«Rock Mechanics and Rock Engineering of Geological Repositories
in Opalinus Clay and Similar Claystones»

TRANSIENT DEFORMATION AND EXCAVATIONS IN CLAYSTONES

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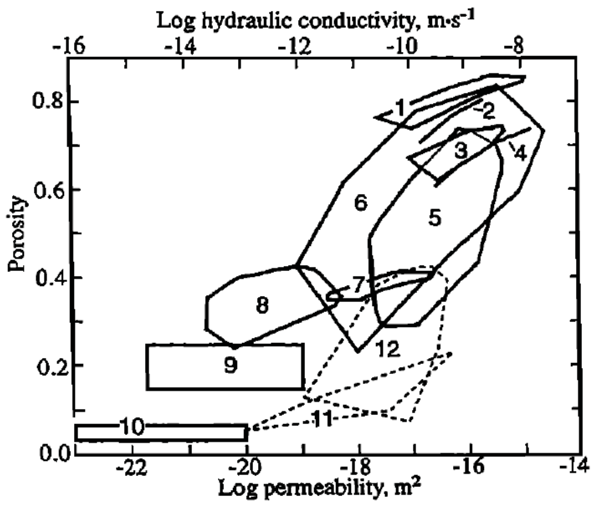
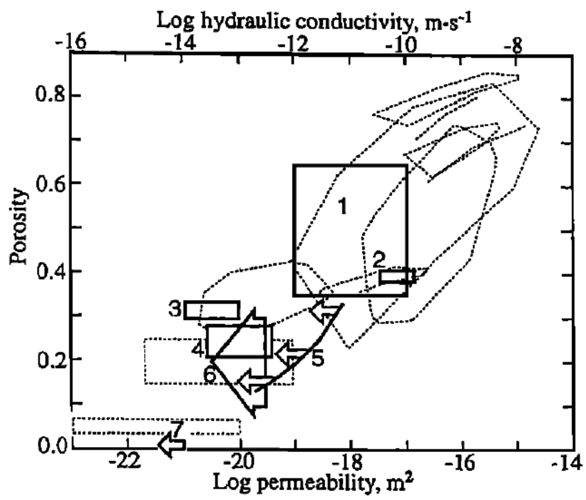
How permeable are clays and shales?

Neuzil, 1994, WRR

Laboratory

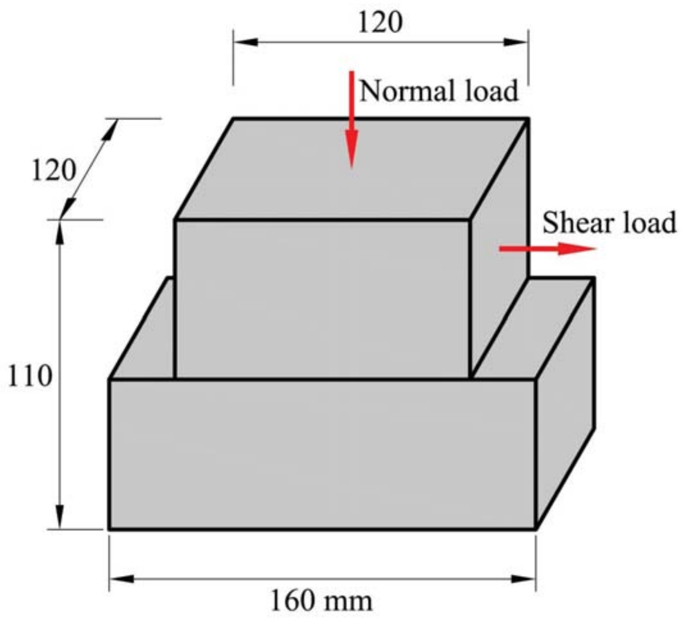


Field (back analysis)

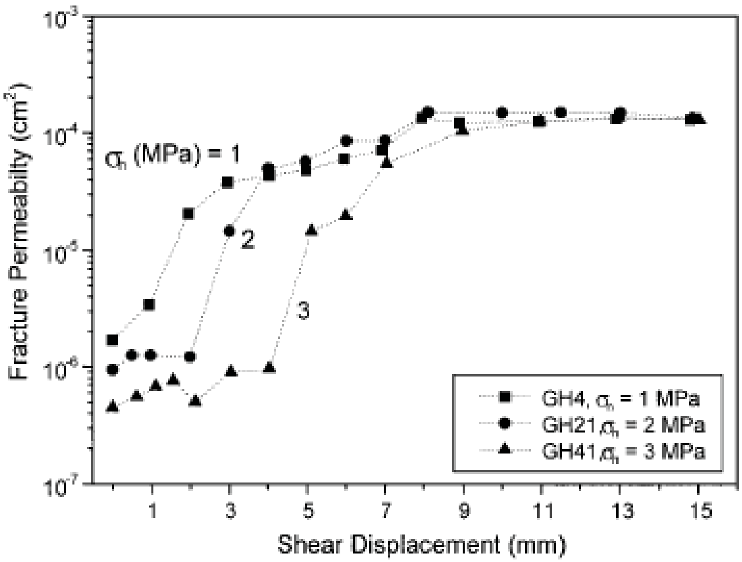


Numerical simulation of a hydraulic shear test on rough granite surfaces

- Granite from Korea *(Lee and Cho, 2002)*
- Fracture surfaces created by a tensile fracture
- Fracture opening measured by means of a 3D laser profilometer. Mean opening was 0.65 mm
- Shear hydraulic tests were performed maintaining constant normal stresses of 1, 2 and 3 MPa

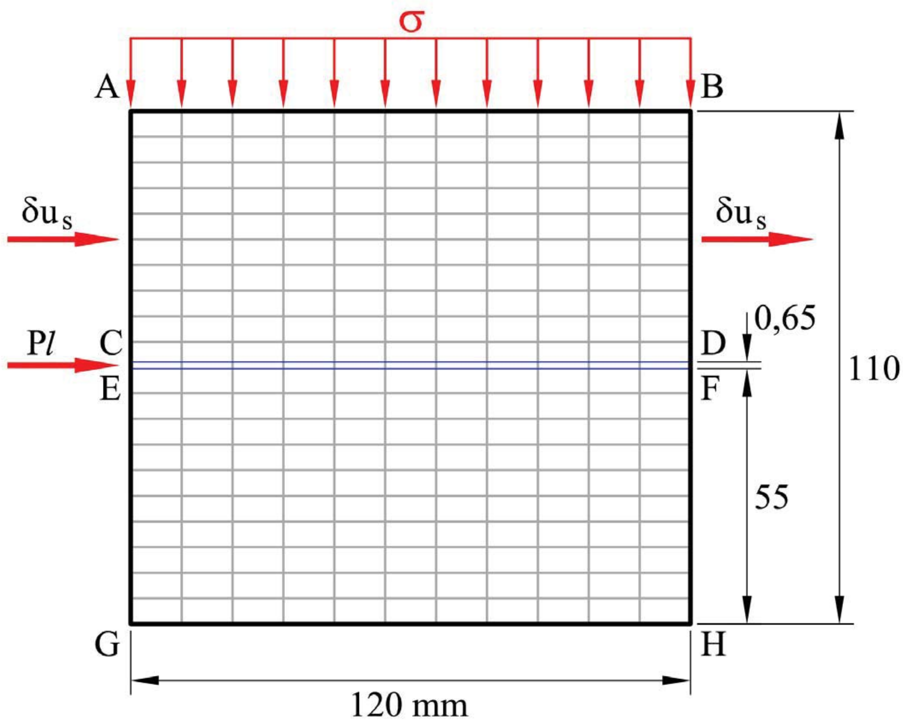


Effect of shear stress on water permeability



- Initial compression reduces permeability, but as shear progresses permeability increases by 2 orders of magnitude.
- Water permeability (Lee and Cho, 2002) shows a similar response in Granite and Marble.

A coupled model



Granite matrix: Mechanical and hydraulic parameters

Mechanical parameters	Symbol	Units	Value
Young's modulus	E	MPa	54100
Poisson's ratio	υ	-	0.29
Porosity	n_0	%	49.0
Hydraulic parameters	**Symbol**	**Units**	**Value**
Intrinsic permeability	k	m^2	1×10^{-16}

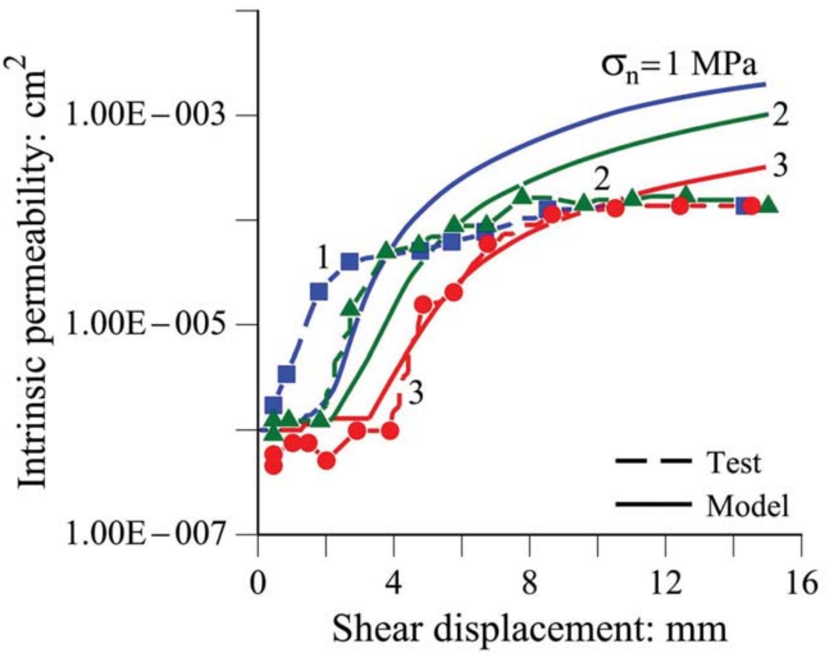
JOINT: Hydraulic parameters

Hydraulic parameters	Symbol	Units	Values
Hydraulic opening	e	mm	0.035
Longitudinal intrinsic permeability	k_l	m^2	10^{-8}
Transversal intrinsic permeability	k_t	m^2	10^{-16}

JOINT: Mechanical parameters

Mechanical parameters	Symbol	Units	Value
Initial normal stiffness parameter	m	MPa	90
Tangential stiffness	K_s	MPa/m	1500
Initial cohesion	c'_0	MPa	0.02
Initial friction angle	φ_0	-	47°
Residual friction angle	φ_{res}	-	37°
Initial opening	a_0	mm	0.65
Minimum opening	a_{min}	Mm	0.065
Viscosity parameter	Γ	s^{-1}	10^{-4}
Stress power	N	-	2.0
Critical displacement for cohesion	u_c^*	mm	15.0
Critical displacement for $\tan\varphi$	$\tan\varphi^*$	mm	15.0
Uniaxial compressive strength	q_u	MPa	151
Model parameter	β_d	-	40
Joint roughness coefficient	JRC	-	2.70

Evolution of permeability during shearing. Model vs. measurements

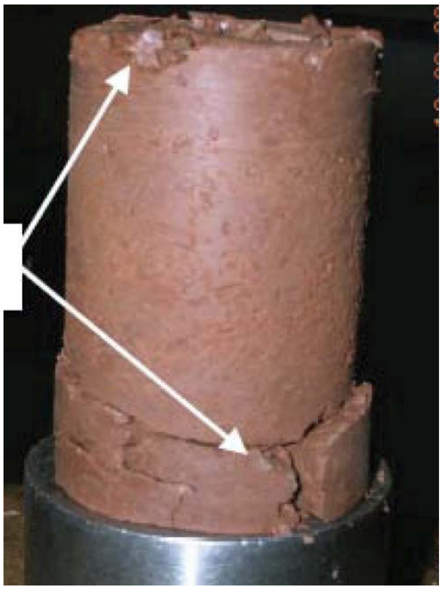


➢ Note:

- Fracture permeability changes slightly during the initial stage of shear
- As dilation develops close to the peak strength, permeability increases dramatically
- When shear displacements reach 7 mm, permeability becomes constant (gouge material)

A laboratory investigation

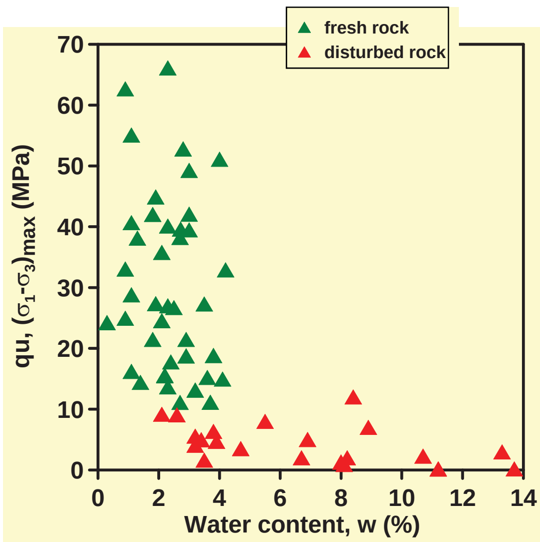
Effects of relative humidity cycling on the degradation of argillaceous rocks

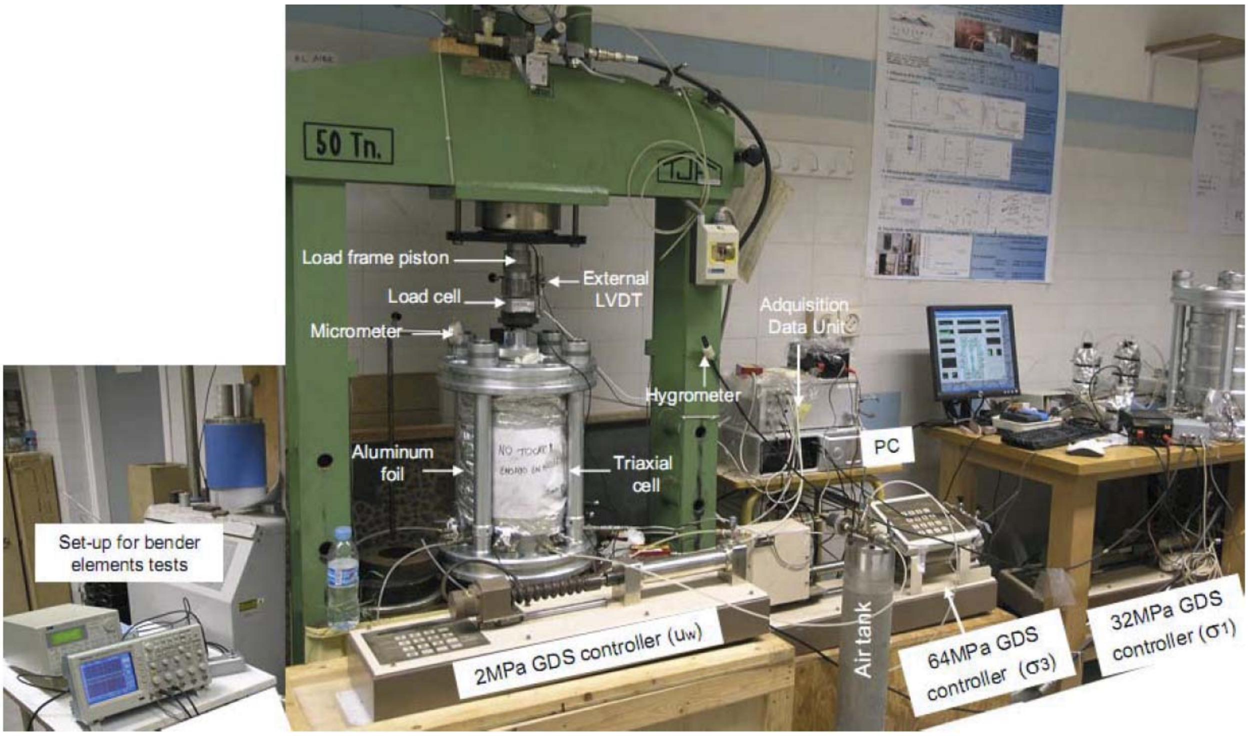


Tertiary Anhydritic Claystone from Lilla Tunnel

Undisturbed material	
Mineralogy relative content (%)	
Quartz	2 – 7
Dolomite	11 – 13
Anhydrite	13 – 28
Gypsum	0 – 7
Clay (Illite & Paligorskite)	51 – 67
Physical and Mechanical Properties	
Gs	2,82 – 2,90
Water content (%)	0,5 – 4,5
Natural density (Mg/m^3)	2,40 – 2,86
q_u (MPa)	17 - 70

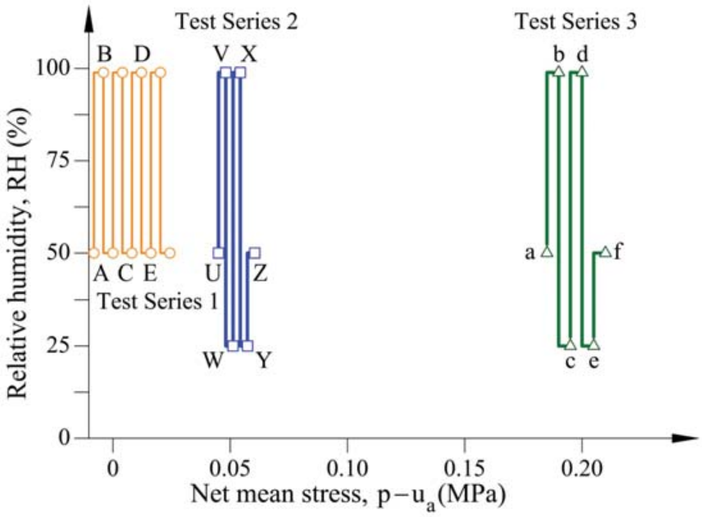
Unconfined compression tests of cores



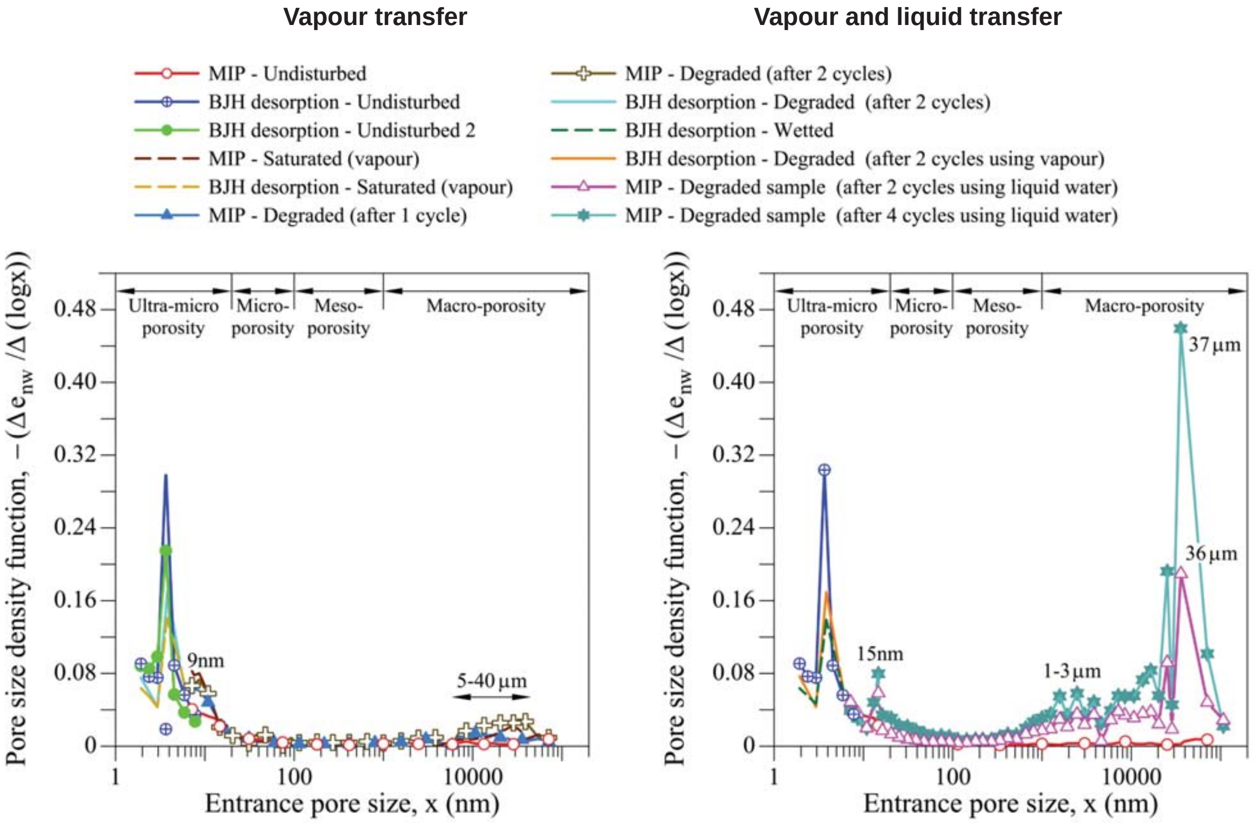


Stress paths applied in tests

Test Series	$p\text{-}u_a$ (kPa)	N_{max}	RH_{min} - RH_{max} (%)	Fluid	Time (days)
1	0	4	50-99	Vapour	390
2	50	2	20-99	Vapour	300
3	200	2	20-99	Vapour	300
4	0	Soaking	50-99	Liquid water	2

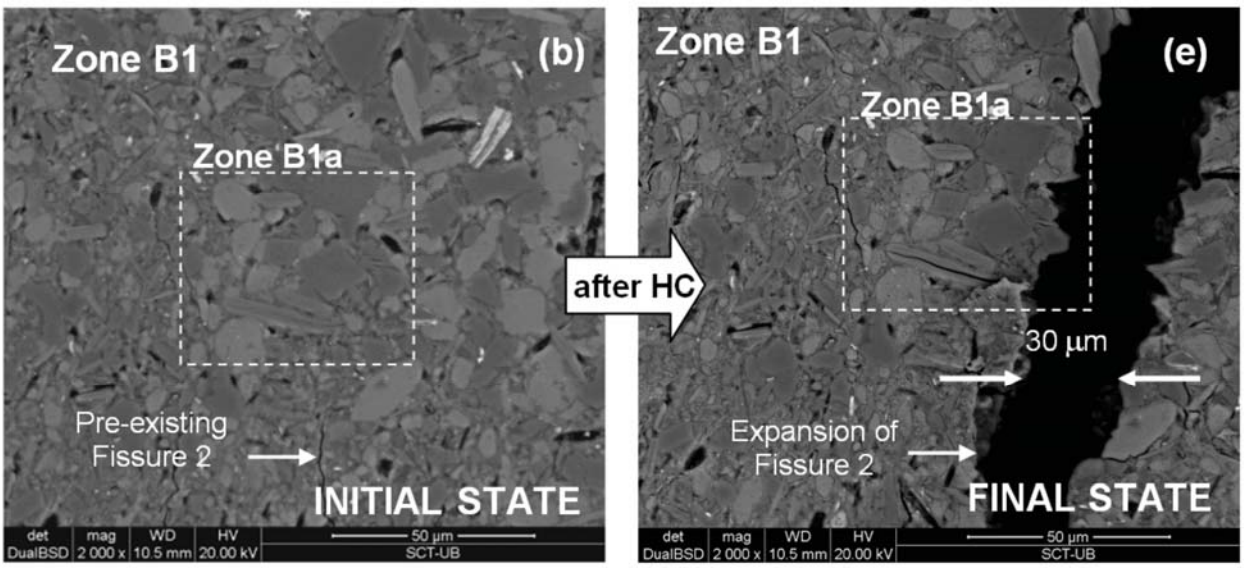


Evolution of pore sizes modes during degradation

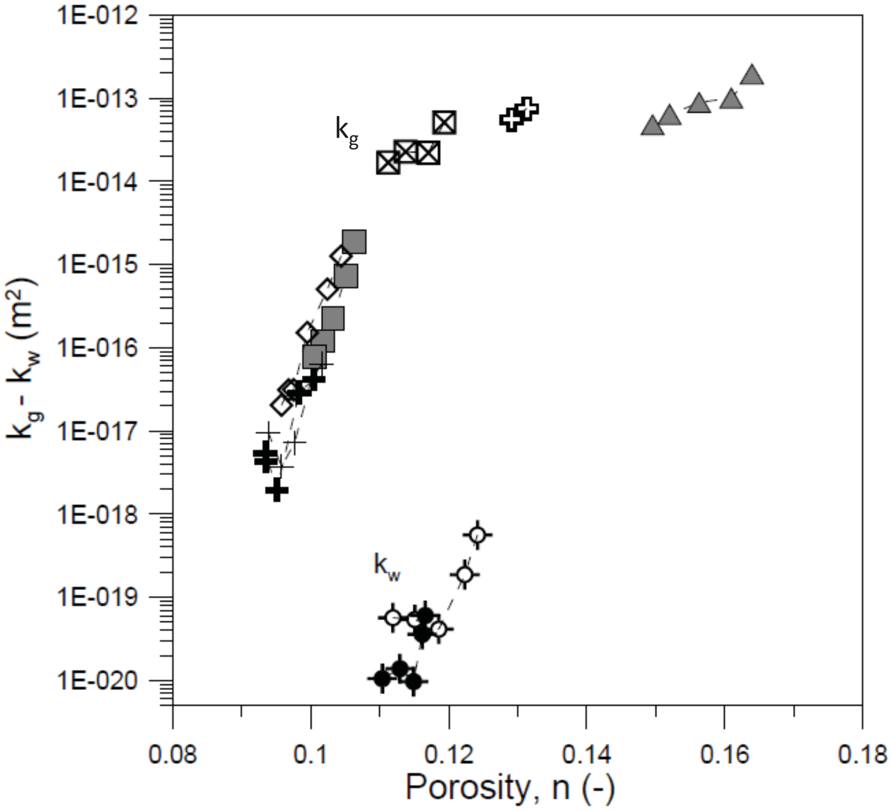


Evolution of pore sizes during degradation

SEM photomicrographs



“Intrinsic” gas and water permeability of Lilla claystone subjected to several (degradation) suction cycles at different stress levels



?

How to model the development of preferential paths?

A simple model for preferential paths

Main ideas:

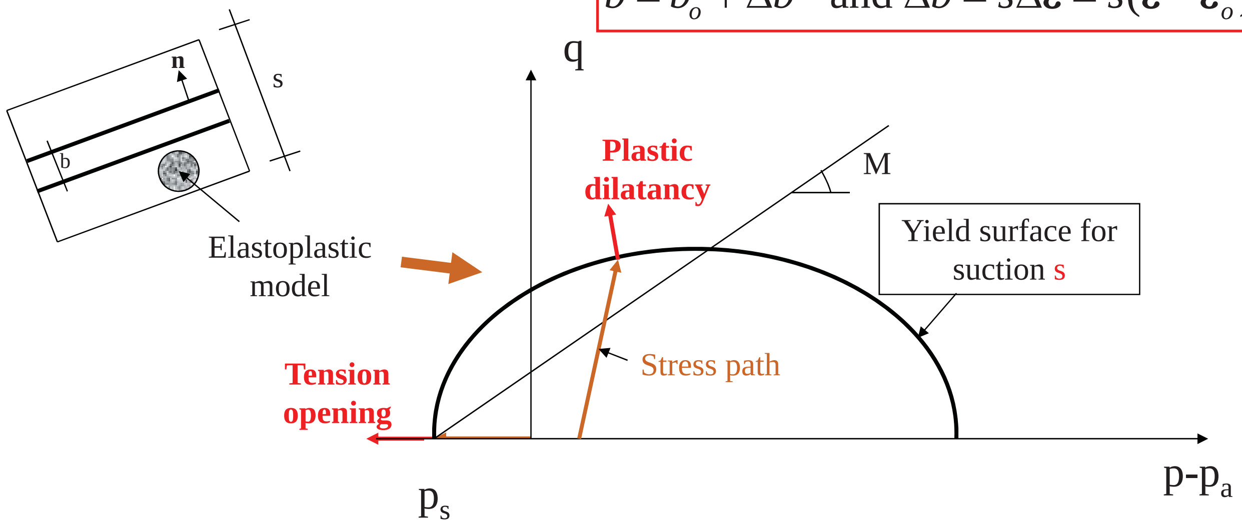
- Flow takes place along a given surface/plane/preferential path
- The path is included in a “damaged” zone
    - Interfaces
    - Shear zones
    - Schistosity/Sedimentation planes

  and/or develops as a result of deformations

- Normal deformations to the reference plane result in fracture opening. Flow properties are modified accordingly (strong anisotropy of flow properties is induced)

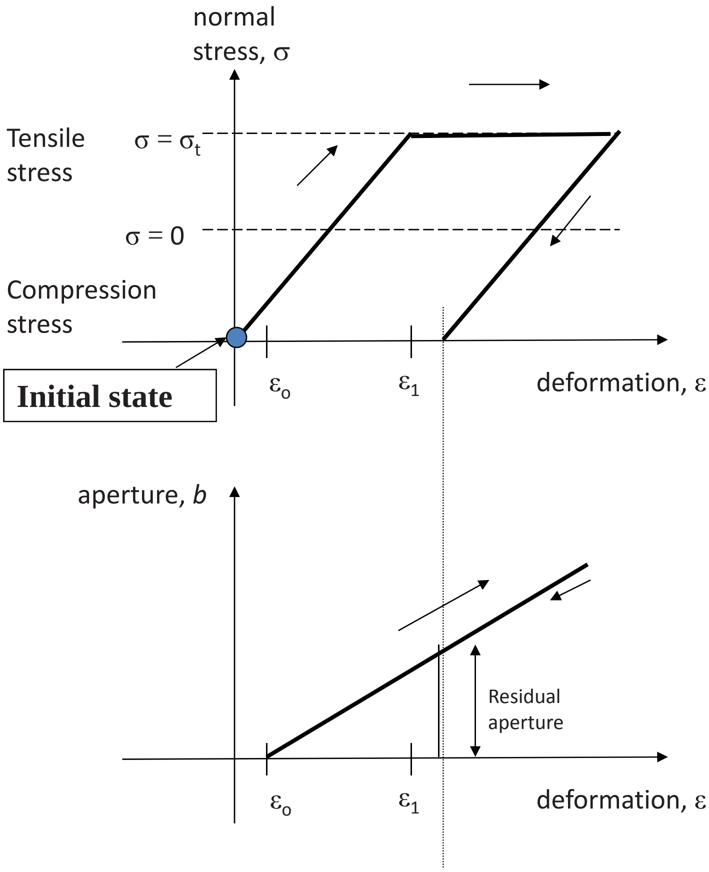
Accumulation of normal deformations in a given plane within a fractured zone

$$\boxed{b = b_o + \Delta b \quad \text{and } \Delta b = s\Delta\varepsilon = s(\varepsilon - \varepsilon_o)}$$



- Model based on elastoplastic BBM
- Suction changes (drying-wetting) induces shrinkage/swelling
- Tensile strength depends on current suction

Tension opening



$\boldsymbol{\varepsilon_o}$: threshold deformation to start fracture opening

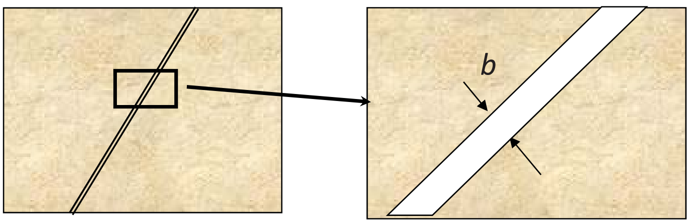
$\boldsymbol{\varepsilon_1}$: deformation corresponding to tensile strength

σ_t: tensile strength of the fracture

Cases:

- Existing fracture
  $\sigma_t = 0$, $\boldsymbol{\varepsilon_o} \approx 0$
- Non existing fracture:
  $\sigma_t \neq 0$ and $\boldsymbol{\varepsilon_o = \varepsilon_1} \neq 0$

Hydraulic characterization of embedded fracture element



- Intrinsic permeability (laminar flow):

$$k_{fracture} = \frac{b^2}{12}$$

- Equivalent permeability of fracture:

$$k_{equivalent} = k_{fracture}\frac{b}{a} = \frac{b^3}{12a}$$

- Equivalent permeability of element:

a : Reference length

$$k_{element} = k_{fracture}\frac{b}{a} + k_{porous}\frac{a-b}{a} \cong \frac{b^3}{12a} + k_{porous}$$

Updating the hydraulic characterization of fracture element

- Capillary air entry pressure: $$P = \frac{2\sigma}{b} = \frac{2\sigma}{\square\ \sqrt[3]{k_{fracture}}}$$

  (Laplace)

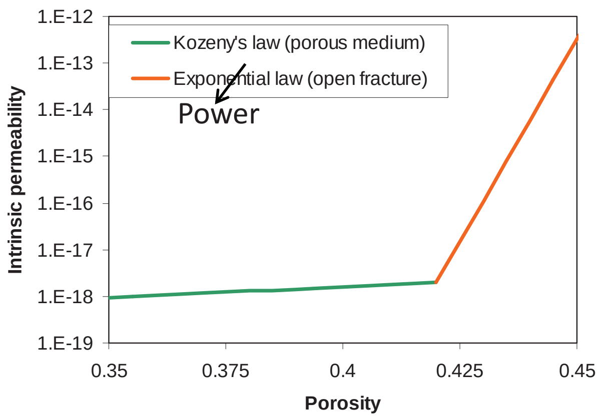
$$\boxed{P = P_o \frac{\sqrt[3]{k_{fracture\_o}}}{\sqrt[3]{k_{fracture}}}}$$

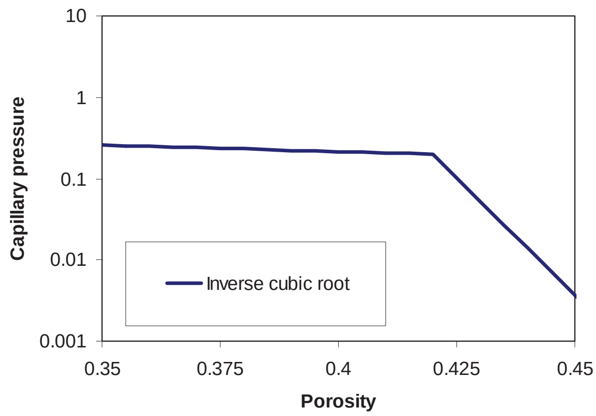
- Updated permeability: $$\boxed{k_{new} = k_{old} \frac{b_{new}^3}{b_{old}^3}}$$

- Permeability function for A material that changes the structure from porous to fractured medium:

- Capillary entry pressure for van Genuchten law calculated as:

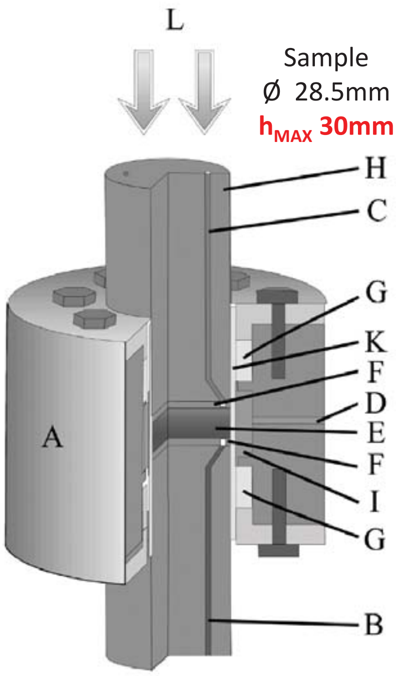
$$P = P_o \left(\frac{k_o}{k} \right)^{1/3}$$



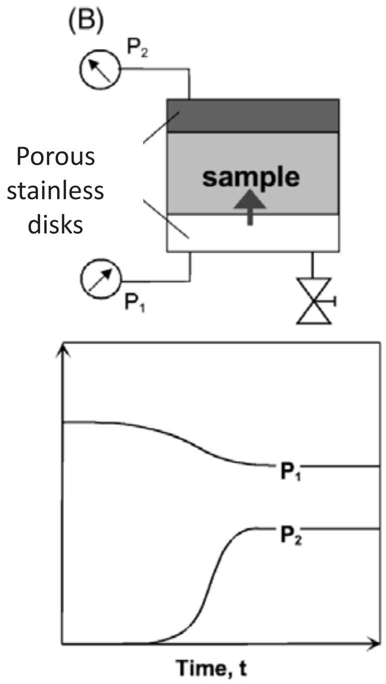


Model performance
Laboratory

Triaxial tests on Tertiary mudstone from the Norwegian shelf (1500 m deep). Gas flow tests. Hildebrand et al. (2002)

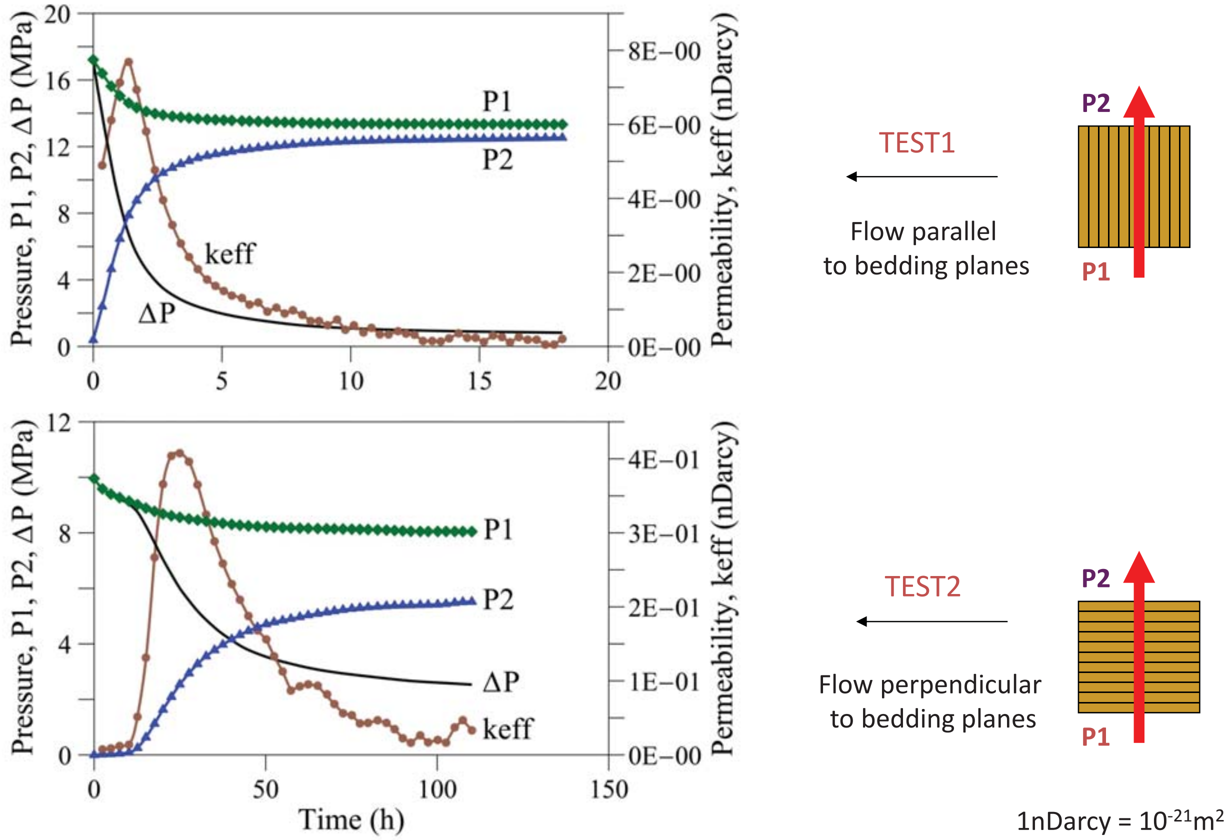


Isotropic confining pressure = 30MPa

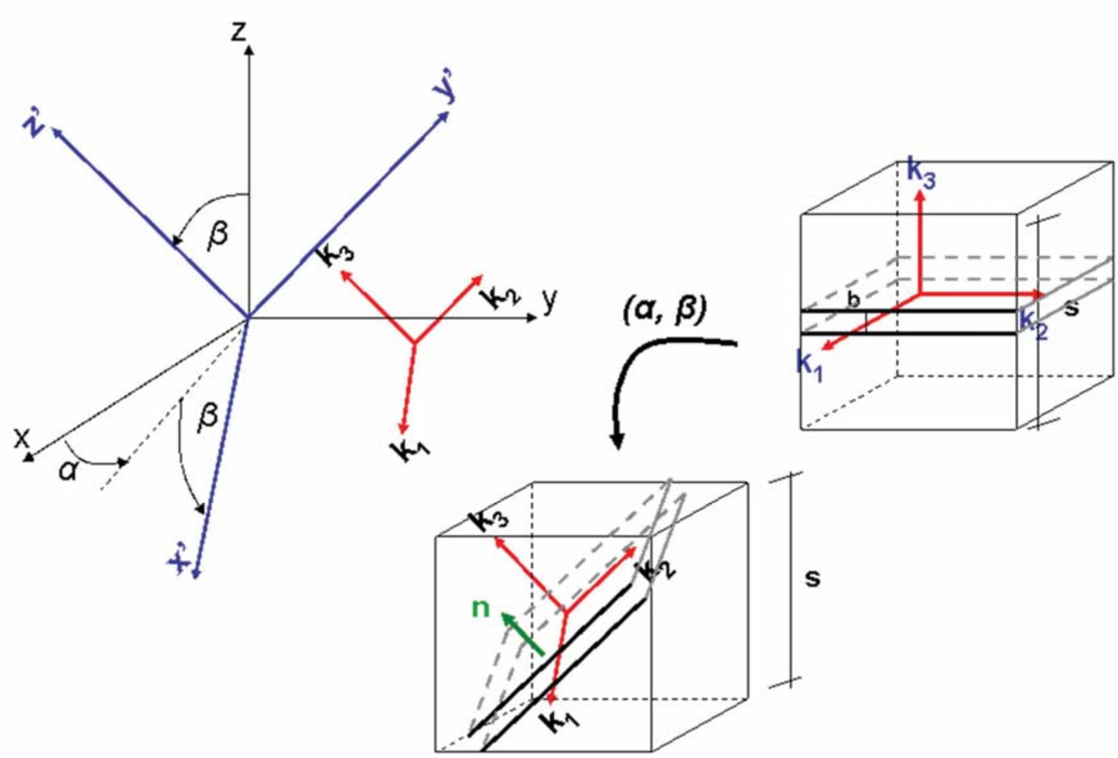


Experimental layout

Results



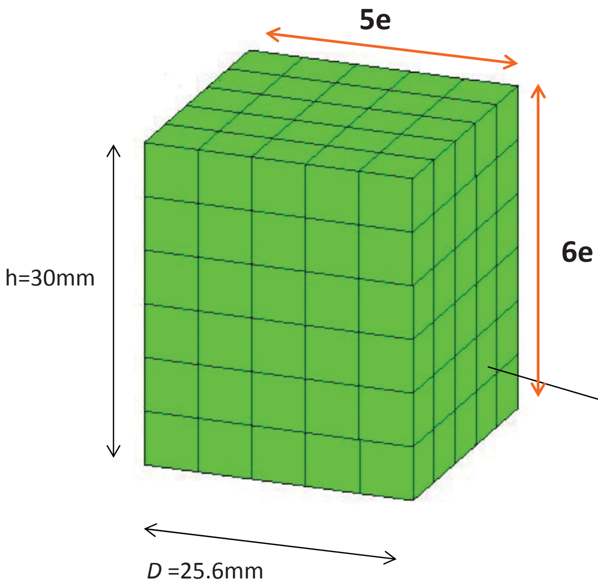
MODEL: ANISOTROPY IN PERMEABILITY



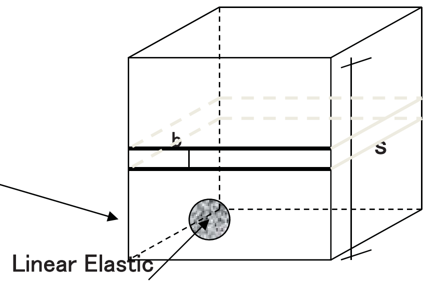
+ Elastic cross anisotropy

Geometry

3D model
150 Quadrilateral elements → Sample
+
50 Quadrilateral elements → upstream volume
50 Quadrilateral elements element →downstream volume
(high permeability)

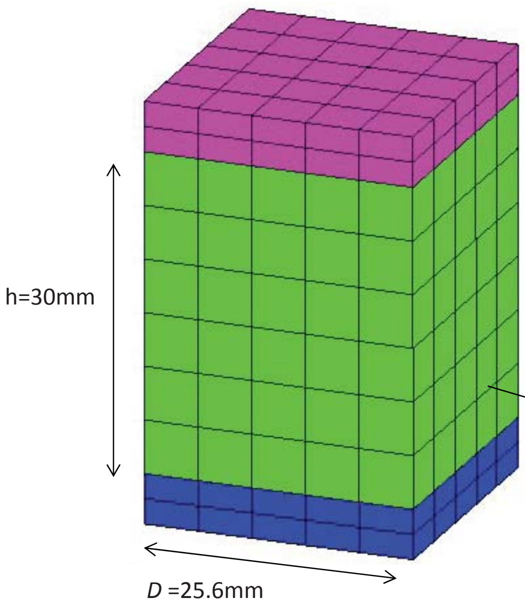


All elements include
a discontinuity



Model

Geometry



All elements include
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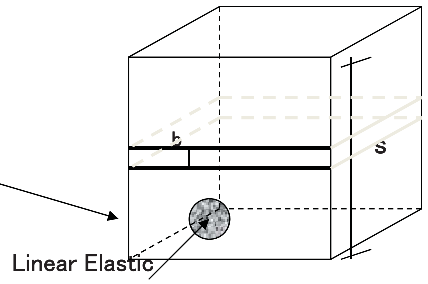
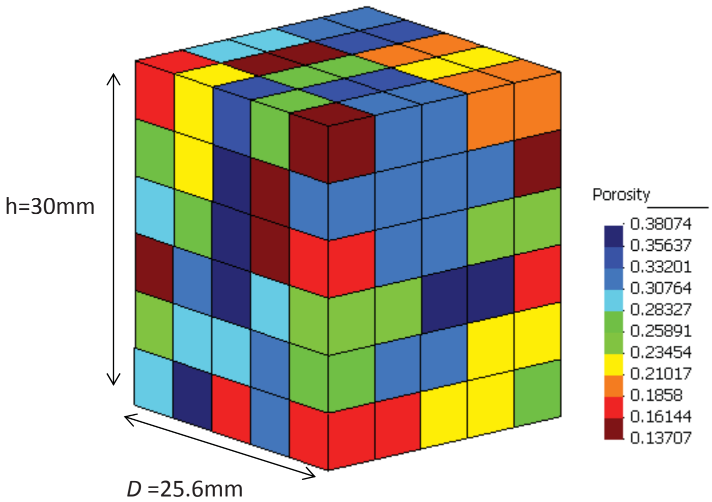


Geometry

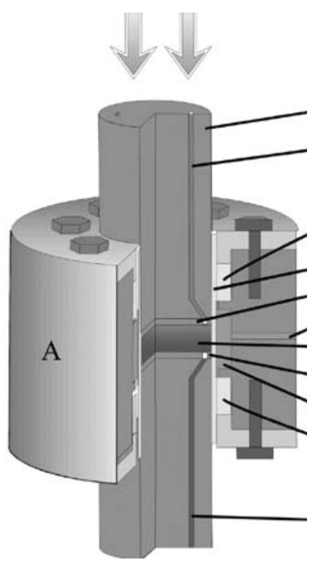


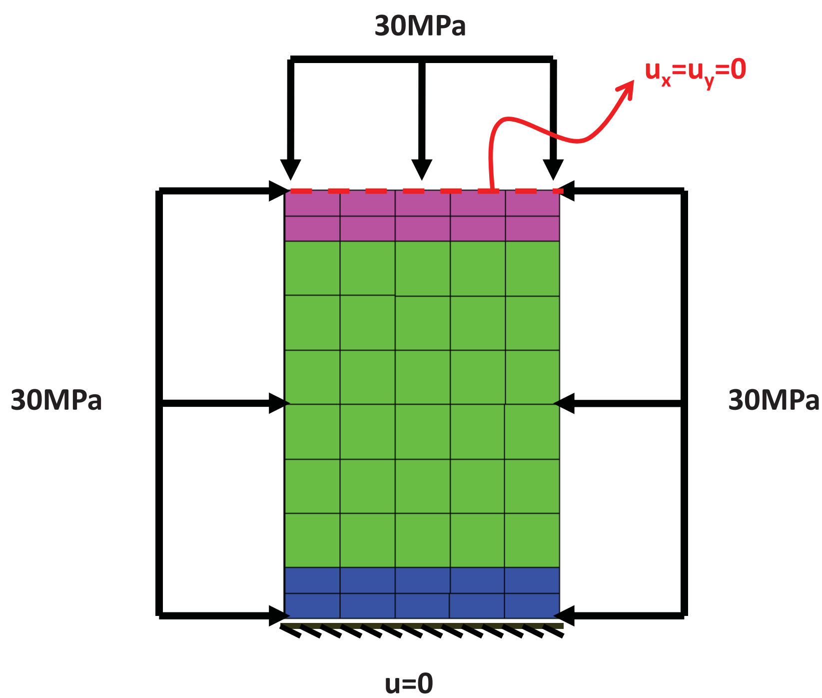
Initial Porosity fields

Uniform distribution
No spatial correlation

Average n=0.261
Variances 8.7×10^{-4}
3.3×10^{-3}
4.5×10^{-3}

Mechanical boundary conditions





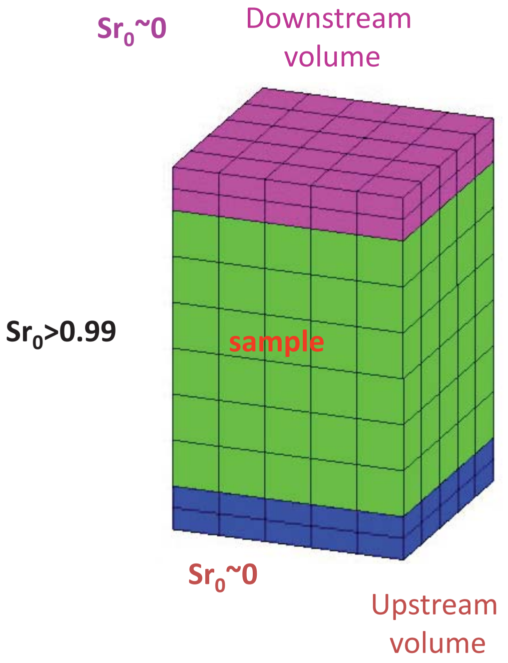
Initial conditions

• Initial stresses

$\sigma_x = \sigma_y = \sigma_z = 30\text{MPa}$

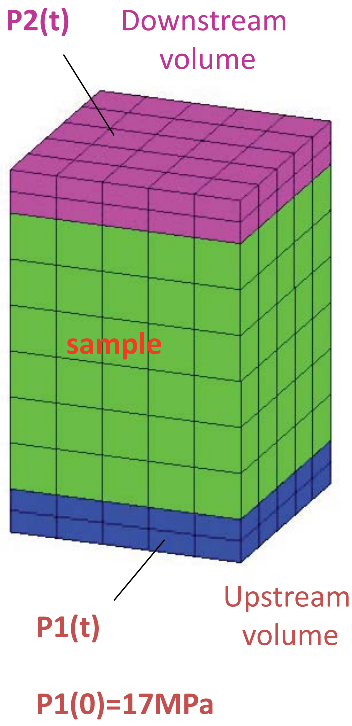
• Initial pressures

$p_g = 0.1\text{MPa}$
$p_w = -0.1\text{MPa}$

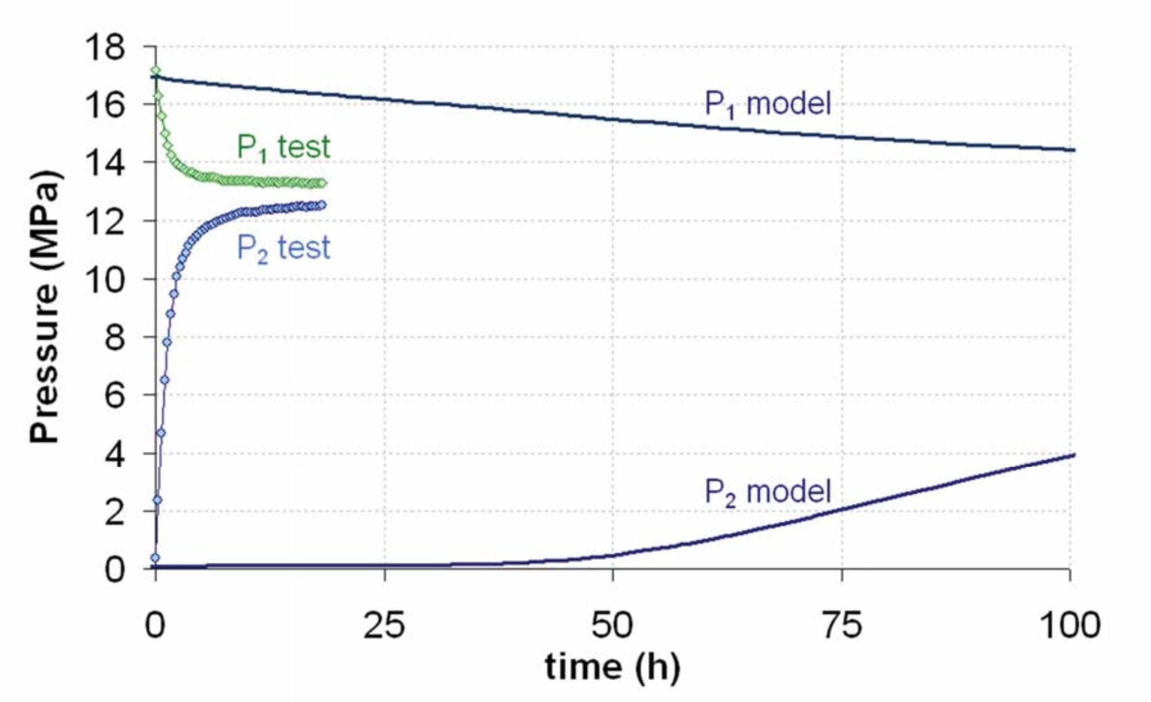


Steps of the analysis

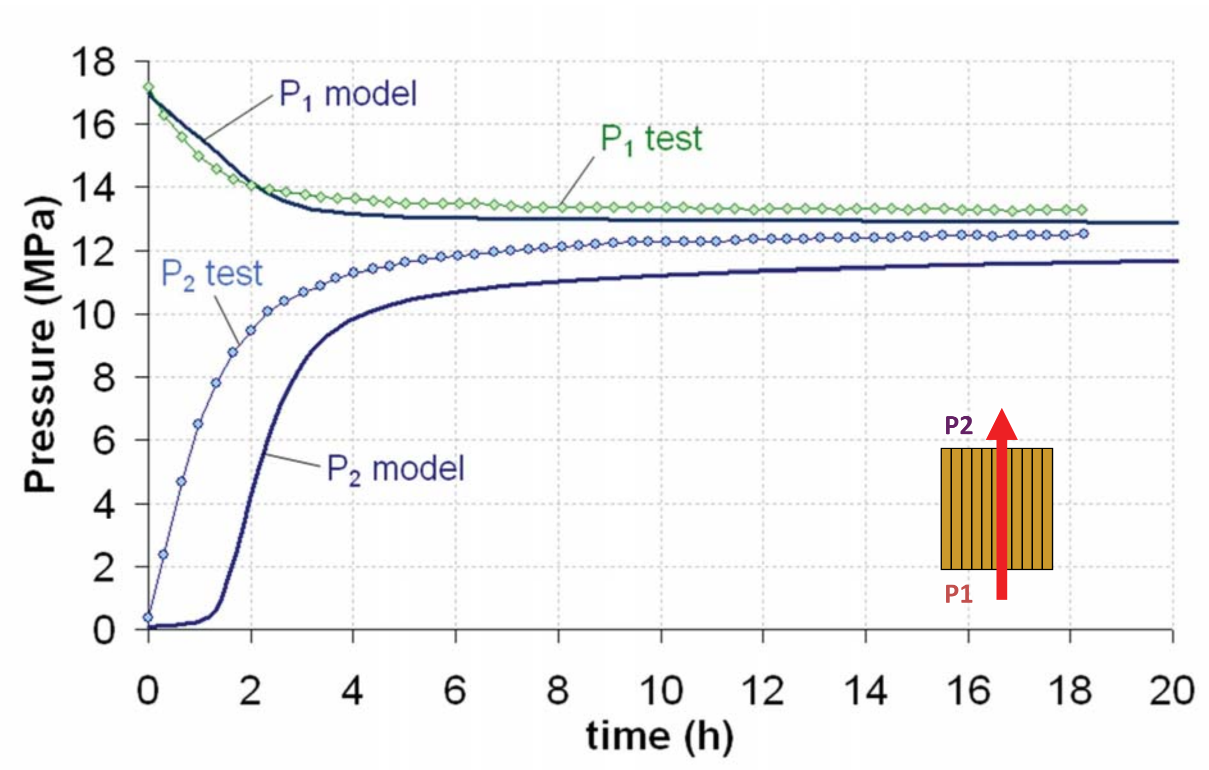
Time (days)	Stage
-1-0	Initial Stress Equilibrium Under **30MPa** Confining Stress
0-0.0006	Pressure Ramp at Upstream Compartment $P_{initial} \rightarrow$ **P1**
0.0006-0.0009	Constant Upstream Pressure **P1**
0.0009-200	De-activation of Upstream Boundary Condition (**P1 decay**)



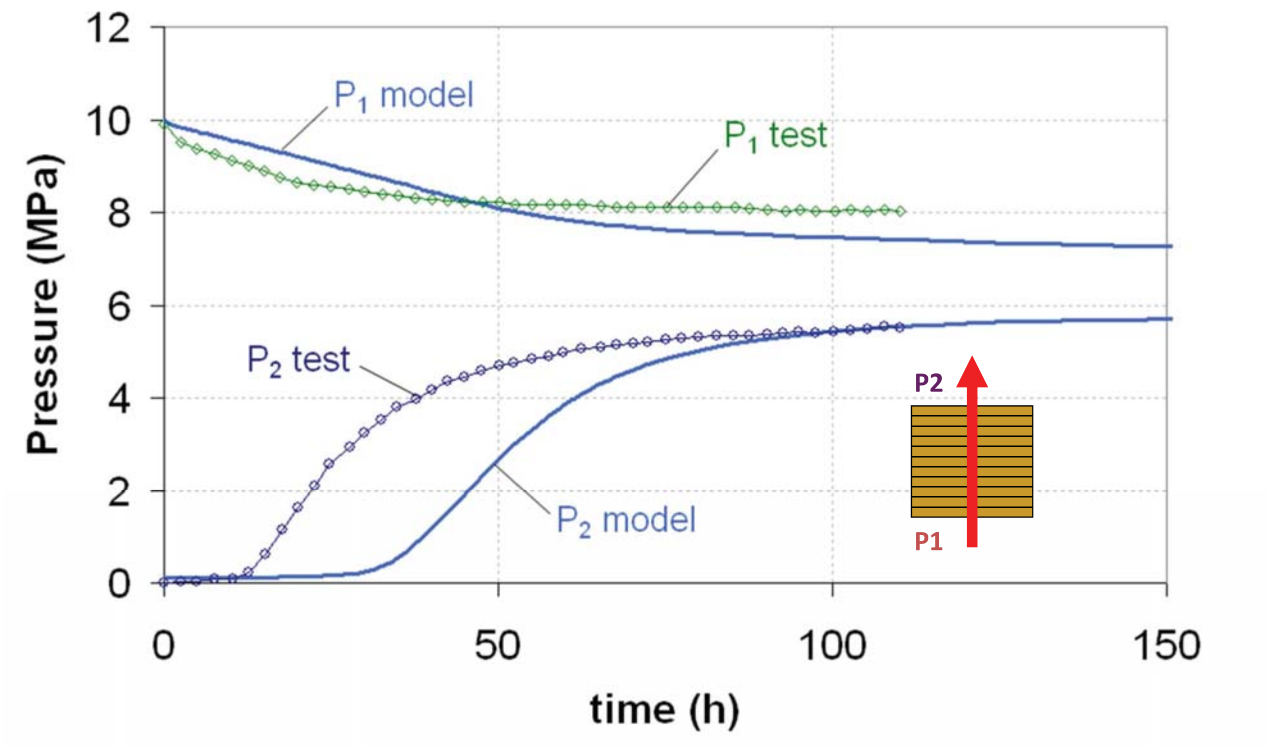
TEST 1. CONVENTIONAL COUPLED DEFORMATION-TWO-PHASE FLOW



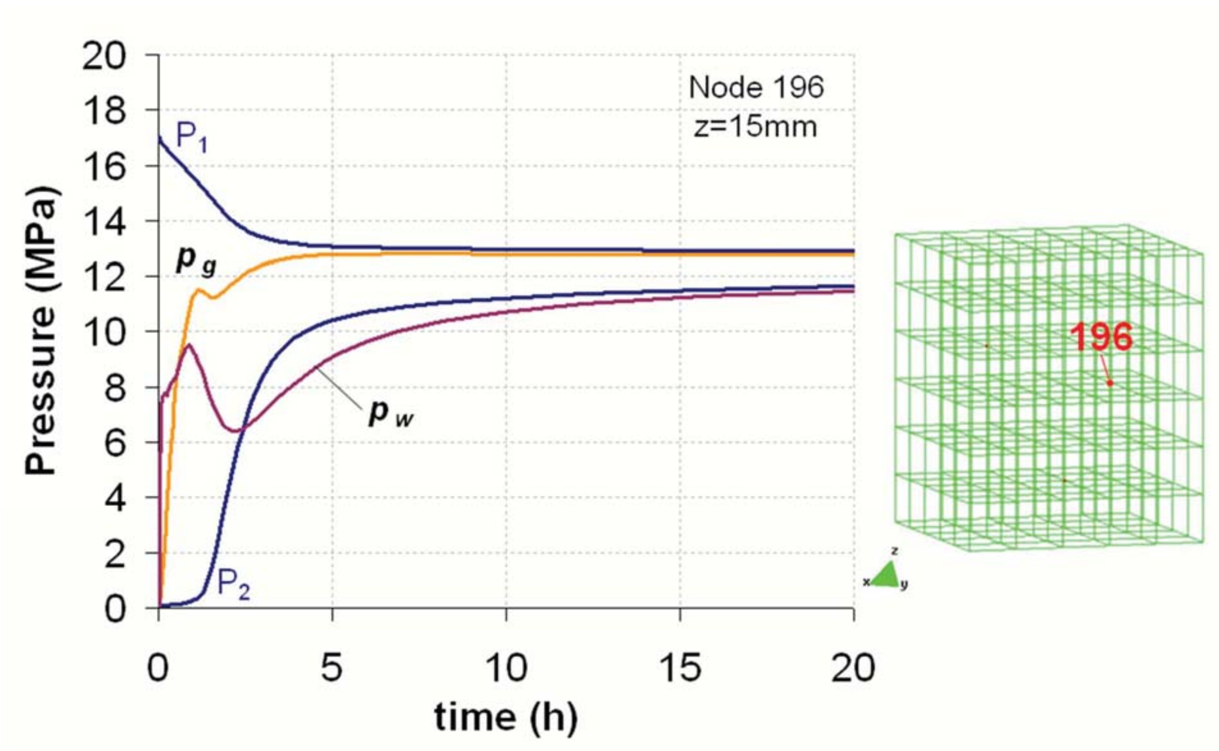
TEST 1. COUPLED DEFORMATION-TWO-PHASE FLOW + **EMBEDDED FRACTURE**



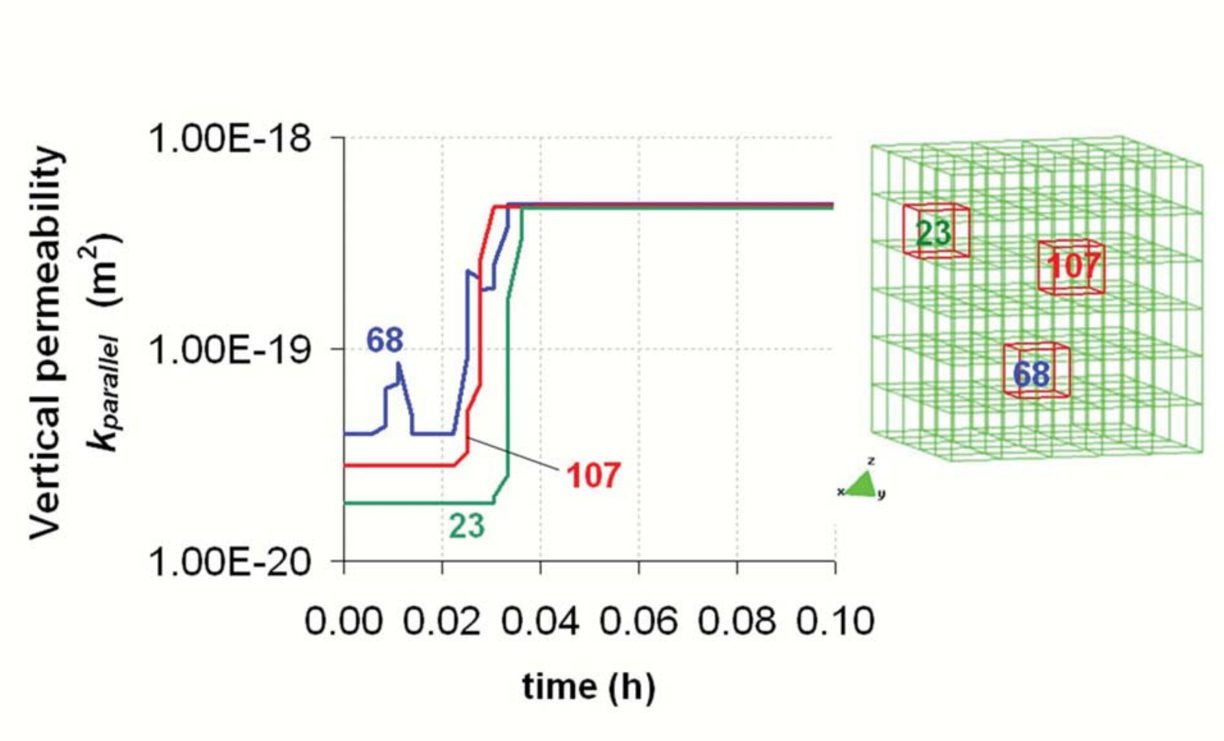
TEST 2. COUPLED DEFORMATION-TWO-PHASE FLOW + **EMBEDDED FRACTURE**



Test 1. Gas and water pressure evolution at node 196



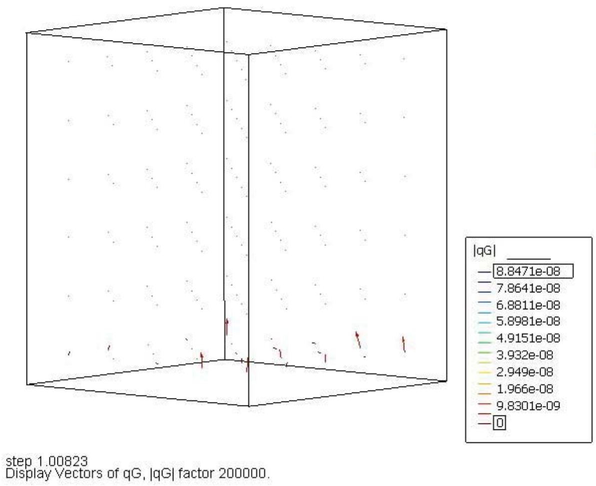
Test 1. Vertical permeability evolution of the elements indicated



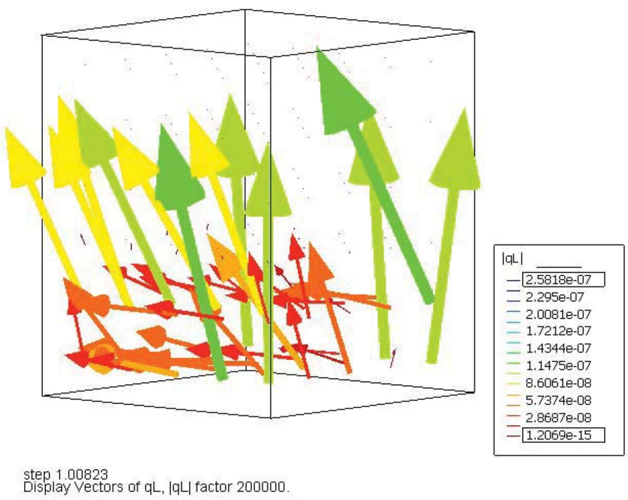
TEST 2

t = 0.19752 h

GAS flux vectors



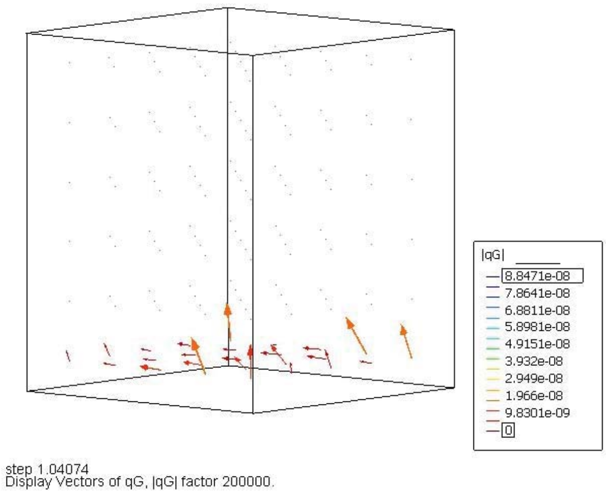
WATER flux vectors



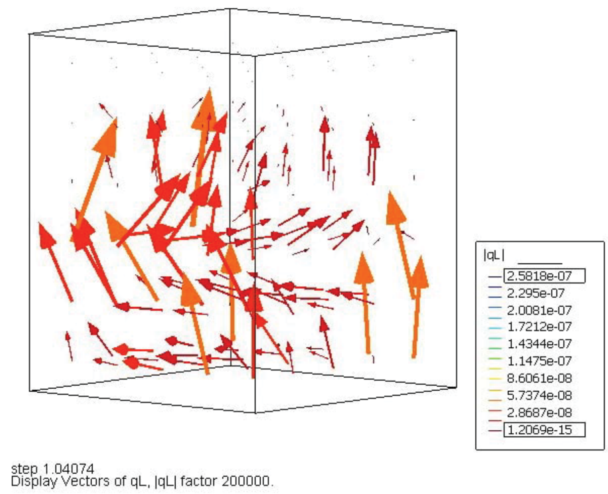
TEST 2

t = 0.09776 h

GAS flux vectors



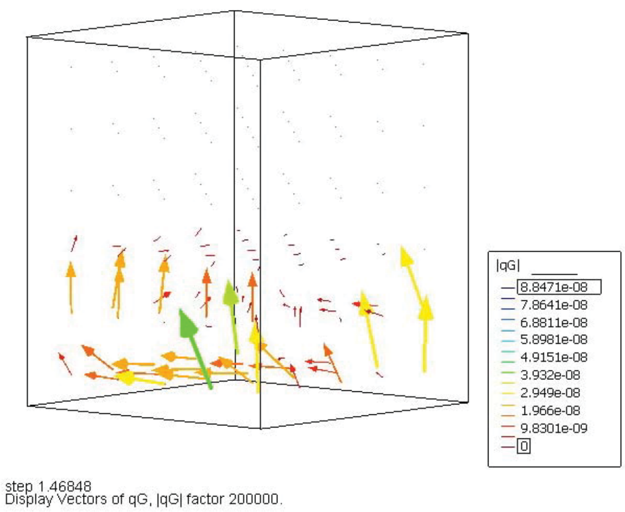
WATER flux vectors



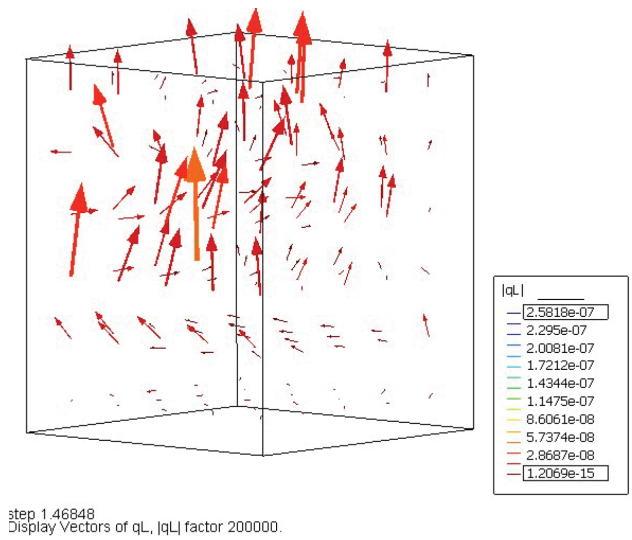
TEST 2

t = 11.24 h

GAS flux vectors



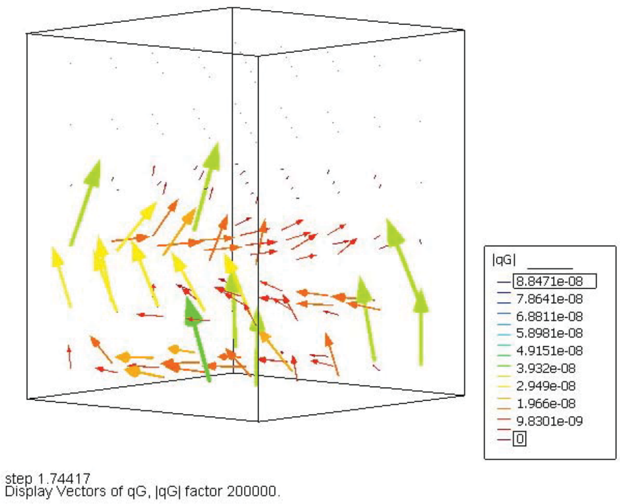
WATER flux vectors



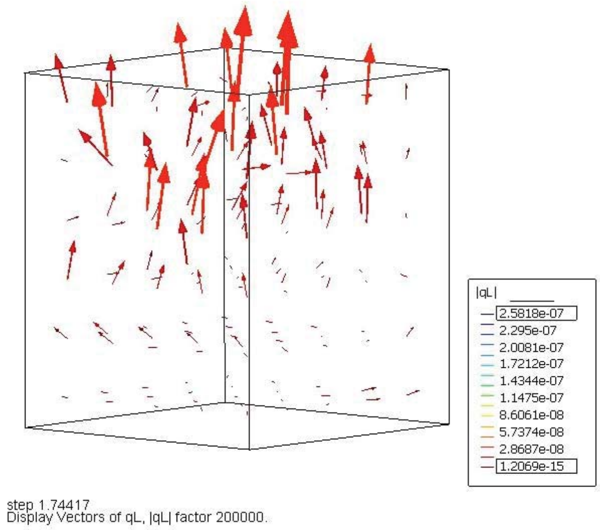
TEST 2

t = 17.85 h

GAS flux vectors



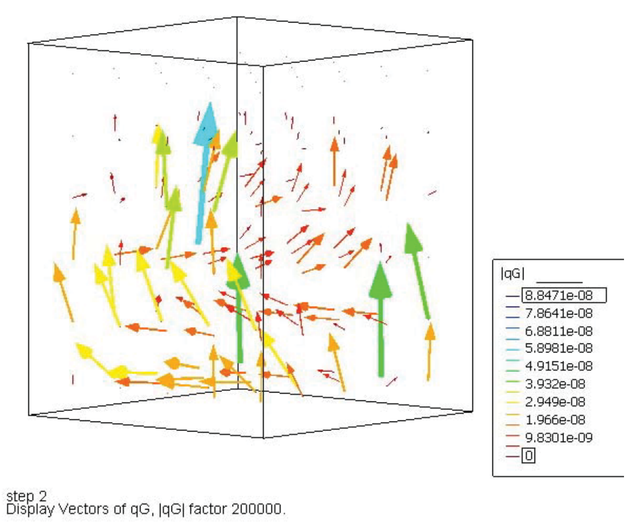
WATER flux vectors



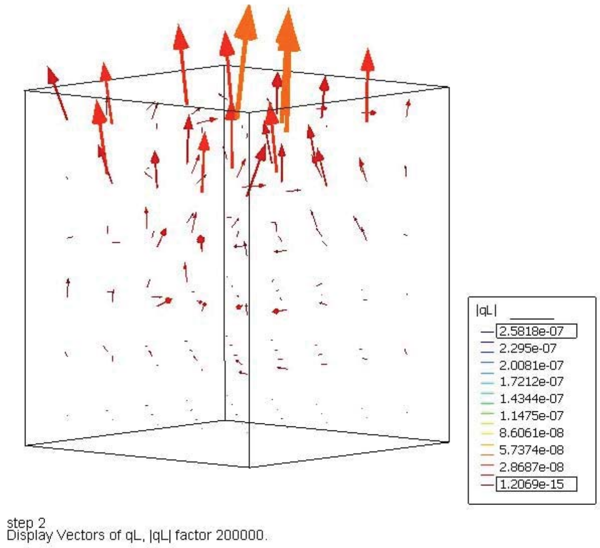
TEST 2

t = 24 h

GAS flux vectors



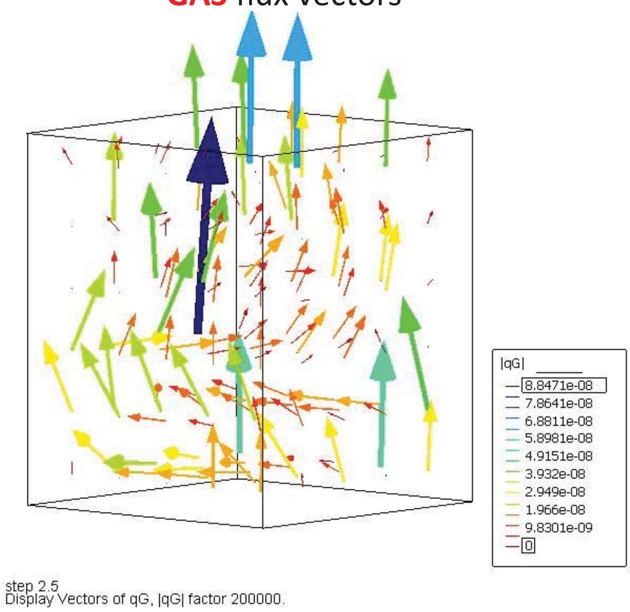
WATER flux vectors



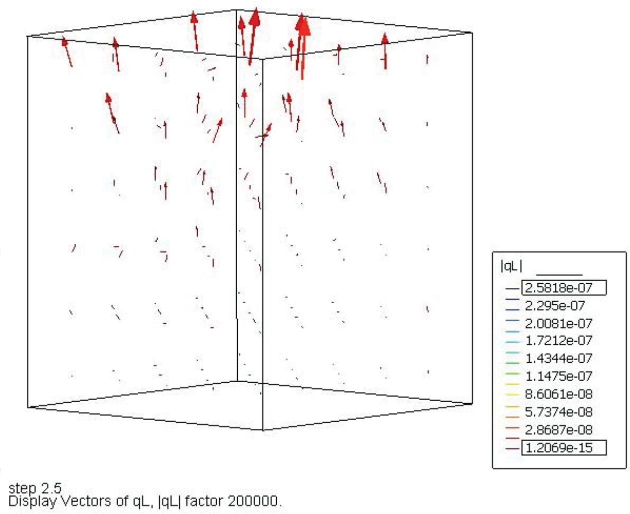
TEST 2

t = 36 h

GAS flux vectors



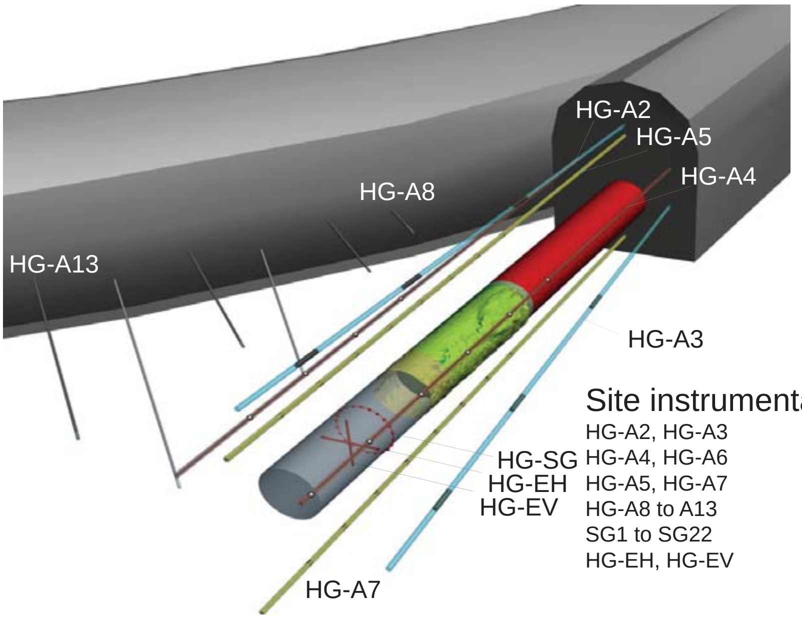
WATER flux vectors



Model performance
Field

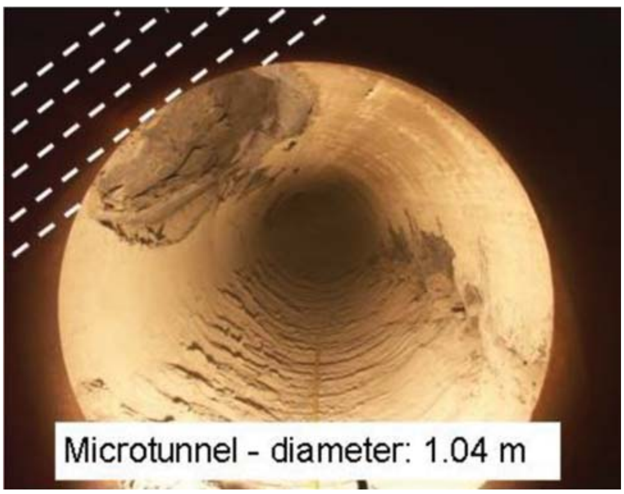
A field experiment: HGA Test in Opalinus Clay

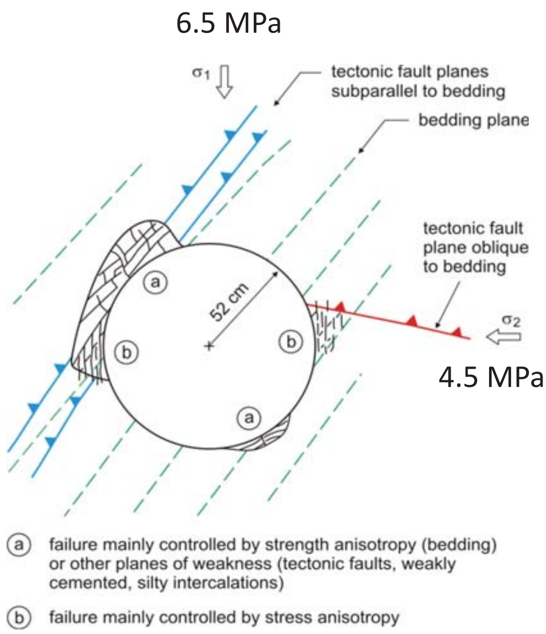
Geometry



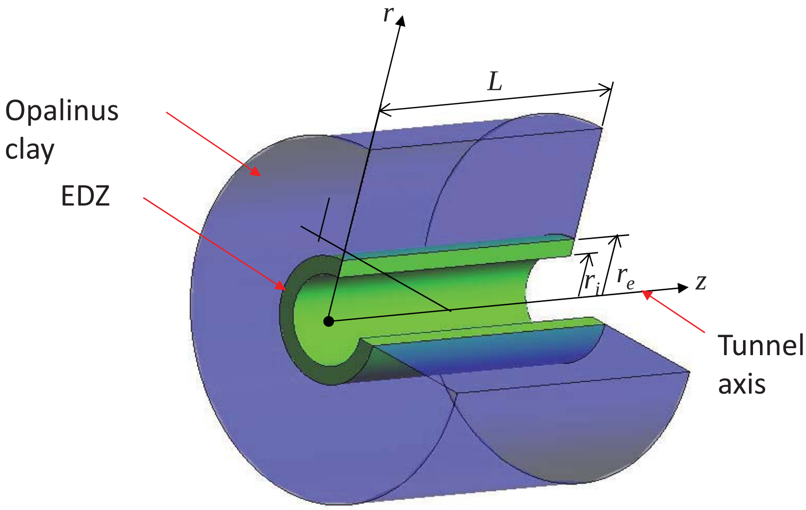
Site instrumentation:

HG-A2, HG-A3	Multipacker systems
HG-A4, HG-A6	Deflectometer chains
HG-A5, HG-A7	Inclinometer chains
HG-A8 to A13	Minipiezometers
SG1 to SG22	Strain gages
HG-EH, HG-EV	Horizontal/vertical extensometer





Marschall et al (2006, 2008)

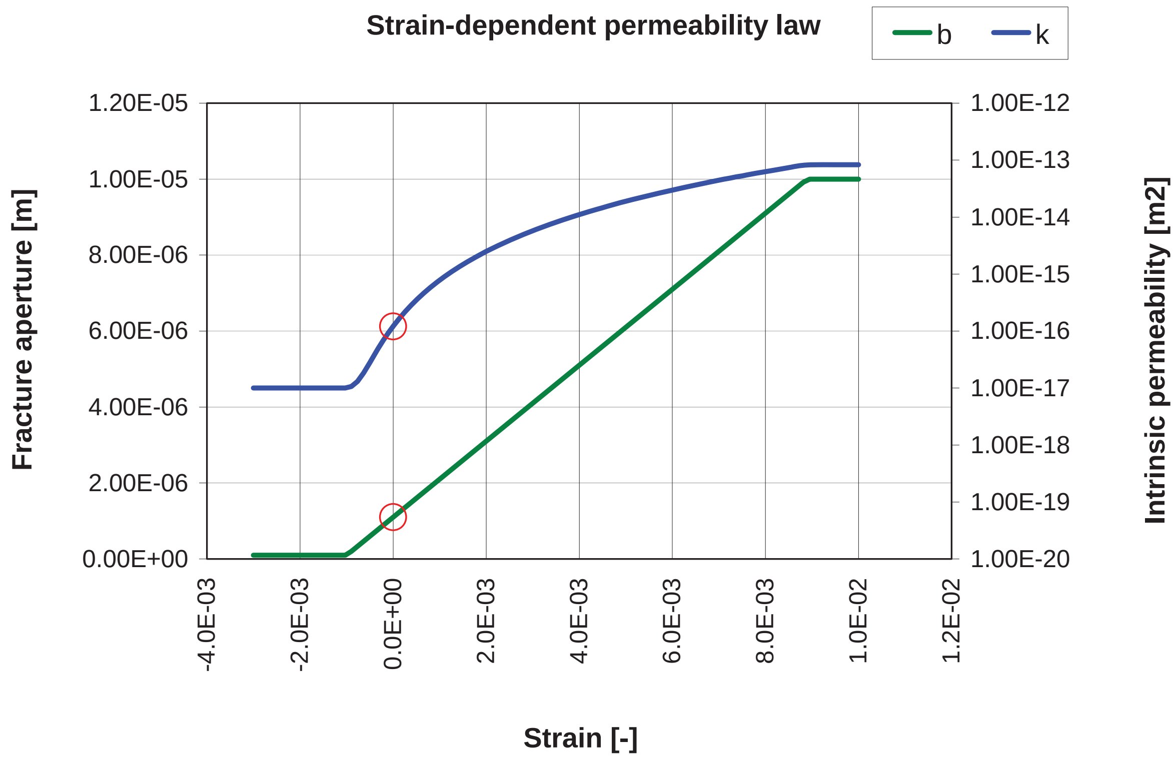


Permeability of EDZ

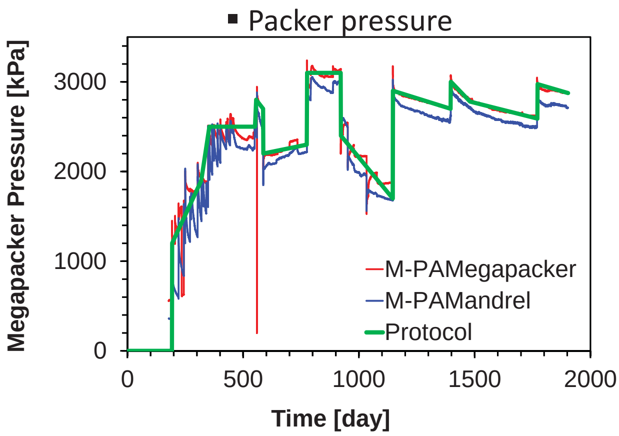
$$\boldsymbol{k}(\varepsilon_{vol}) = \boldsymbol{k}_{matrix} + \frac{1}{12a}[b(\varepsilon_{vol})]^3 \boldsymbol{I}$$

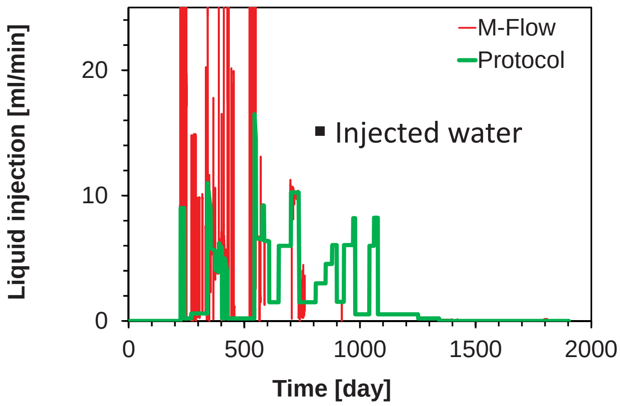
a: Spacing between discontinuities

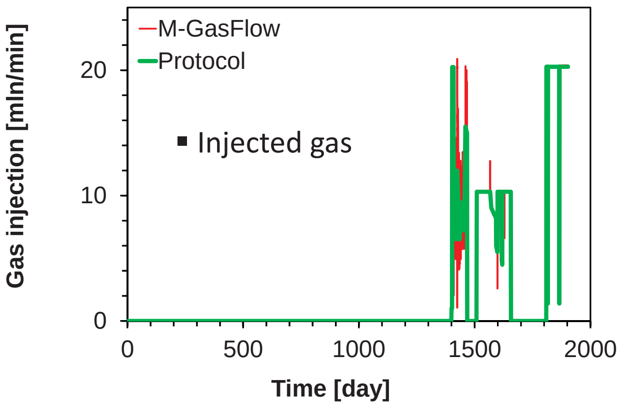
$$b(\varepsilon_{vol}) = \begin{cases} b_0 & \varepsilon_{vol} \le \varepsilon_{vol0} \\ b_0 + (\varepsilon_{vol} - \varepsilon_{vol0})a & \varepsilon_{vol0} \le \varepsilon_{vol} \le \varepsilon_{vol0} + (b_{max} - b_0)/a \\ b_{max} & \varepsilon_{vol0} + (b_{max} - b_0)/a \le \varepsilon_{vol} \end{cases}$$



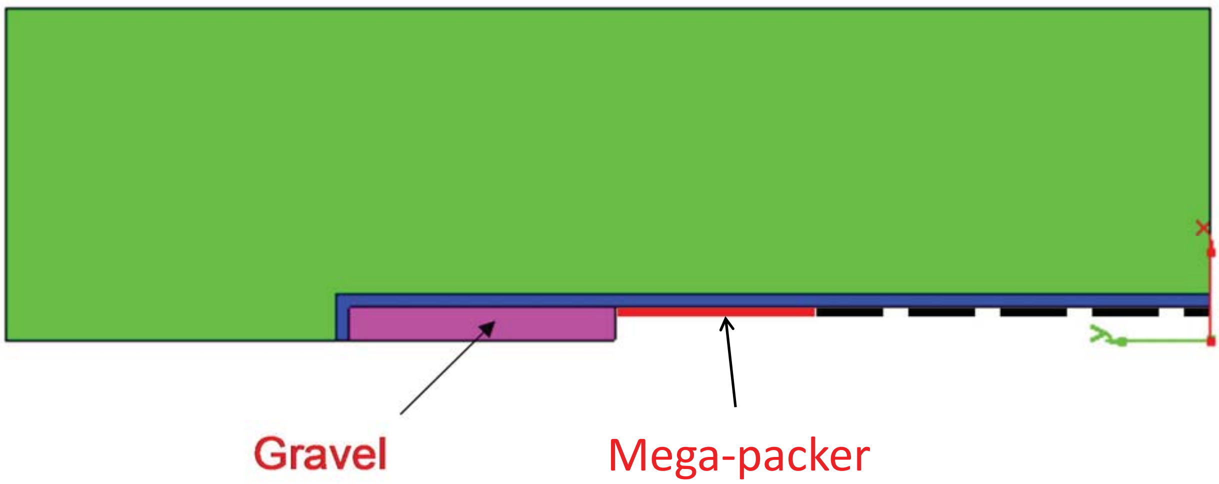
Packer pressure and injected flow rates



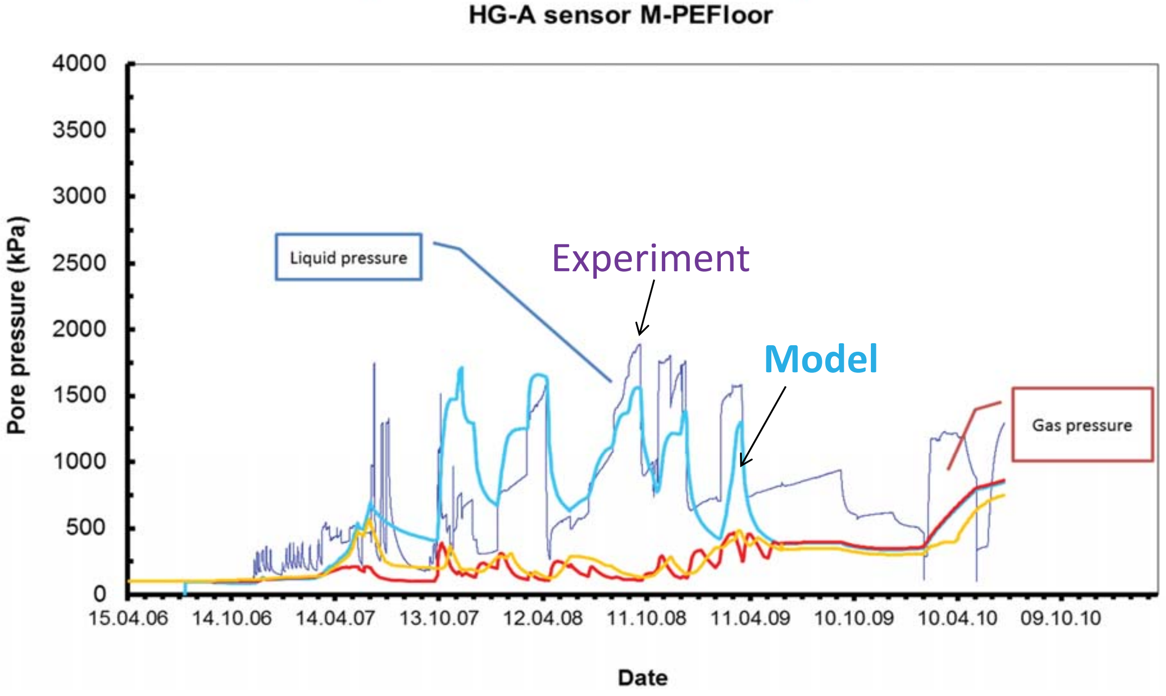




Code_Bright: 2D Axisymmetric Modelling

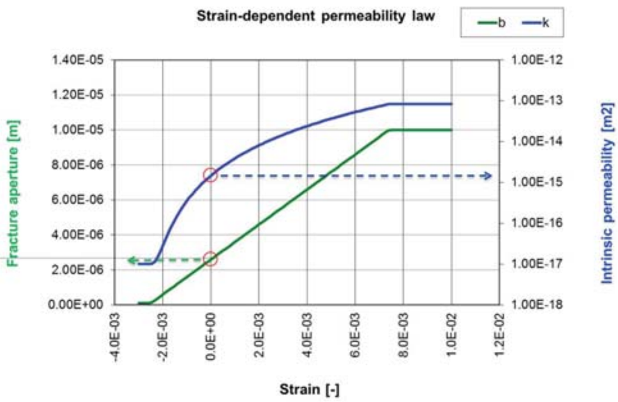


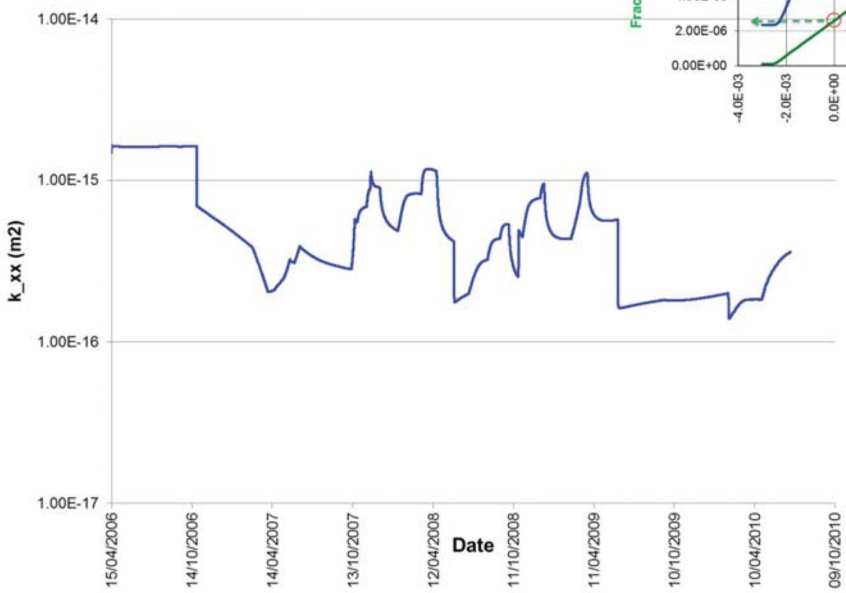
Computed and calculated pressures



	k_0	b_0	a	ε_0	b_{max}	E'_{EDZ}	Ag
	m2	m	m	-	m	MPa	-
Case6 UNSAT	1e-17	1e-7	1e-3	-2.5e-3	1e-5	800	1

Calculated evolution of permeability of EDZ





CONCLUSIONS

- In shales and claystones permeability is explained by preferential paths, existing or induced by tensile strains (stress and suction controlled)
- The modelling approach outlined is simple and can readily be implemented in regular THM codes
- The method captures the response observed in specimen testing as well as in larger "in situ" experiments

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TRANSIENT DEFORMATION AND EXCAVATIONS IN CLAYSTONES

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