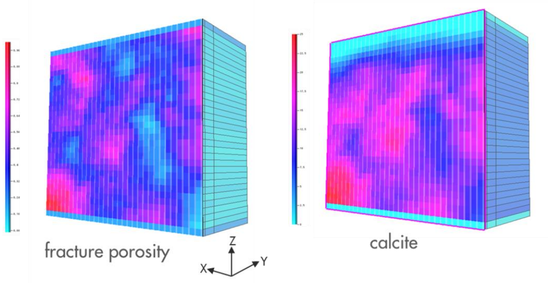


Darcy flow + analytical elastic contact mechanics

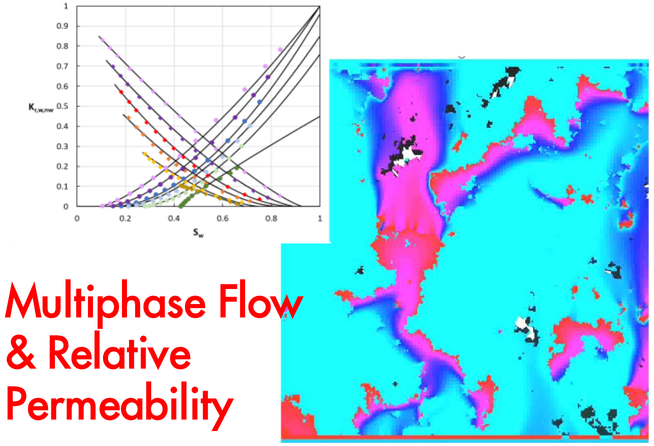




Reactive Transport Modelling



Multiphase Flow & Relative Permeability



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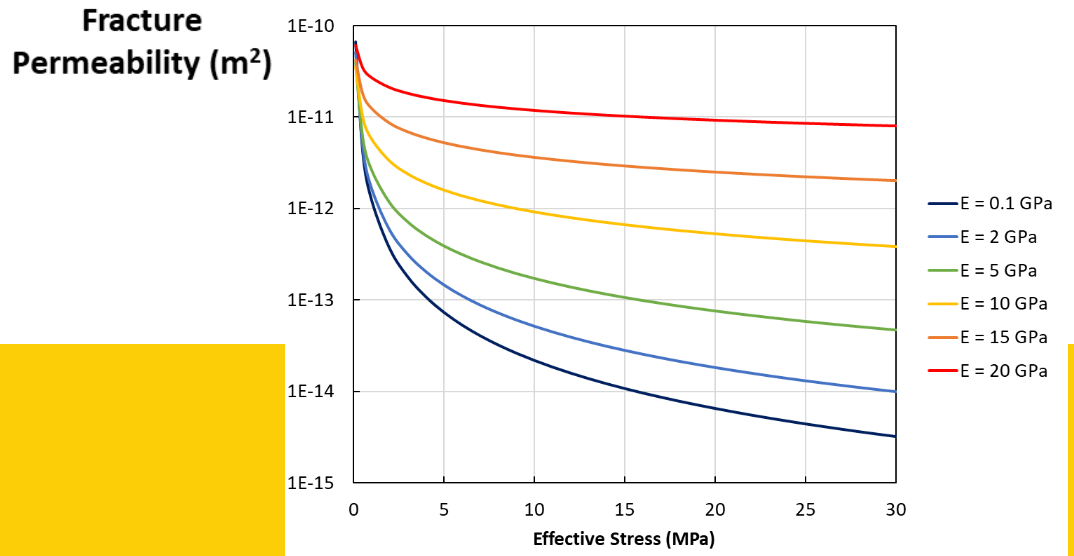
INTEGRATED GEOLOGICAL CO_2
LEAKAGE RISK ASSESSMENT

Empirical Fracture Permeability-Stress Modeling



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Mudrock Fracture Permeability

effective stress

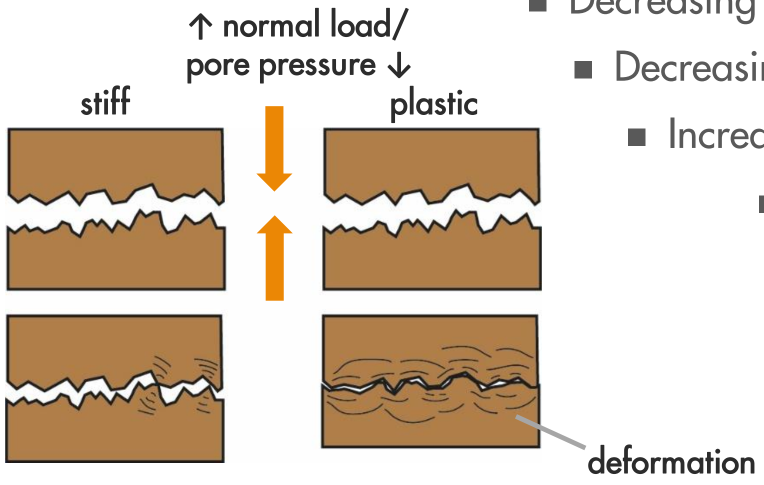
pore pressure

$$\sigma_e = \sigma - u$$

total stress

Key Questions

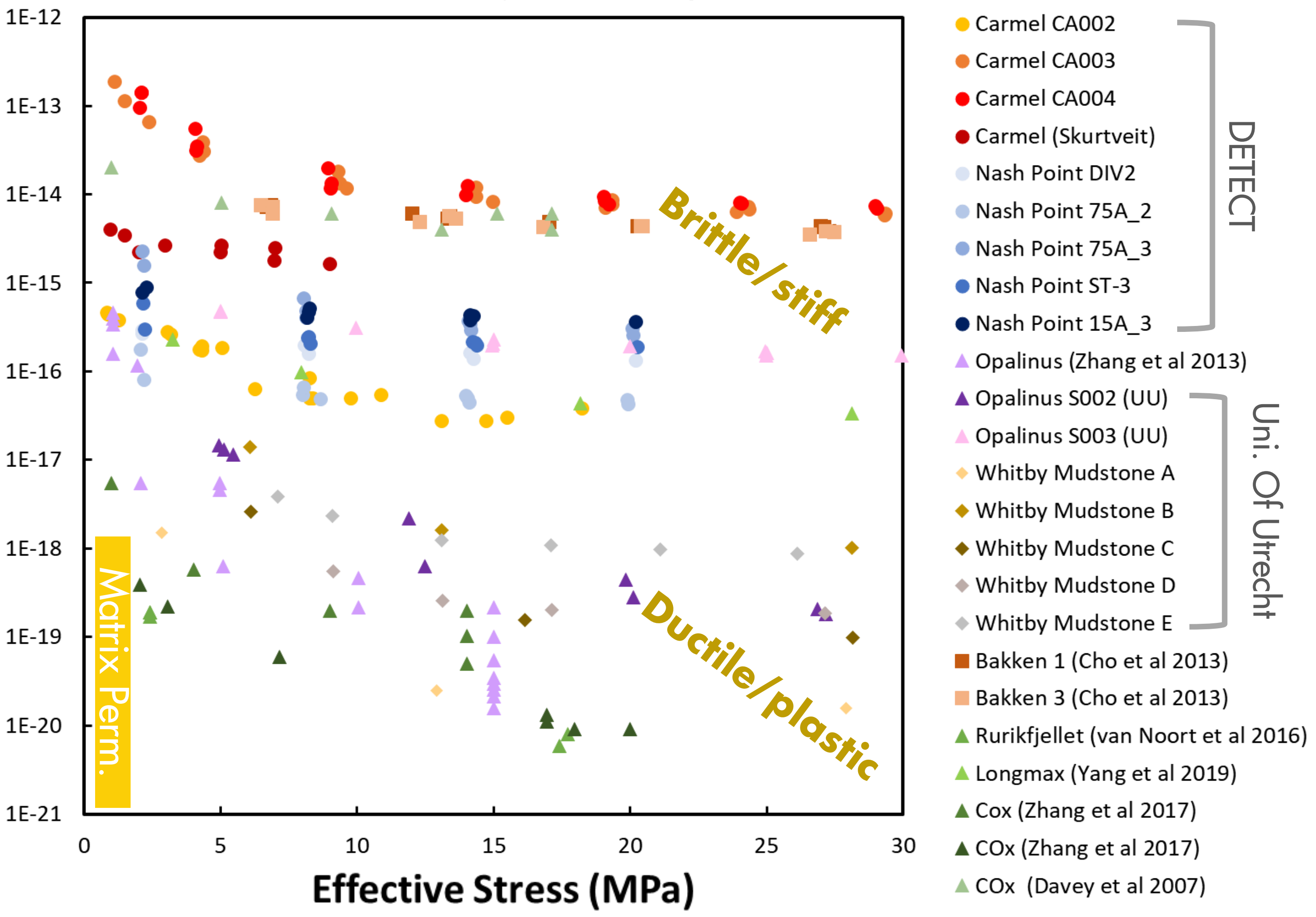
- What are the intrinsic permeabilities of mudrock fractures?
- How does this relate to rock mechanic properties, fracture surface properties and diagenesis?
- How do we predict these in reservoir seals without core?



- Decreasing rock stiffness
  - Decreasing grain size
    - Increasing ductility
      - Diagenesis

Core Permeability (m^2)

Fractured Mudrock Core Plug Permeability



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Predicting Mudrock Fracture Permeability

Empirical Model Development

- Fracture permeability can be extracted from core plug data

plug perm, matrix perm., fracture perm, fracture porosity

$$k_{core} = k_m + k_f \cdot \phi_f$$

fracture porosity

$$\phi_f = \frac{4 \cdot b}{\pi \cdot d}$$

Core diameter

$$k_f = \frac{b^2}{12}$$

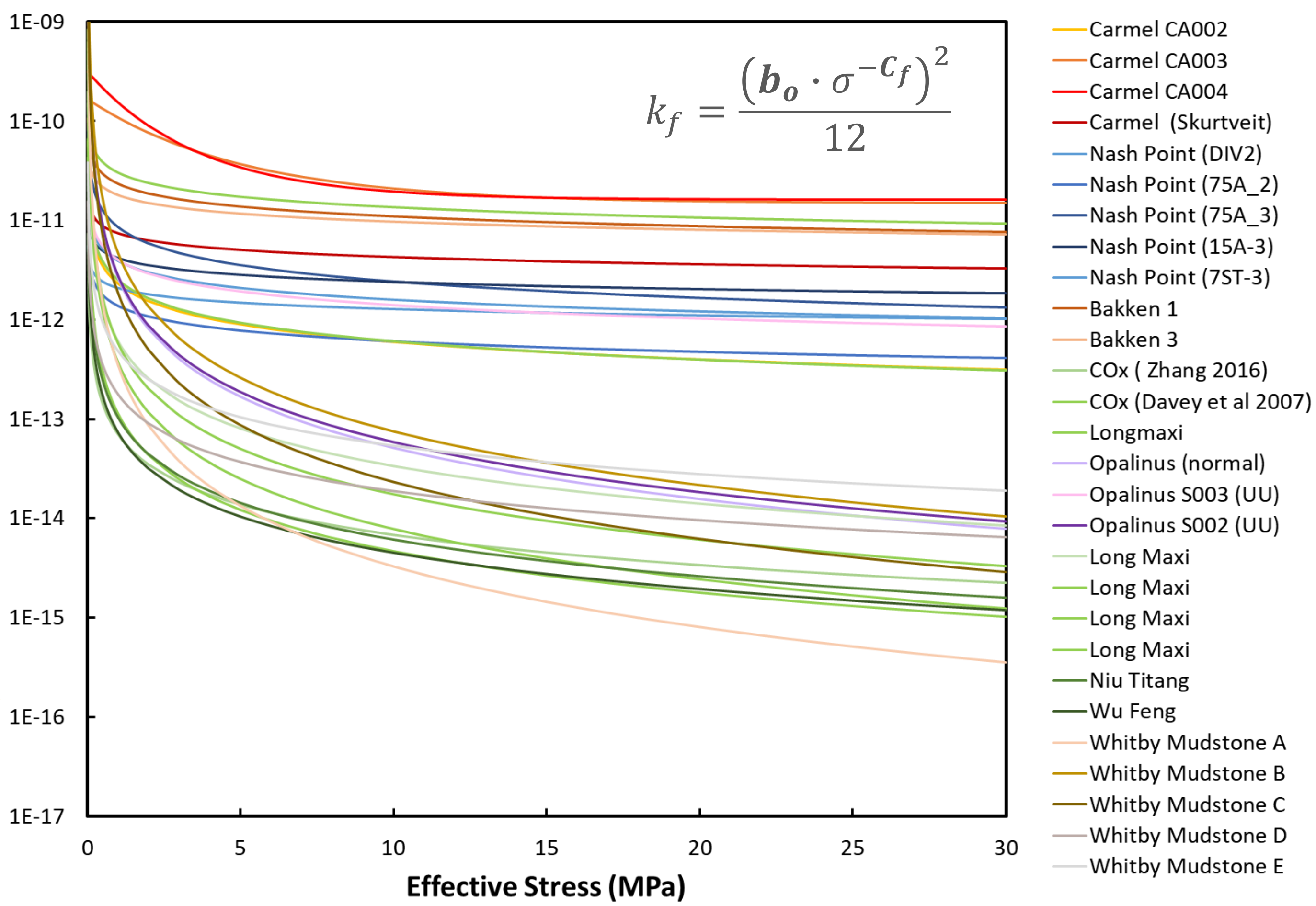
fracture aperture

$$\boxed{k_{core} = k_m + s \cdot \frac{1}{12} \cdot \frac{4}{\pi d} \cdot b^3}$$

fracture aperture, effective stress, fracture compressibility

$$\boxed{b = b_o \cdot \sigma^{-c_f}}$$

c.f. Chou et al. unstressed aperture



- Decreasing rock stiffness
- Increasing fracture compressibility

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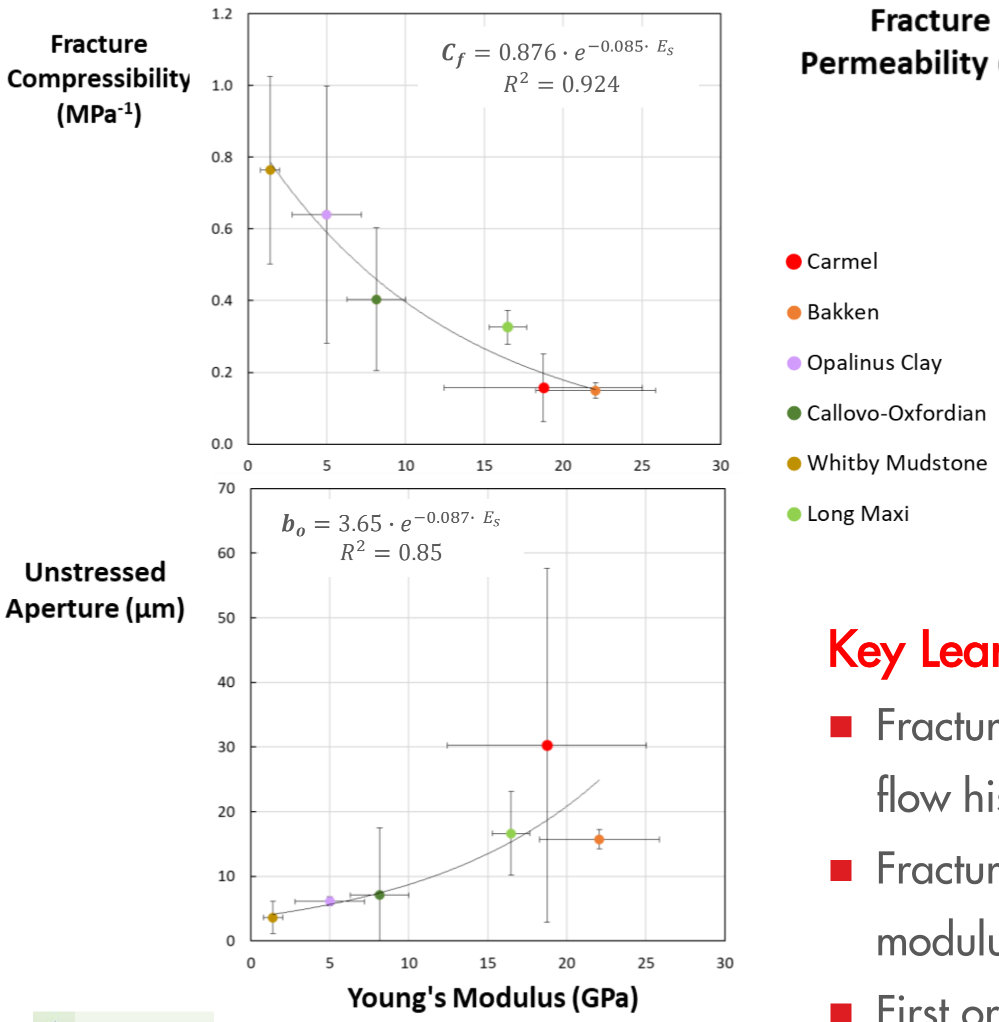
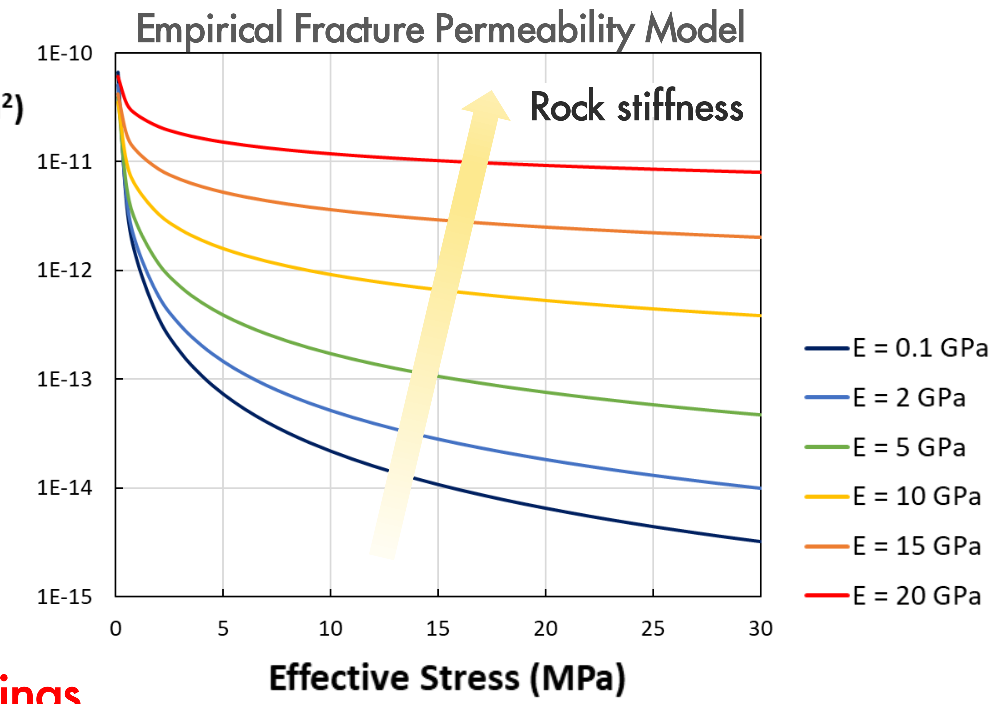
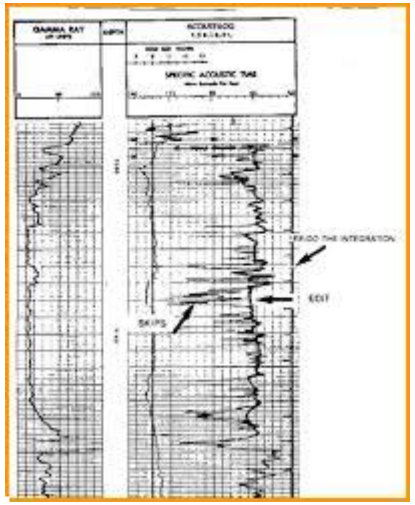
Empirical Fracture Permeability Model







Sonic Log derived Youngs Modulus

Key Learnings

- Fracture mechanical properties depend on bulk rock properties, deformation and fluid flow history
- Fracture compressibility and unstressed aperture correlated to rock stiffness (Youngs modulus)
- First order prediction of fracture flow properties using log derived Youngs Modulus

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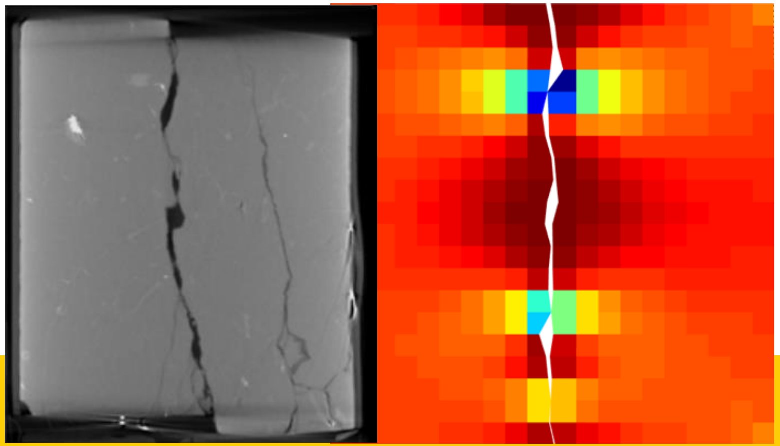
Numerical Fracture Permeability-Stress Modeling

2



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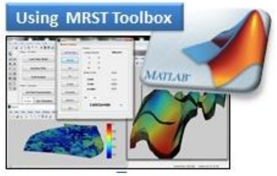
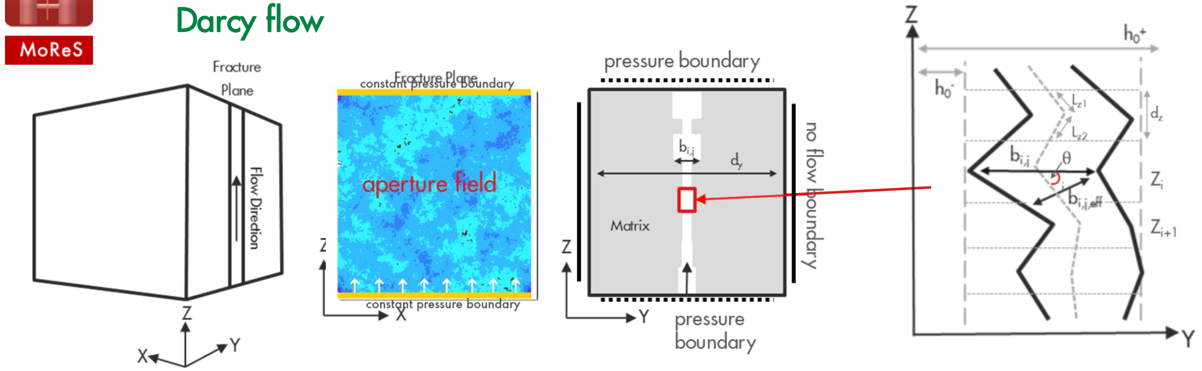
Numerical Modelling of Single Phase Fracture Permeability



Darcy flow



effective permeability

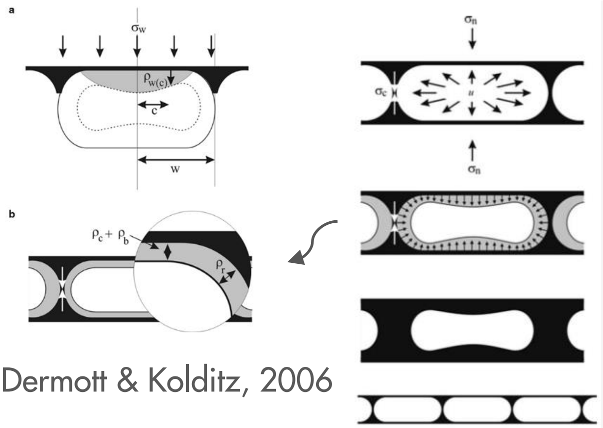
$$k_{i,j,eff} = b_{i,j,eff}{}^3/(12 \cdot d_y)$$

$$\Delta f_v = \Delta V_r + \Delta V_c + \Delta V_w$$

radial deformation

box deformation

wall deformation



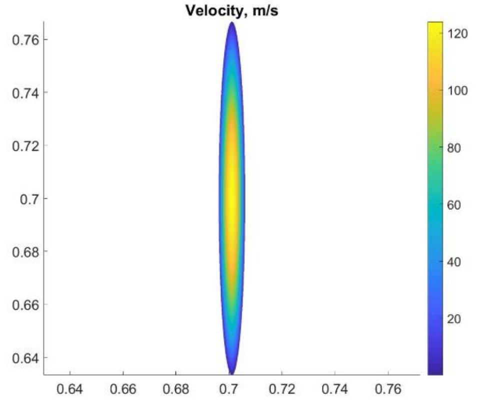
McDermott & Kolditz, 2006

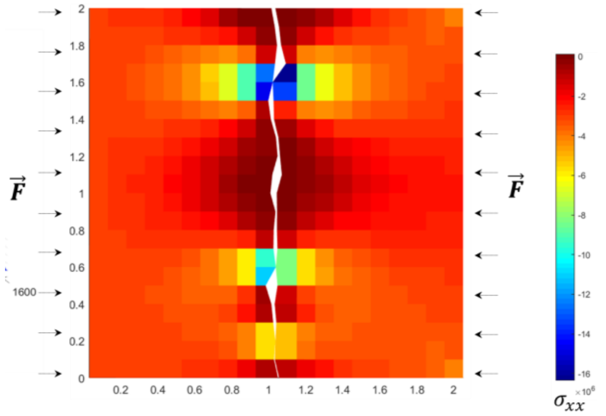
Semi-analytical contact mechanics

Darcy flow (MoReS)

- Modified local (gridblock) cubic law computes permeability accounting for tortuosity due to fracture roughness
- Linear-elastic volumetric deformation of asperities and pores

Stokes flow



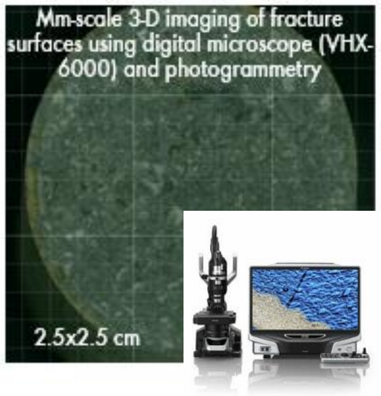


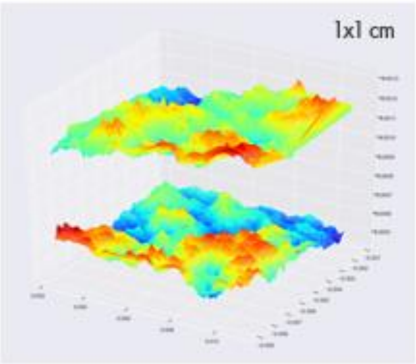
Numerical contact mechanics

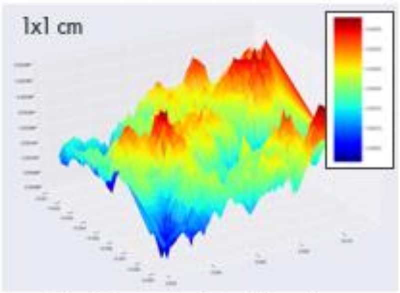
Navier-stokes (MRST)

- Stokes solver for flow
- 2D sections only
- Lagrangian multiplier based numerical contact mechanics (normal and tangential contact interactions)
- Linear-elastic model

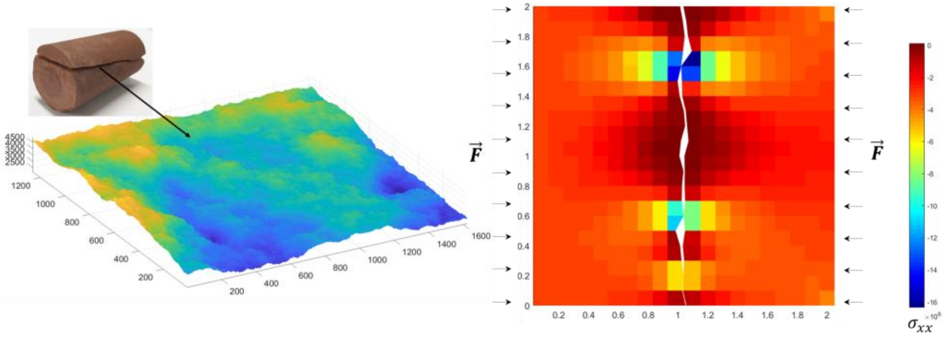
Comparison of empirical, numerical & experimental stress-permeability

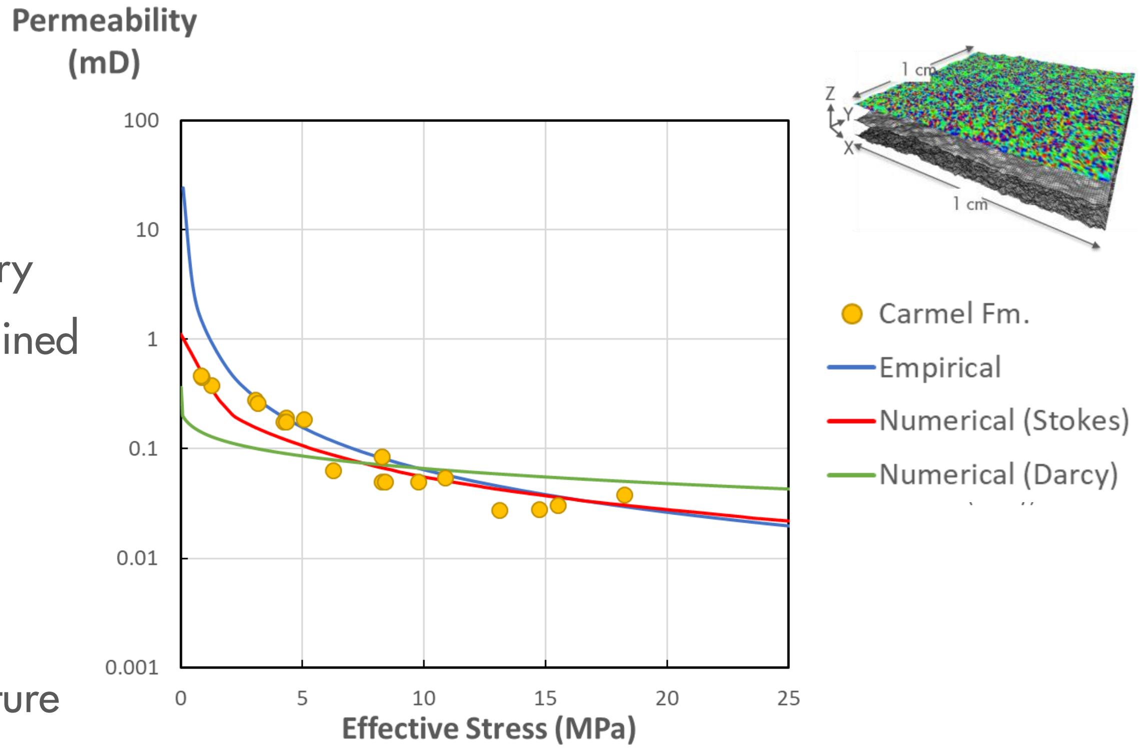

Mm-scale 3-D imaging of fracture surfaces using digital microscope (VHX-6000) and photogrammetry





Top: Reconstruction of aperture distribution [in m] between the two fracture surfaces (left)



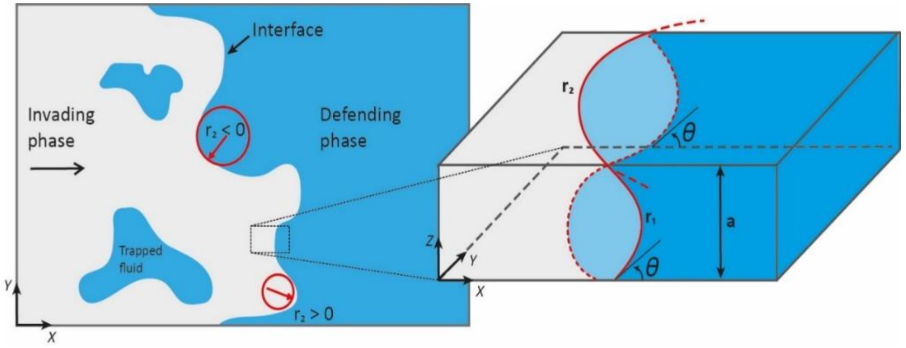


Key Learnings

- Accurate mapping of fracture surface topography using photogrammetry
- Good agreement between numerical hydromechanical simulations obtained by adjusting mating of fracture surfaces
- Darcy flow model and analytical contact mechanics under-estimates fracture compressibility
- Empirical model may overestimate fracture permeability at low stresses
- For low stiffness rocks modeling approaches tend to underestimate fracture compressibility as they don't capture plastic and ductile deformation

Single Fracture Scale: Two Phase Relative Permeability Numerical Modeling

3



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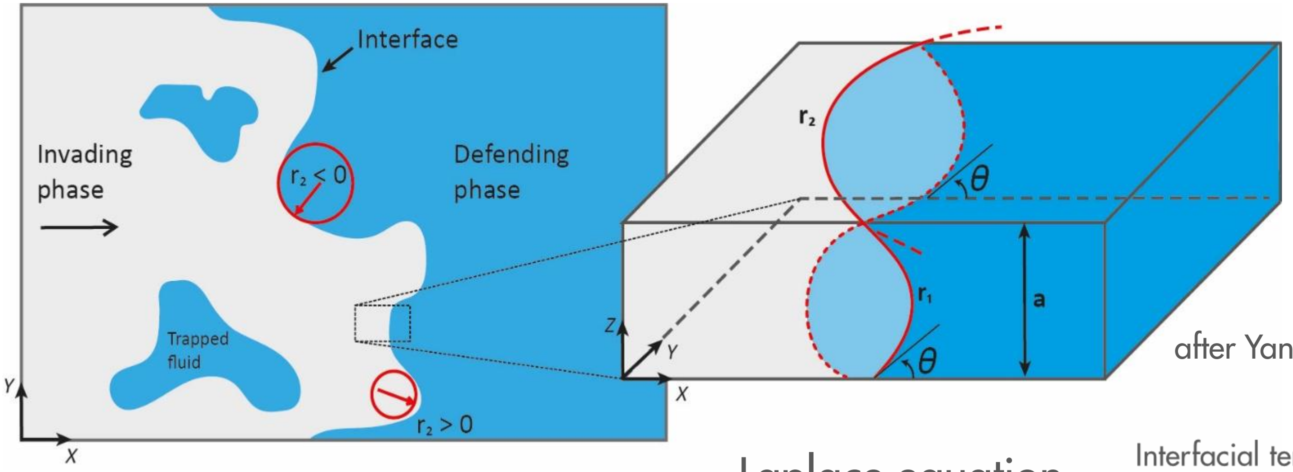
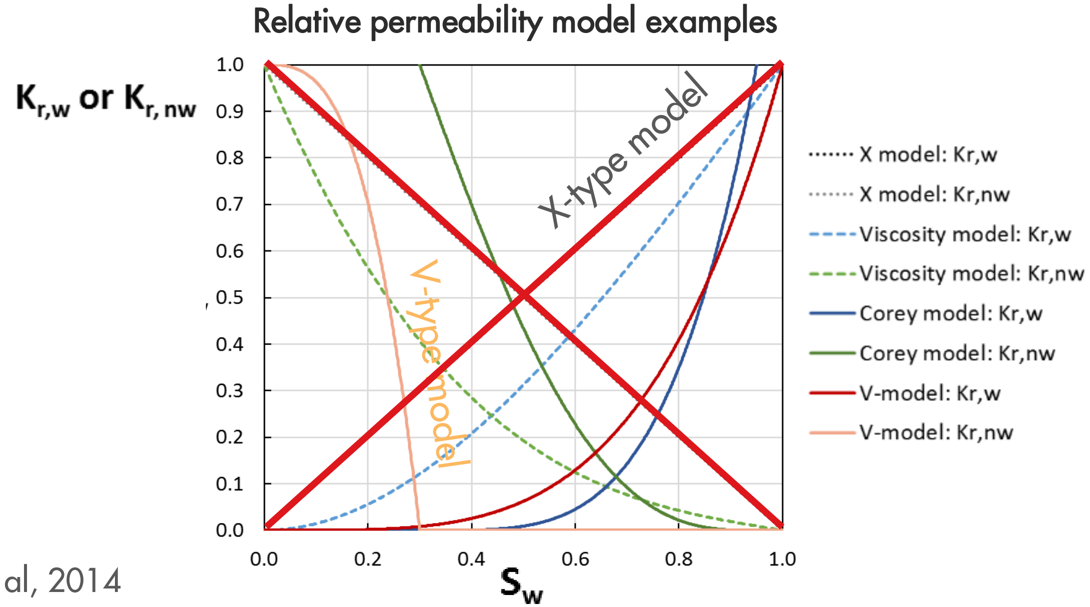
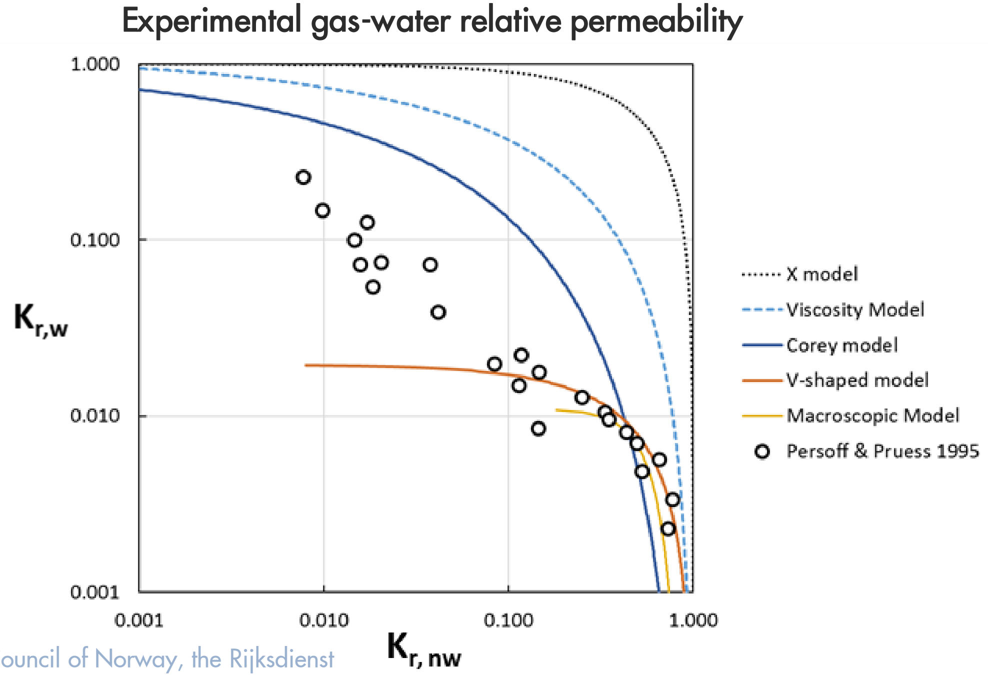
CO_2-brine relative permeability in rough fractures



after Yang et al, 2014



Relative permeability model examples



Experimental gas-water relative permeability

Laplace equation

Interfacial tension

$$P_e = P_{nw} - P_w = \gamma\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

$$R_1 = \frac{a}{2\cos\theta}$$

Contact angle

Key questions

- Do fine fractures exhibit capillarity in small apertures?
- How does fracture roughness and a heterogenous aperture field impact relative permeabilities?
- What is the impact of viscous versus capillary forces?
- How does the relative permeability evolve during fracture closure/opening?

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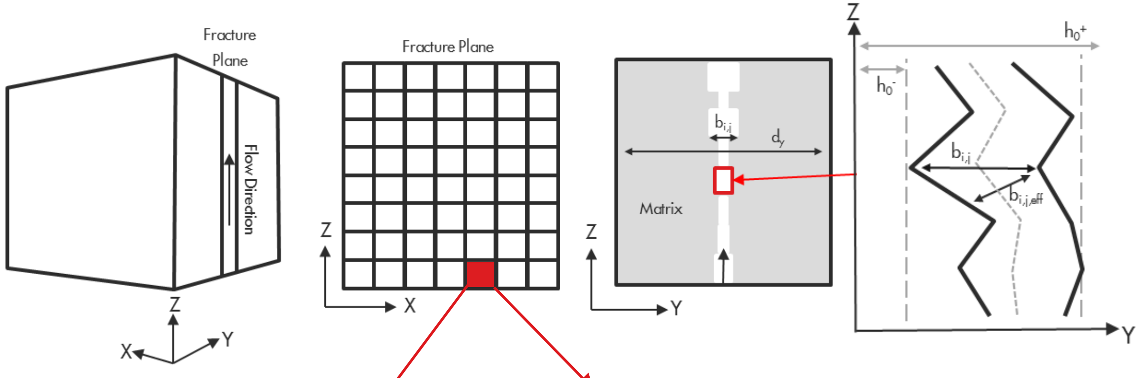
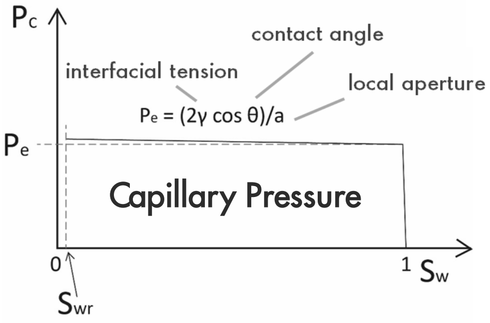
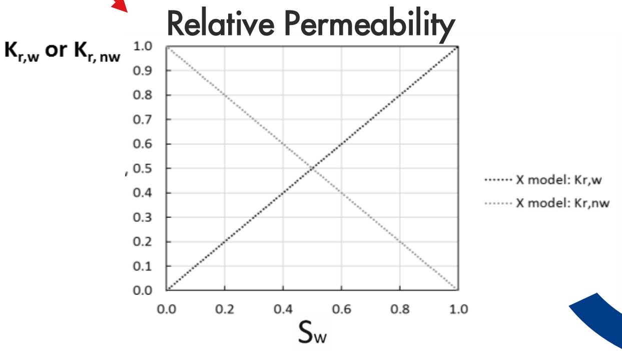
Numerically Derived Relative Permeability

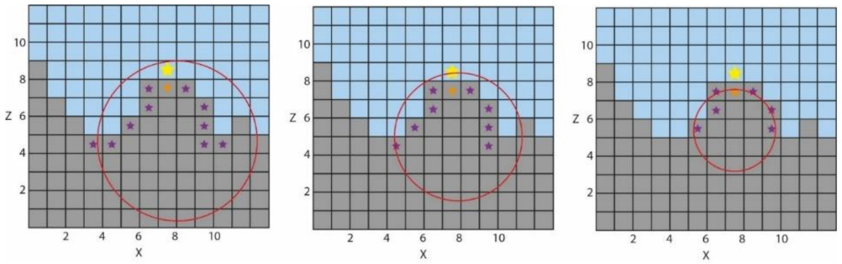
Synthetic fracture surfaces of varying roughness



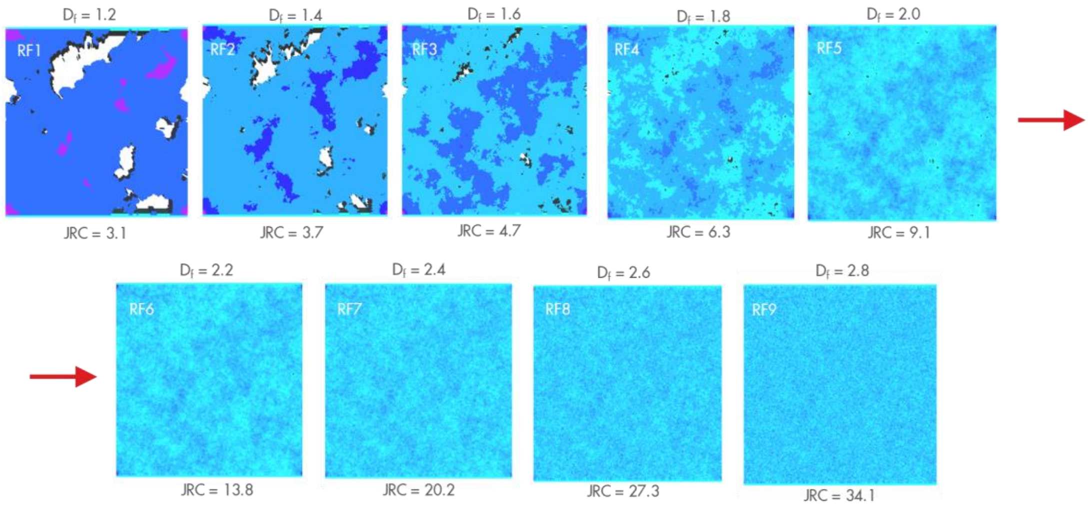


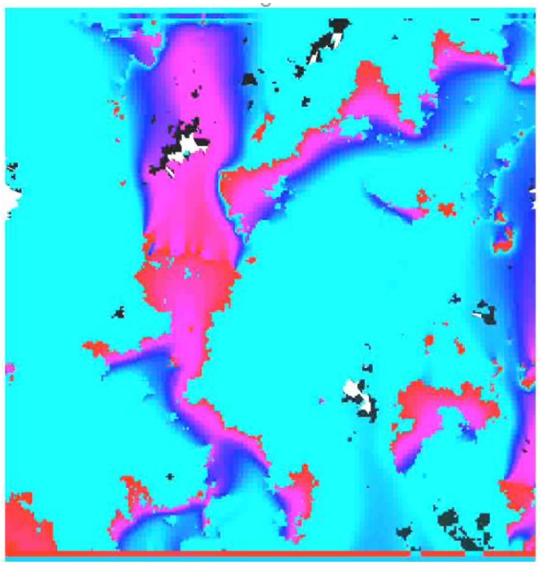


In-plane curvature



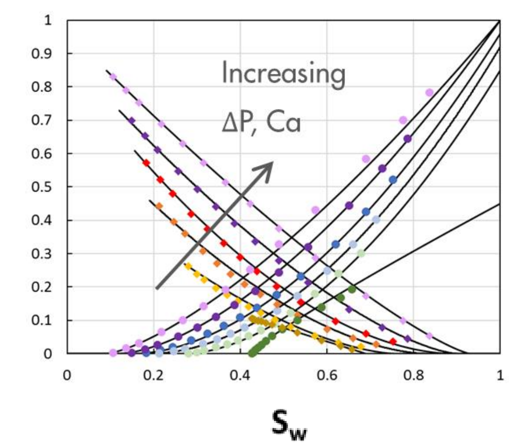
Synthetic fracture surfaces of varying roughness





Numerical Simulation

Parameter state dependent relative permeability model



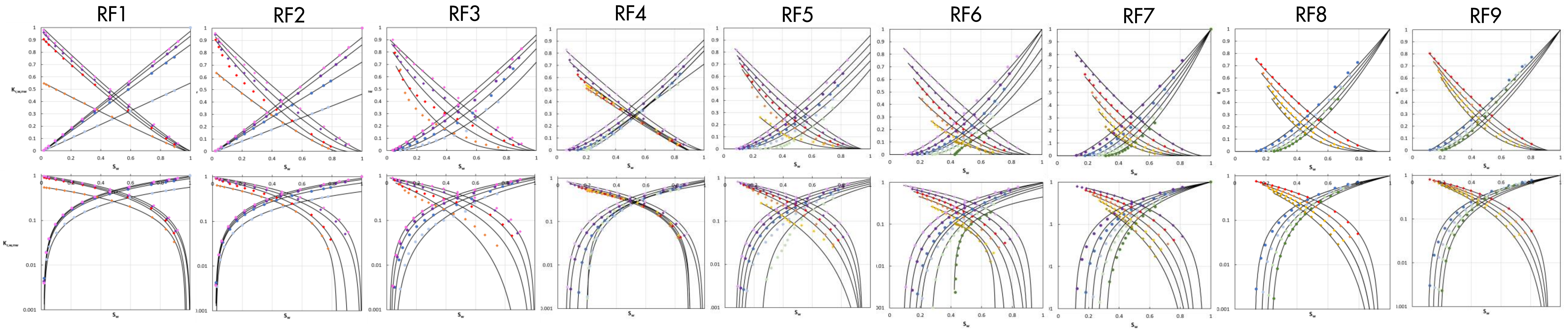
Relative permeability curves

Increasing roughness →

Capillary no.
velocity
pressure drop

$$Ca = [(\mu \cdot v)/IFT] \propto \Delta P$$

viscosity
interfacial tension



Wetting phase

endpoint k_r

residual saturation

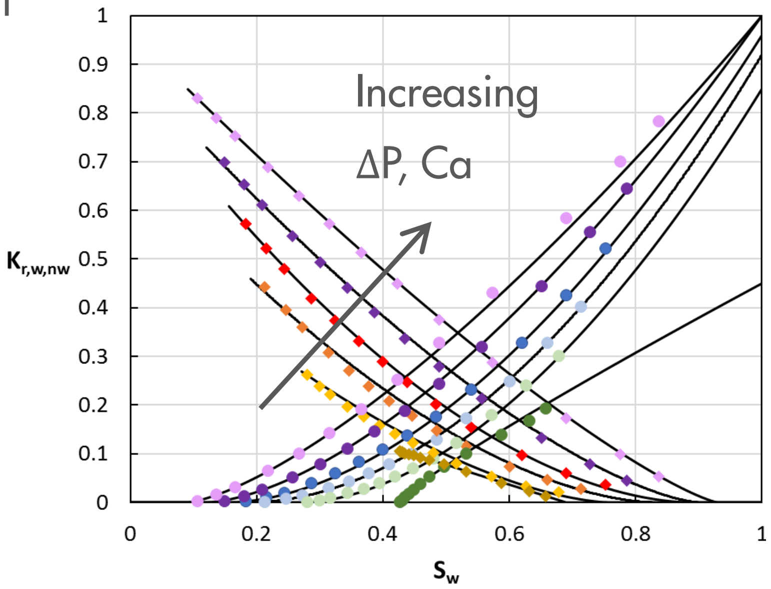
exponent

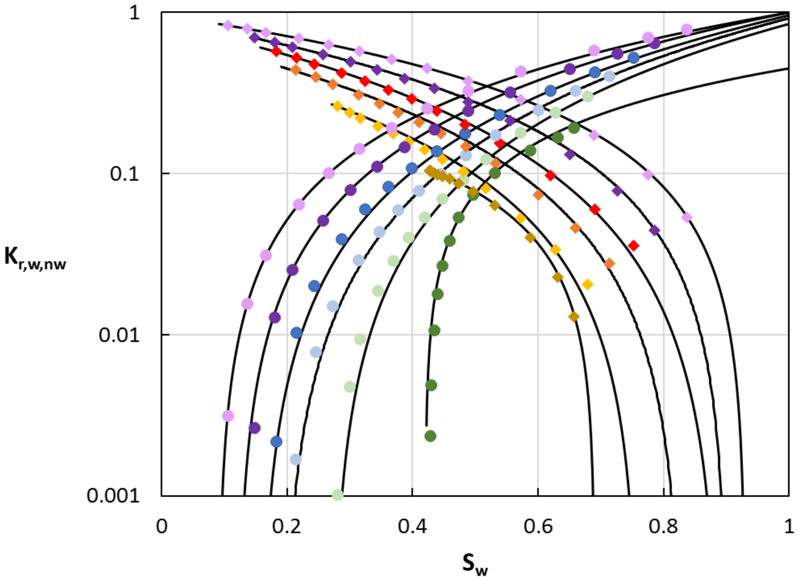
$$k_{r,w} = k_{rmax,w} \cdot \left(\frac{S_w - S_{wr}}{S_{ws} - S_{wr}}\right)^{\eta}$$

satiated saturation

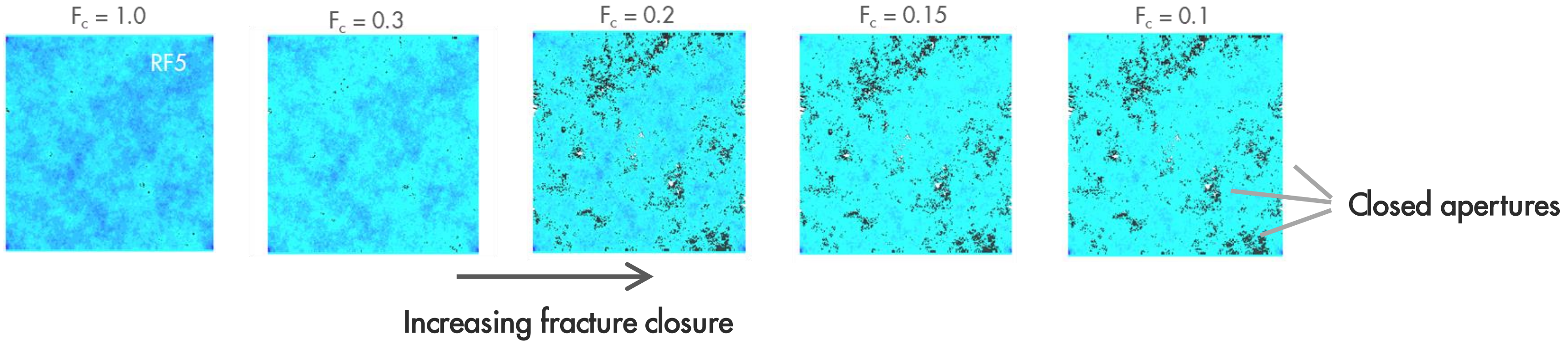
Non-wetting phase

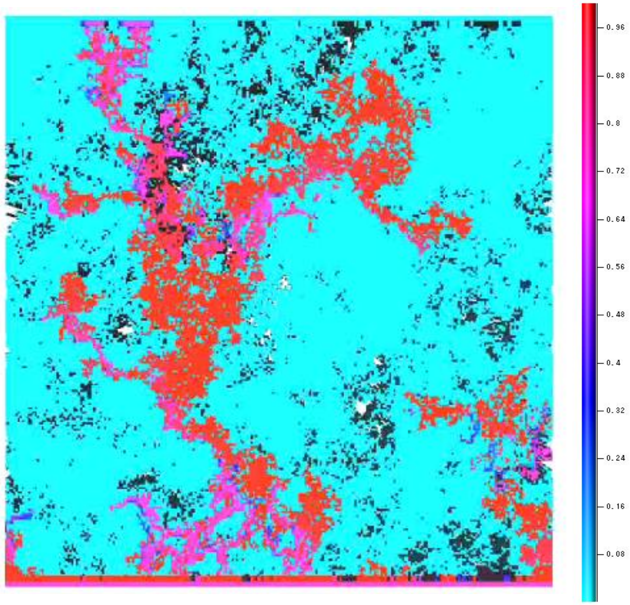
$$k_{r,nw} = k_{rmax,nw} \cdot \left(\frac{S_{nw} - S_{nwr}}{S_{nws} - S_{nwr}}\right)^{\eta}$$



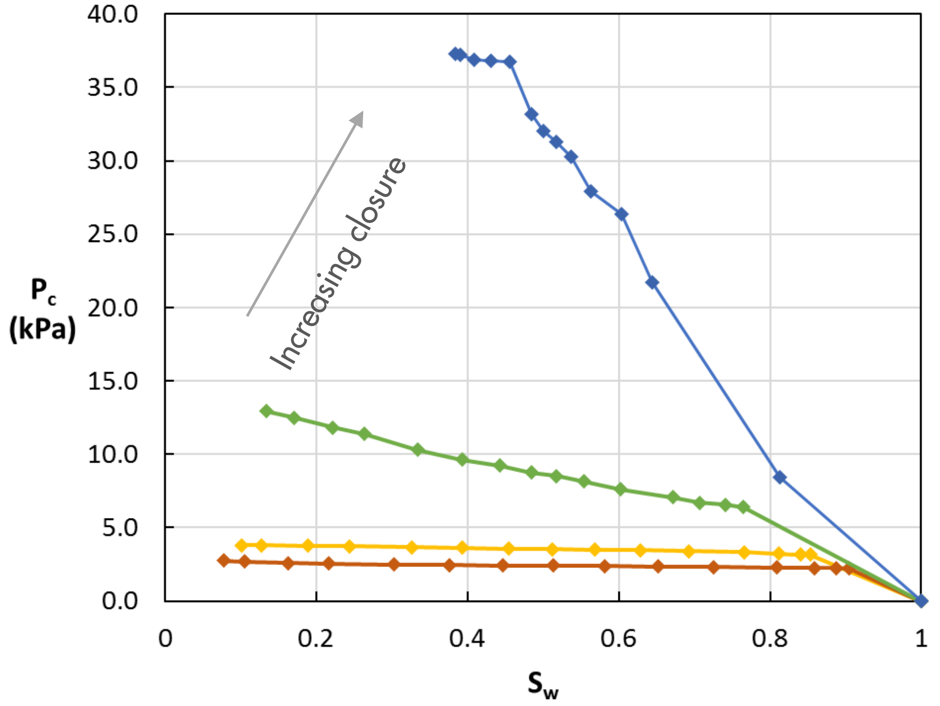


Impact of fracture closure on relative permeability





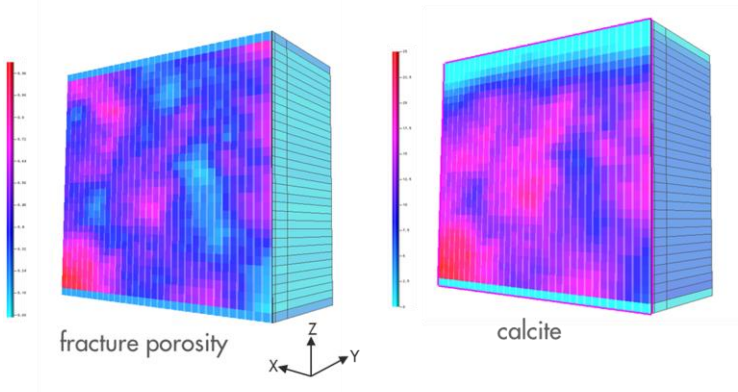
CO_2 saturation



Key Learnings

- CO_2-brine relative permeability depends strongly fracture roughness, capillary number and fracture closure
- Low capillary number or high closure leads to increase in capillarity, greater water trapping, higher phase interference and lower CO_2 relative permeability
- Capillary barrier behavior of fractures are sensitive to fracture roughness and closure

Reactive Transport Modeling



4

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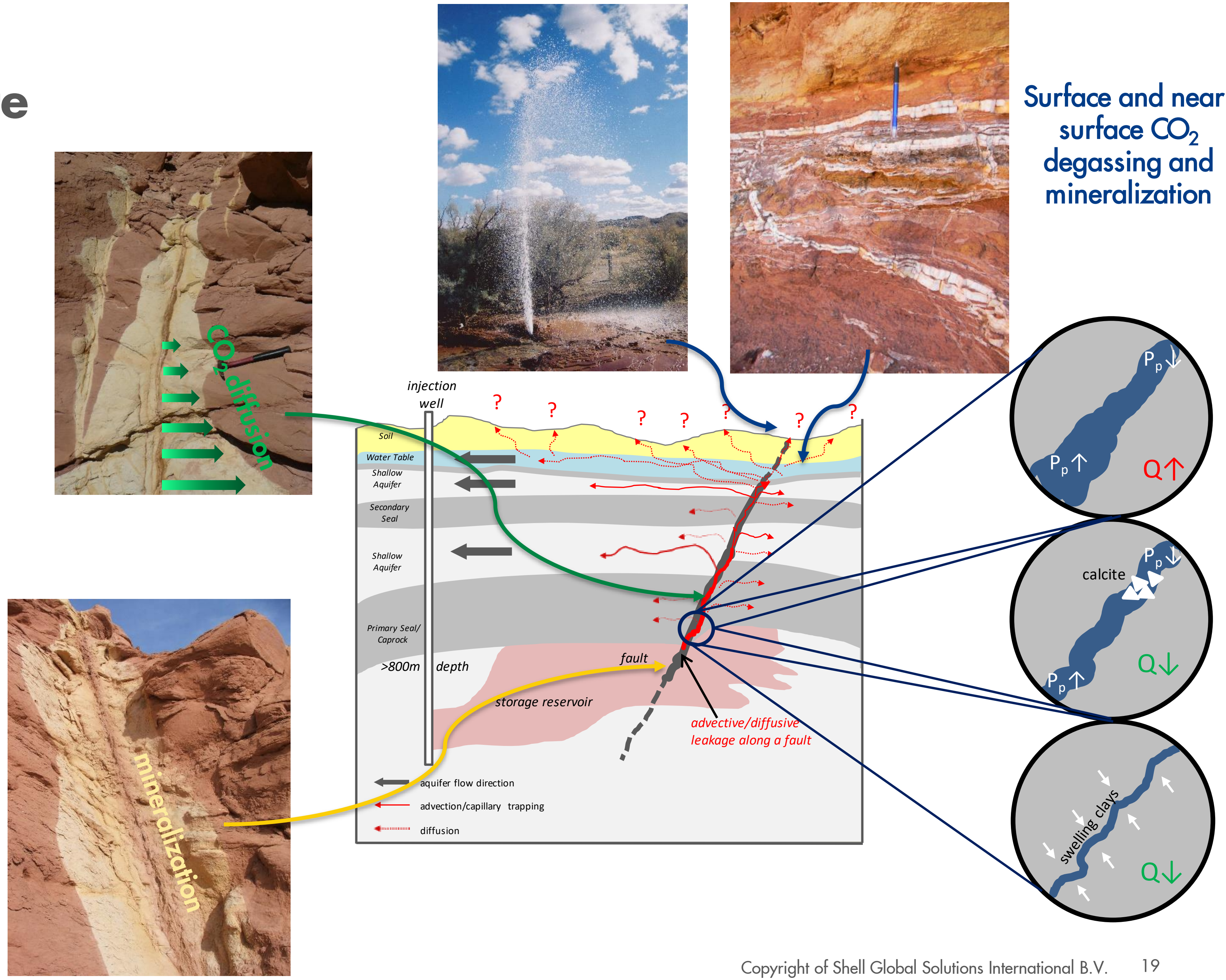
CO_2 leakage & fracture mineralization

Key questions

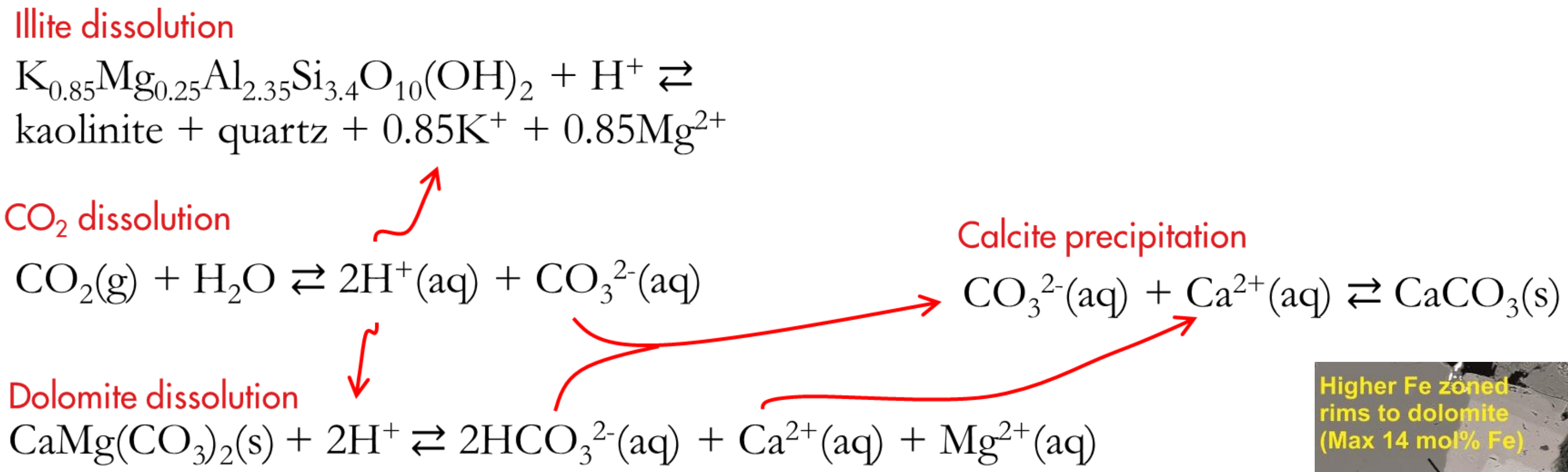
- Will CO_2-brine-mineral reactions lead to fracture opening or closing behavior?
- What mechanisms drive fracture closure (e.g. coupled mineral reactions, degassing) and under what conditions?
- What are realistic fracture closure timescales?
- Can constitutive models be developed that allow reactive process at small and meso-scale to be capture in large-scale models?



Surface and near-surface CO_2 degassing and mineralization

Fluid rock reactions in mudrock fractures

Fracture Mineralization



Illite dissolution

$K_{0.85}Mg_{0.25}Al_{2.35}Si_{3.4}O_{10}(OH)_2 + H^+ \rightleftarrows$ kaolinite + quartz + $0.85K^+ + 0.85Mg^{2+}$

CO_2 dissolution

$CO_2(g) + H_2O \rightleftarrows 2H^+(aq) + CO_3^{2-}(aq)$

Calcite precipitation

$CO_3^{2-}(aq) + Ca^{2+}(aq) \rightleftarrows CaCO_3(s)$

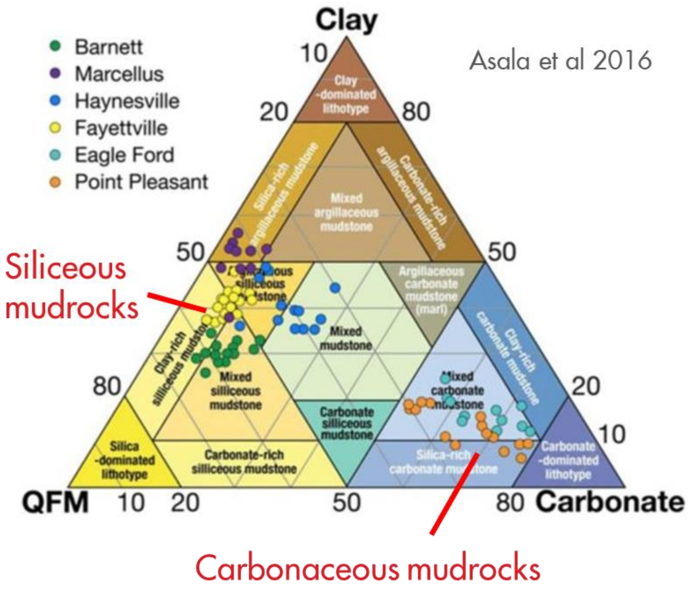
Dolomite dissolution

$CaMg(CO_3)_2(s) + 2H^+ \rightleftarrows 2HCO_3^{2-}(aq) + Ca^{2+}(aq) + Mg^{2+}(aq)$

Fe-Chlorite dissolution

chlorite + 16 CO_2 + 4.375 Ca^{+2} + 9 $H_2O \rightarrow$ 7.25 HCO_3^- + 0.625 Fe^{+2} + 14.75 H^+ + kaolinite + quartz + 4.375 ankerite

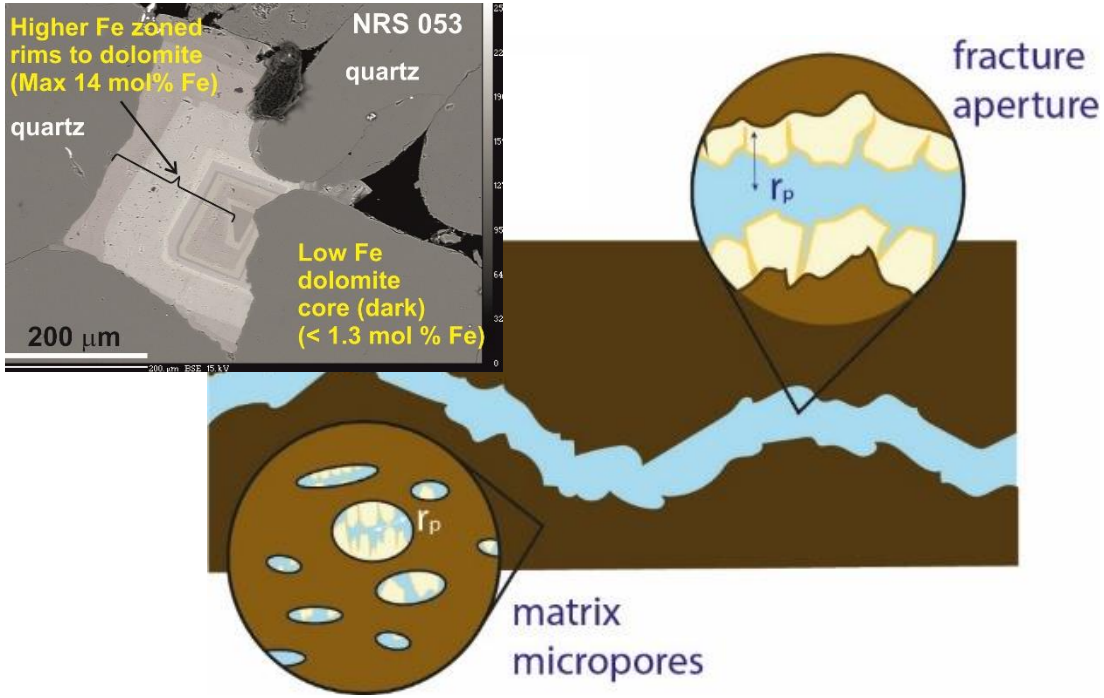
Ankerite precipitation



Asala et al 2016

Siliceous mudrocks

Carbonaceous mudrocks



2.5D Reactive Transport Model

Reactive Fluid Flow in Rough Fractures

- Mineralization in fracture plane coupled to reactive transport in fracture walls
- Mixed kinetic-diffusion controlled model for reactions in wall-rock
- 2.5D model incorporates diffusive transport in fracture wall in the kinetic expression

Reaction Front Diffusion Length

Mineral fraction

$$L = \left[\left(1 - \left(1 - \frac{b_{i,j}}{d_y}\right) \cdot \left(\frac{m}{m_0}\right)\right) \cdot d_y\right] - b_{i,j}$$

Initial mineral fraction

Diffusion controlled reaction rate

$$R_{diff} = \frac{D_{eff} \cdot \varphi_{rock} \cdot \rho_{H_2O}}{L} \cdot \frac{A_{diff}}{kg_{H_2O}} \cdot (C_{eq} - C_{bulk})$$

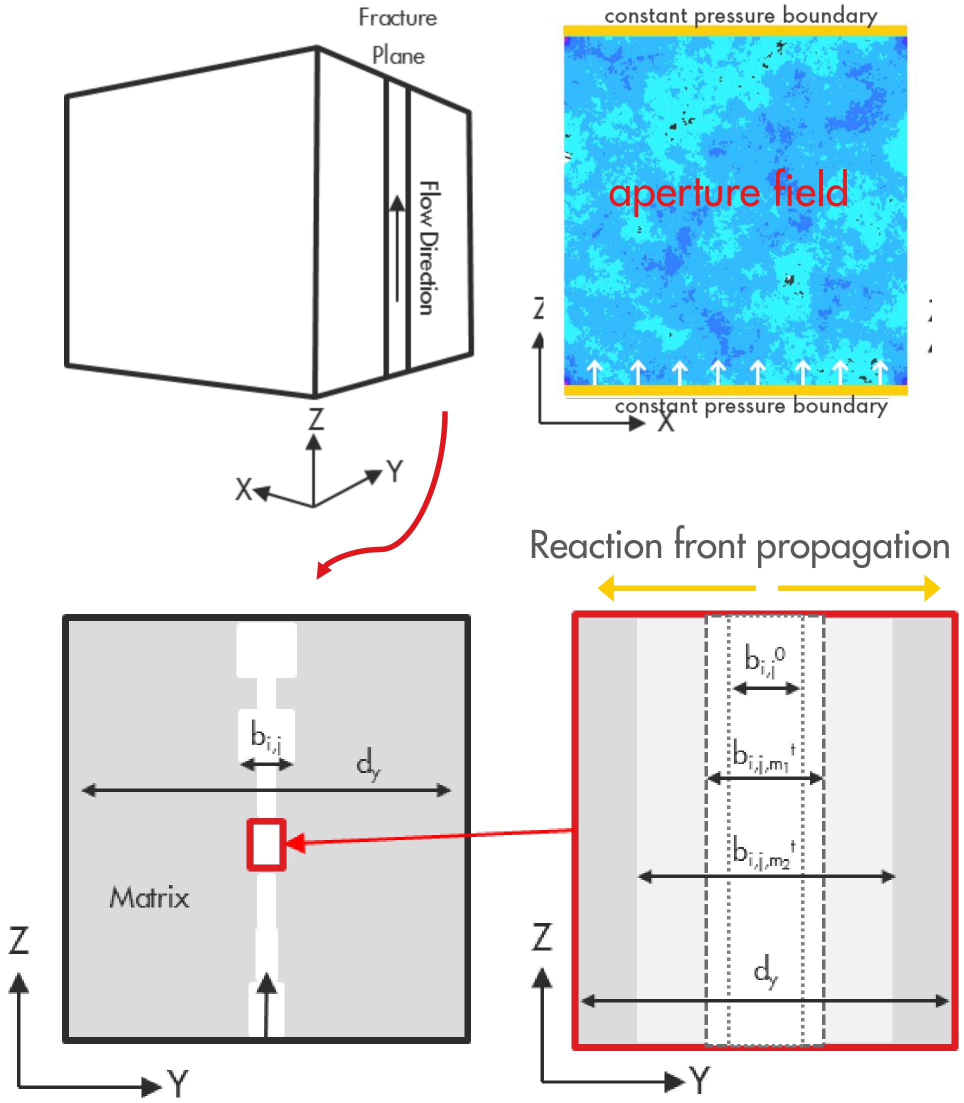
Surface reaction controlled reaction rate

$$R_{surf} = K_{surf} \cdot A_{rxn} \cdot (1 - SR_{min})$$

c.f. Deng et al. 2016

Reactive surface area

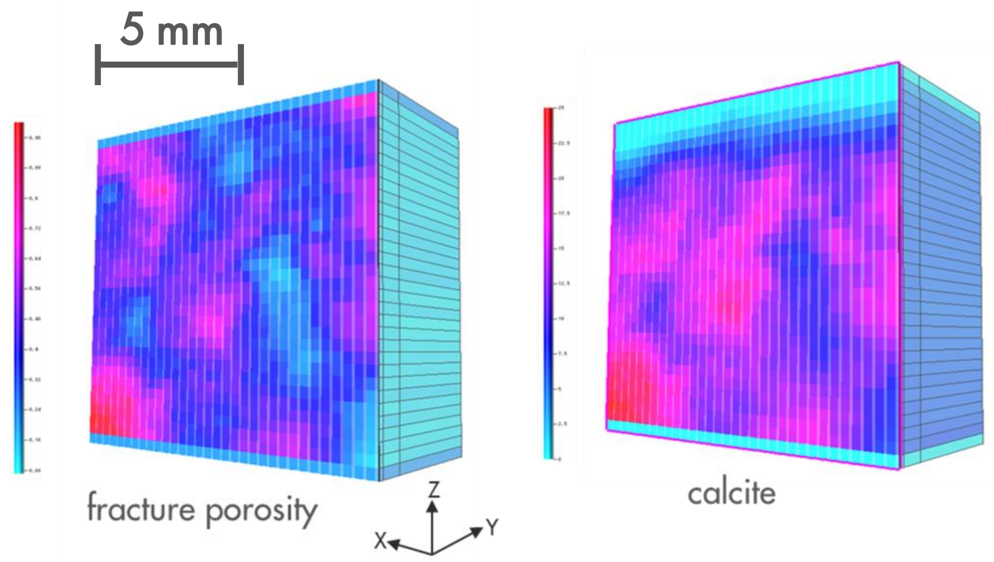
$$A_{rxn} = (2 \cdot A_{diff} \cdot (1 - \varphi_{rock}) \cdot m_0)/kg_{H_2O}$$



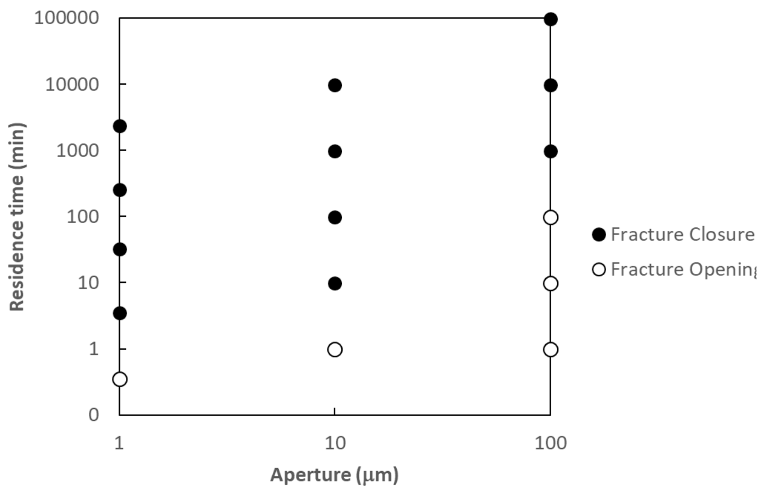
Single Phase Reactive Transport Model

Results

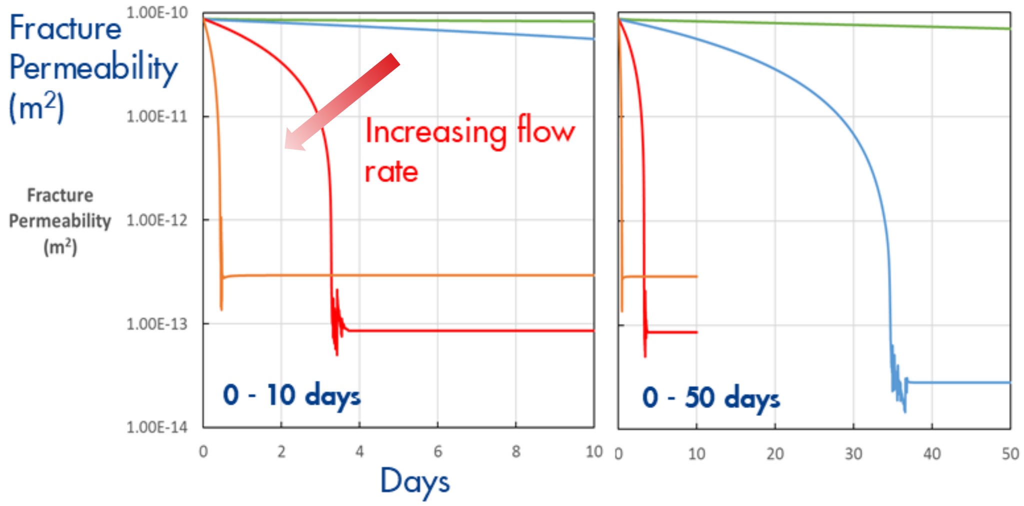
- Fracture opening on closing behavior depends on fluid residence time
- Rate of fracture mineralization depends on flow rate
- Fracture porosity-permeability evolution impacted by fracture roughness



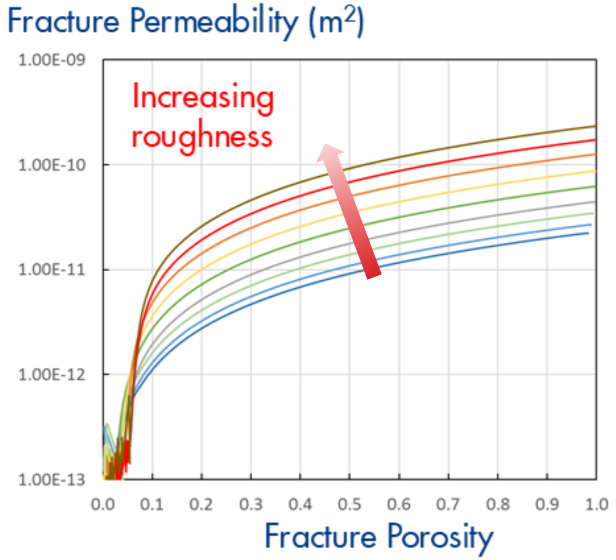
Fluid residence time



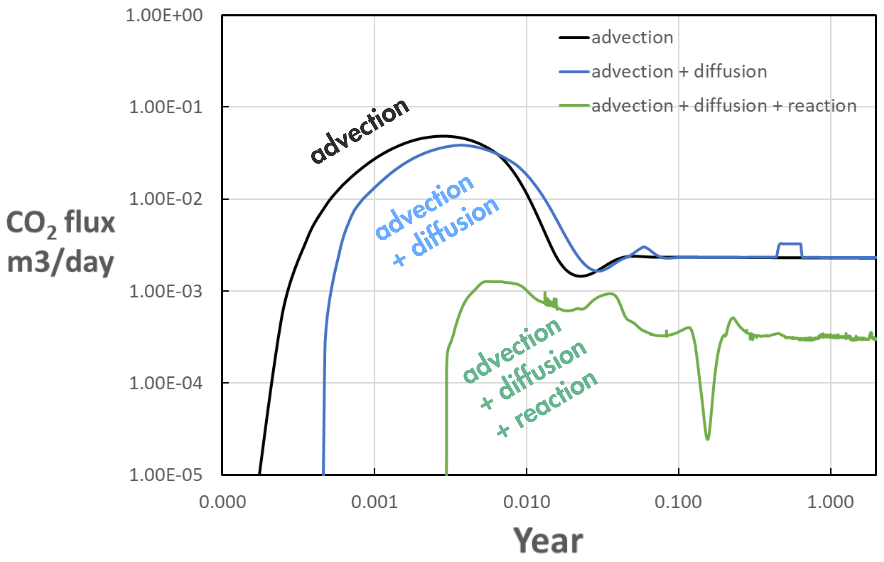
Flow rate

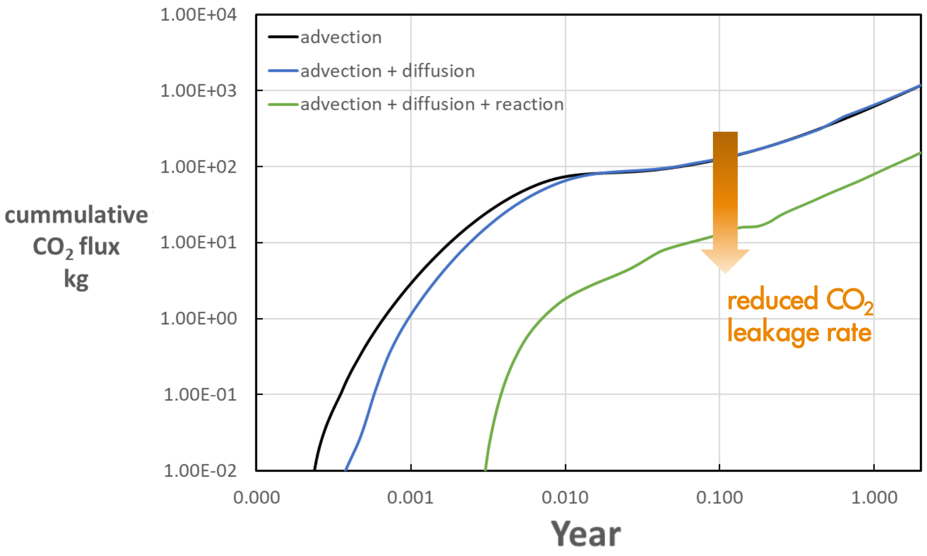


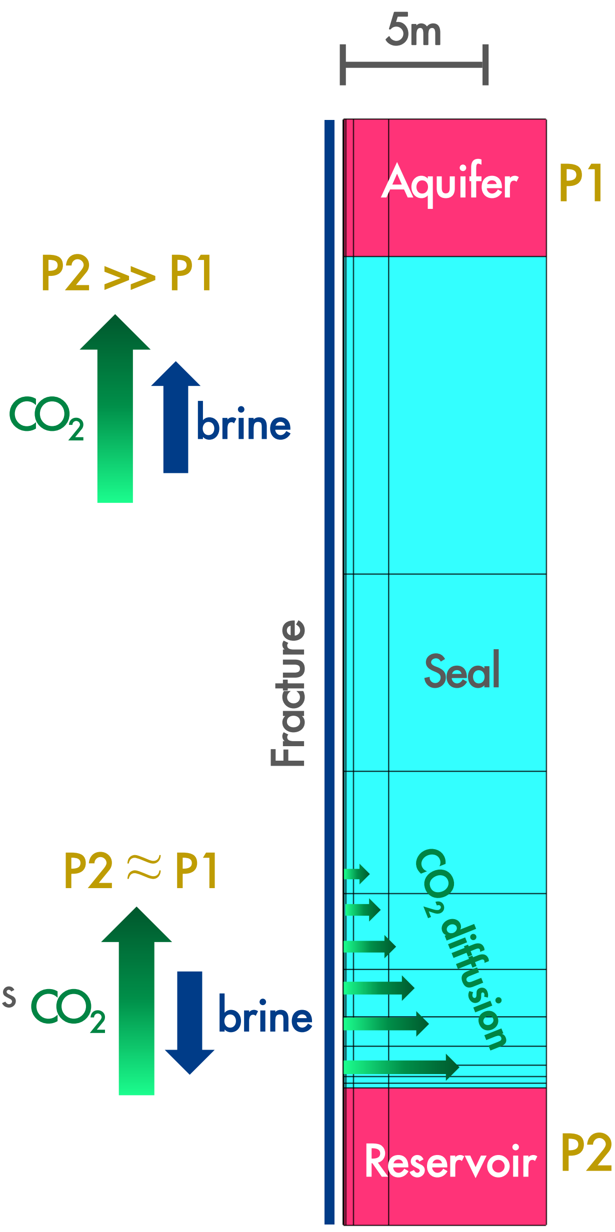
Porosity-permeability



Multiphase Reactive Transport Modelling







Key Learnings

- Silicate mineral reactions drive fracture closure & retard CO_2 leakage rates by consuming CO_2
- Fracture closure sensitive to fluid flow rates, diffusion rates, mineralogy and fracture surface properties
- Two phase flow systems reduce fracture closure rates by lowering water flux and generate counter current flows without significant reservoir overpressure
- Realistic fracture closure times for investigated mineralogies are on order of 100 to 1000 years
- Simulations are computationally intensive – limits ability to investigate large parameter space

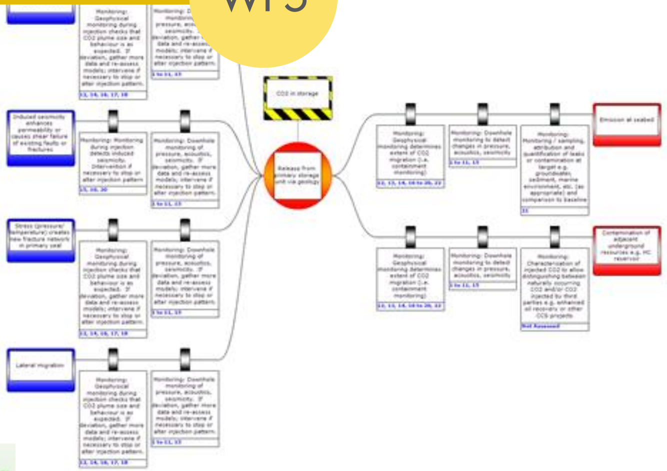
DETECT workflow

The goal of DETECT is to assess geological leakage risks related to fault and fractures in caprocks

WP5

Geological Leakage Risk Assessment

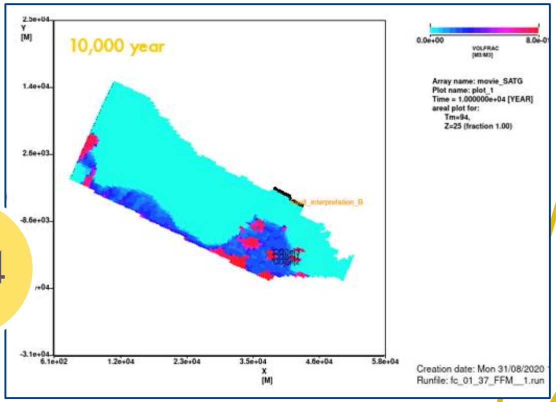
Incorporate all modelling and monitoring barriers in a qualitative bowtie risk assessment framework with associated quantitative scenario modelling tool



WP4

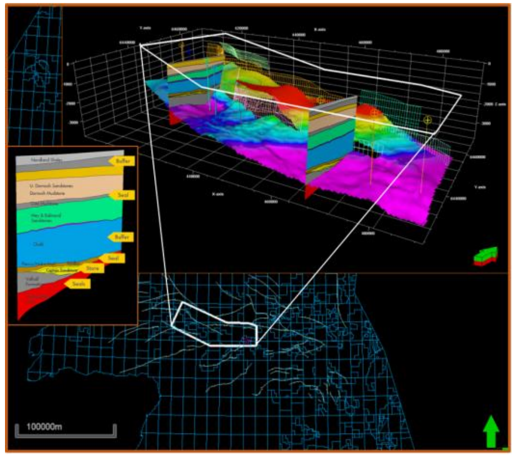
Identify active monitoring barriers relevant for site and expected leakage rates

Modelling results inform effectiveness of passive barriers (in seals and secondary storage units)



Probabilistic dynamic simulation using uncertainty ranges on all (parametrized) controls

Estimation of leakage rate distribution and likelihood at each caprock in CO_2 storage complex



WP3

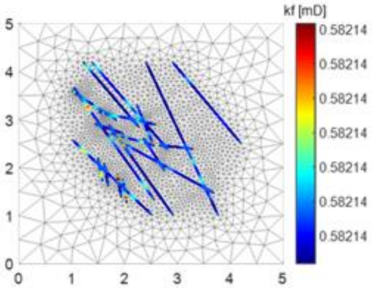
Hydromechanical coupling using lab-derived stress-permeability relations and analytical stress-state model

Effective fracture + matrix vertical permeability, RLP, CPR for each cell in seal derived from numerical up-scaling

Simulate flow in fracture networks in caprocks

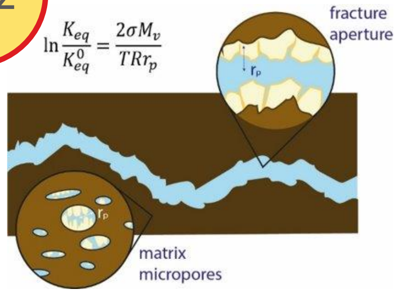
Scaling relations based on meso/fine-scale modelling & analogues

Characterise background stresses and log-derived rock transport and geomechanical properties



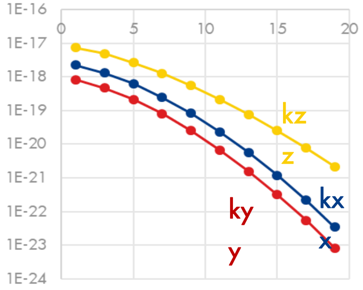
WP2

Experimentation and numerical modeling to characterise single fracture processes



$$\ln \frac{K_{eq}}{K_{eq}^{0}} = \frac{2\sigma M_v}{TRr_p}$$

Quantifying the impact of small-scale physics on CO_2-brine flow at fine-scale



Characterise fault-fracture networks using analogue derived scaling relations: fault throw-length-frequency

Accelerating CCS Technologies

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