DETECT

INTEGRATED GEOLOGICAL
CO_2 LEAKAGE RISK
ASSESSMENT

WP2 – Fracture flow, mineralisation, clay swelling



2

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Accelerating
CCS
Technologies

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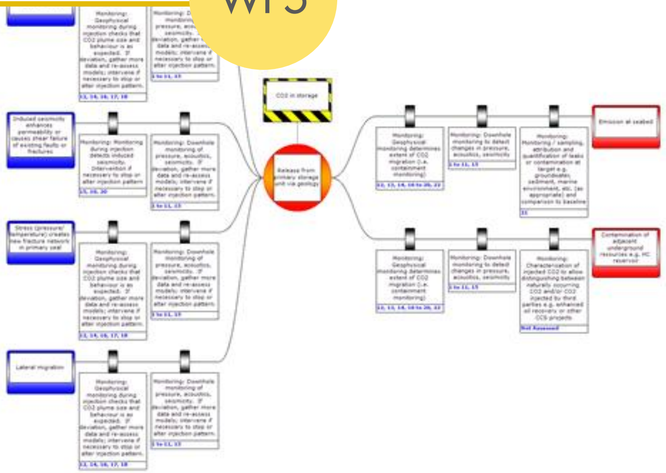
DETECT workflow

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

WP5

Geological Leakage Risk Assessment

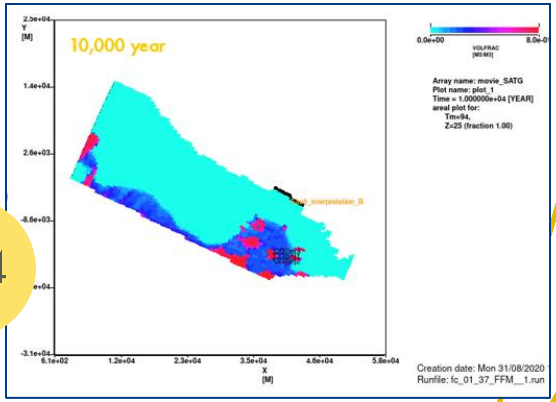
Incorporate all modelling and monitoring barriers in a qualitative bowtie risk assessment framework with associated quantitative scenario modelling tool



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

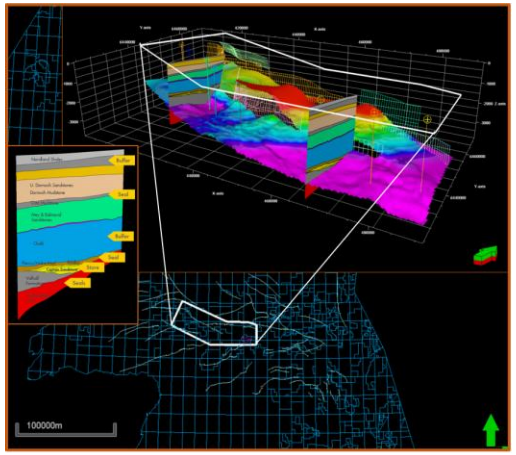
Hydromechanical coupling using lab-derived stress-permeability relations and analytical stress-state model

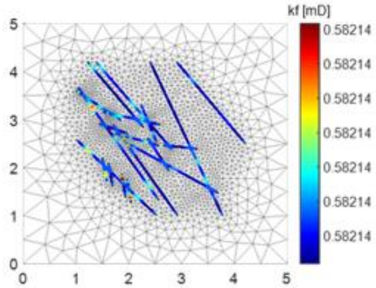
Effective fracture + matrix vertical permeability, RLP, CPR for each cell in seal derived from numerical up-scaling

Simulate flow in fracture networks in caprocks

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

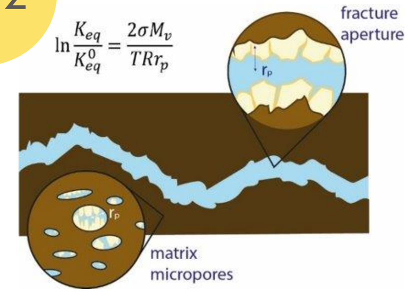
Characterise background stresses and log-derived rock transport and geomechanical properties





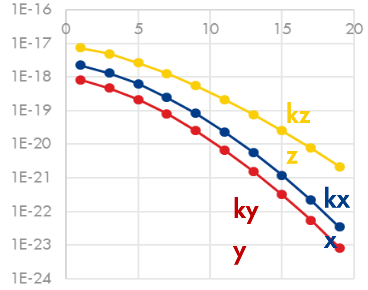
WP2

Experimentation and numerical modeling to characterise single fracture processes



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

Quantifying the impact of small-scale physics on CO2-brine flow at fine-scale



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

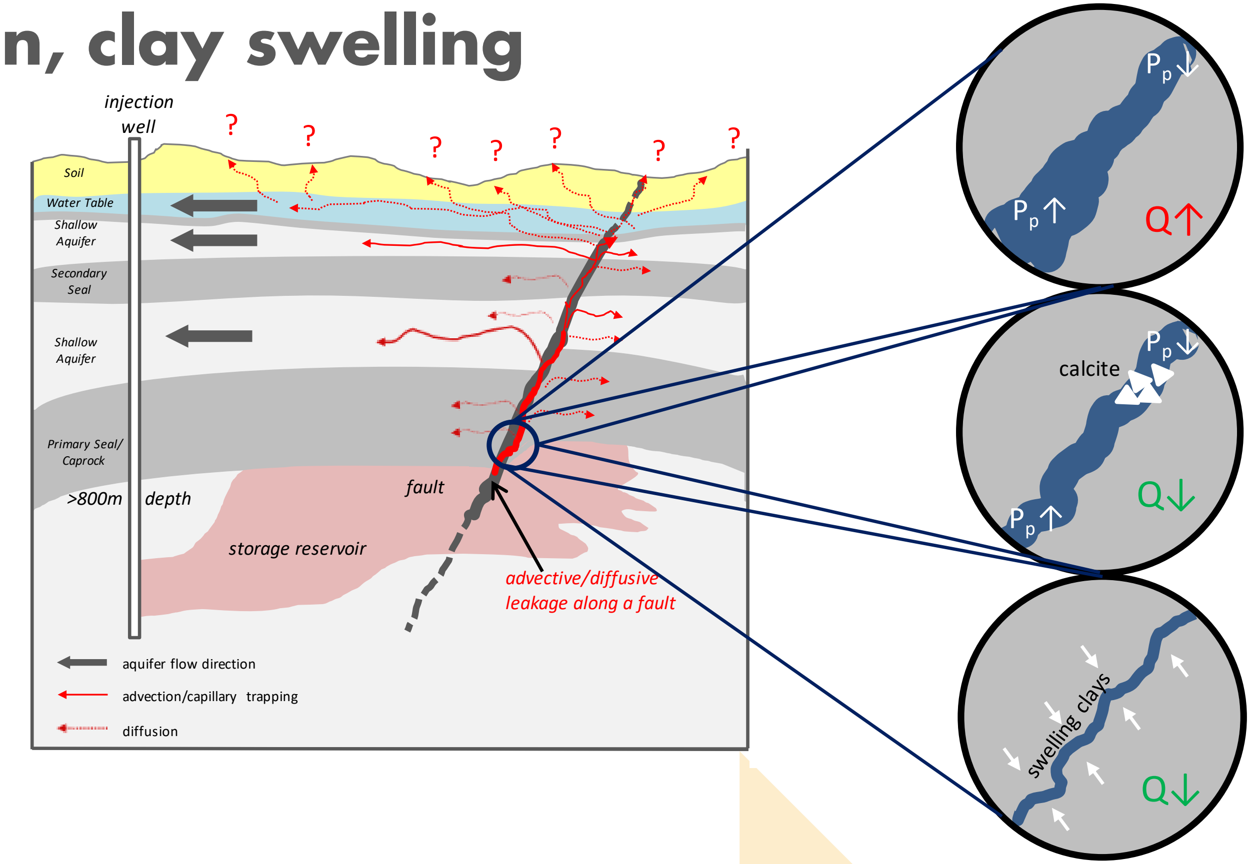
WP2 – Fracture flow, mineralisation, clay swelling

Objectives

- **Pressure:** Identify and analyse factors controlling fracture flow as a function of pore pressure, confining stress, mineralogy or strength parameters
- **Clay swelling:** Significantly improve fundamental understanding of the impact of CO_2 induced expansion of swelling clays in fractures
- **Mineralisation:** Determine effects of CO_2-induced water-rock interactions on transport through fractures

Collaboration

- Heriot-Watt University, RWTH Aachen University, Shell IRD



WP2.T1. Fracture Flow: stress-permeability relations

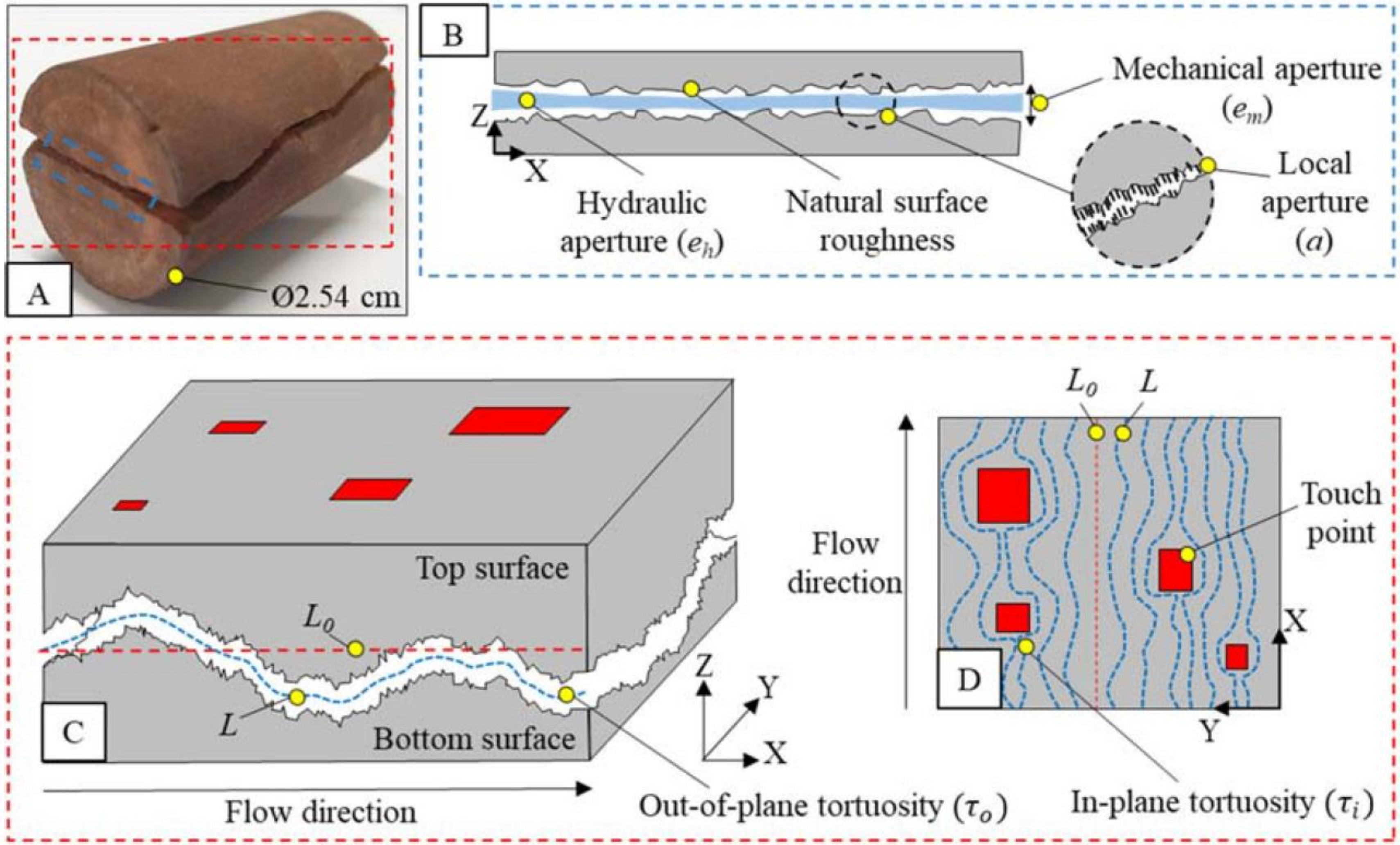
WP2.T2. Mineralisation: mineralisation in fractures

WP2.T3. Clay Swelling: clay swelling affecting fracture apertures

Field work to obtain fracture networks in caprock analogues

- Carmel shale, Green River, Utah core drilled in 2012
- Tight carbonates, Crato, Brazil
- Opalinus shale from Mont Terri
- Nash Point Shale, Bristol Channel
- Mercia mudrock, Midlands and Bristol Channel, UK
- Kimmeridge Shale, Kimmeridge, UK
- Konusdalen, Svalbard, Norway

WP2.1. – Stressed Permeability Concept



WP2.1 - Stressed Permeability

plug perm

matrix perm.

fracture perm

fracture porosity

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

fracture porosity

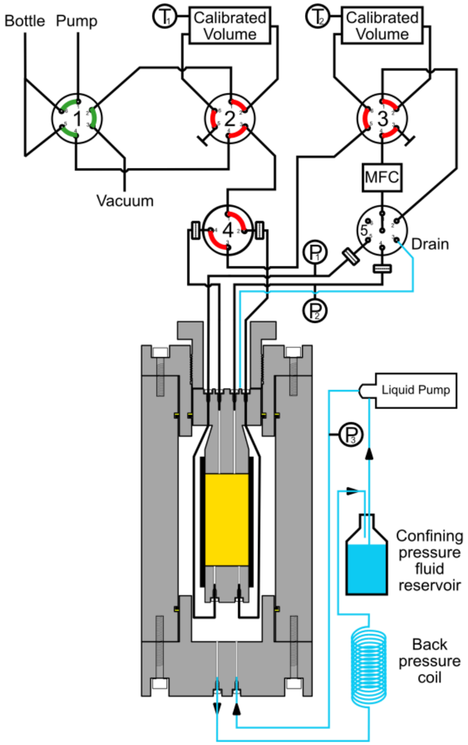
$$\phi_f = \frac{4 \cdot b}{\pi \cdot d}$$

Core diameter

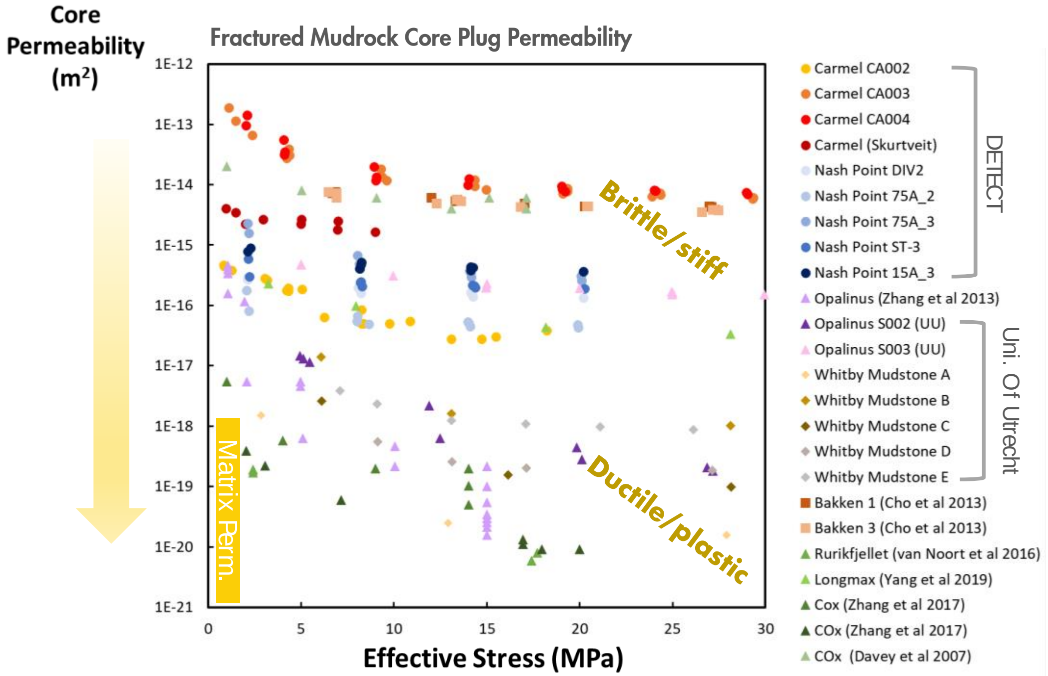
$$k_f = \frac{b^2}{12}$$

fracture aperture

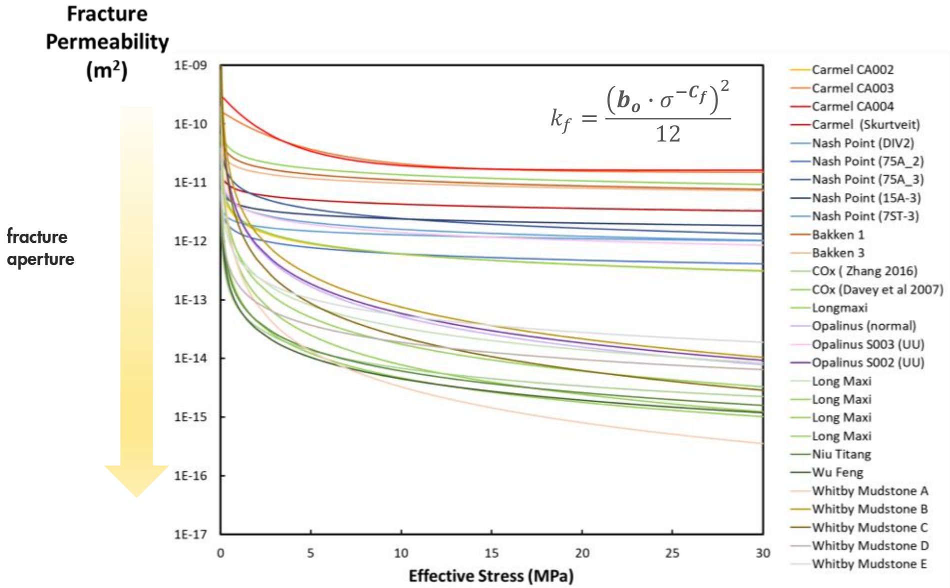
$$\boxed{k_{core} = k_m + s \cdot \frac{1}{12} \cdot \frac{4}{\pi d} \cdot b^3}$$

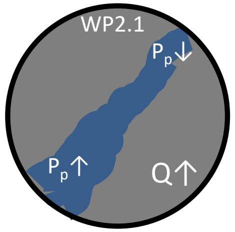


A Core permeability vs applied stress

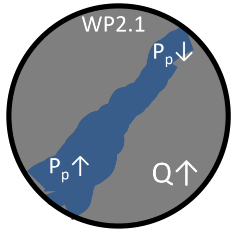


B Fracture Aperture vs applied stress



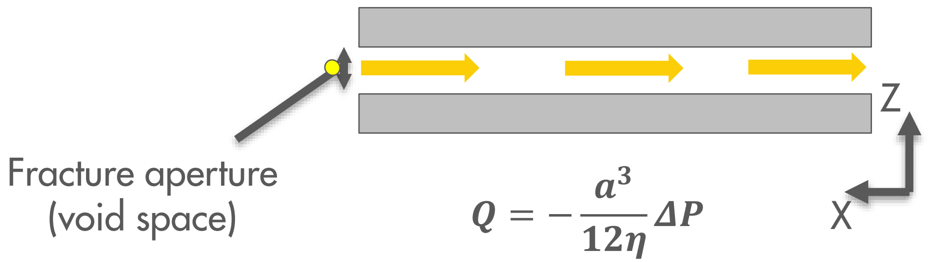


WP2.1. – Fluid Flow in Fractures



- Interplay between geometrical and chemical heterogeneity of the wall-rock and effective stress.
- On the single fracture scale, the magnitude and distribution of aperture governs fluid flow.

Simplified View of a Fracture

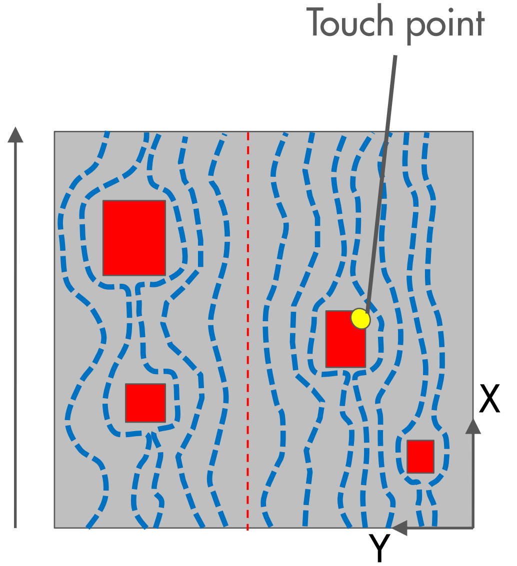


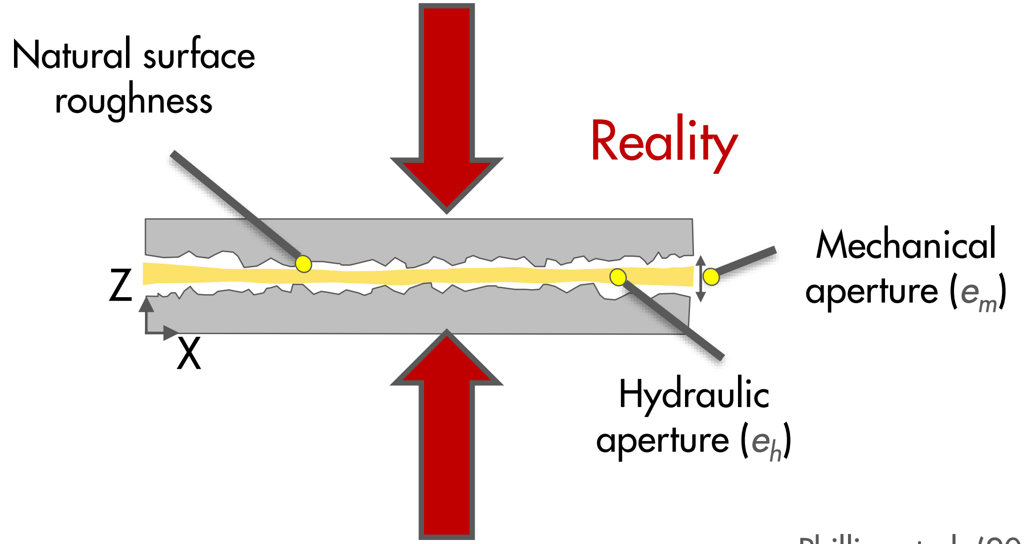
Fracture aperture (void space)

$$Q = -\frac{a^3}{12\eta}\Delta P$$

Touch point

Flow direction





Natural surface roughness

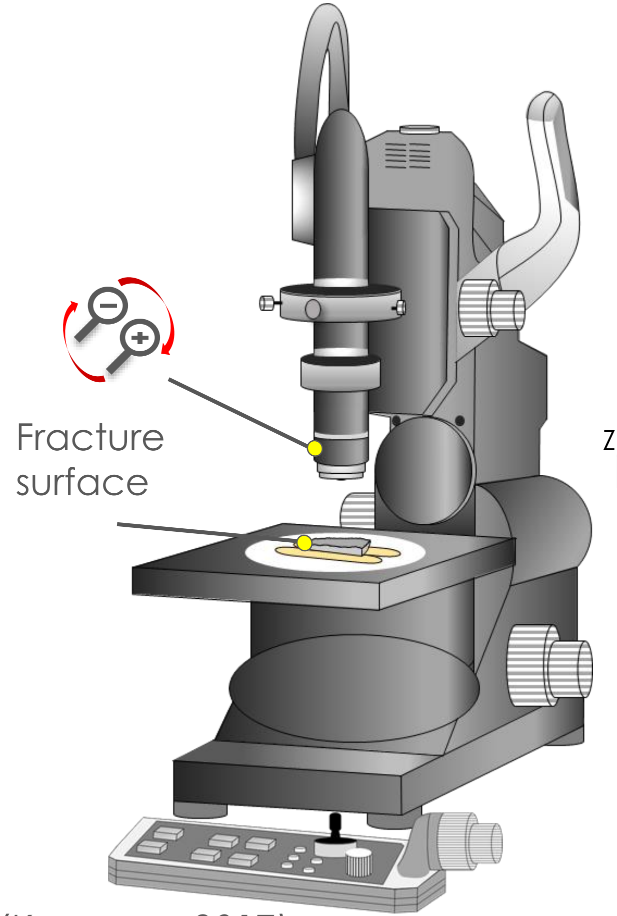
Reality

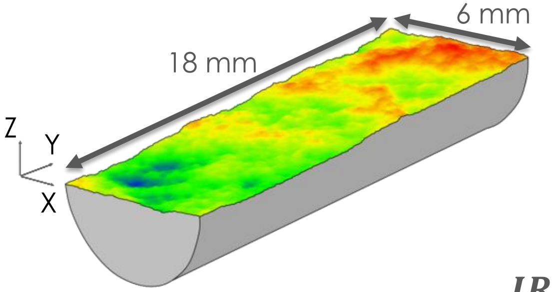
Mechanical aperture (e_m)

Hydraulic aperture (e_h)

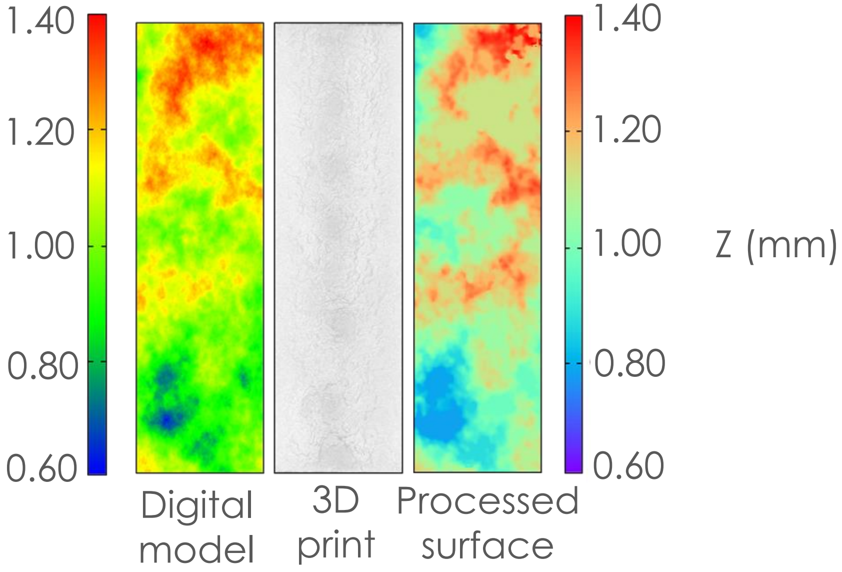
Phillips et al. (2020) - Earth Science Reviews

WP2.1. – Surface Roughness Analysis

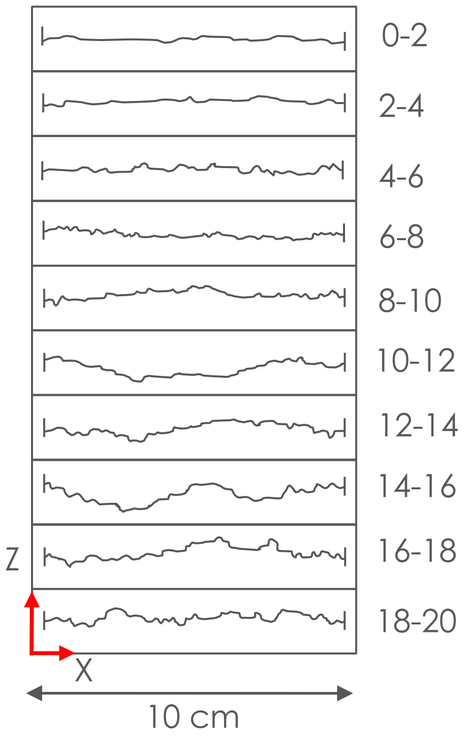




(Keyence, 2017)



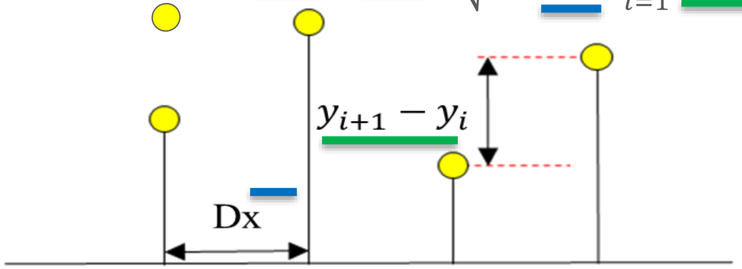
Typical roughness profiles



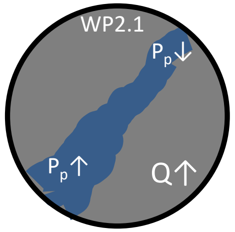
(Barton and Choubey (1977) – Rock Mechanics.)

Joint Roughness Coefficient (JRC)

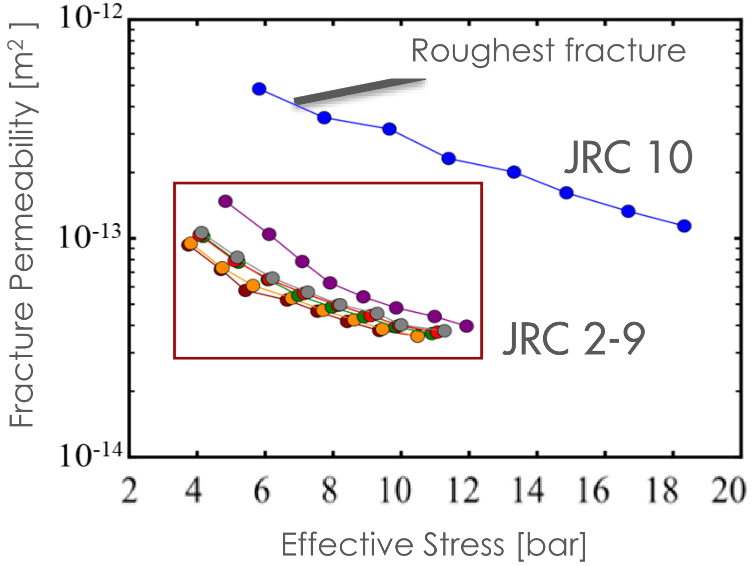
$$JRC = 37.2 + 32.47\, \log Z_2 \qquad Z_2 = \sqrt{\frac{1}{M(\mathrm{D}x)^2}\sum_{i=1}^{M}(y_{i+1} - y_i)^2}$$

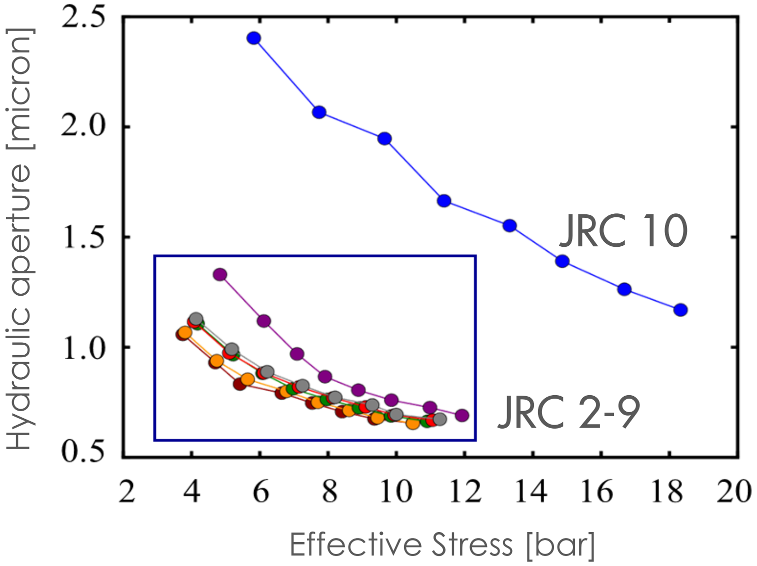


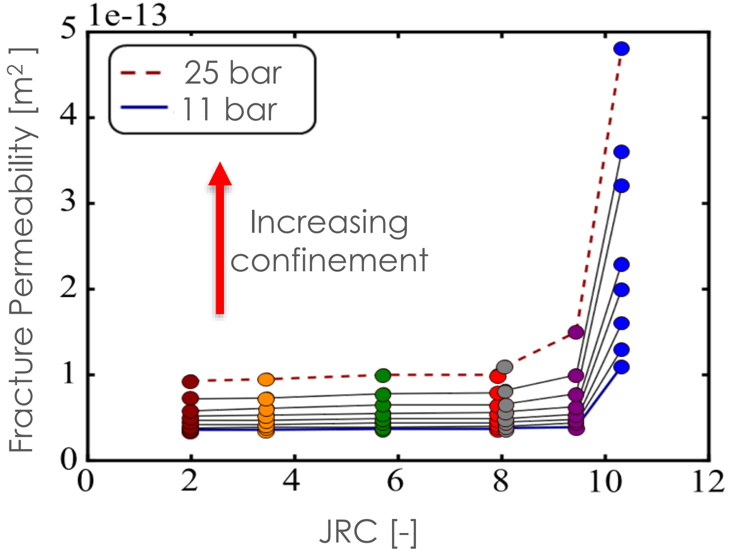
(Tse and Cruden, 1979)

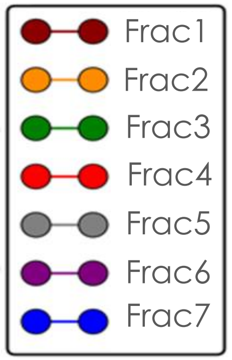


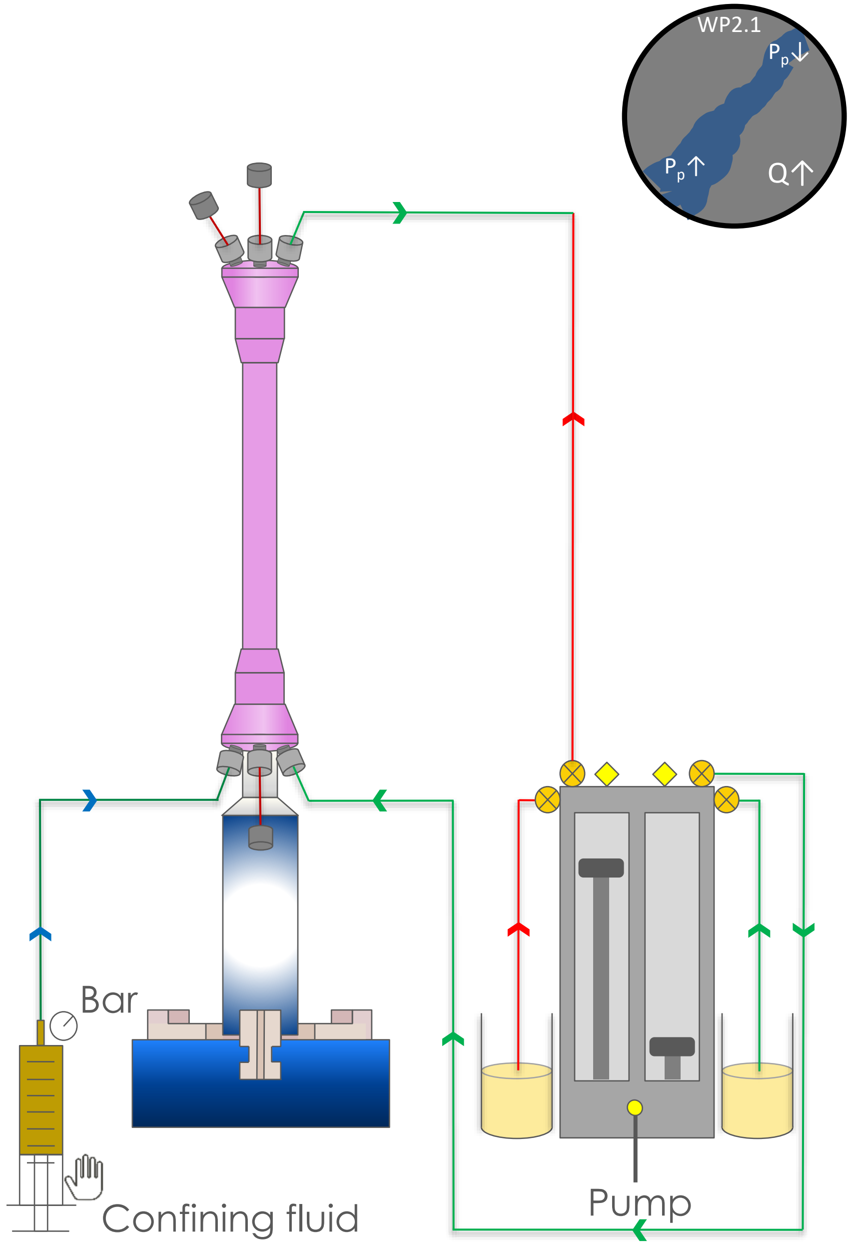
WP2.1. – Controlled Roughness – Experiments





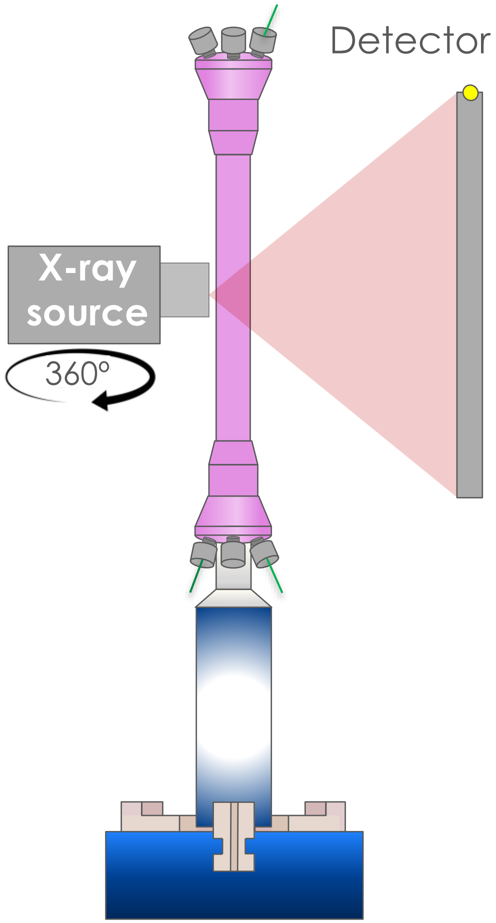


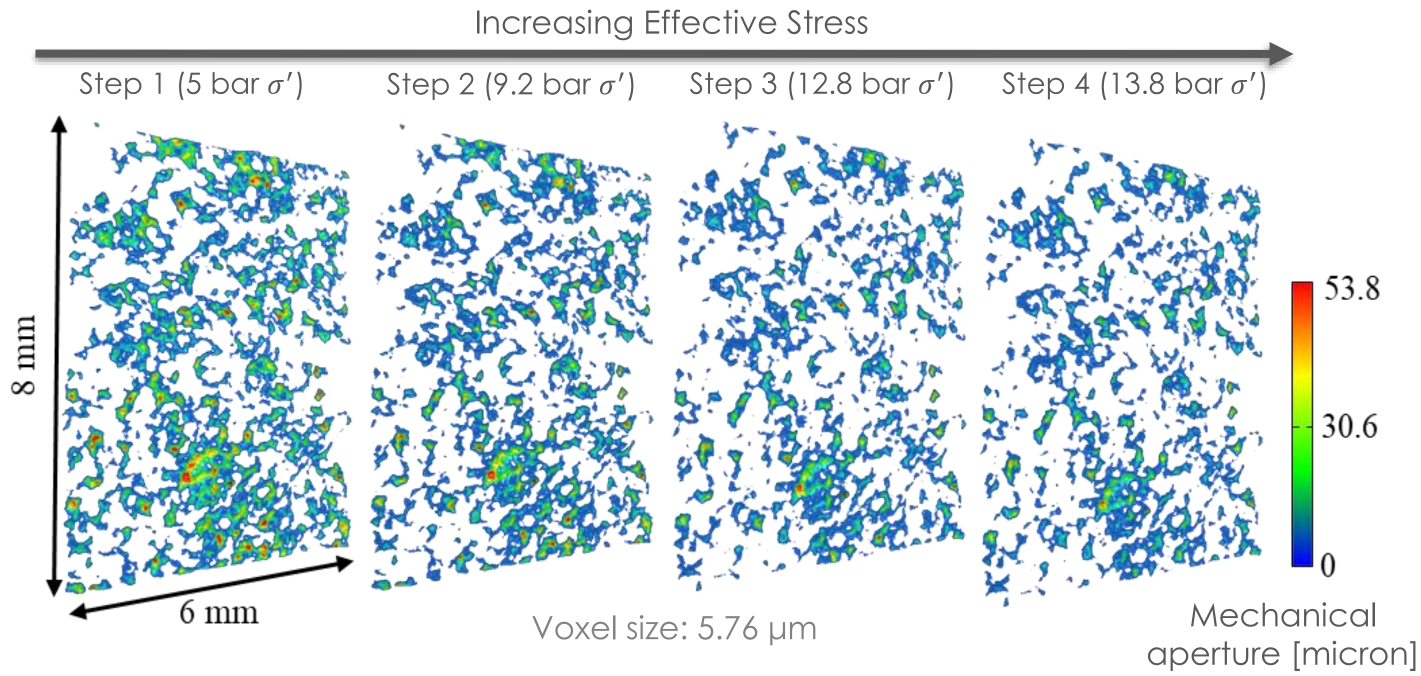


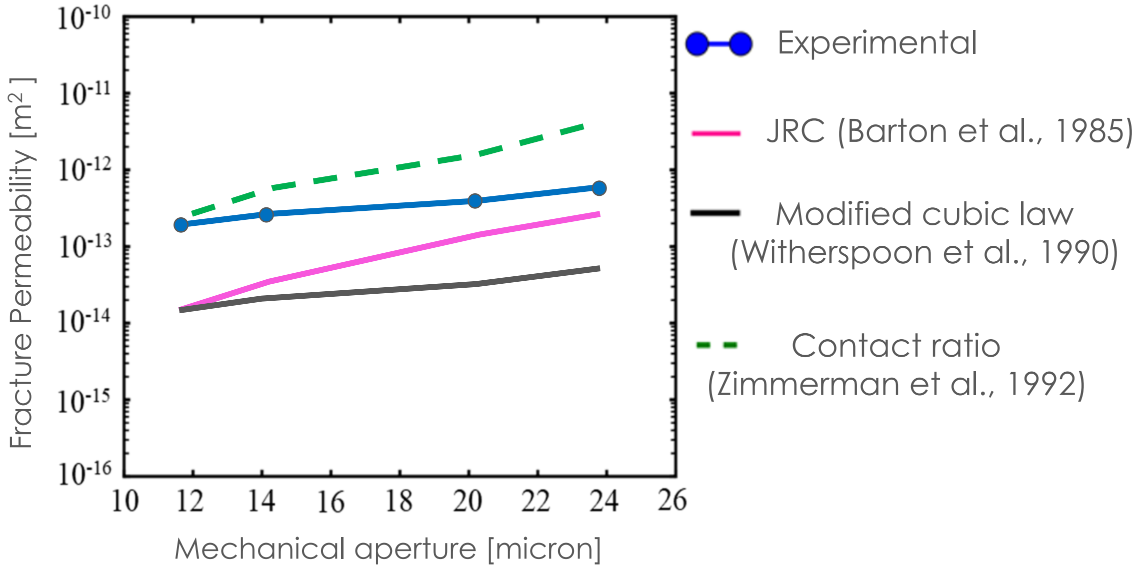


Phillips et al. WRR, in review

Micro-CT Insights

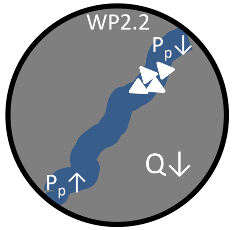






Phillips et al. WRR, in review

WP2.2 –Mineralization



"Depressurization and consequent degassing of CO_2-saturated fluids leaking through fractures in cap rocks has often been suggested to result in **self-sealing** through carbonate precipitation"

- concept was confirmed numerically
- but substantial uncertainty on **mechanisms**, many essential **parameters controlling locus, volume and speed of mineralization**
- very little experimental data available to verify or refine geochemical models of carbonate precipitation and dissolution during fracture flow

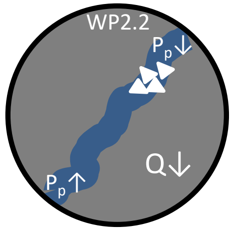
Key issues:

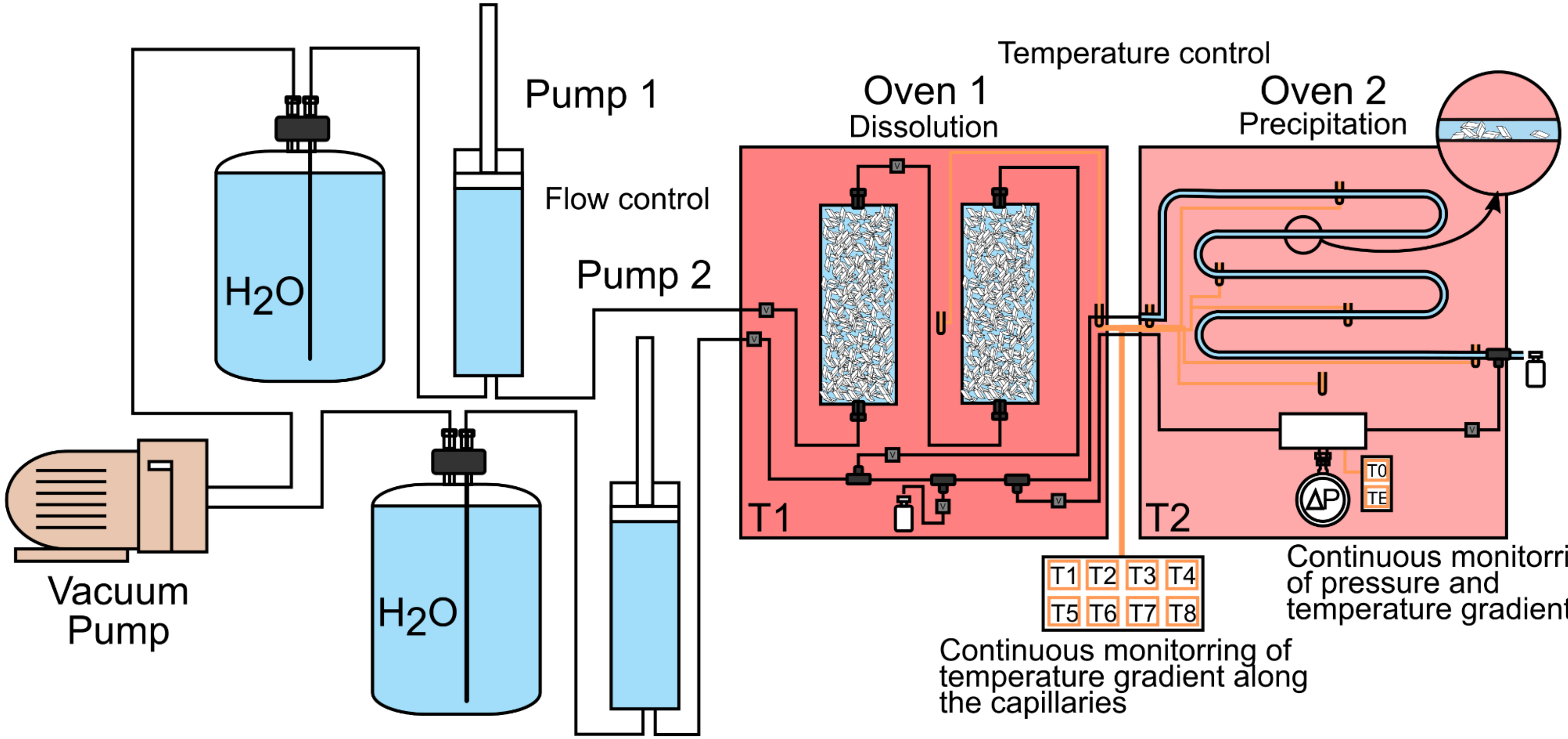
- Effect of saturation
- Effect of mineralogy – crystal seeds
- Effect of flow rate

→ **Porosity - Permeability**

WP2.2 – Mineralization – 3 staged experiments

1. Capillary systems





Continuous monitorring of temperature gradient along the capillaries

Continuous monitorring of pressure and temperature gradient

Narrow diameter transparent capillaries

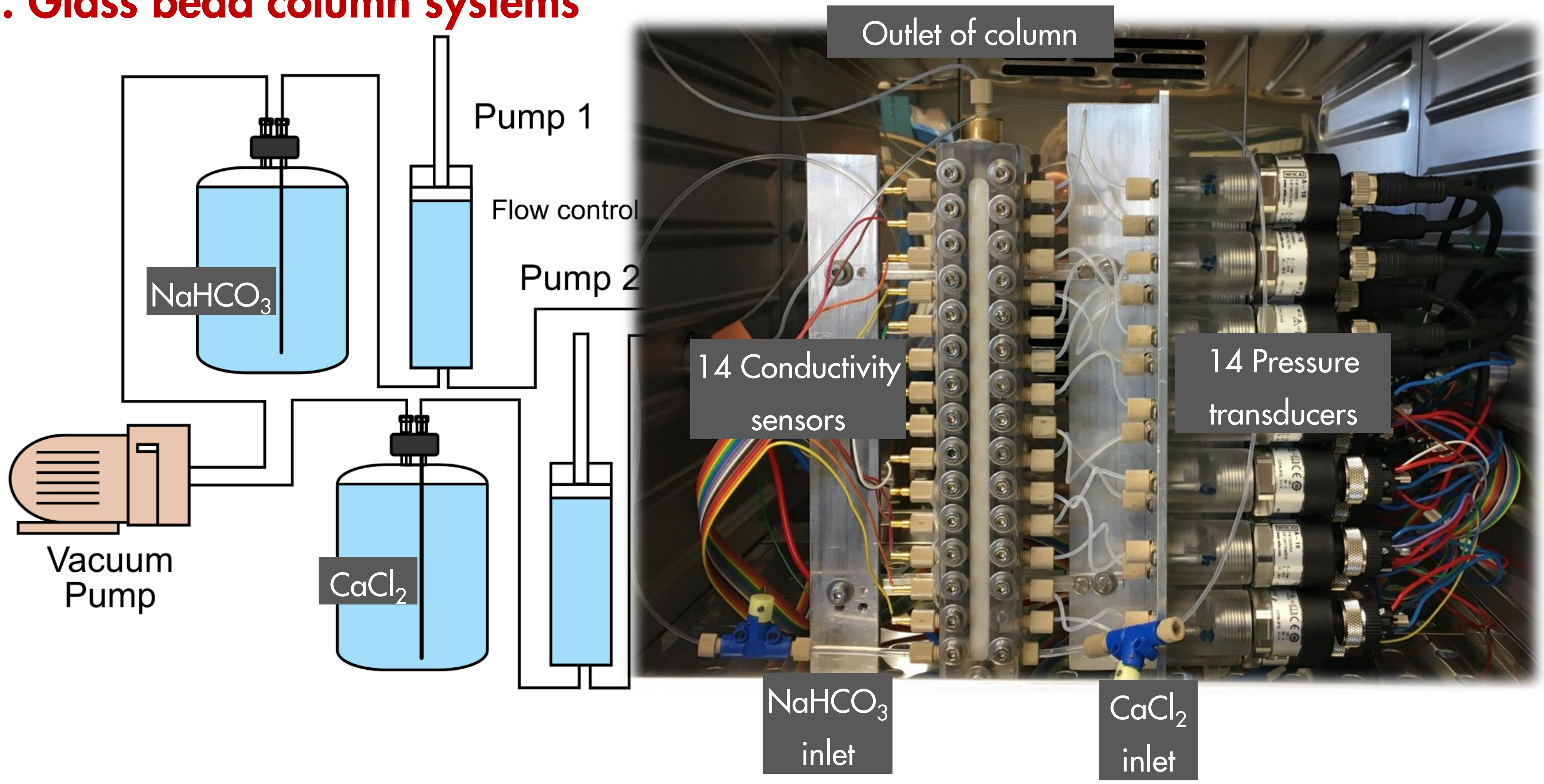
=> Constant pressure gradient

=> Visual observations

- Variation of
  - Crystal system
  - Saturation
  - Flow rate
  - Capillary size

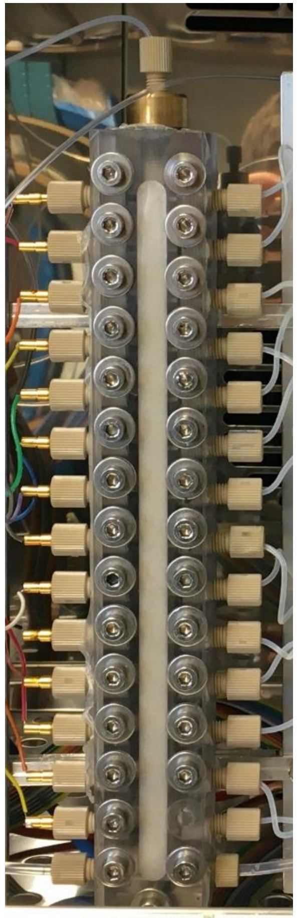
WP2.2 –Mineralization – 3 staged experiments

2. Glass bead column systems

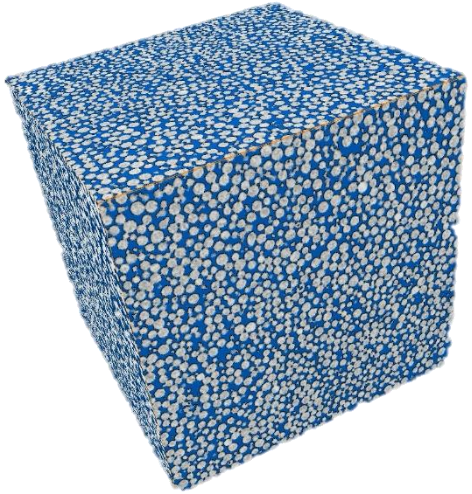


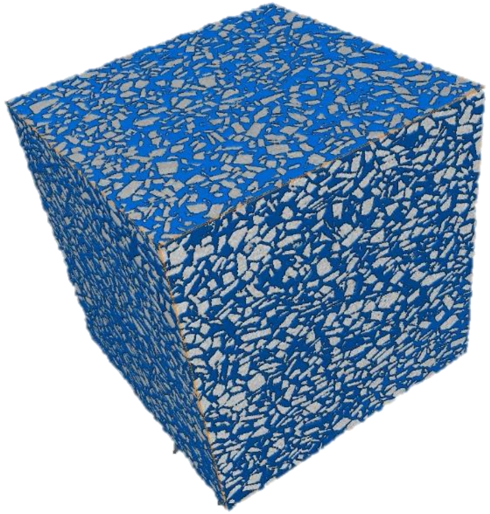
WP2.2 –Mineralization – 3 staged experiments

2. Glass bead column systems



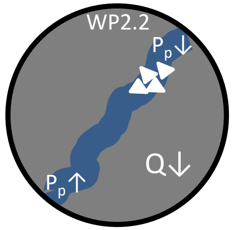
- Experiment 1
  - 100% Glass Beads (100-200µm)
  - 1-1 mixture of 30mmol/l $CaCl_2$ and 30mmol/l $NaHCO_3$; 30°C
  - 13 days
- Experiment 2
  - 20wt% Calcite (100-200µm), 80wt% Glass Beads (100-200µm)
  - 1-1 mixture of 30mmol/l $CaCl_2$ and 30mmol/l $NaHCO_3$; 30°C
  - 16 days
- Experiment 3
  - Lower 100% GBs – Middle 100% Calcite – Top 100% GBs
  - 1-1 mixture of 30mmol/l $CaCl_2$ and 30mmol/l $NaHCO_3$; 30°C
  - <4 days

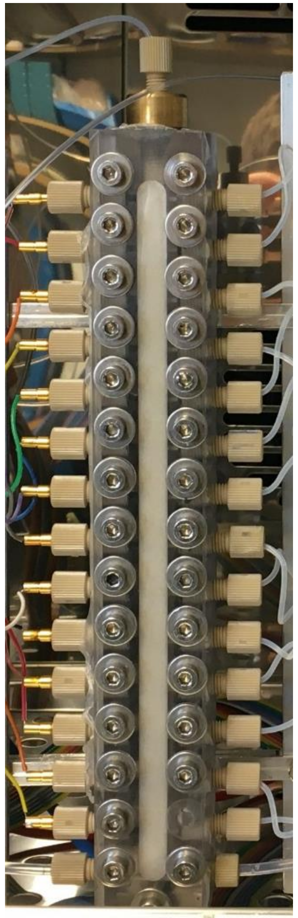




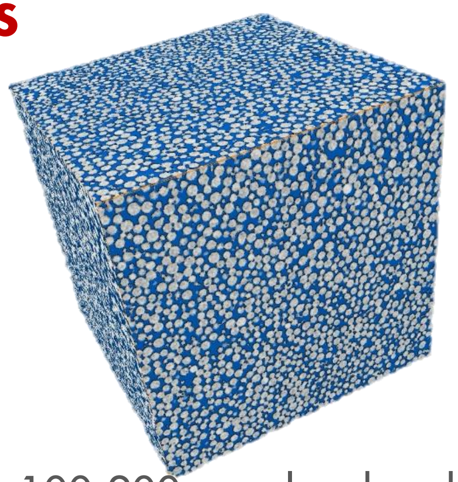
WP2.2 – Mineralization

2. Glass bead column systems

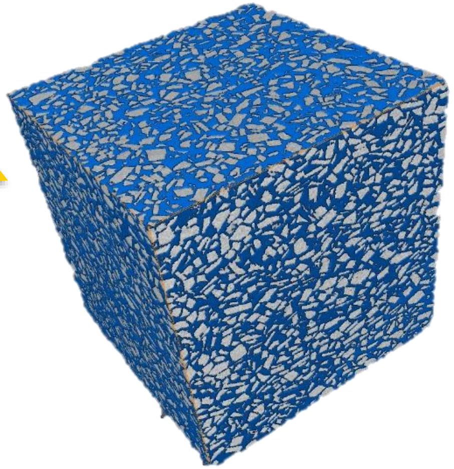




Porosity (CT)

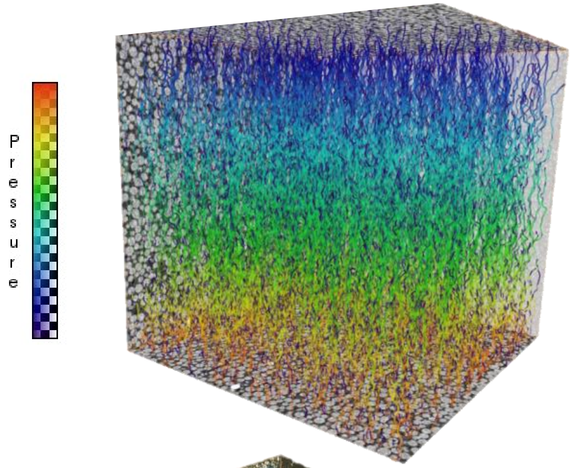


100-200 µm glass beads

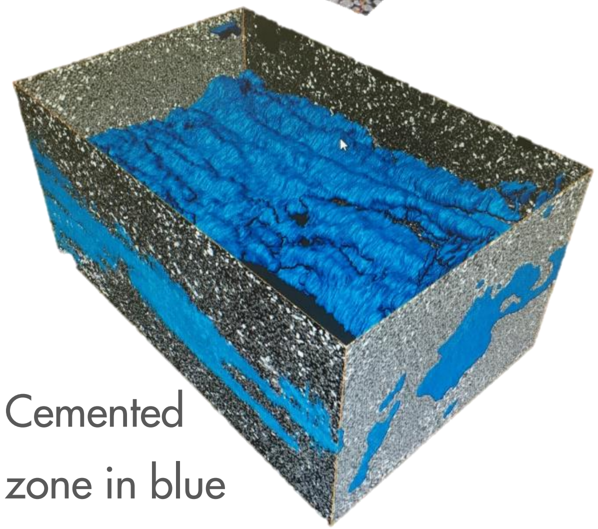


100-200 µm calcite

Permeability



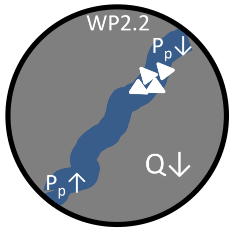
Darcy	Before	After
GB Top	25	17
Calcite	58	27
GB Bottom	28	18



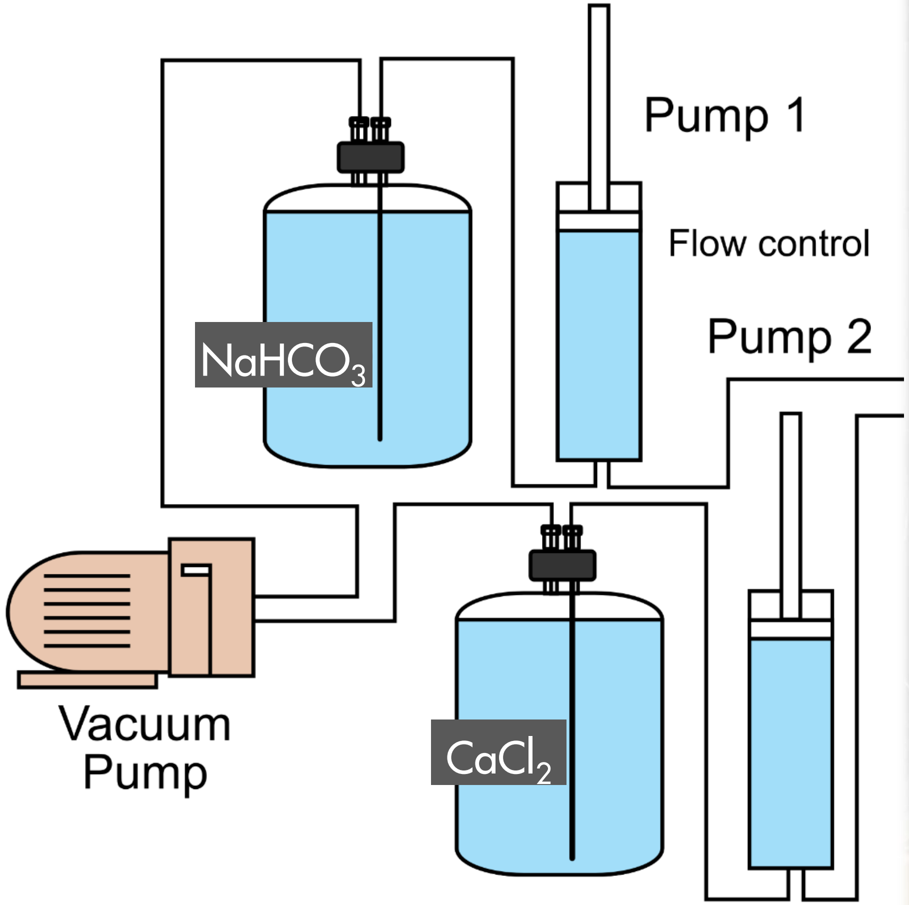
Cemented zone in blue

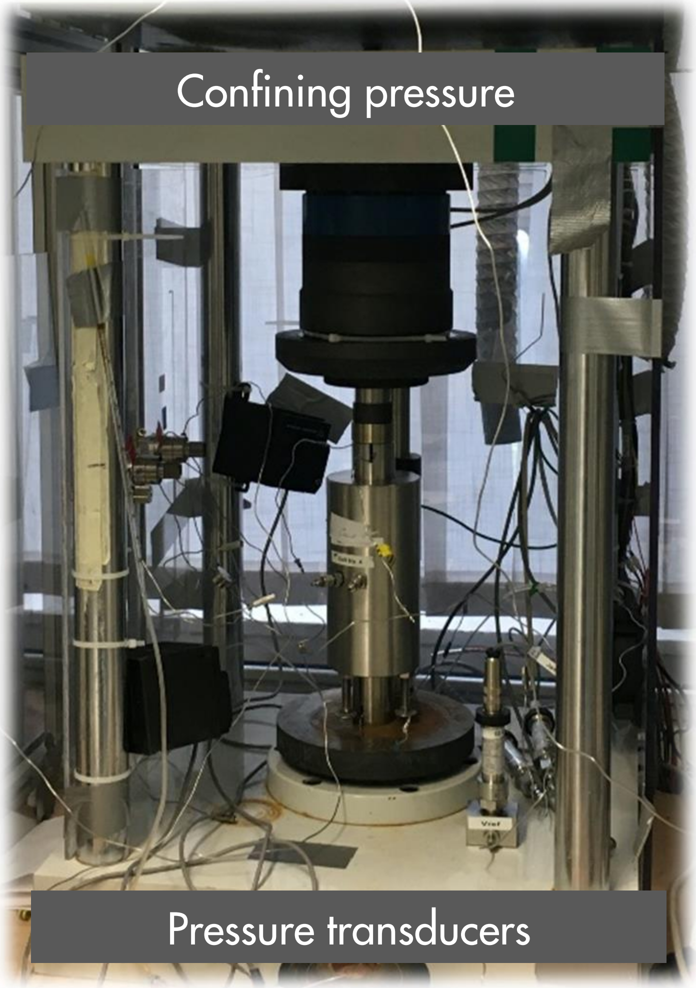
- Preferential flow & cementation path (~ fracture)
- Effect of calcite: most cementation at first contact

WP2.2 –Mineralization



3. Fractured rock plugs

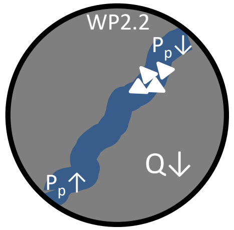




Plugs of differing mineralogy with fractures

- Initial equilibration with synthetic pore water (PHREEQC)

WP2.2 –Mineralization

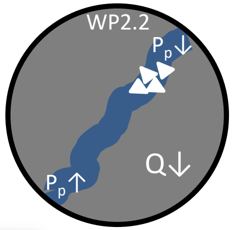


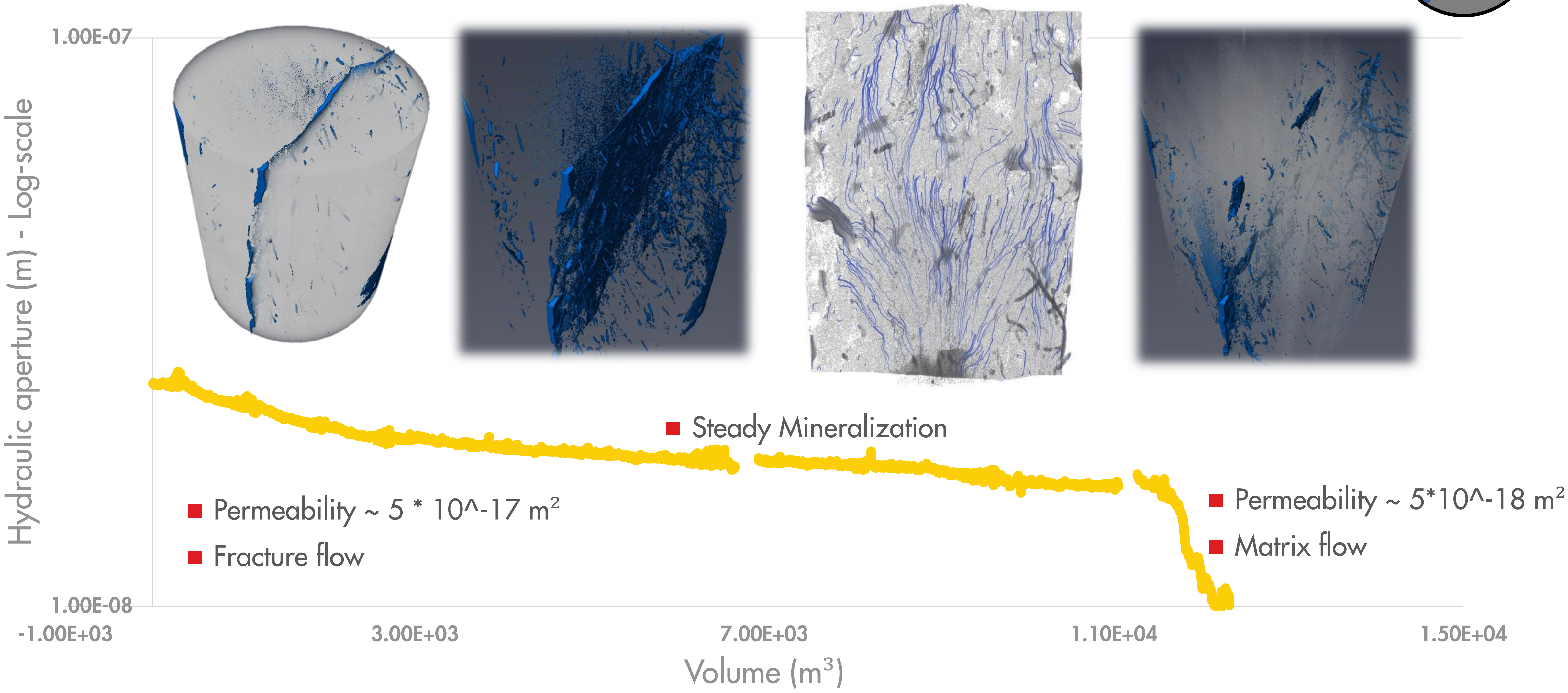
Mineralogy (wt%)	BR18HC010 - Crato	Utah 1 – Carmel 611-611.7ft	Utah 2 – Carmel 639.8 ft	Utah 3 – Carmel 591 ft	Utah 4 – Carmel 646 ft
Calcite	**92.08**	**55.22**	**3.09**	**14.70**	**29.10**
Dolomite	5.42	0.64	2.53	8.48	1.57
Hematite	-	0.27	1.08	0.30	0.47
Quartz	0.42	29.92	43.52	26.15	40.89
Albite	-	-	0.26	0.37	-
K-feldspar	-	3.74	14.65	12.66	2.46
Fluorite	0.94	-	-	-	-
Rutile	-	0.13	0.42	0.17	-
Muscovite/Illite	-	4.19	**29.15**	**26.72**	9.89
Smectite	-	-	**6.43**	**7.60**	-
Amorph/Unknown	1.14	5.89	0	2.97	7.90

Matrix porosity 2.26%
Grain density 2.69

! Utah 2 and 3 clay-sealed completely !

WP2.2 – Mineralization – Crato limestone (92% calcite)





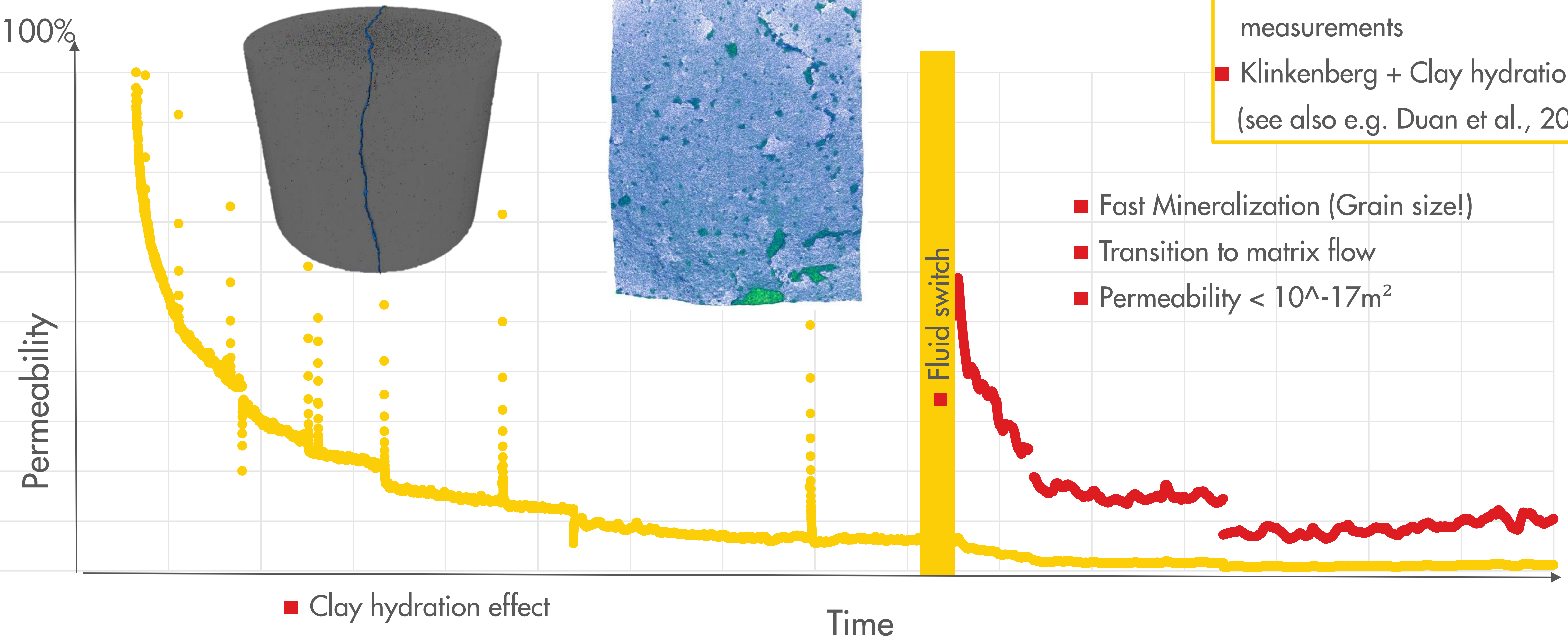
- Steady Mineralization

- Permeability ~ 5 * 10^-17 m^2
- Fracture flow

- Permeability ~ 5*10^-18 m^2
- Matrix flow

WP2.2 – Mineralization – Utah-Carmel (7% smectite)

- Permeabilities are several order of magnitudes lower than the dry measurements
- Klinkenberg + Clay hydration (see also e.g. Duan et al., 2020)

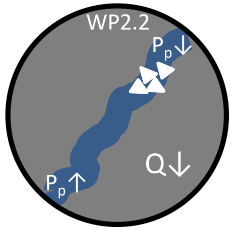


- Fluid switch

- Fast Mineralization (Grain size!)
- Transition to matrix flow
- Permeability < $10^{-17} m^2$

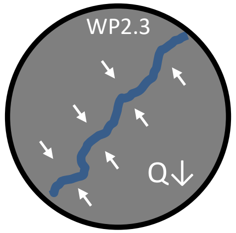
- Clay hydration effect

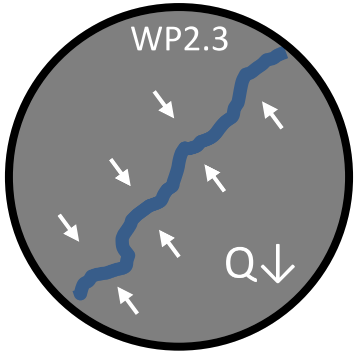
WP2.2 – Reactive Flow Experiments



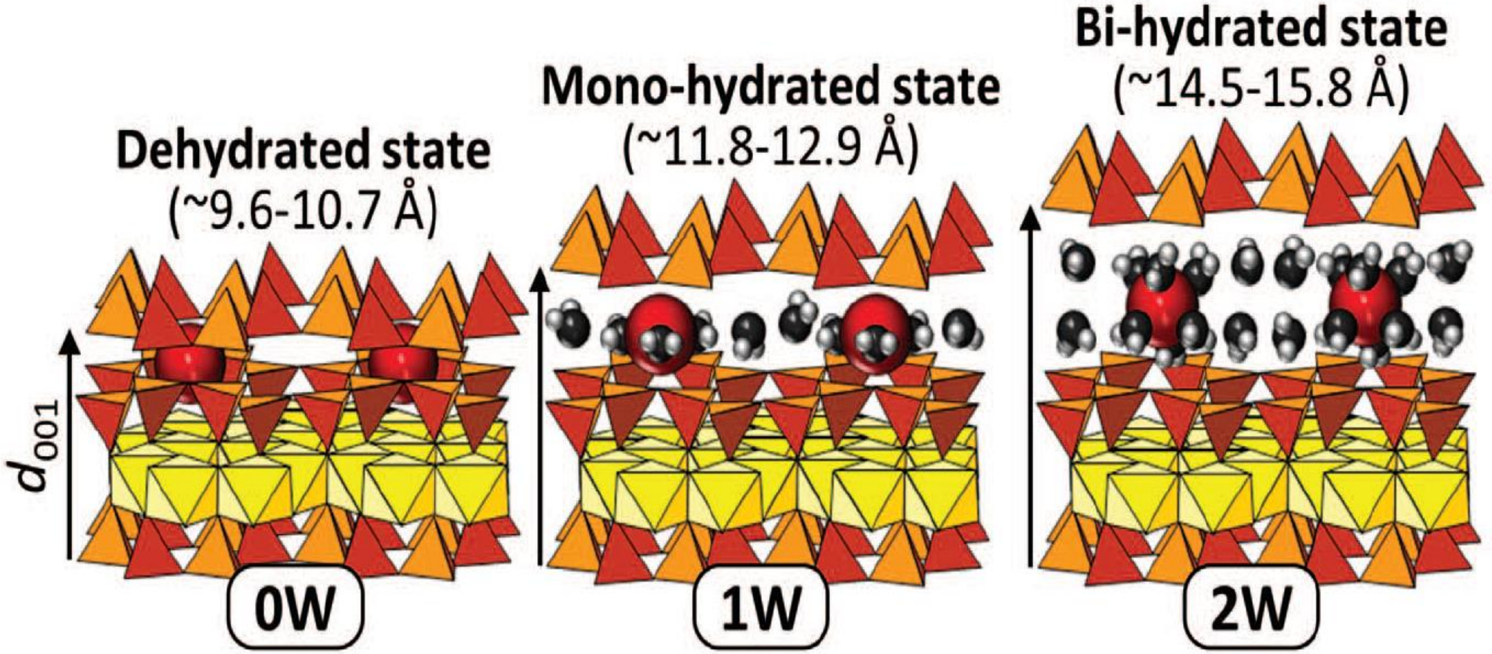
- Carbonate precipitation can have a significant effect on fracture sealing
- Fluid **Saturation** determines
  - if nucleation / crystal growth is likely
  - crystal growth rates
- Availability of **seeds / nucleation sites** (e.g. carbonate) determines crystal growth rates
  - caprock mineralogy and grain sizes are determining factors
- Fracture **flow rate** determines precipitation rates and locations

WP2.3. - Background – Swelling clays





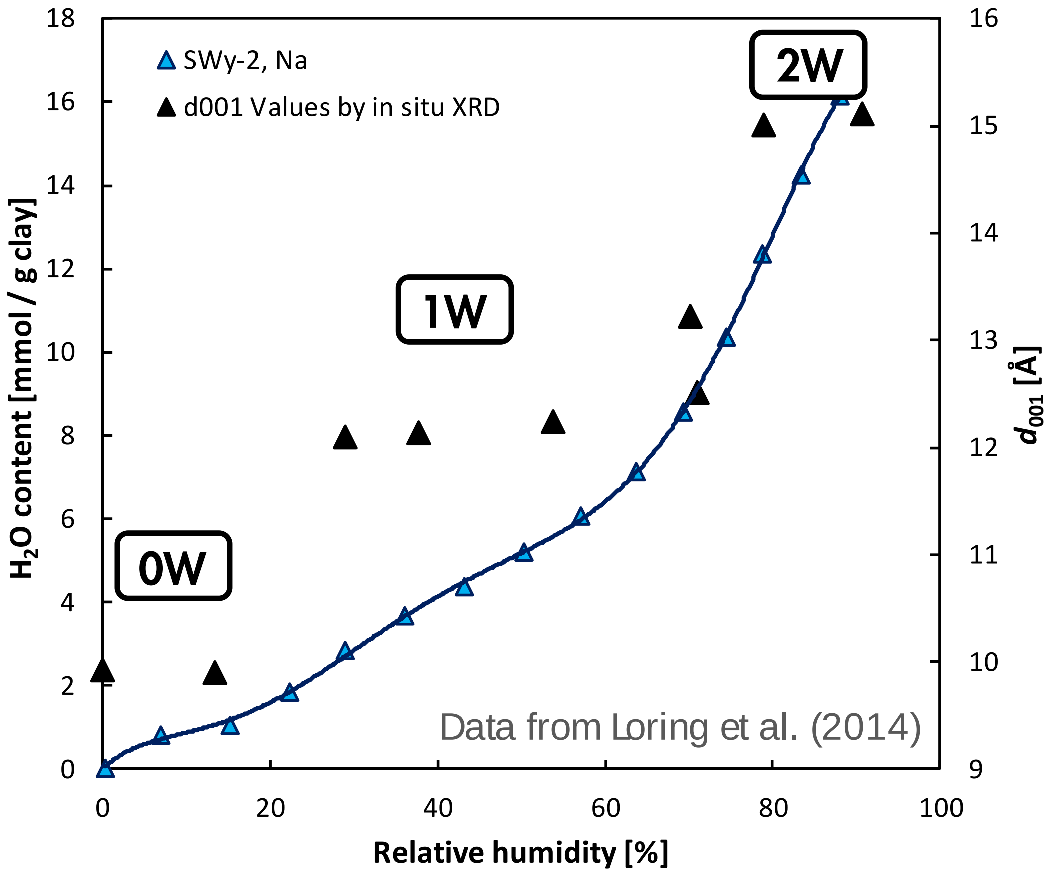
- Swelling clays (e.g. smectite) are abundant in many sealing formations
- T-O-T layer structure plus charge balancing cations (Na^+, Ca^{2+})
- What happens upon exposure to CO_2?
- Which parameters control clay-CO_2 interaction?



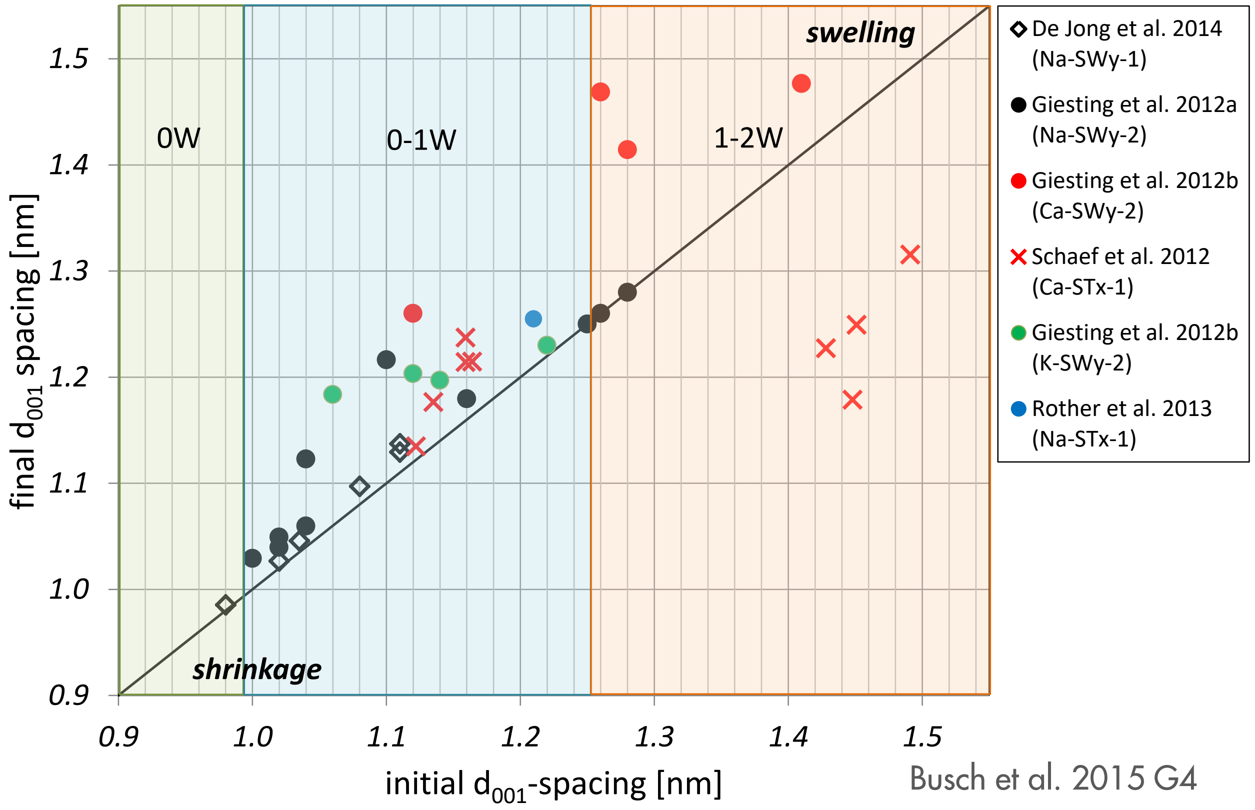
Ferrage et al. (2016)

WP2.3. - Background – Swelling clays

- Swelling clays expand in the presence of water and are compressed when a load is applied
- Similar expansion was observed in the presence of CO2



Data from Loring et al. (2014)

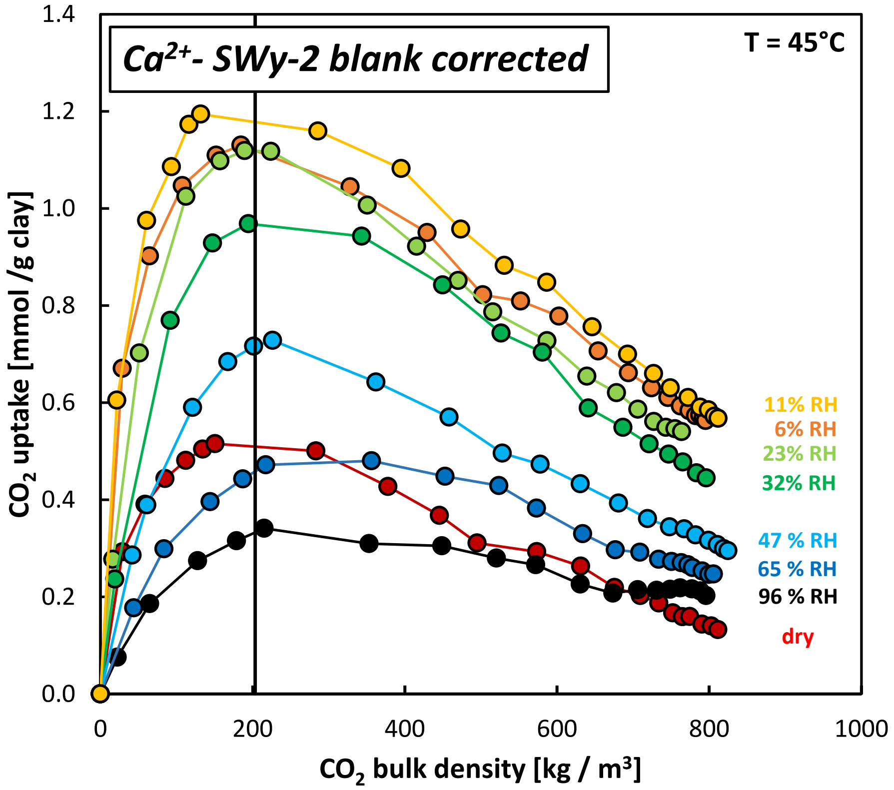


Busch et al. 2015 G4

WP2.3. - High-pressure CO_2 sorption

Objective: accurately determine controls of CO_2 uptake on expandable clays

- CO_2-pressure, water content, charge balancing cations (Na^+, Ca^{2+})



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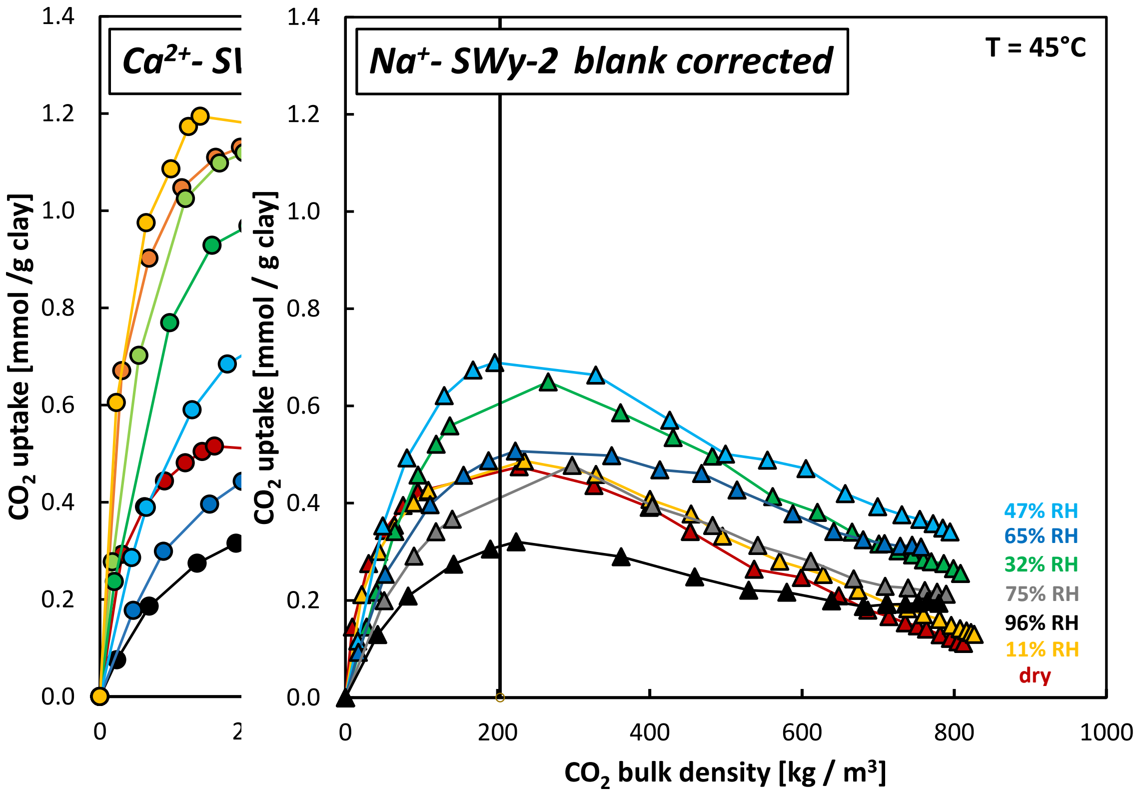

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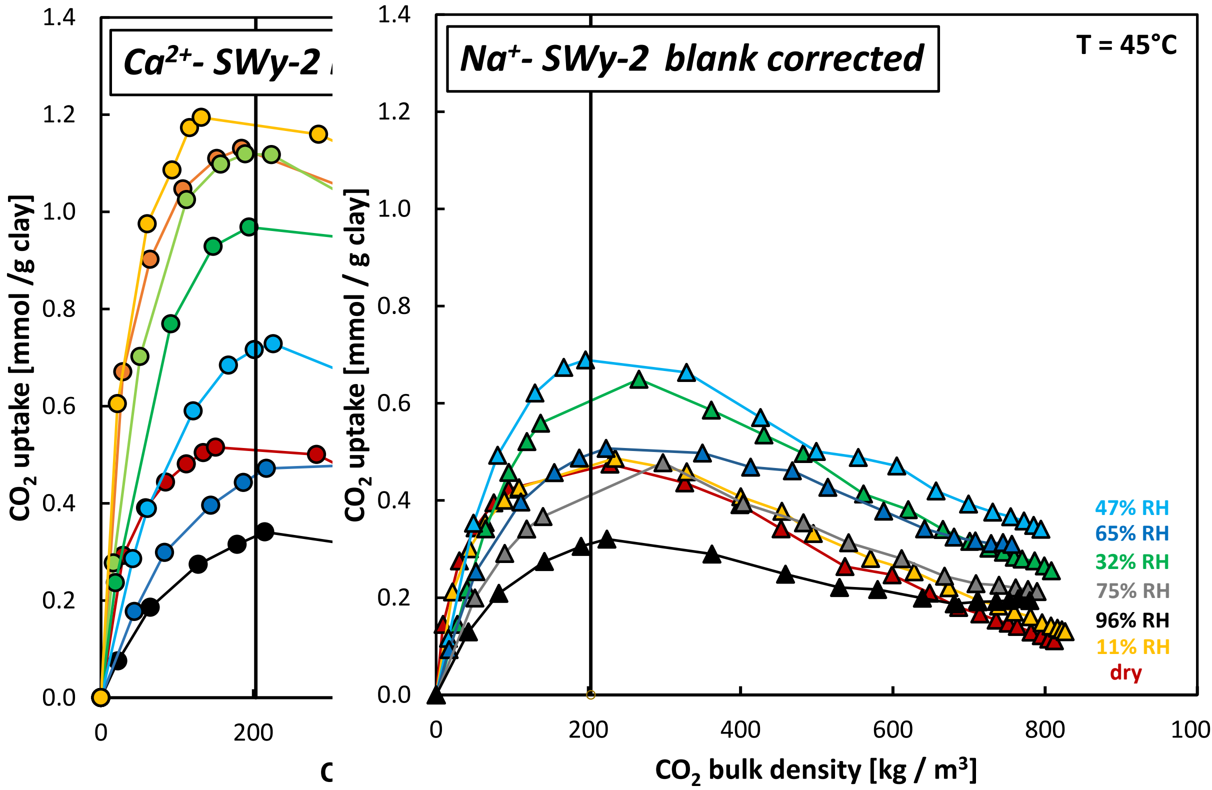
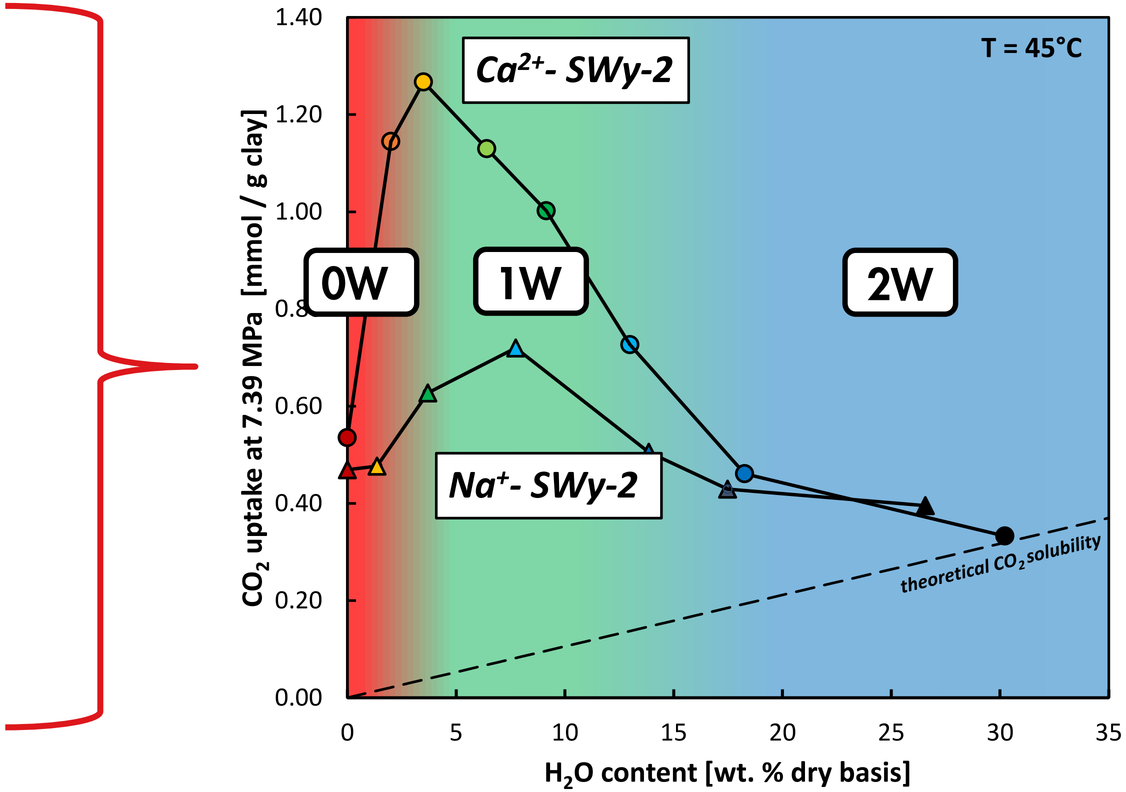
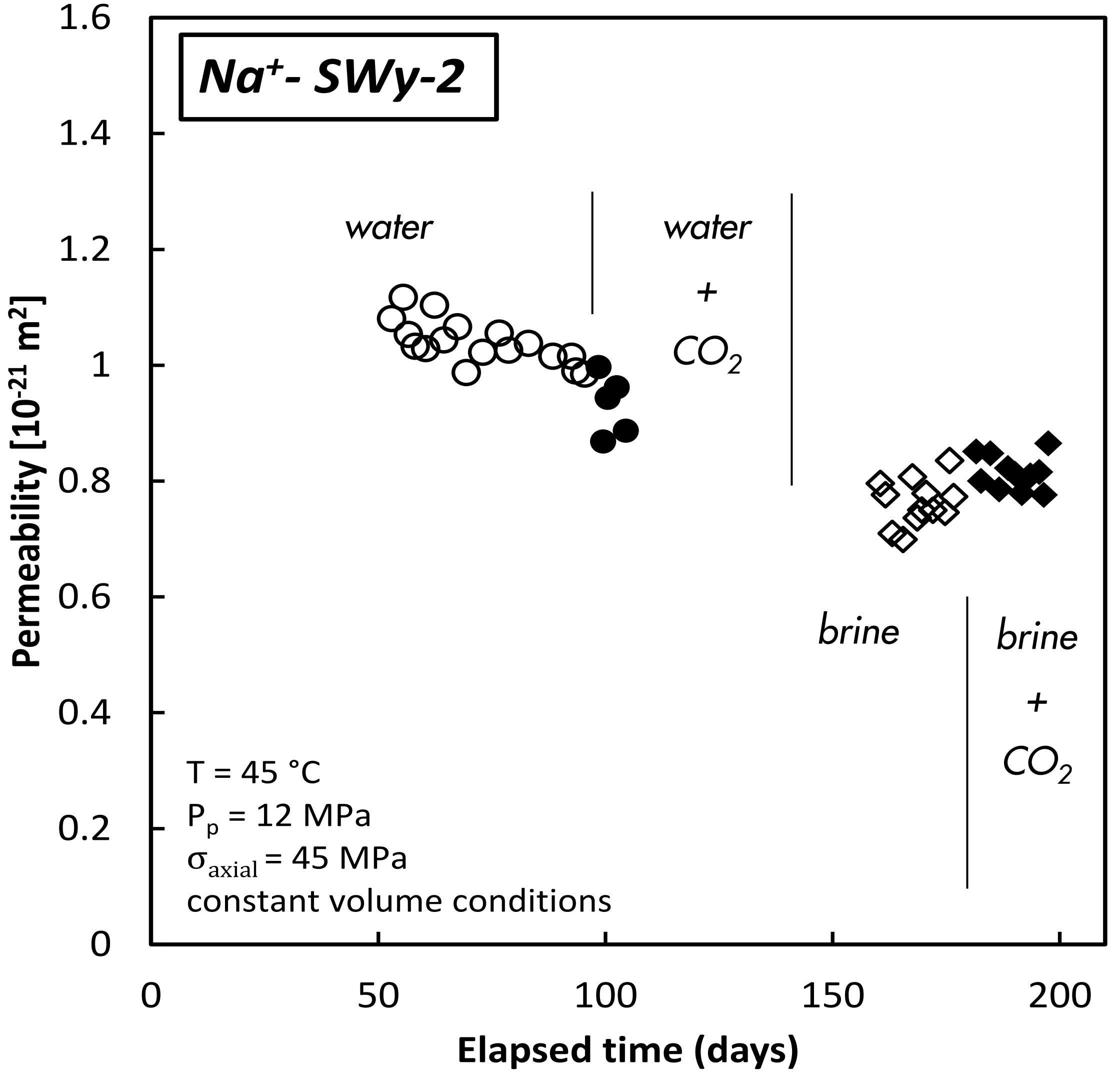


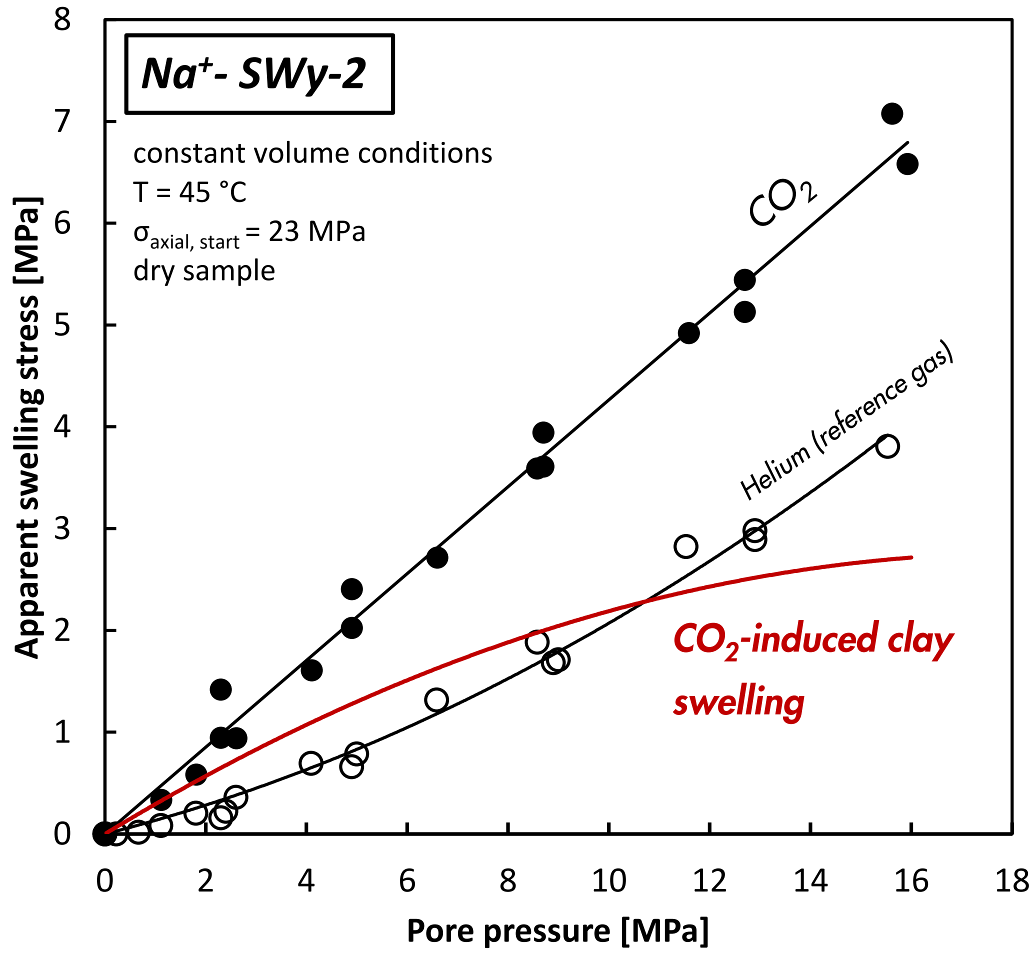


WP2.3. - Clay swelling at fully saturated conditions

- Long-term flow experiments on expandable clays at relevant in-situ conditions
- Flow of dissolved CO_2 has no significant effect on permeability and clay swelling
- Clay swelling effects on fault leakage through a fully saturated caprock must not be considered for risk analysis



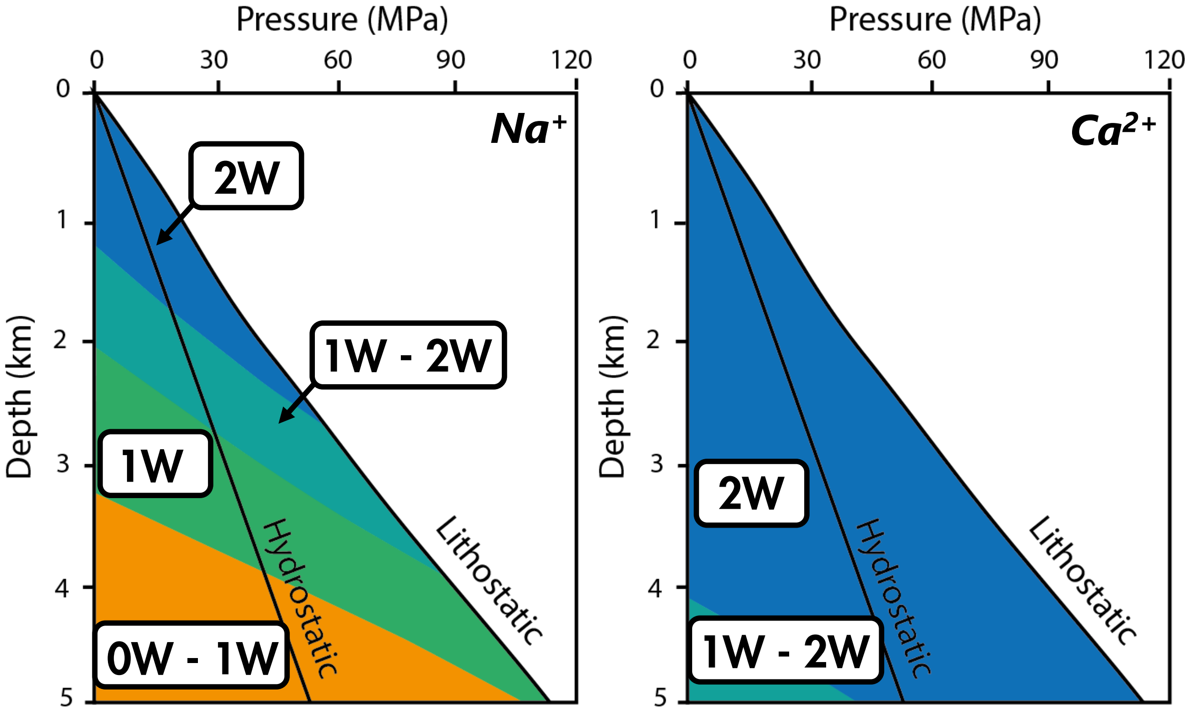
WP2.3. - Clay swelling for partially hydrated clays



- Swelling and flow experiments on **partially saturated clays** as a function of CO_2 pressure and water content
- CO_2-induced clay swelling
  - increases with CO_2 pressure
  - does not significantly decrease fluid flow
- Clays in caprocks could potentially swell when partially hydrated

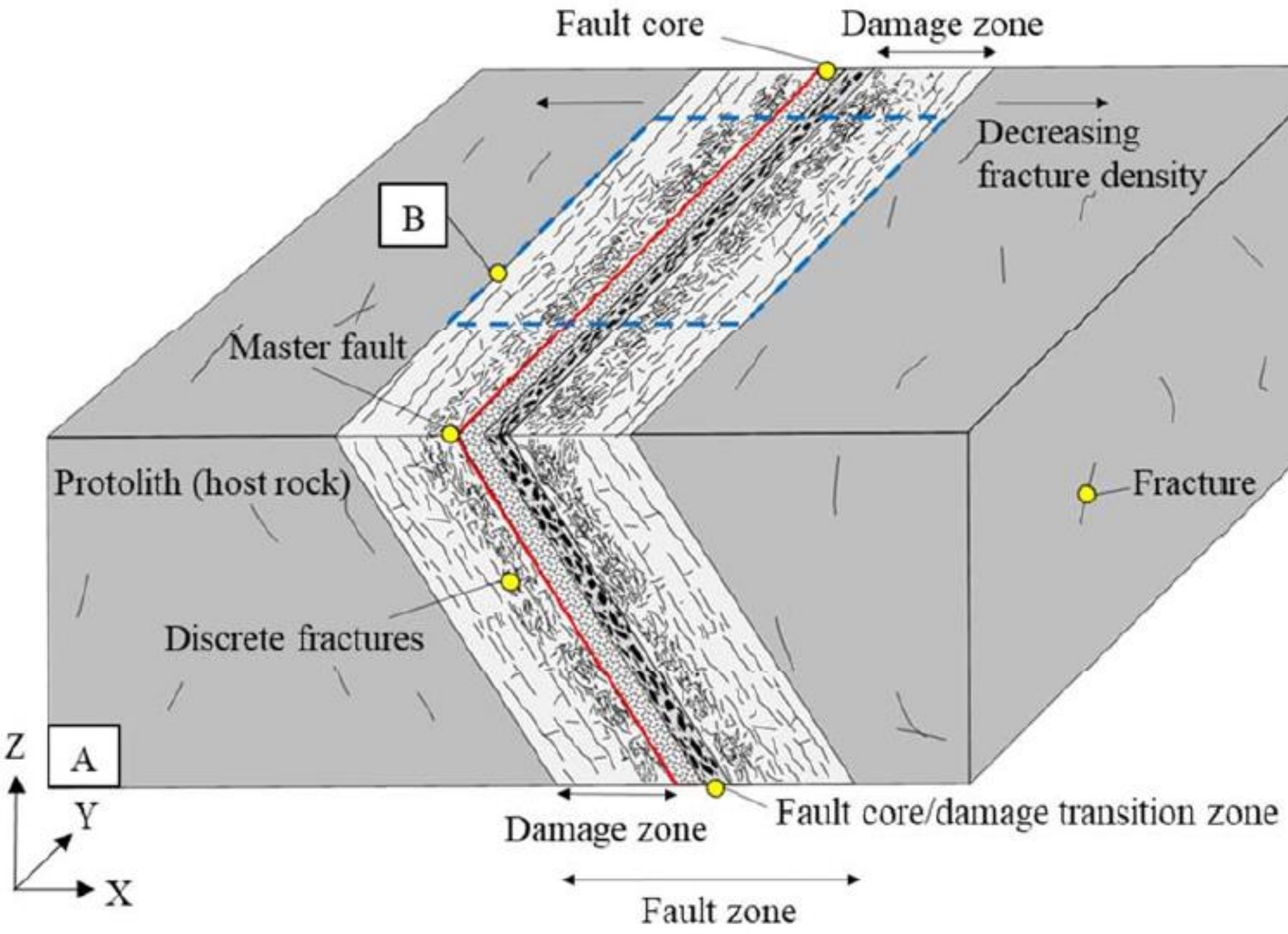
WP2.3. - Relevance of clay swelling for fractures flow

- **CO2-induced clay swelling is unikely** as a self-sealing mechanism in caprock fractures and/or matrix
  - Highest sorption and swelling at hydration states of 0-1 which typically occurs at depths larger than planned for CO_2 storage
  - No change in permeability observed under fully water-saturated conditions
- Dry-out effects could decrease hydration to favourable conditions



modified after Bird (1984)

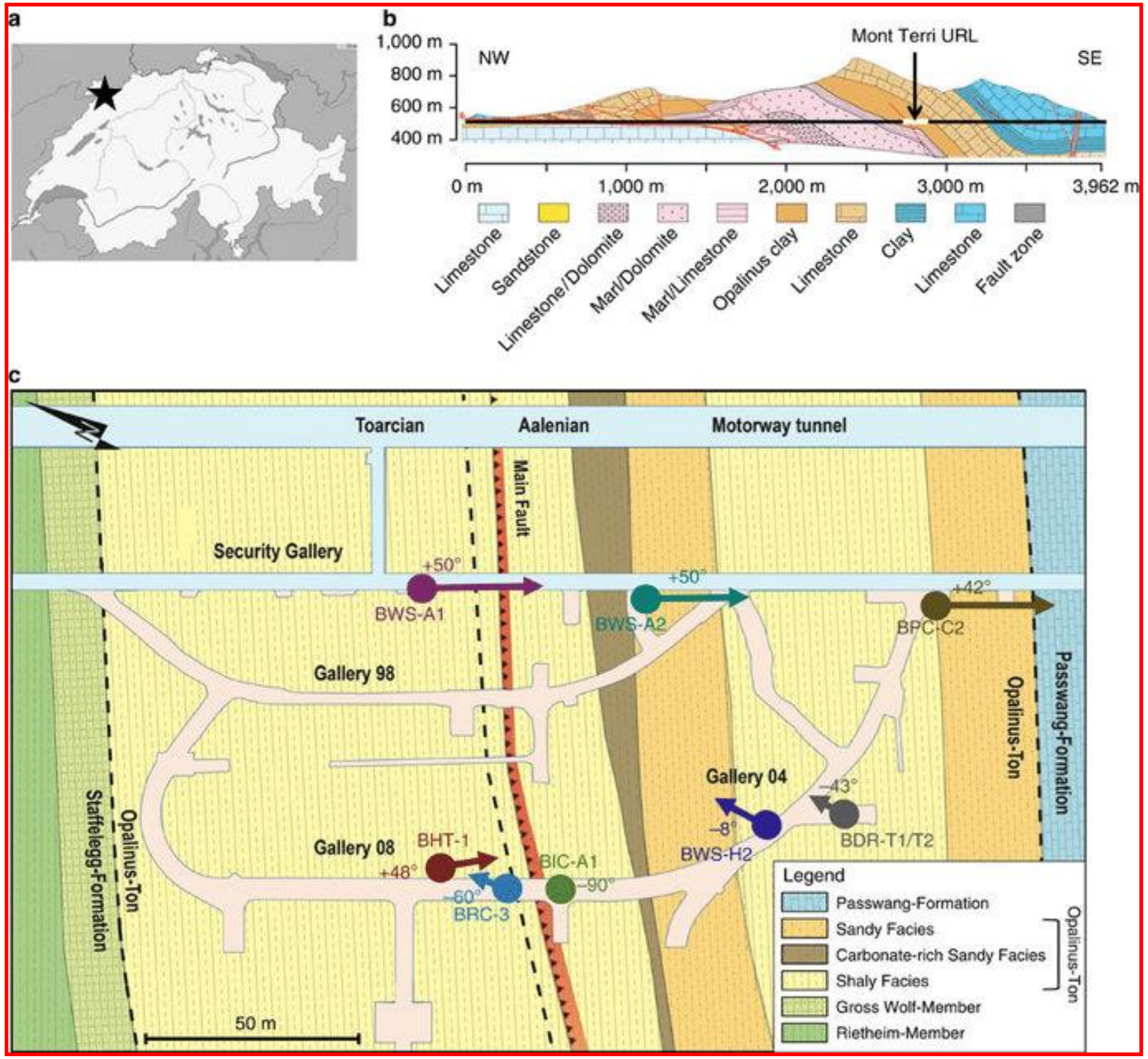
Fault Attributes and detailed fracture network structure



Field work to obtain fracture networks in caprock analogues

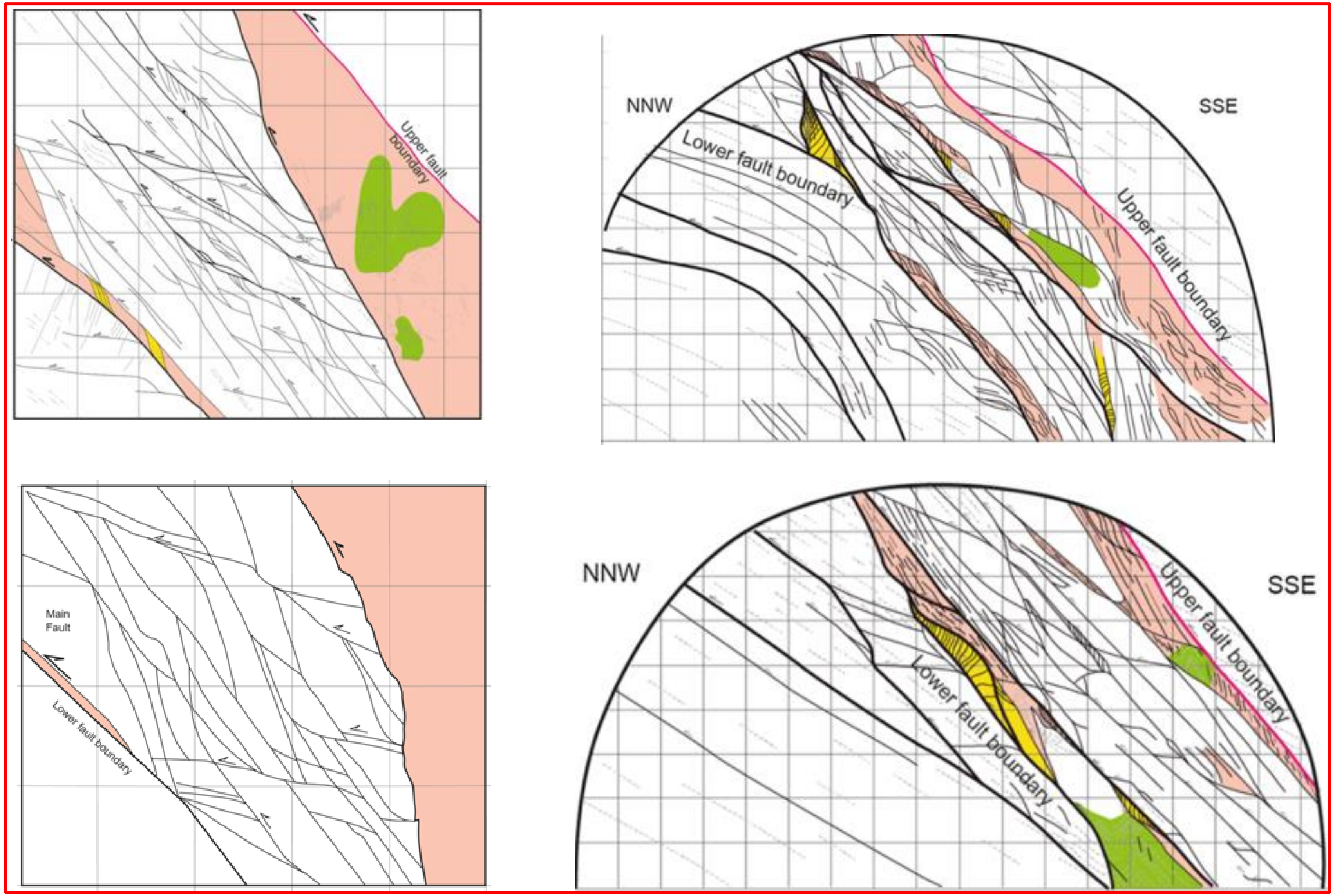
- Carmel shale, Green River, Utah core drilled in 2012
- Tight carbonates, Crato, Brazil
- Opalinus shale from Mont Terri
- Nash Point Shale, Bristol Channel
- Mercia mudrock, Midlands and Bristol Channel, UK
- Kimmeridge Shale, Kimmeridge, UK
- Konusdalen, Svalbard, Norway

Mont Terri Underground Laboratory – Main Fault



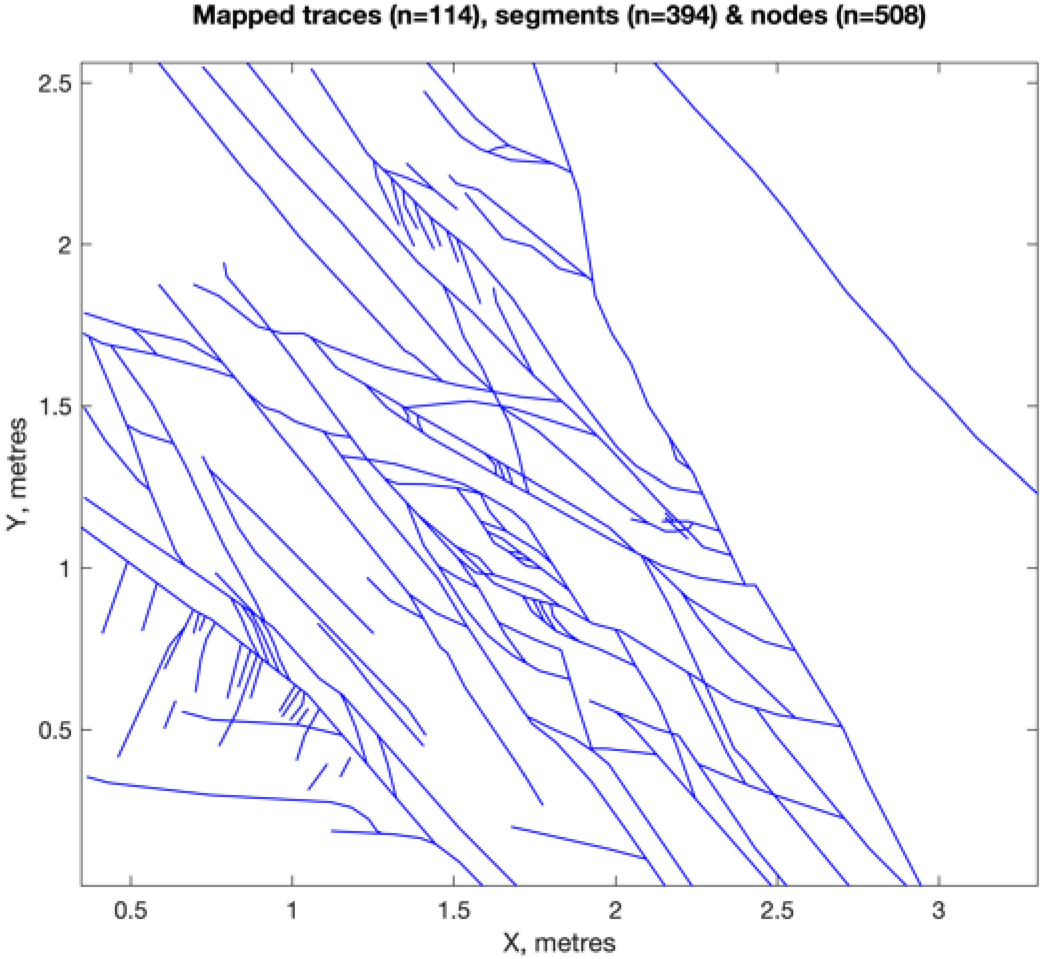
Bagnoud et al. 2016 Nat Com

Mont Terri Underground Laboratory – Main Fault



Bagnoud et al. 2016 Nat Com

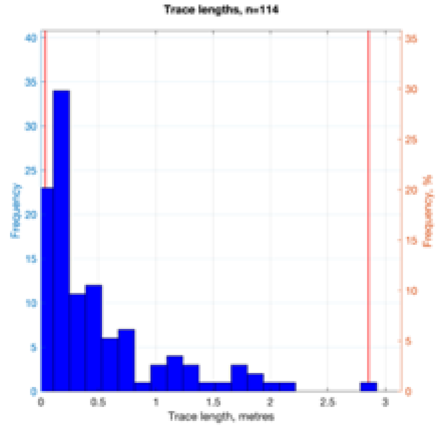
Window Ga08E – Fracture Network

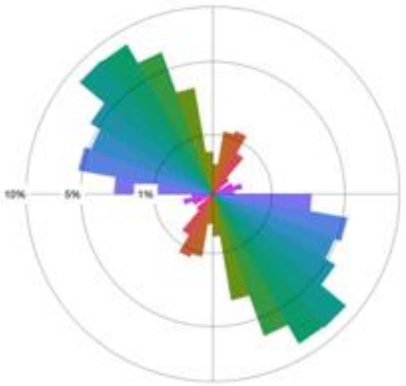


Outcrop data – FracPaQ

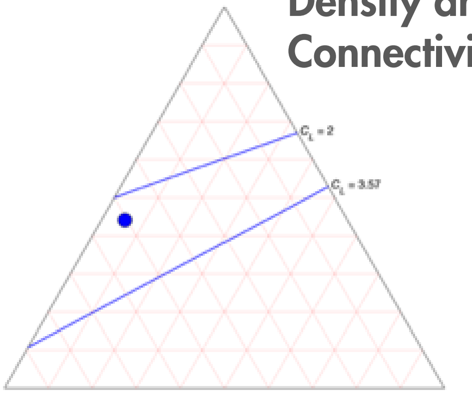
- Information on fault and fracture attributes (i.e., length, orientation) and on geometrical relationships (i.e., density and connectivity) analysed with FracPaQ (Healy et al., 2017).

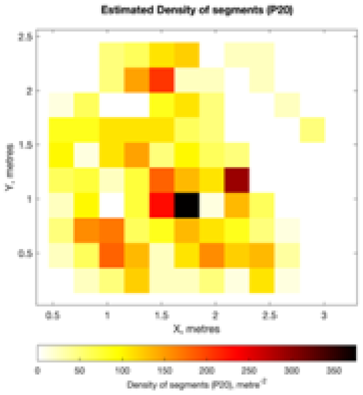
Length and Orientation

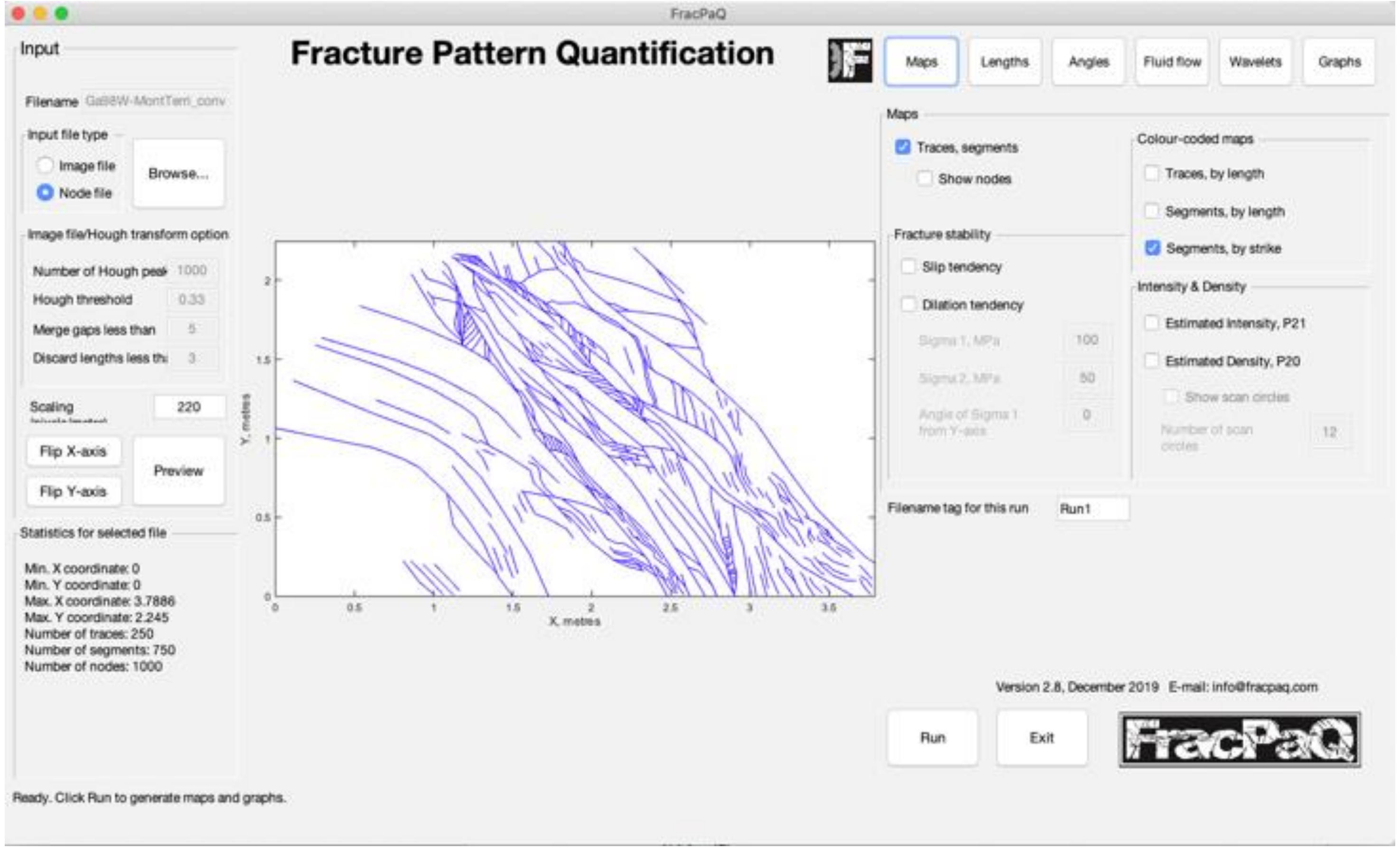




Density and Connectivity







Input

Filename GaB8W-MontTerri_conv

Input file type
○ Image file
● Node file

Image file/Hough transform option
Number of Hough peak 1000
Hough threshold 0.33
Merge gaps less than 5
Discard lengths less th 3

Scaling 220

Statistics for selected file

Min. X coordinate: 0
Min. Y coordinate: 0
Max. X coordinate: 3.7886
Max. Y coordinate: 2.245
Number of traces: 250
Number of segments: 750
Number of nodes: 1000

Maps
☑ Traces, segments
☐ Show nodes

Fracture stability
☐ Slip tendency
☐ Dilation tendency
Sigma 1, MPa 100
Sigma 2, MPa 50
Angle of Sigma 1 from Y-axis 0

Colour-coded maps
☐ Traces, by length
☐ Segments, by length
☑ Segments, by strike

Intensity & Density
☐ Estimated Intensity, P21
☐ Estimated Density, P20
☐ Show scan circles
Number of scan circles 12

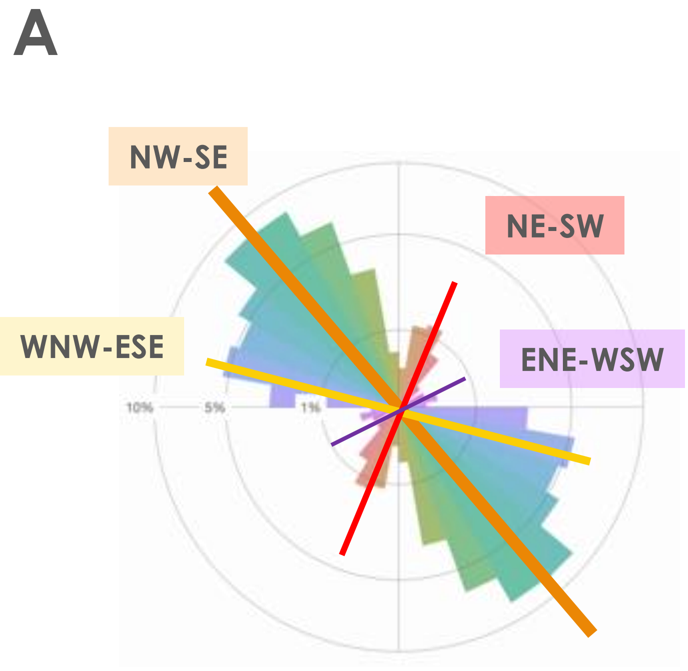
Filename tag for this run Run1

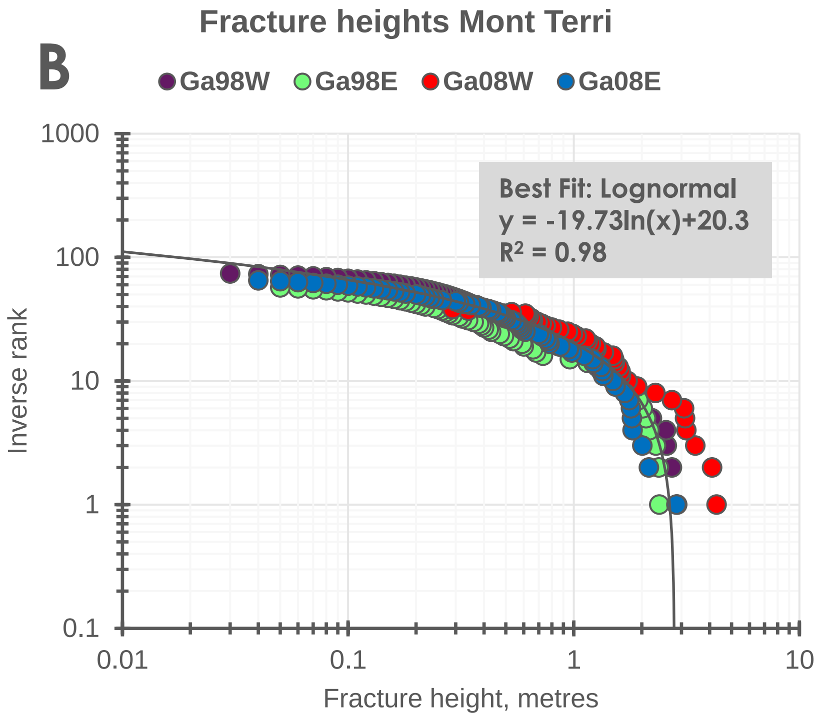
Version 2.8, December 2019 E-mail: info@fracpaq.com

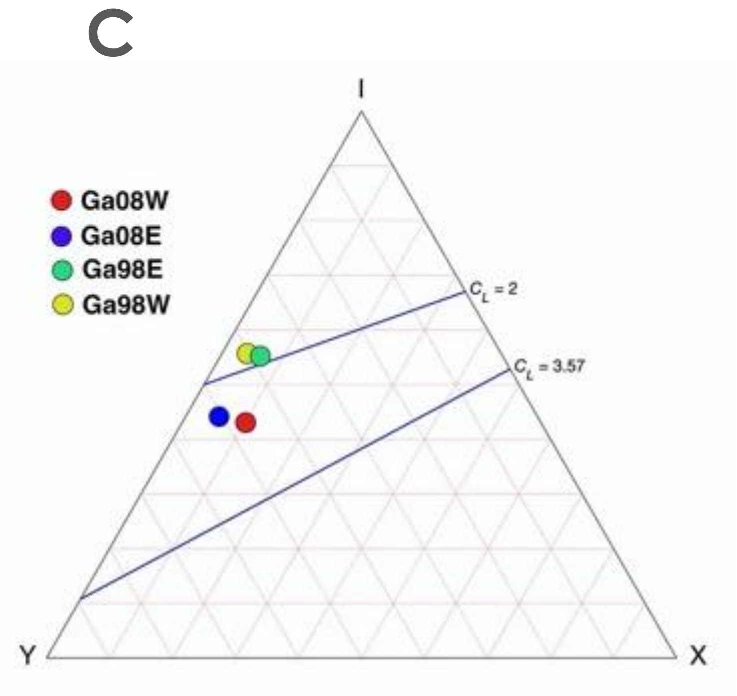
Ready. Click Run to generate maps and graphs.

Fracture network – Mont Terri

- Orientation of faults and fracture is coherent in all four windows in the 2 galleries.
- Galleries with more fracture abundance, show a higher spread in fracture lengths.
- Connectivity in all 4 networks is predominately ensured through abutment (Y-nodes), possibly indicating a coeval formation of the fracture sets.





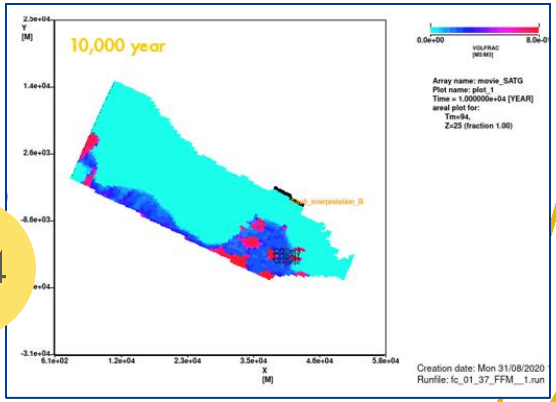


Summary and way forward

- Suitable input data is paramount for setting uncertainty limits feeding into upscaled modelling and risk assessment of fault leakage
- Difficulty is in location of and access to representative case studies providing suitable and non-weathered outcrops of fault zones hosted in low permeability strata as well as related sample material
- While Mont Terri is an exception, the way forward is analysing combinations of field case studies and a wide range of caprock sample material for lab testing involving different mineralogy or mechanical properties
- We conclude that stress (pore pressure) and chemistry need to be considered in assessing fracture flow while clay swelling seems to have a minor effect

DETECT workflow

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



WP4

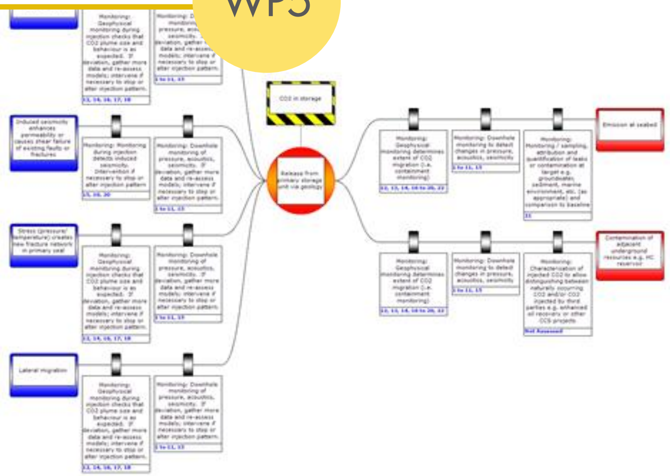
Identify active monitoring barriers relevant for site and expected leakage rates

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

Geological Leakage Risk Assessment

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

WP5



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

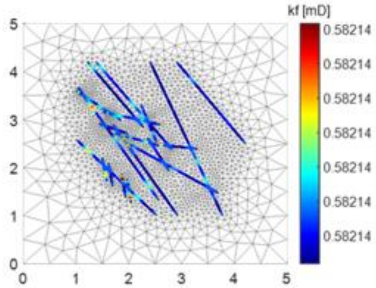
Hydromechanical coupling using lab-derived stress-permeability relations and analytical stress-state model

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

Simulate flow in fracture networks in caprocks

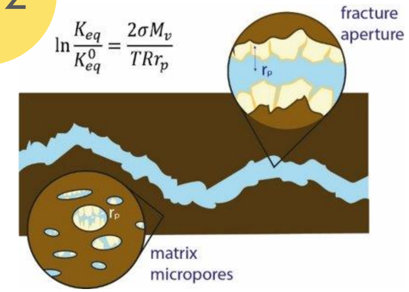
Scaling relations based on meso/fine-scale modelling & analogues

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

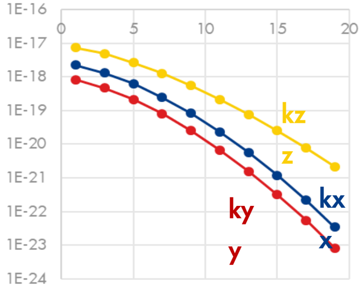


WP2

Experimentation and numerical modeling to characterise single fracture processes


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

Quantifying the impact of small-scale physics on CO2-brine flow at fine-scale



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

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