

The SELFRAC project

F. Bernier

SELFRACT Exchange Meeting

Monday 4 October 2004



Why the SELFRAC project?

- What is EDZ-EdZ?
 - At the time, no clear terminology
 - Definitions related to mathematical model
- How is EDZ created?
- How does EDZ evolve?
 - Sealing/Healing
- How is EDZ handled in PA?
 - What is the impact of EDZ on performance?
- How can we control it?

Two clays has been studied

- The Opalinus Clay
 - Indurated clay
 - Mt. Terri underground laboratory
- The Boom Clay
 - "Plastic" clay
 - HADES underground laboratory
- Fracturing scheme around excavations has been well characterised

Understanding and quantification of

- A Increase of permeability related to crack proliferation around excavation in clays
- B Decrease of permeability by sealing/healing process

The SELFRAC consortium

- Co-ordinator
EIG EURIDICE (SCK•CEN - NIRAS/ONDRAF)
- Partners
NAGRA, SOLEXPART, LMS(G3S),
L3S,KUL,EPFL
- Budget: 2000 K€
(EC Contribution: 900 K€)
- Duration: 36 months (Start in December 2001)



The measurable objectives are

- Review and reporting of the state of the art
- Terminology: EDZ/EdZ, sealing/healing
- Experimental characterisation of processes A and B
 - More than 90 laboratory tests
- Improvements and development of constitutive models to simulate processes A and B
- Four in-situ tests
- Comparison of numerical simulations and experimental results
- Conclusions and recommendations about the long-term performance of a nuclear repository

Synthesis of the EDZ cluster conference

Chin-Fu Tsang



The scope of the workshop covers:

- Crystalline rock, salt, clays (indurated/plastic)
- The present understanding of the nature and properties of EDZ
 - impact of construction techniques
 - importance of repository conditions
 - evolution of the EDZ
- Practical consequences for different repository stages
 - design, construction, operation, closure
- Impact on safety

EDZ versus EdZ

- The Excavation Disturbed Zone (EdZ) is a zone with hydromechanical and geochemical modifications, without major changes in flow and transport properties. Within the EdZ there are no negative effects on the long-term safety
- The Excavation Damaged Zone (EDZ) is a zone with hydromechanical and geochemical modifications inducing significant changes in flow and transport properties. These changes can, for example, include one or more orders of magnitude increase in flow permeability.

Sealing/Healing

- Sealing is a reduction of fracture permeability by any hydromechanical, hydrochemical, or hydrobiochemical processes.
- Healing is sealing with loss of memory of the pre-healing state.

Many similarities in the EDZ processes within the rock types

- Observation
 - Concepts
 - Testing methodologies
 - Numerical models
- are often transferable

The EDZ behaviour is a dynamic problem dependent on changing conditions which varies from open-drift period to closure period

The excavation stage

- The stress redistribution is the key cause of the EDZ
 - giving rise to tension, compression and shear
- EDZ processes are intrinsically anisotropic
 - anisotropic properties of the rock
- Influence of the excavation method
- A back-pressure from a rock support system can help to limit the EDZ

Open-Drift stage

- Ventilation dehydrates the rock near the drift surfaces
 - strengthening of the rock
 - changing creep properties =>retarding self-sealing
- Air entering the rock
 - oxidation
 - two phase flow
- EDZ cut-off to prevent high-permeability continuous flow path

Closure stage

- The system becomes fully saturated
- Heating phase followed by cooling phase
- Sealing by
 - dilatancy
 - creep
 - swelling
 - consolidation
 - newly formed minerals

- The assumption that the presence of an EDZ provides a fast pathway for the escape of radionuclides to the biosphere is now recognised as an oversimplification!
- Transport solute require the evaluation of the total flow system
- If the high-permeability zone is surrounded by low-permeability regions, or the hydraulic gradient is sufficiently low, there will be an insufficient supply of flowing water in the EDZ to impact the repository performance

- A full scientific evaluation of all conditions is not necessary for PA of a repository
 - a high level of understading is required
 - to provide confidence building
- Good performance assessment can be made through conservative bounding, scoping, and sensivity studies

Bottleneck issues

- Need to study anisotropic behaviour in deformation and flow within the EDZ
- Need to study seal-rock interface and effectiveness of drift seal and EDZ cutoffs
- Need to conduct comprehensive performance assessment studies of EDZ

Thank to

- Pierre Berest, Robert Charlier, Udo Hunsche, Pekka Särkkä, Pierre Berest, Peter Blümling, Wernt Brewitz, Jesus Carrera, Robert Charlier, Frank Hansen, Udo Hunsche, Roland Pusch, Jonny Rutqvist, Pekka Särkkä, Tilmann Rothfuchs, Klaus Wieczorek, Xavier Sillen and all participants
- ANDRA, ENRESA, GRS, NAGRA, SKB NIRAS/ONDRAF, POSIVA, and SCK.CEN

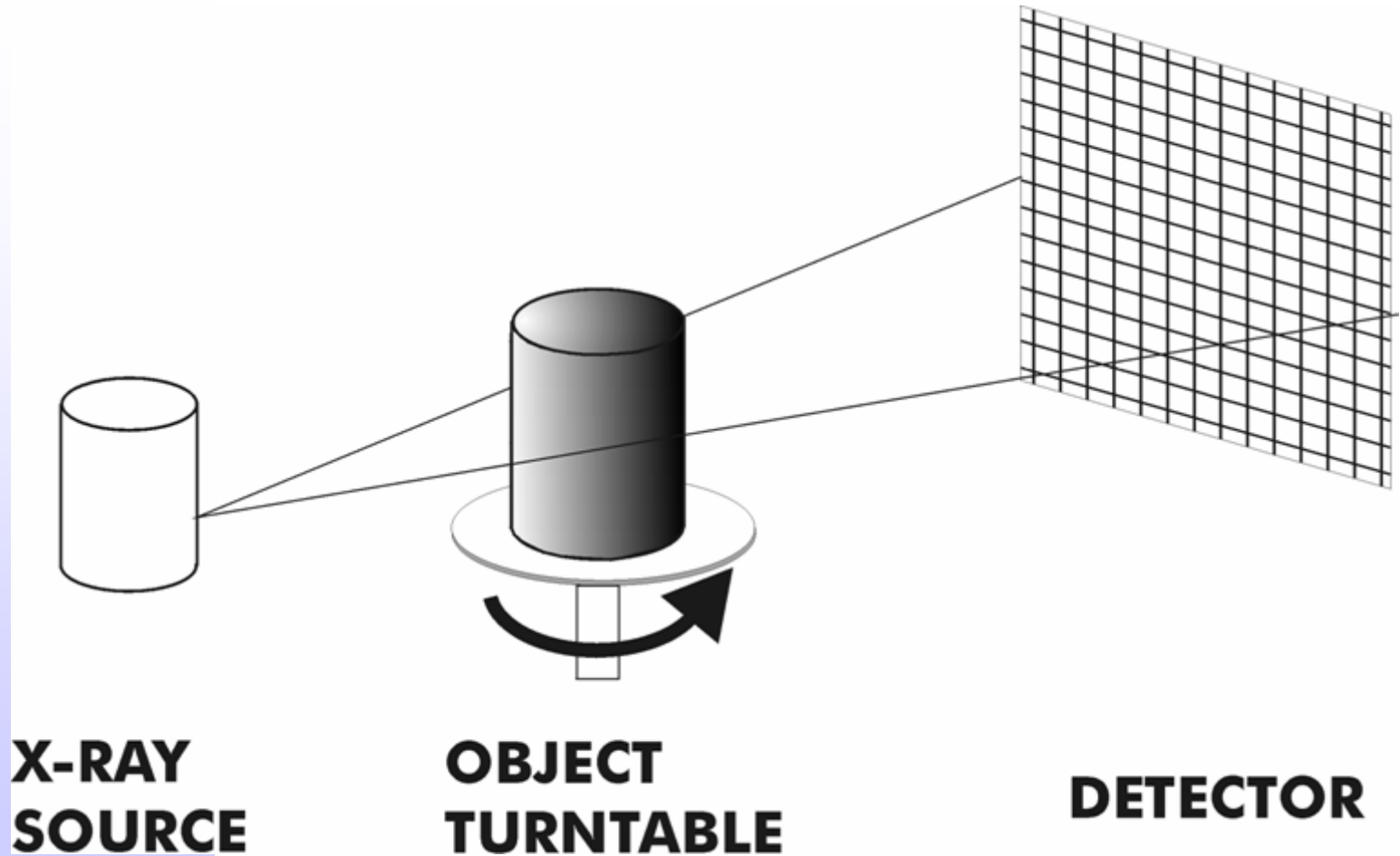


Characterisation of fracture evolution during permeability measurements by means of μ CT

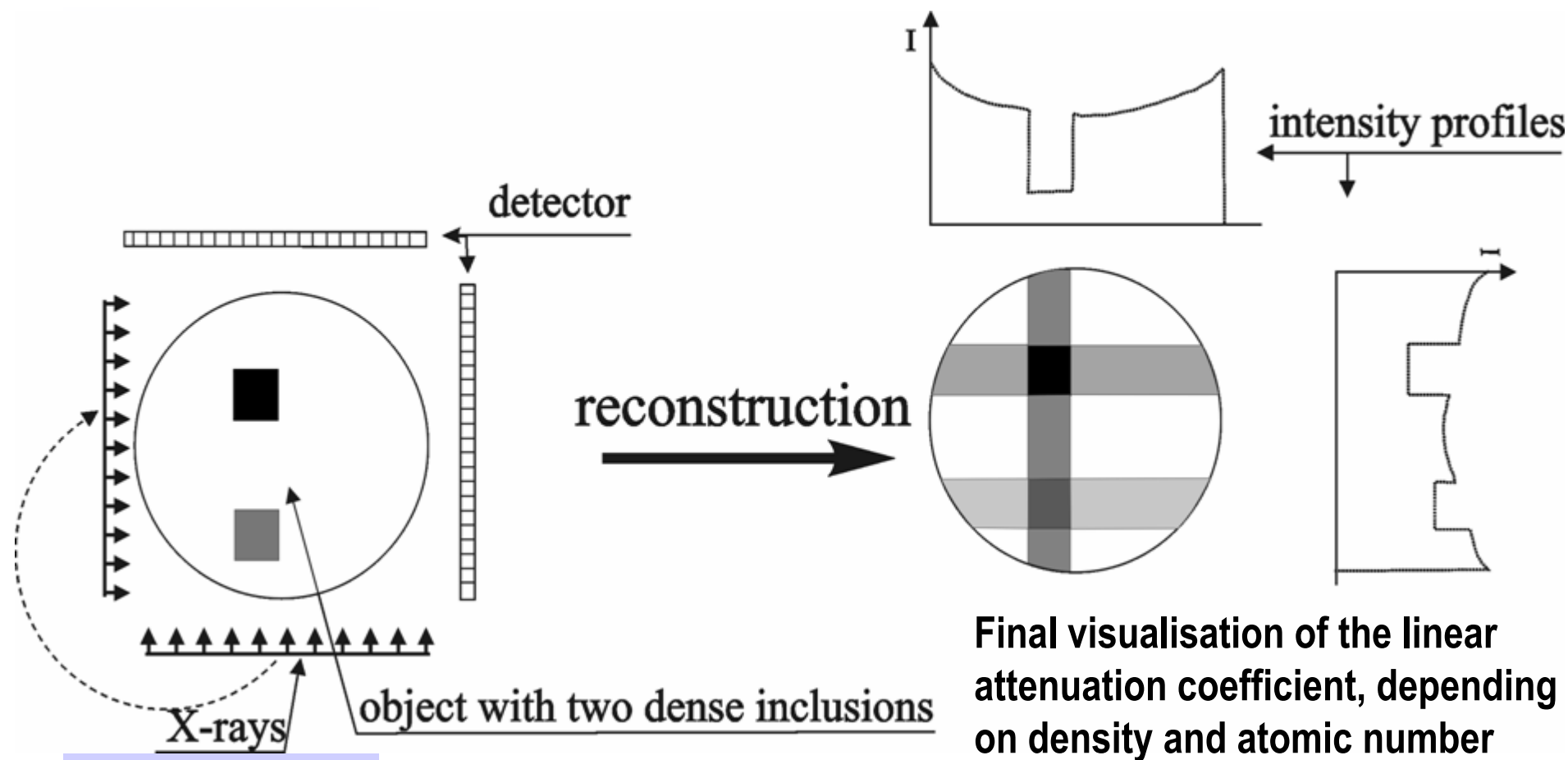
Maarten Van Geet
Waste & Disposal

- Basic principles of μ CT
- Calibration of fracture apertures
- Permeability tests in permeameter cells
 - Boom Clay samples
 - Opalinus Clay samples
- Permeability tests in isostatic cells
 - Boom Clay samples
 - Opalinus Clay samples
- Conclusions

μ CT contains three major parts



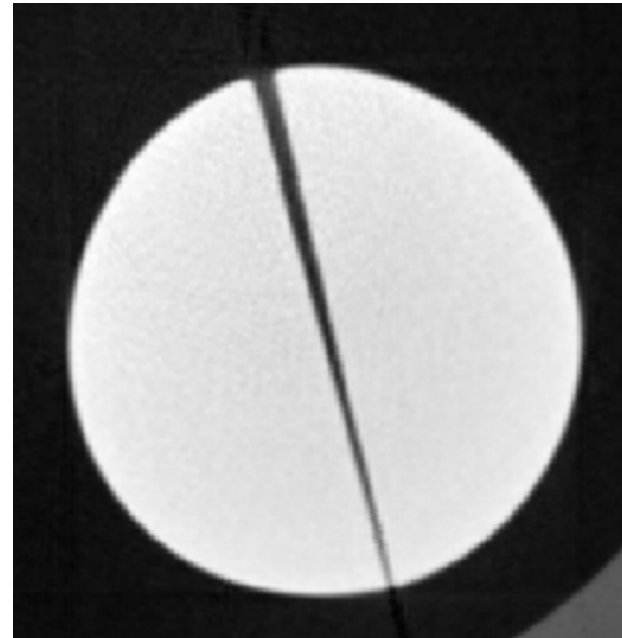
During reconstruction radiographs at many angles are back-projected



Final visualisation of the linear attenuation coefficient, depending on density and atomic number

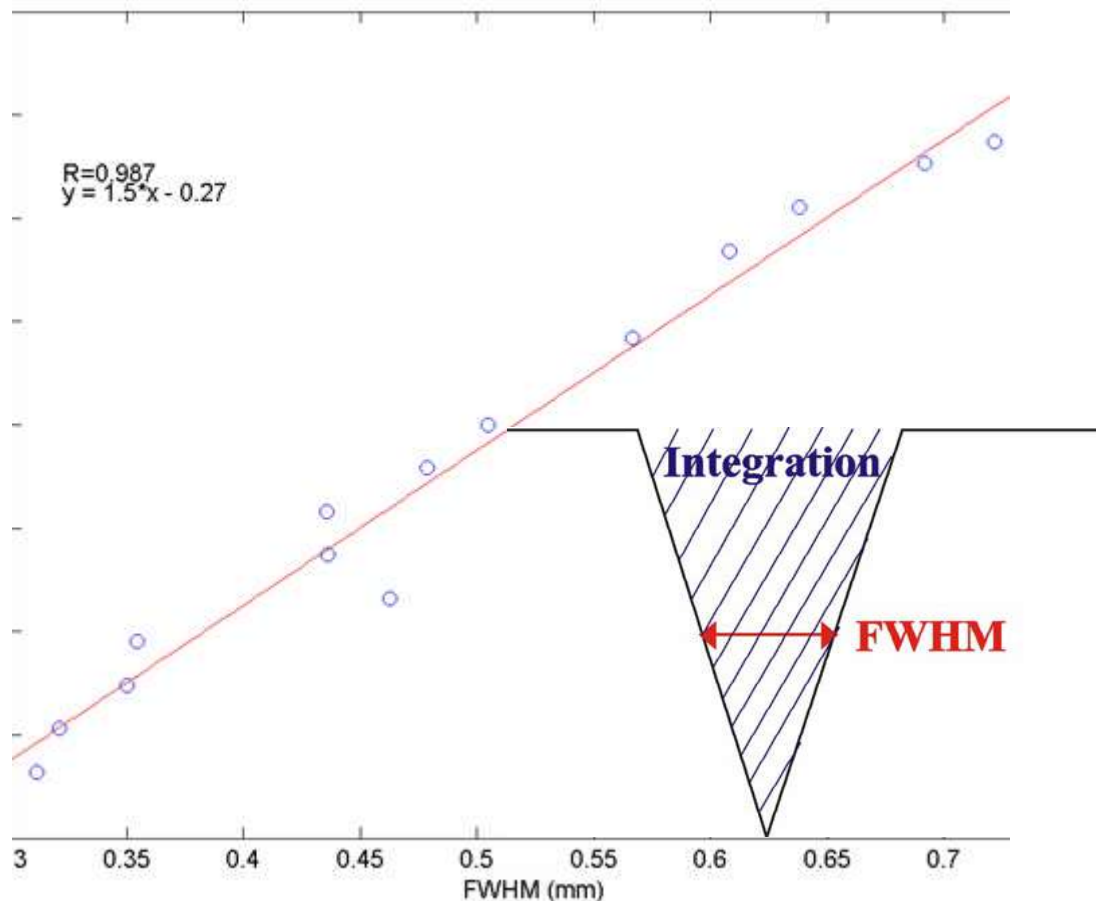
Experimental procedure for fracture characterisation

- Same set-up as permeameter cell measurements
- Glass sample of 2cm diameter
- Artificial fractures from 60 μ m to 800 μ m



Experimental procedure for fracture characterisation

- Two techniques
 - Full width at half maximum
 - Integration of missing mass
- FWHM can be used, even when fractures are partly filled

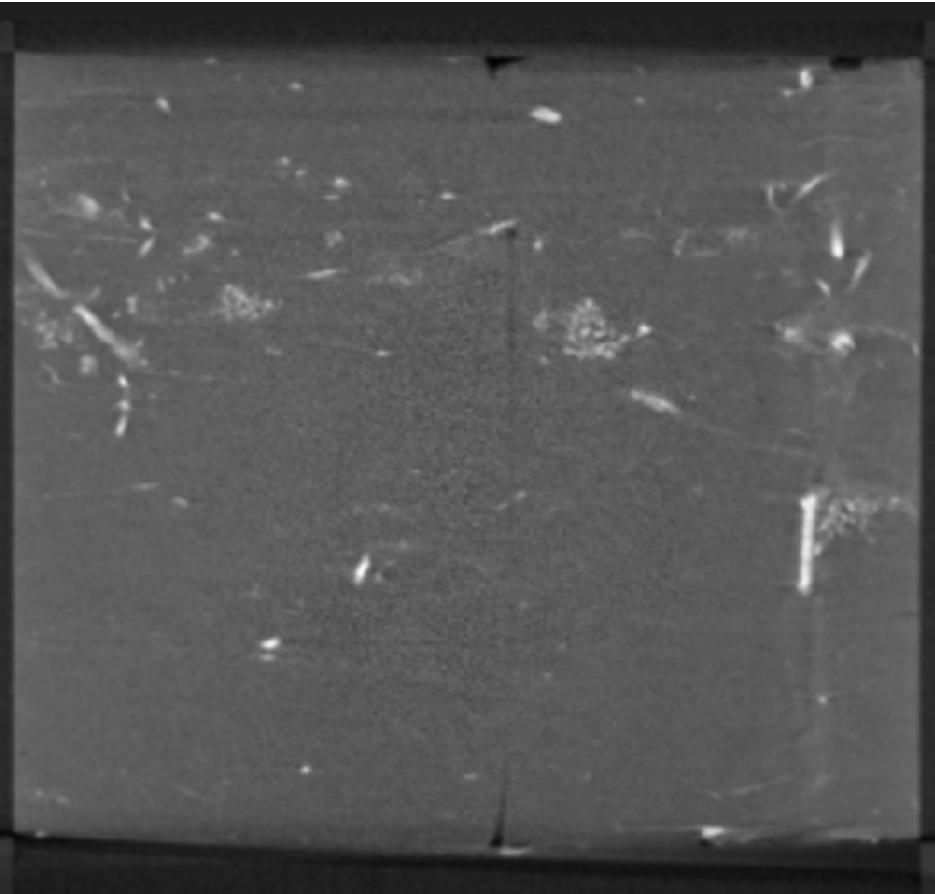
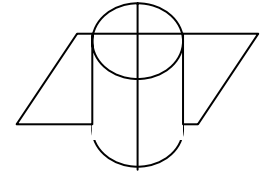


Boom Clay: permeameter cell

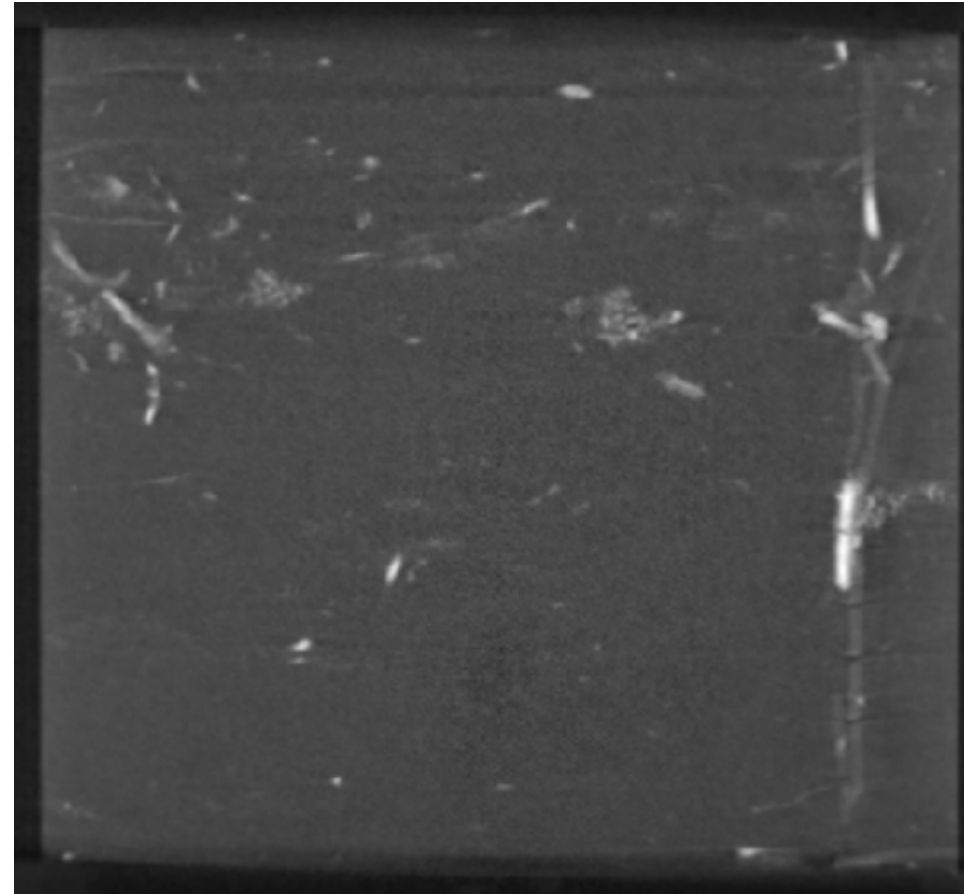
- Cylindrical object: 38 mm diameter
30.3 mm high
- voxelsize: around 100x100x100 μm
- Pressed into Plexiglass cell while cutting with iron wire
- Permeability test with synthetic Boom Clay water

hours		4.5		60		29		197	
action	scan1	Perm test	scan2	-	scan3	Perm test	scan4	Perm test	scan5

Boom Clay: General view on fracture evolution

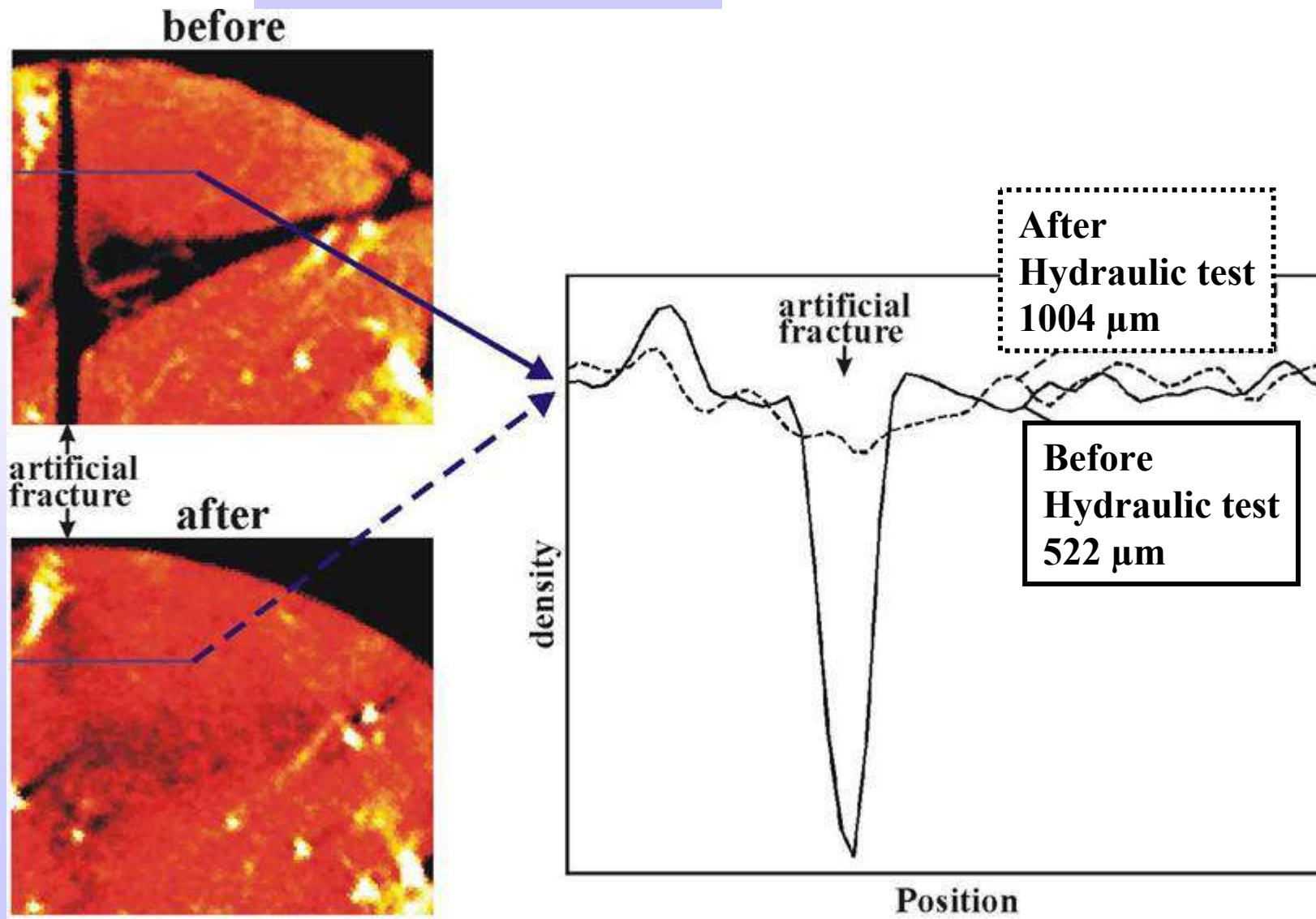


Central transect, scan 1
Majority of fracture $< 100\mu\text{m}$



Central transect, scan 2

Boom Clay: Evolution of fracture at top



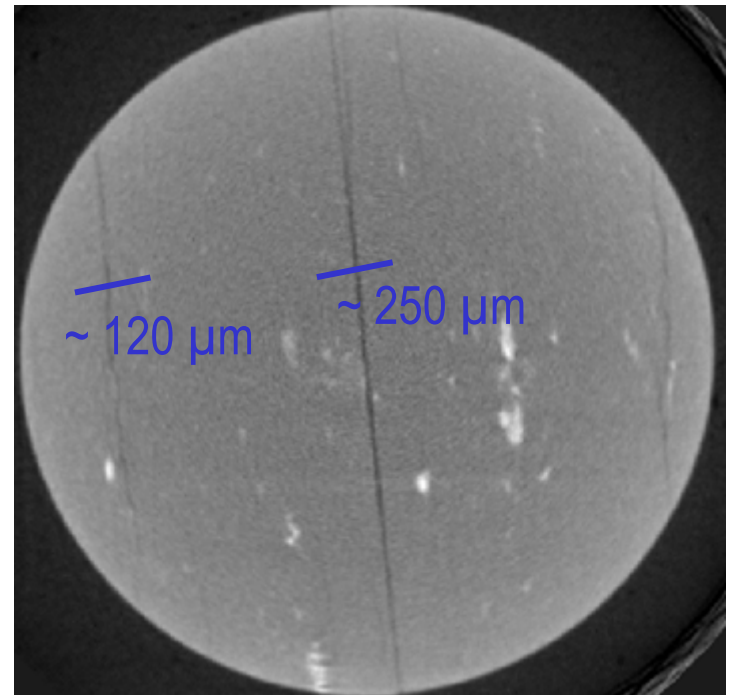
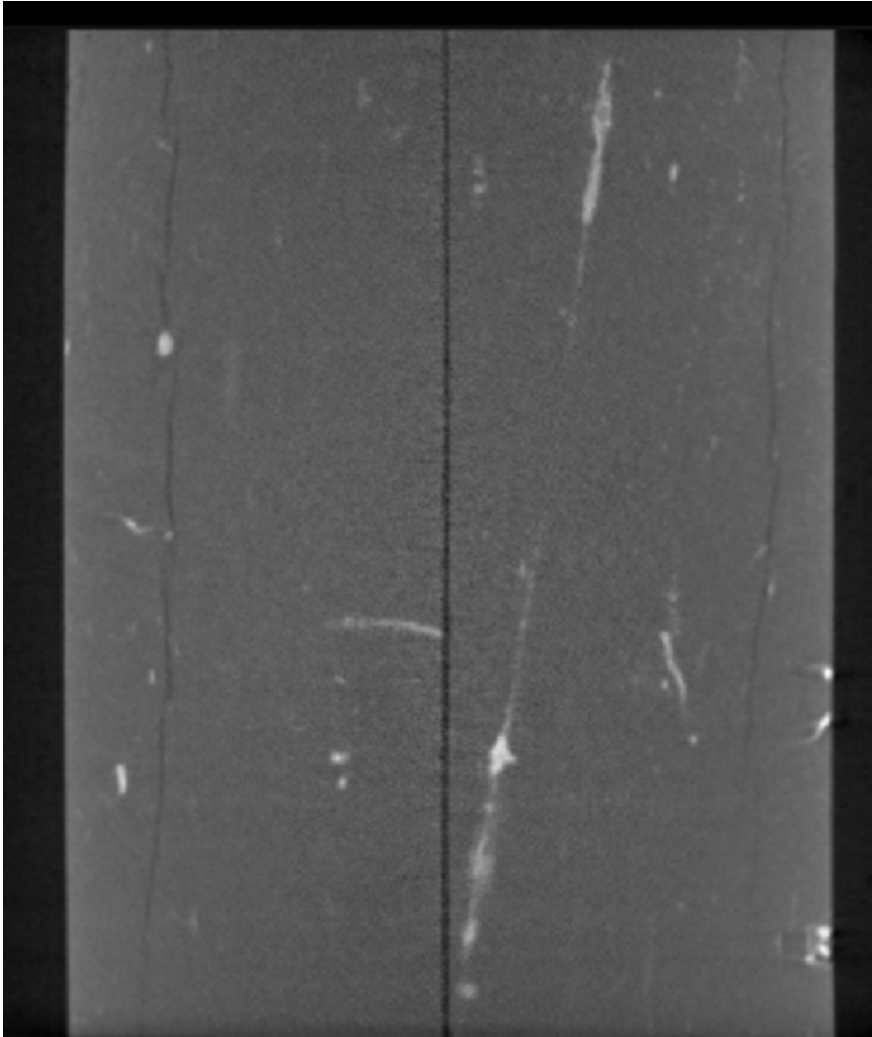
Opalinus Clay: permeameter cell

- Cylindrical object: 38 mm diameter
51.3 mm high
- voxelsize: around 100x100x100 μm
- Pressed into Plexiglass cell while cutting with iron wire
- Permeability test with Ca(OH)_2 saturated Pearson A3 water

days		29	
action	scan1	Perm test	scan2

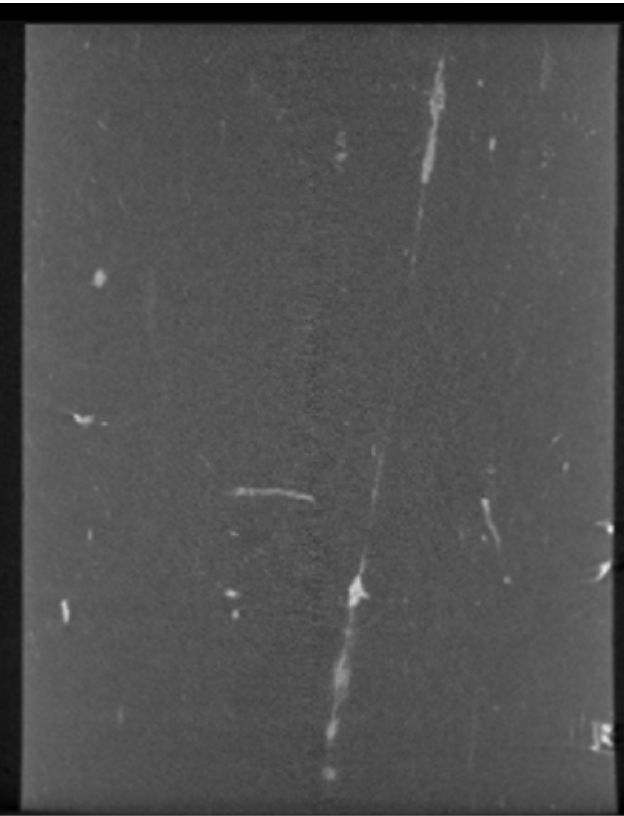
Opalinus Clay: status before permeability test

Artificial fracture +
fractures along bedding plane

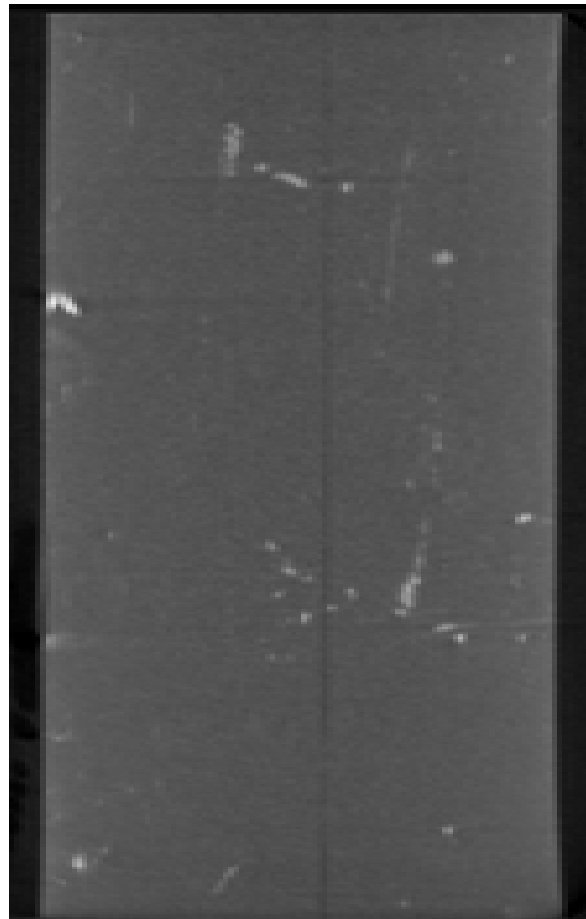


Opalinus Clay: after permeability test

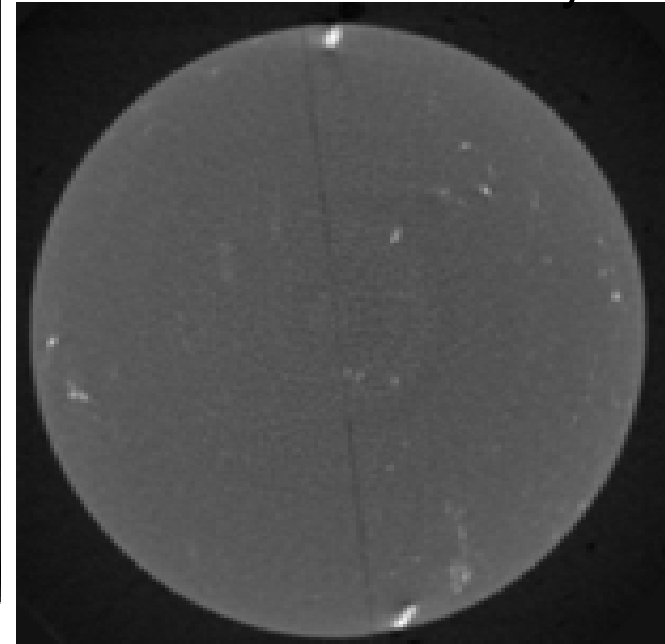
Central transect



Boundary transect

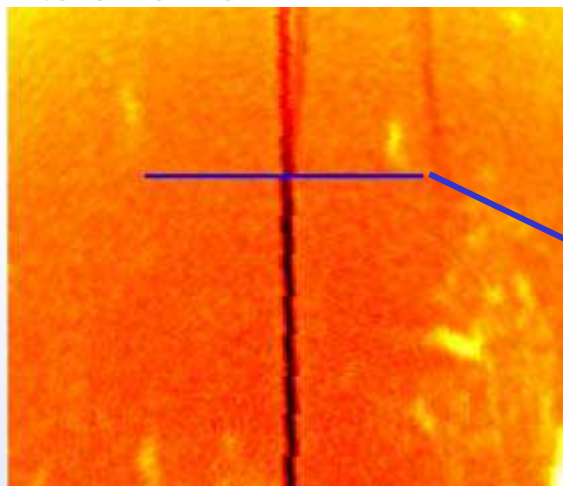


Single slice
Notice difference between
Centre and boundary

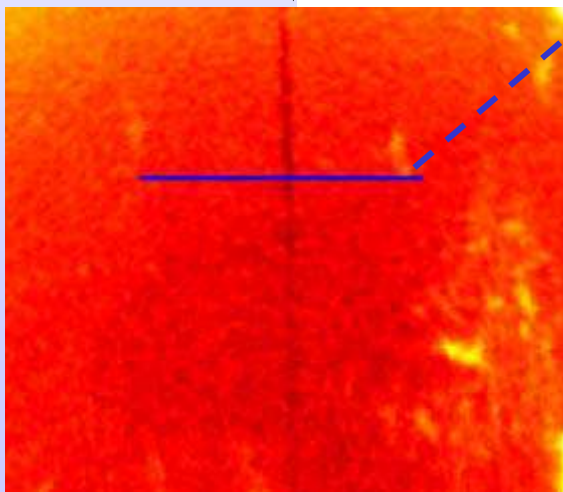


Opalinus Clay: evolution of fracture near boundary

before

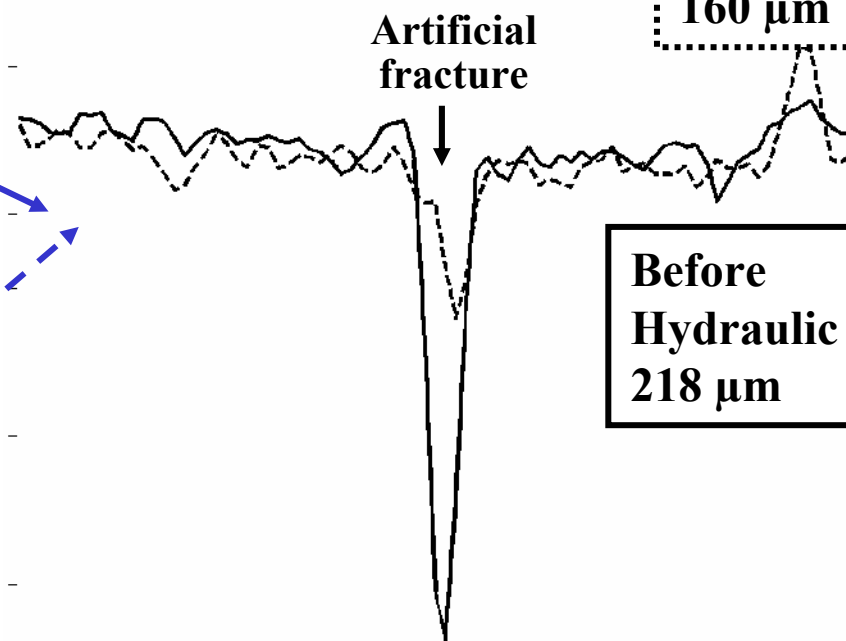


after



↑ Artificial fracture
↓

Density



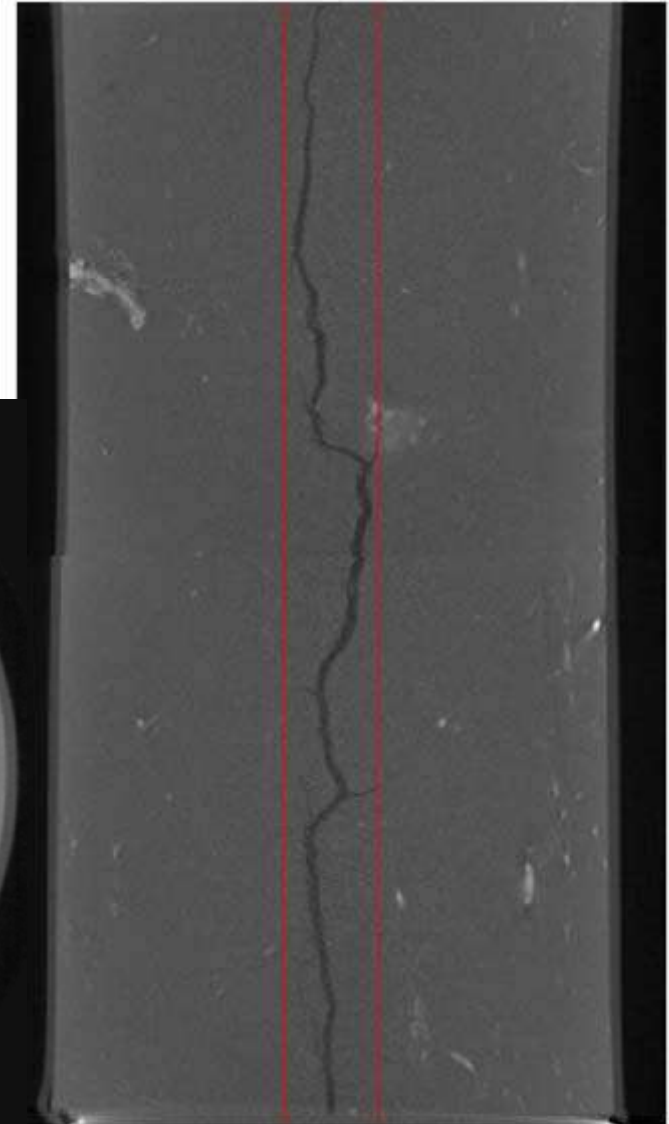
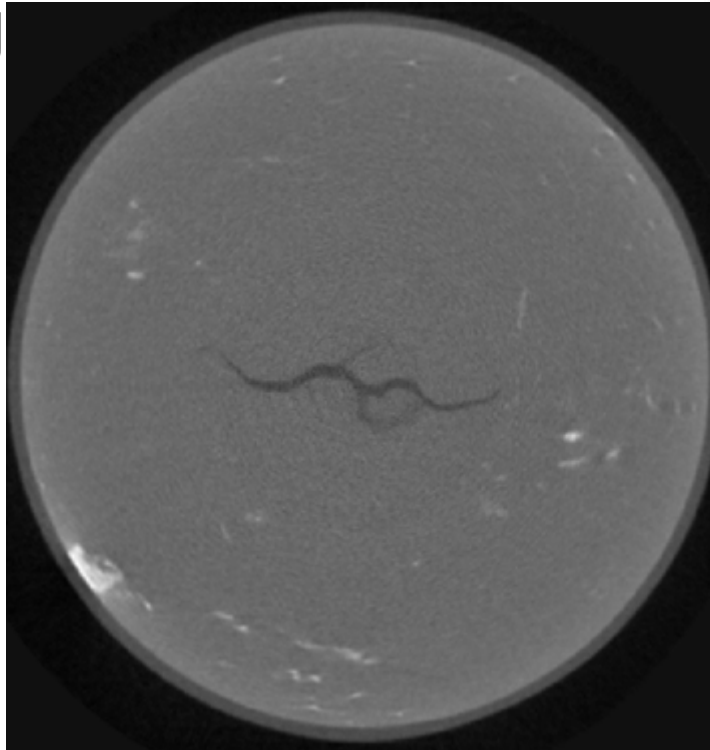
**After
Hydraulic test
160 μm**

**Before
Hydraulic test
218 μm**

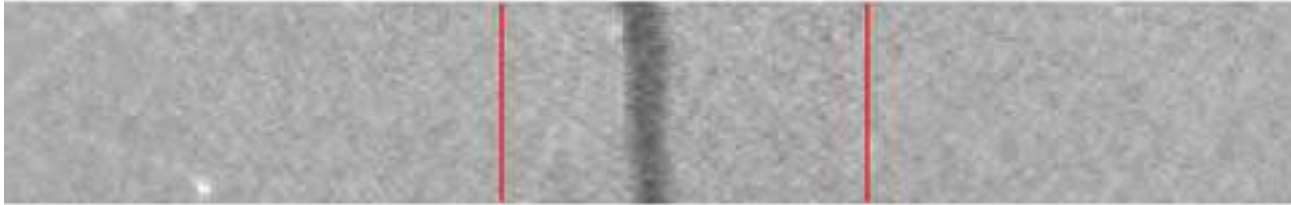
Position

Boom Clay: isostatic cells, central hole of 12 mm

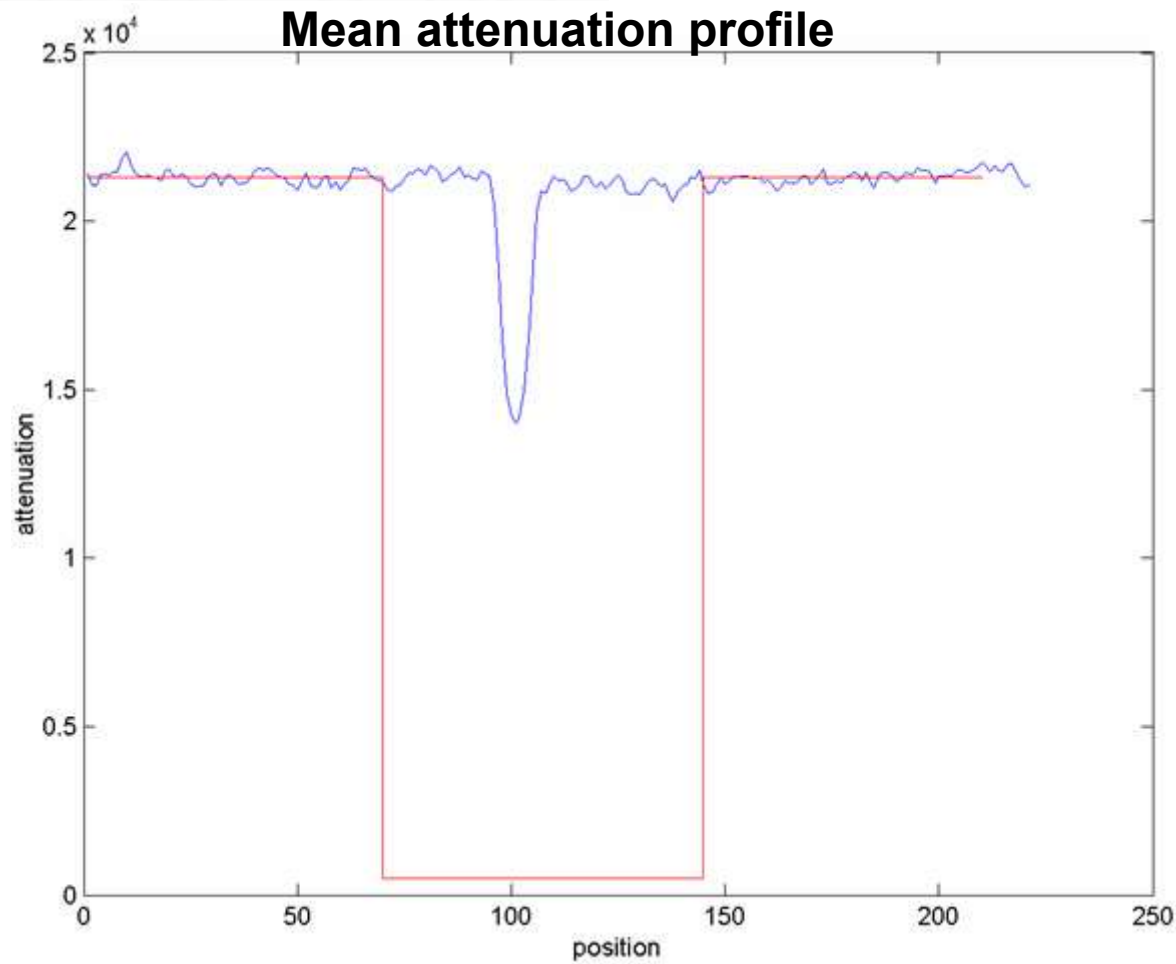
- fracture is present, located at the original position of the hole
- Up to 2mm in width
- Up to 3 cm long



Boom Clay: Isostatic cell, central hole of 12 mm



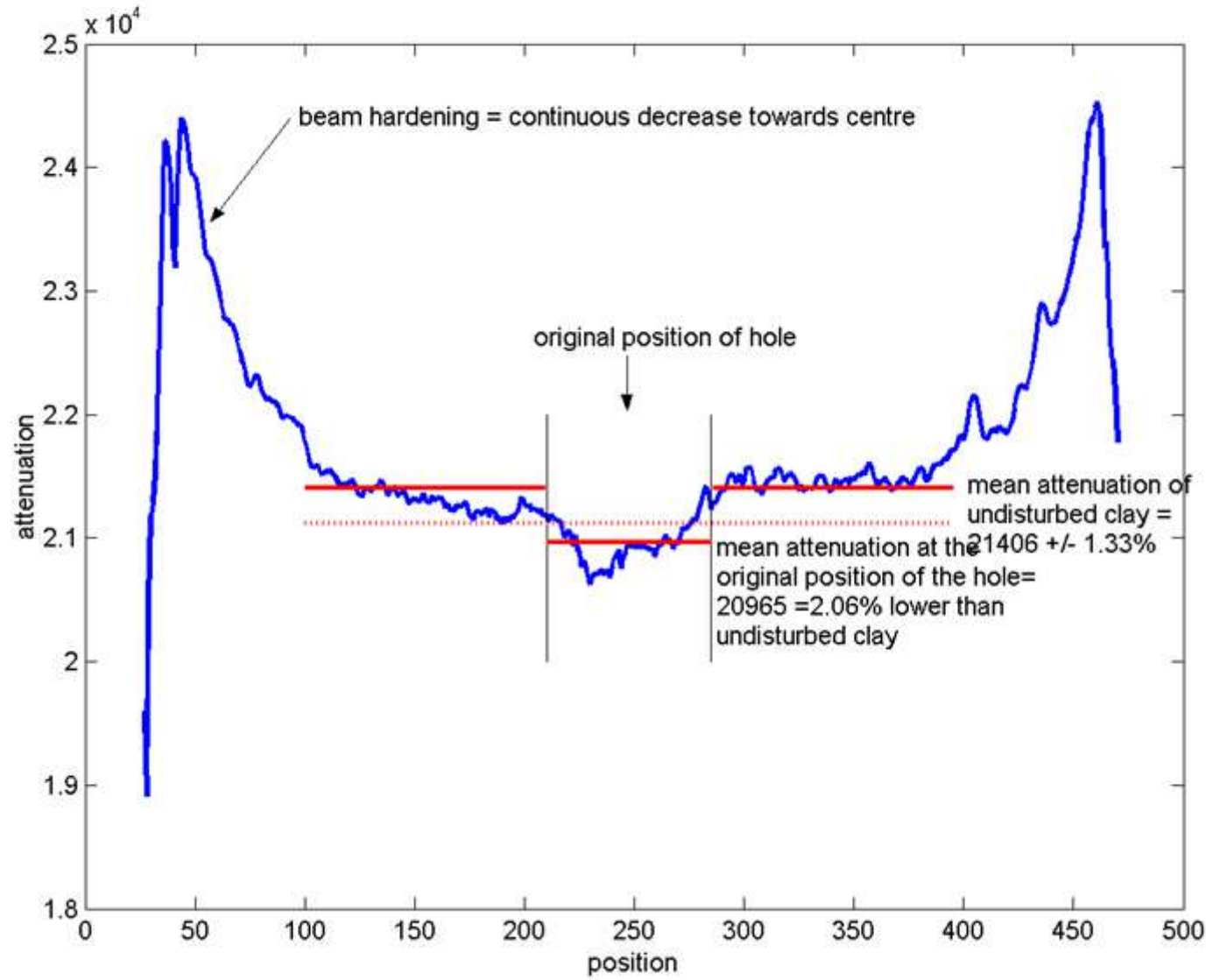
Major continuous fracture has higher density than air → some infill and/or water might be present



Boom Clay: Isostatic cell, central hole of 12 mm

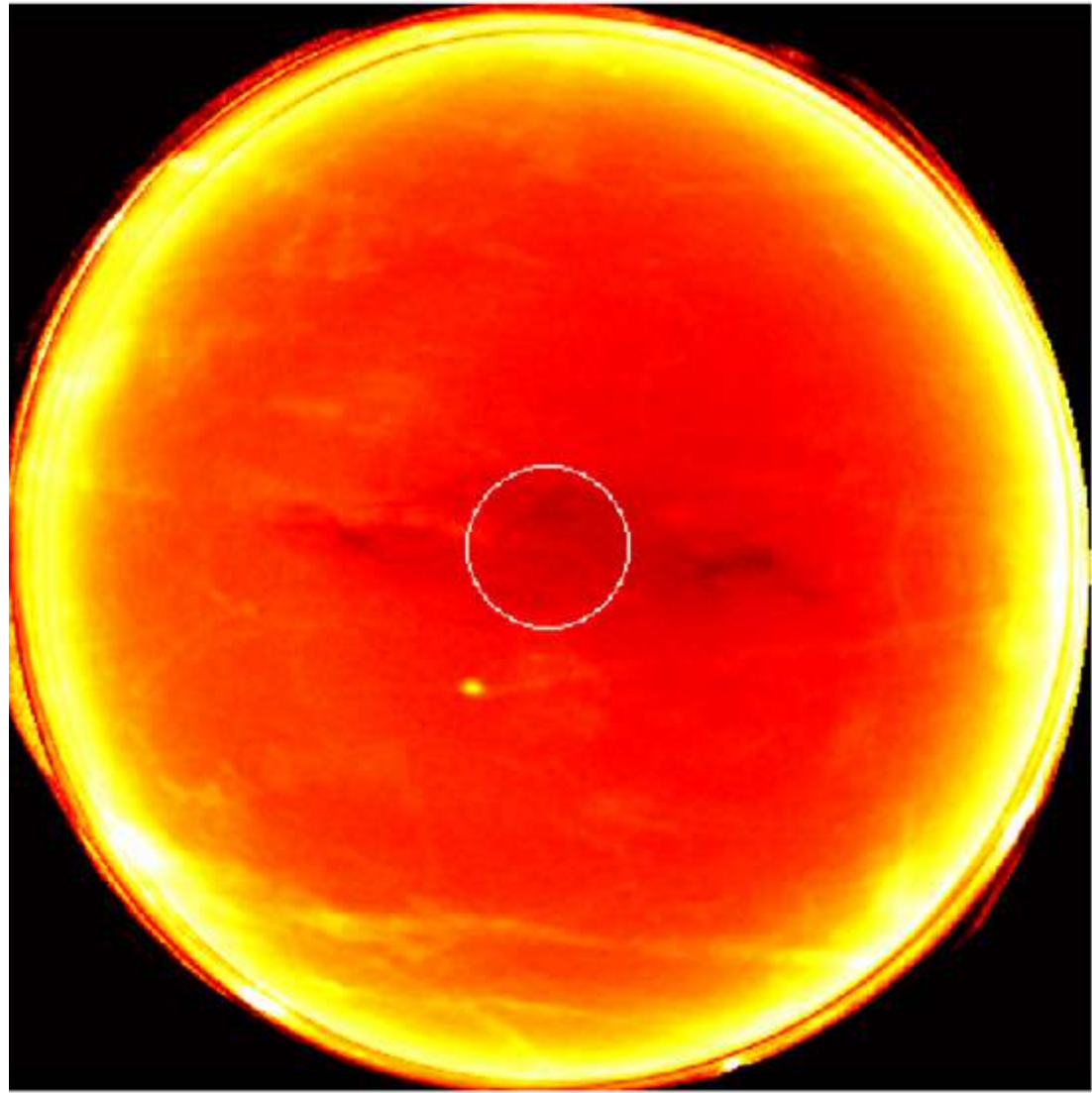


- Choose cut-off value to extract fractures
- Calculate mean attenuation only in clay



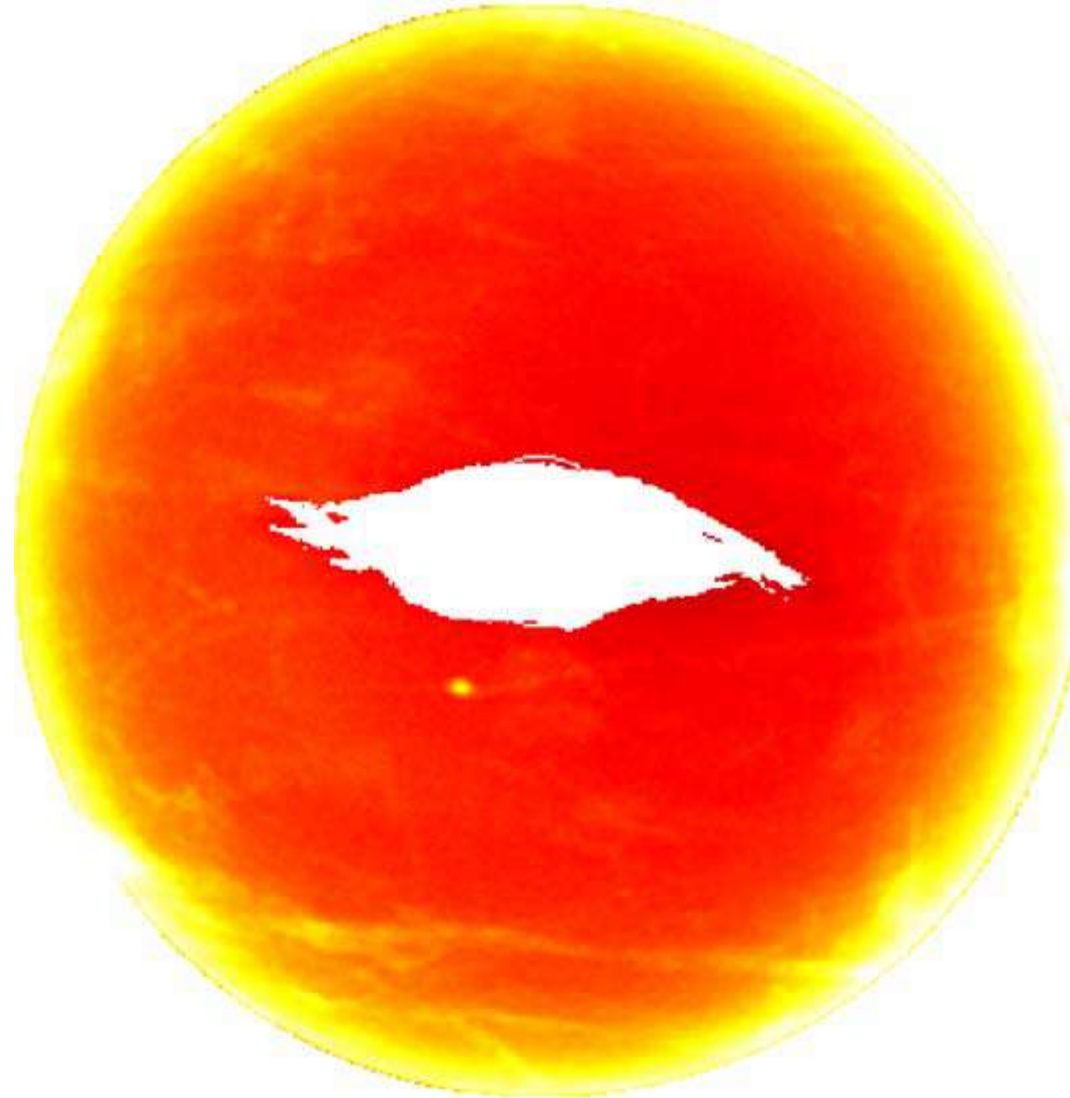
Boom Clay: Isostatic cell, central hole of 12 mm

- Supposed that central hole was positioned exactly in the middle of the sample
- Mean attenuation over scanned volume, neglecting the fracture (3D procedure of what is shown on previous slide)
- Original position of hole indicated in white ($\sim 113\text{mm}^2$)
- Central zone with low density ($\sim 299\text{mm}^2$) near original position of hole



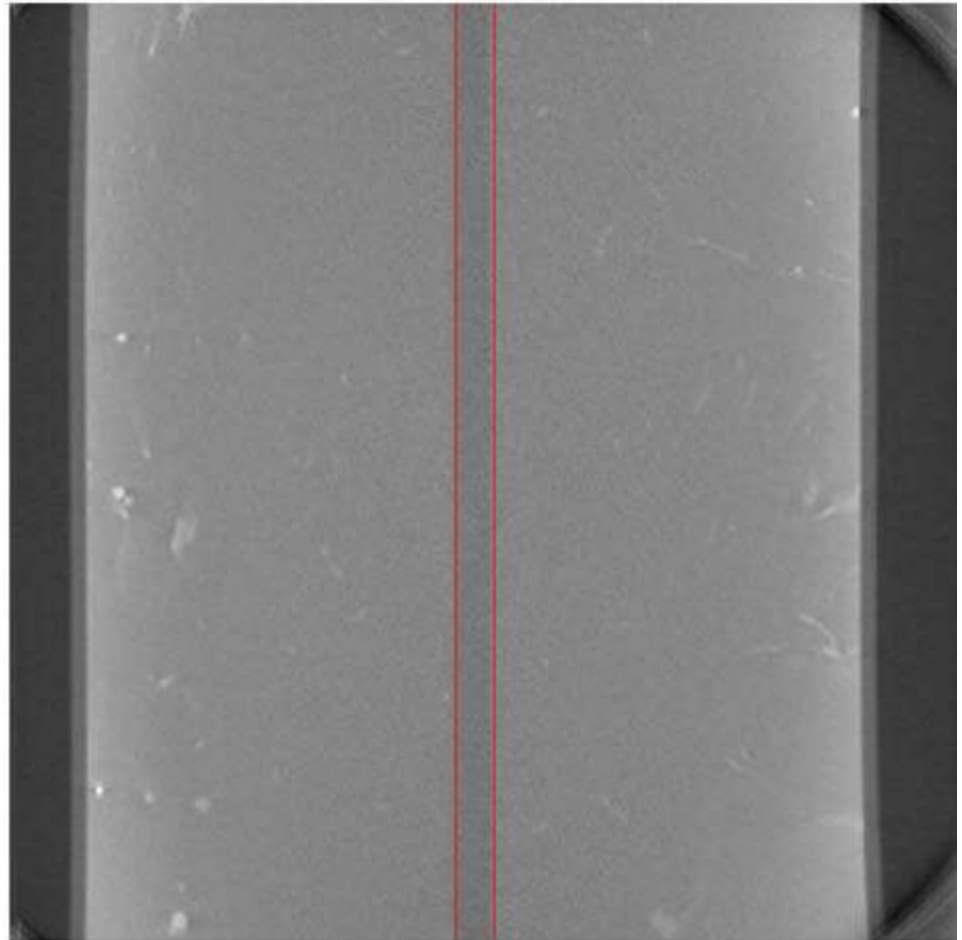
Boom Clay: Isostatic cell, central hole of 12 mm

- The zone where fractures are located is coloured white → fractures only created in the low density zone
- Low density zone and fracture is clearly anisotropic, probably related to orientation of bedding plane



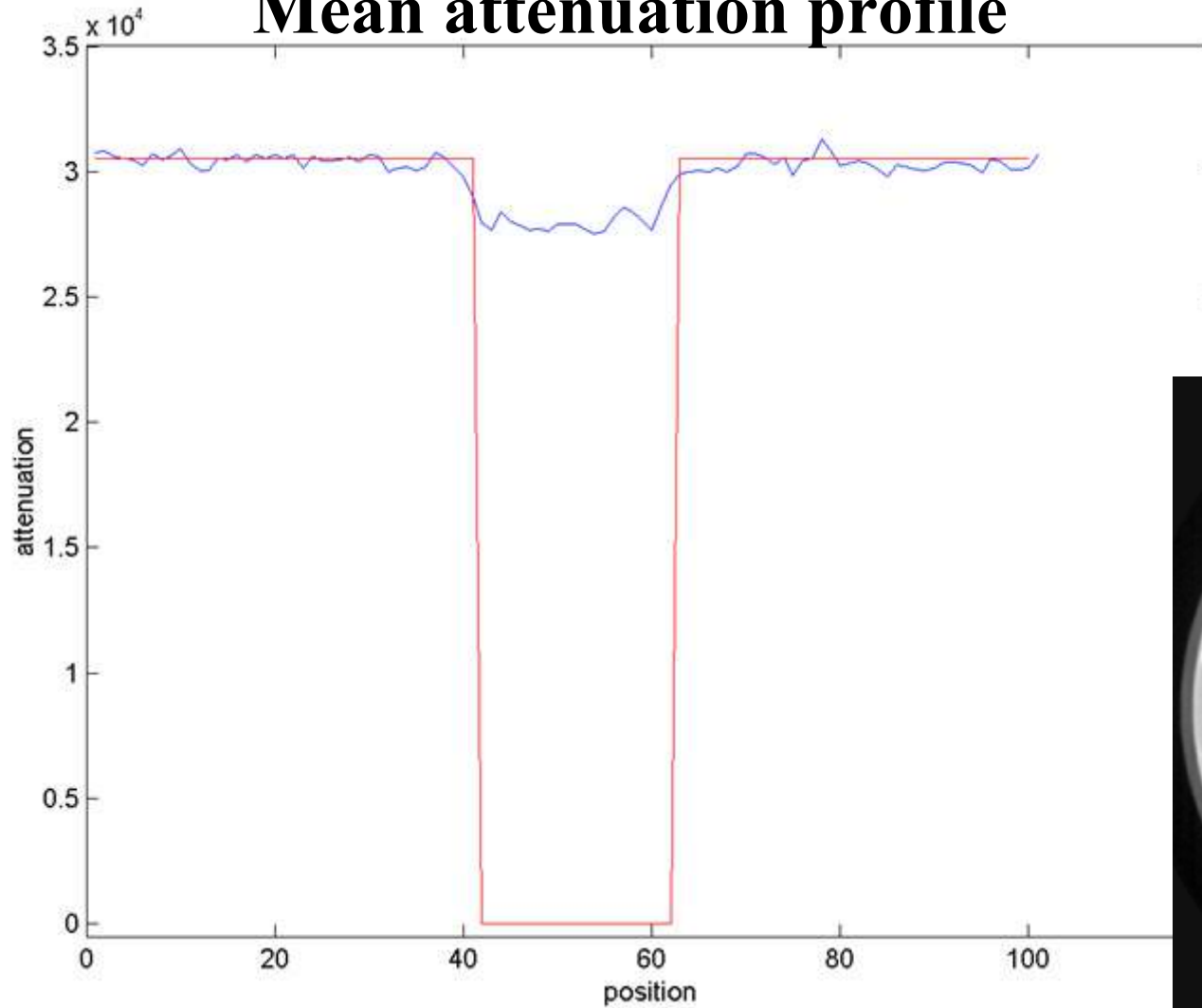
Opalinus Clay: isostatic cell, central hole of 4 mm

A hole is still present
at the original
position with a
similar size

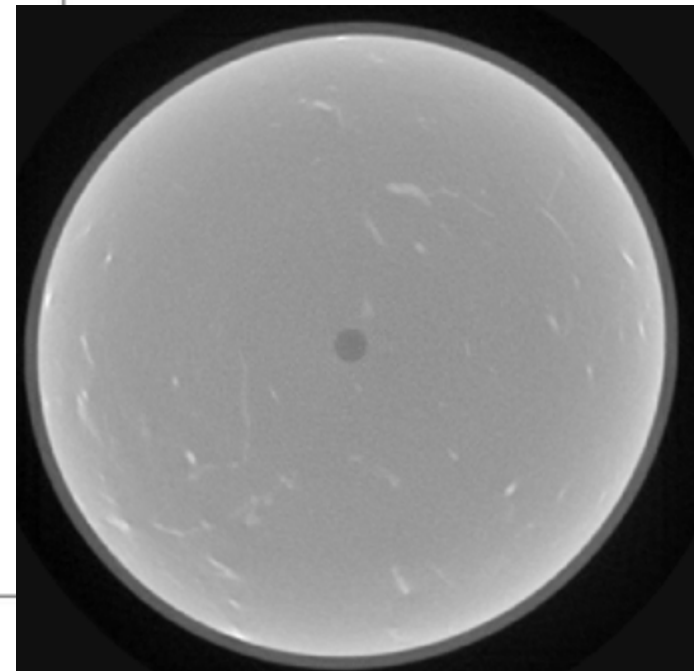


Opalinus Clay: isostatic cell, central hole of 4 mm

Mean attenuation profile

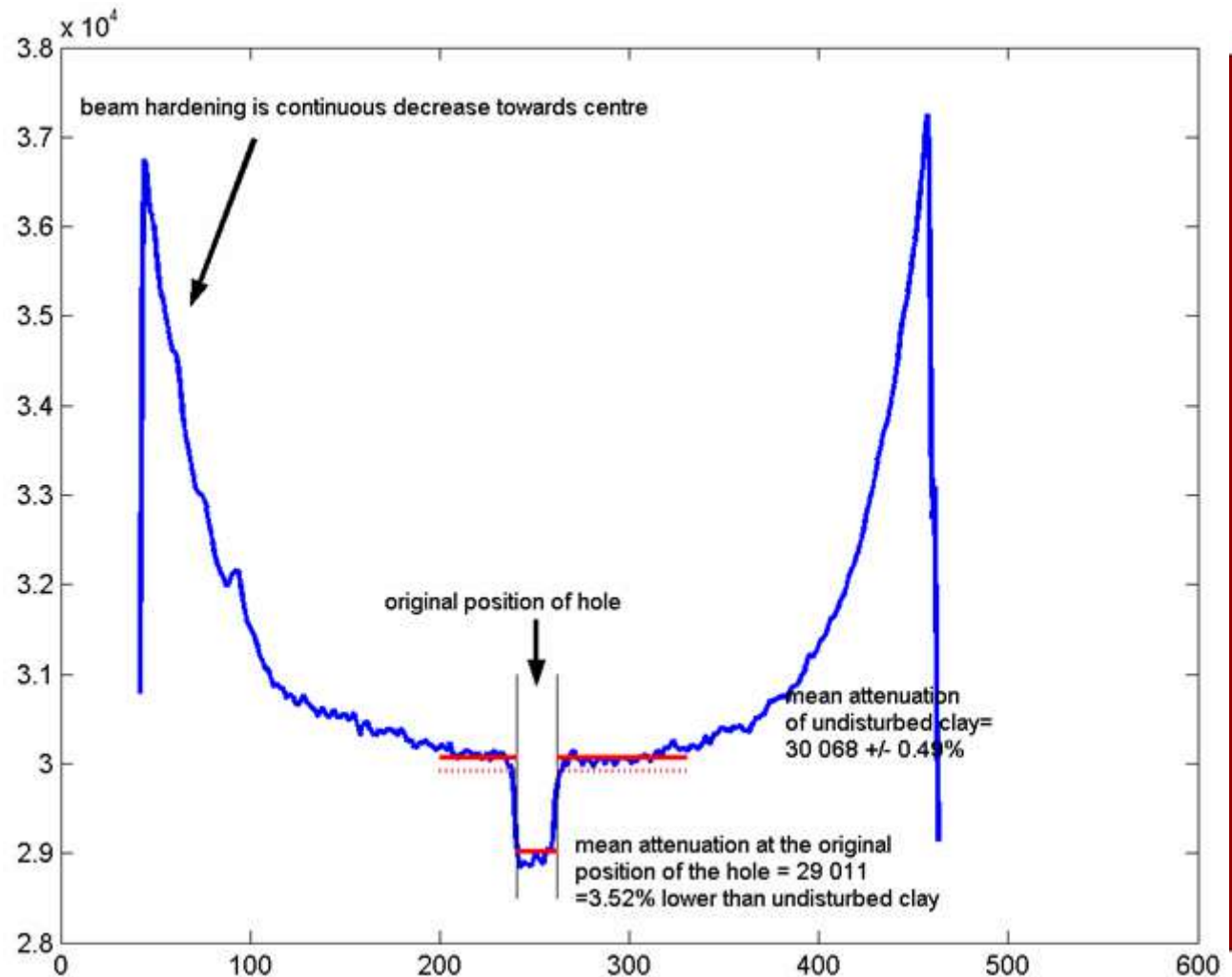


Central hole has a higher density than air $\rightarrow$ infill and/or salt water



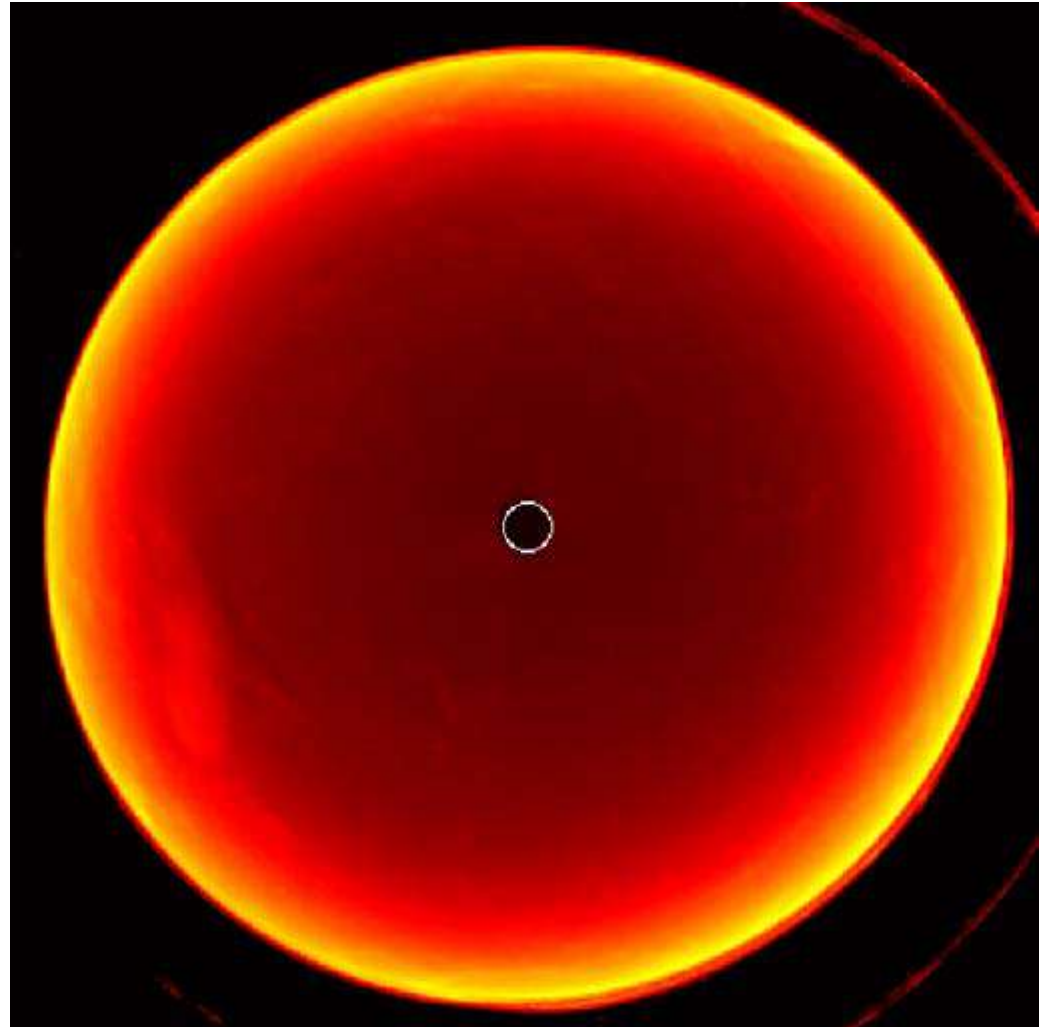
Opalinus Clay: isostatic cell, central hole of 4 mm

- Choose cut-off value to extract fractures
- Calculate mean attenuation only in clay



Opalinus Clay: isostatic cell, central hole of 4 mm

- The hole is at least as large as the original hole
- Original size $\sim 12.6 \text{ mm}^2$
- Manually delineated hole $\sim 12.9 \text{ mm}^2$



Conclusions

- Boom Clay
 - Self sealing is visualised in permeameter cells and isostatic cells
 - Density decrease around the original fracture/hole is noticed due to the self sealing
- Opalinus Clay
 - Self sealing is at least much slower than for Boom Clay
 - Artificial fractures and hole largely remain in permeameter cells and isostatic cells, possibly boundary effects in permeameter cells
 - Natural fractures along bedding plane mostly show self sealing
 - No evidence of density decrease was noticed, which is probably related to the very small self sealing capacity

EDZ & EdZ, Healing and Sealing in the Belgian HLW/MLW Safety and Feasibility Case

Philippe Lalieux

HLW/MLW Disposal Programme Manager

Ondraf/ Niras



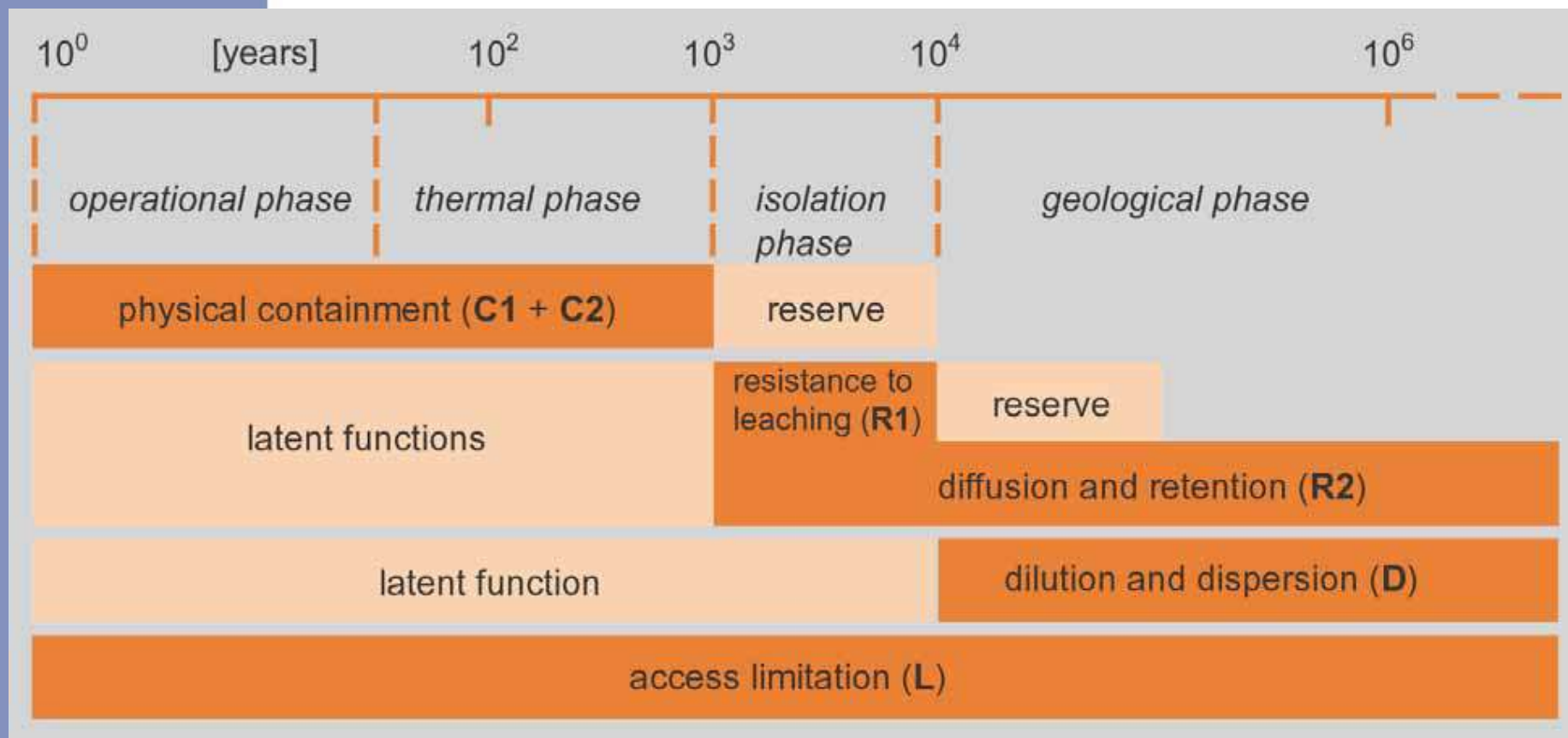
ONDRAF/NIRAS

Long-Term Safety Strategy

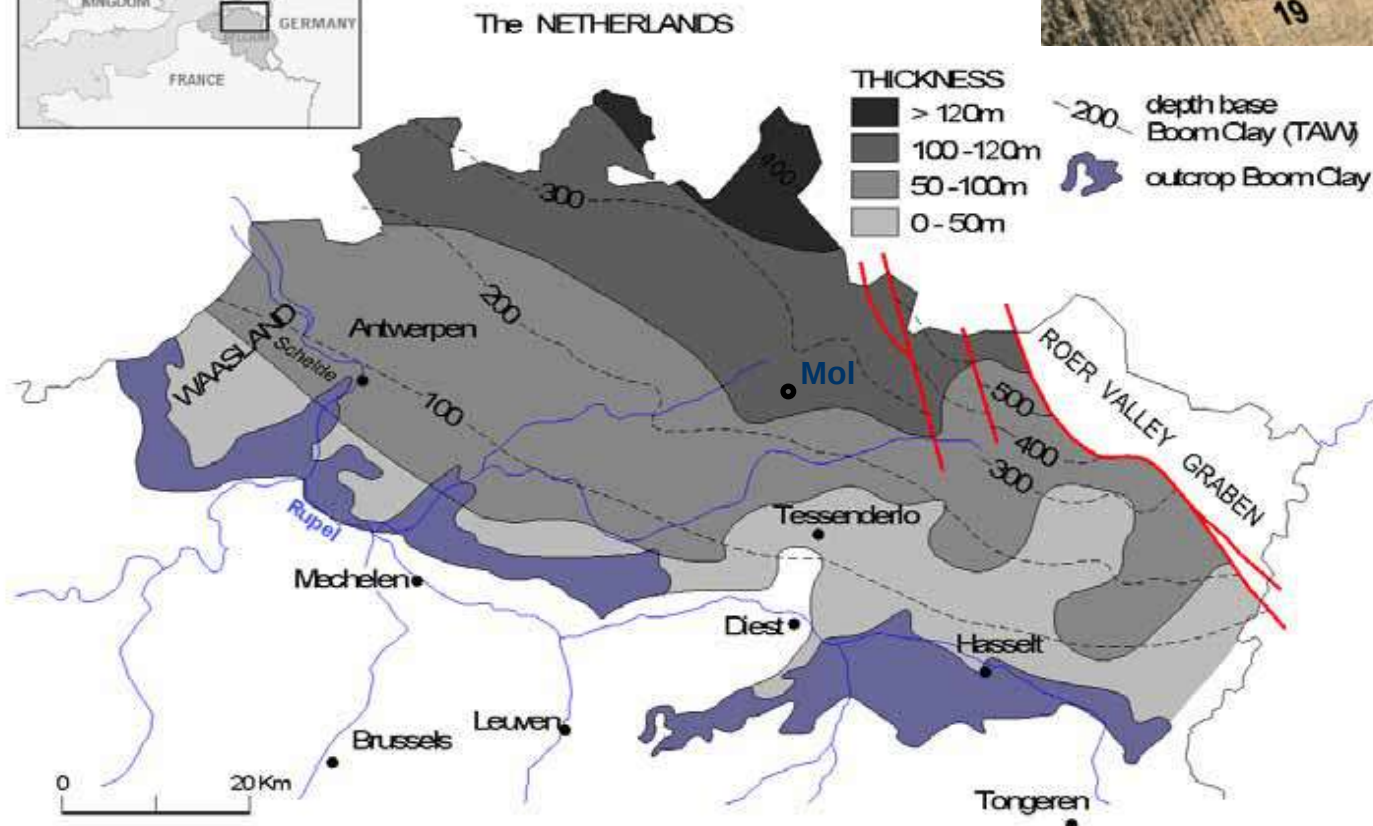
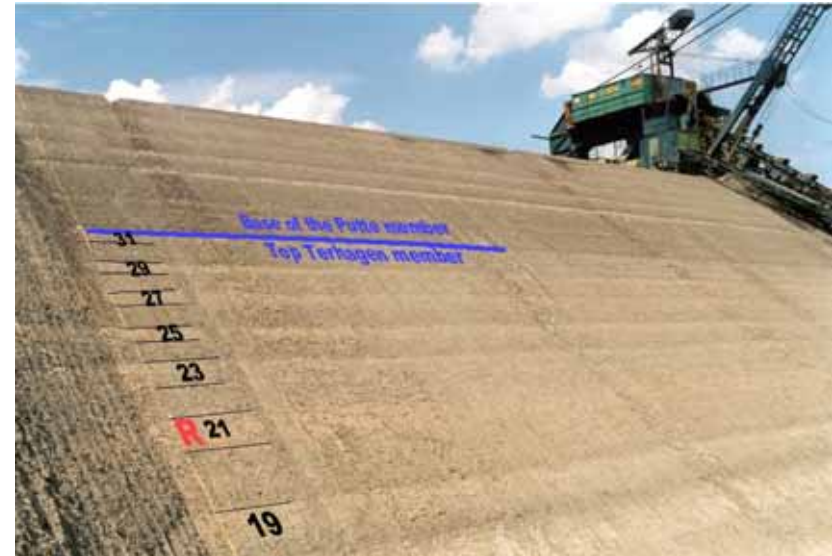
- Safety functions to be ensured / how / when
 - Physical confinement – C
 - Engineered Barrier System
 - Thermal phase (few 100s to few 1000s y)
 - Resistance to lixiviation – R1
 - Waste matrices (glass, spent fuel)
 - >> 10000y
 - Diffusion and retention – R2
 - Host formation (Boom Clay)
 - ~100000 to ~1000000 y



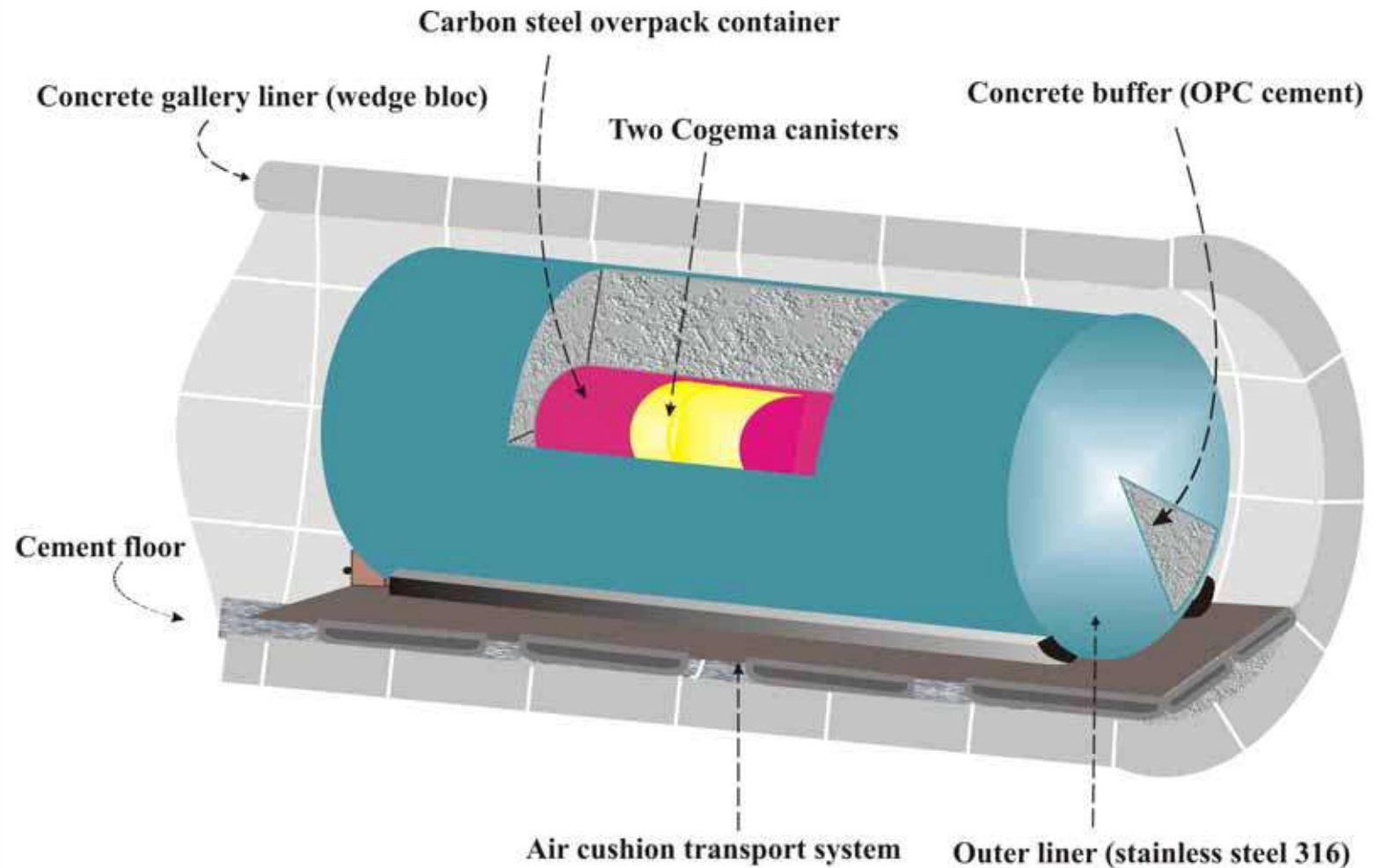
ONDRAF/NIRAS



Boom Clay ad Host Formation

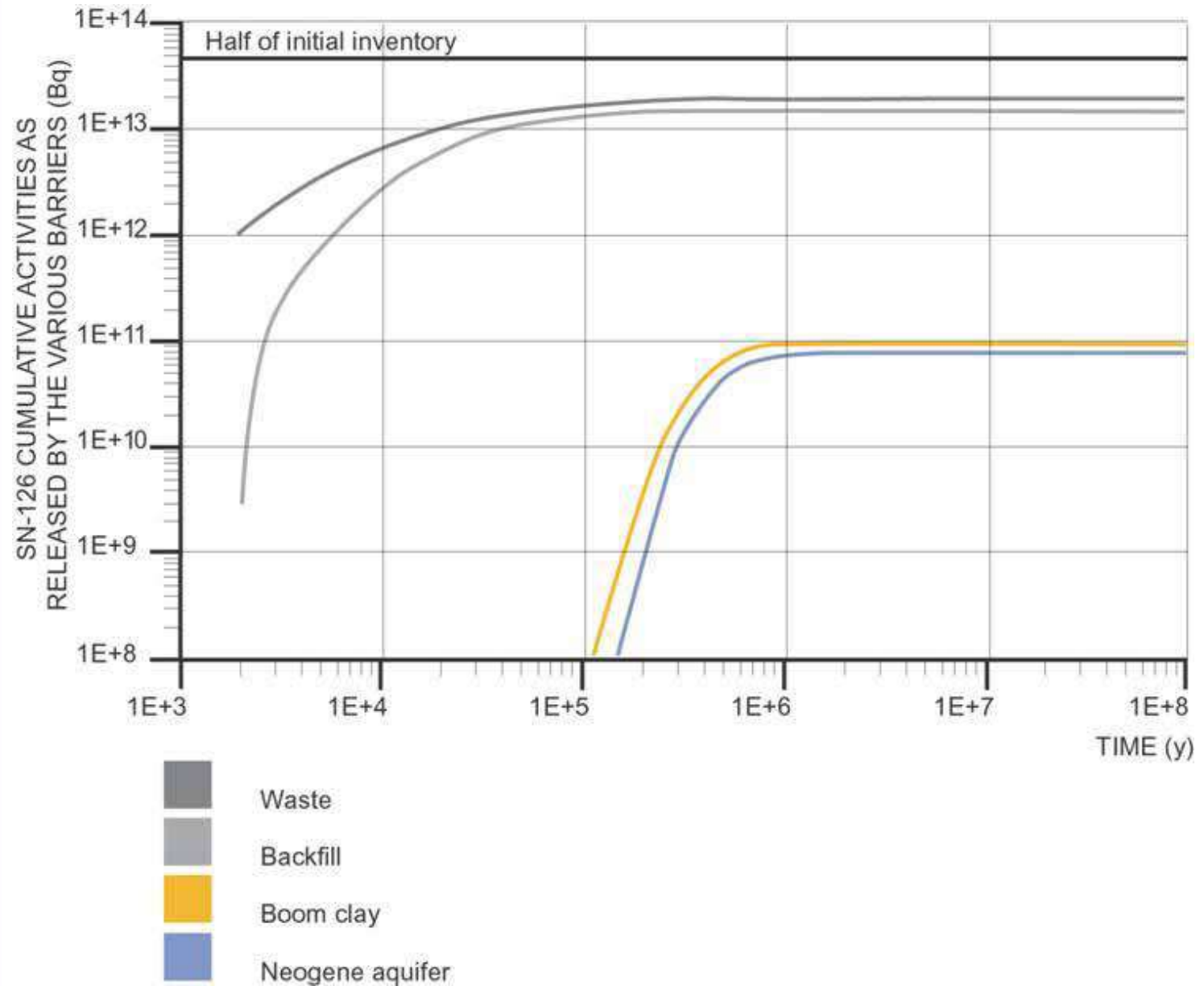


Supercontainer with OPC-based buffer



ONDRAF/NIRAS

Main Contributors to Long-Term Safety (UO₂)



Limitation of repository-induced perturbations to the Boom Clay

- Assessment of THMC perturbations to the Boom Clay and their impacts on the efficiency of the R2 safety function
- Minimization of EDZ
- Assessment of the EDZ and EdZ evolution with time and changing conditions
- How much perturbations can we tolerate without affecting the overall safety (and the reliance of current knowledge)?
- How can these perturbations be handled in PA?
 - Is a mere reduction of the Boom Clay effective thickness adequate?
 - Have water/gas fast pathways scenarios to be considered for radionuclide migration?
 - If yes when? (keep the time perspective)
 - Poor sealing scenario
 - Maintenance of mechanical weaknesses through time

Fracturing and self-sealing in hollow cylinder specimens of Boom Clay and Opalinus Clay

V. Labiouse, S. Escoffier, L. Gastaldo, J-F. Mathier

LMR
LABORATOIRE DE
MÉCANIQUE DES ROCHES

Fracturing and self-sealing in hollow cylinder specimens of Boom Clay and Opalinus Clay

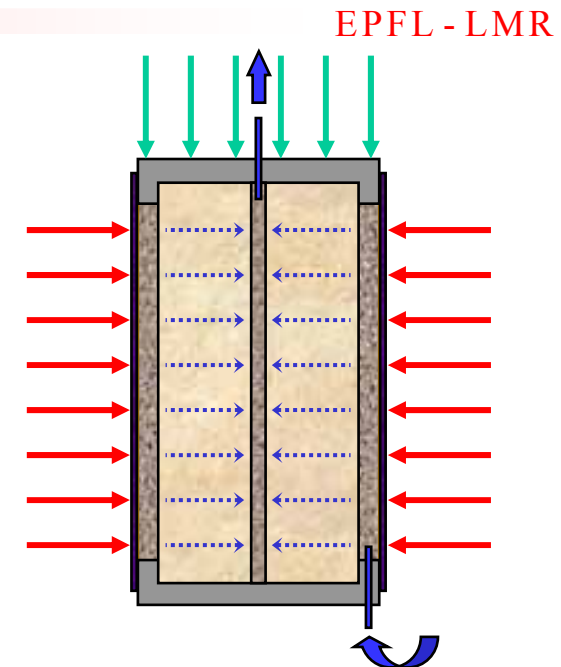
EPFL - LMR

1. Aim of the tests
2. Experimental device and procedure
 - Modified LEGEP cells
 - Testing procedure
3. Results on Boom Clay
4. Current results on Opalinus Clay
5. Conclusions

Aim of the EPFL tests on hollow cylindrical specimens

Check of the permeability changes related to localised crack proliferation (process A) and its potential self-sealing with time (process B)

- 1) Permeability measurement on the undisturbed sample.
- 2) Tensile fracturing of the sample without removing it from the cell.
- 3) Permeability measurement on the fractured sample just after fracturing.
- 4) Confining pressure kept constant and measurement of fluid flow some time after fracturing



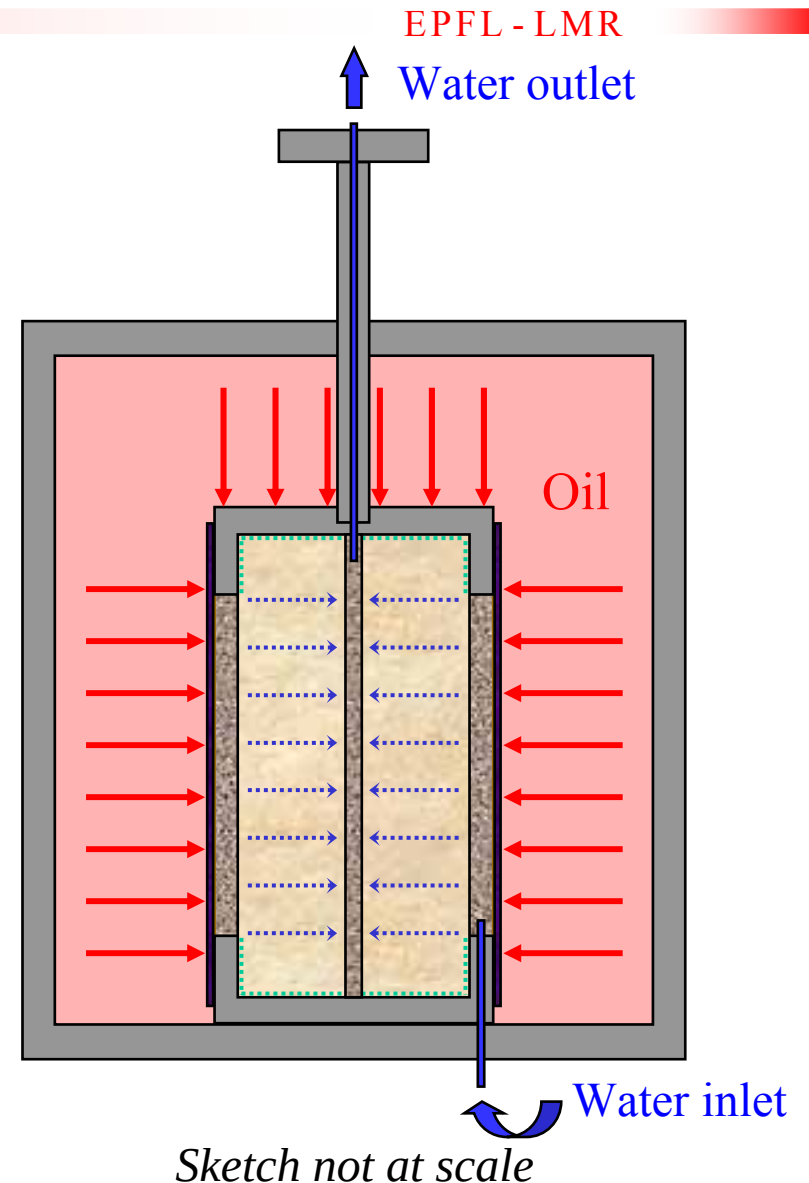
⇒ increase of permeability related to localised crack proliferation

⇒ check of the potential reduction in permeability and thus of the self-sealing capability of the clays

Trial test on Boom Clay



- Hollow cylindrical specimens
- 80 mm external diameter
- 6 mm diameter central hole filled with sand (inner drain)
- Upper and lower parts of the sample glued to caps to allow extension
- Outer drain and neoprene membrane



Trial test on Boom Clay

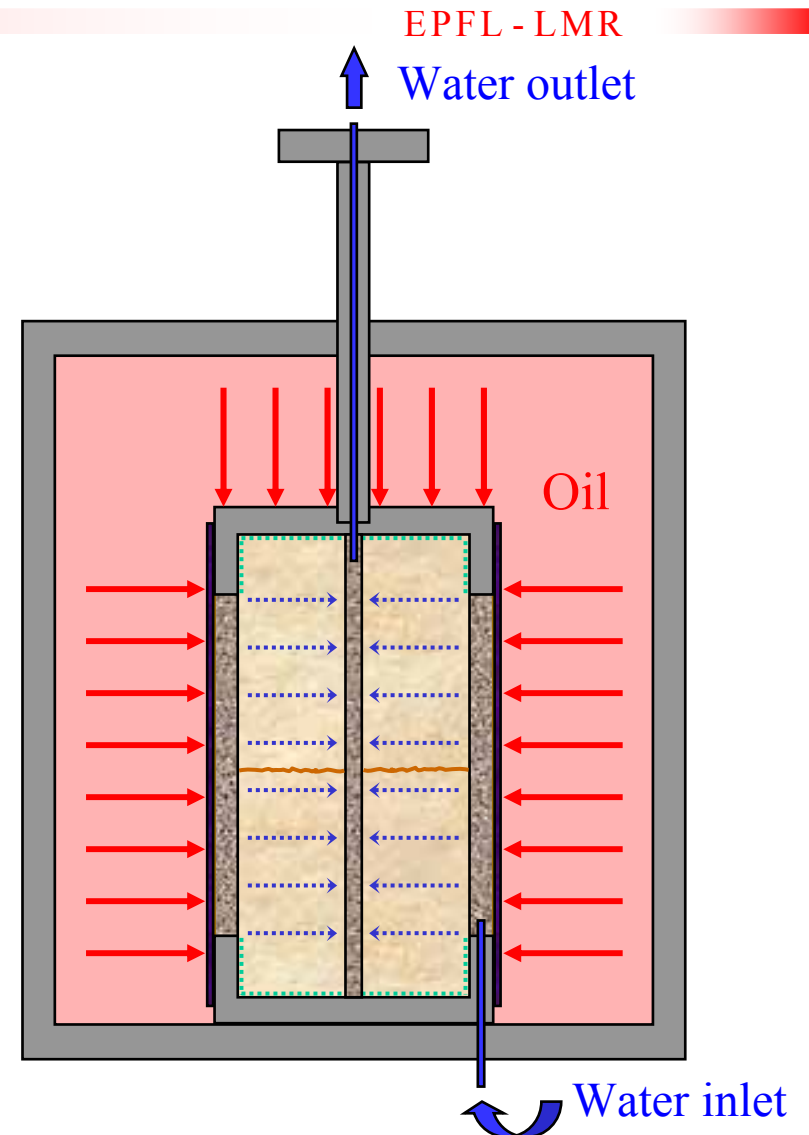
Encouraging results...

- ☺ horizontal fissure generated in the sample
- ☺ permeability measurements in agreement with in situ ones

...but

- ☹ significant convergence of the central hole of the hollow specimen

➔ Need to improve the sample preparation, the testing device and procedure

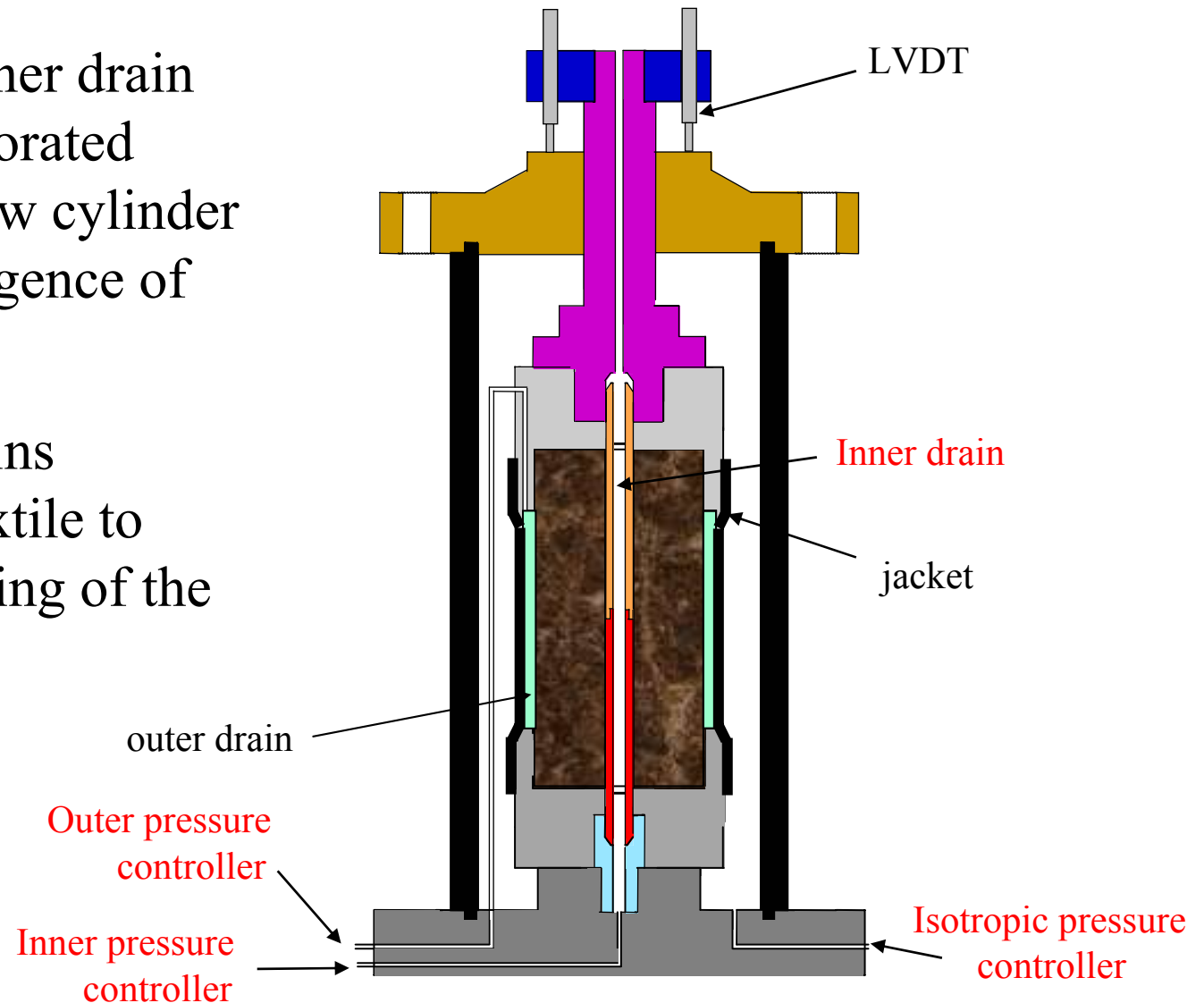


Sketch not at scale

Improvements to the LEGEP cell

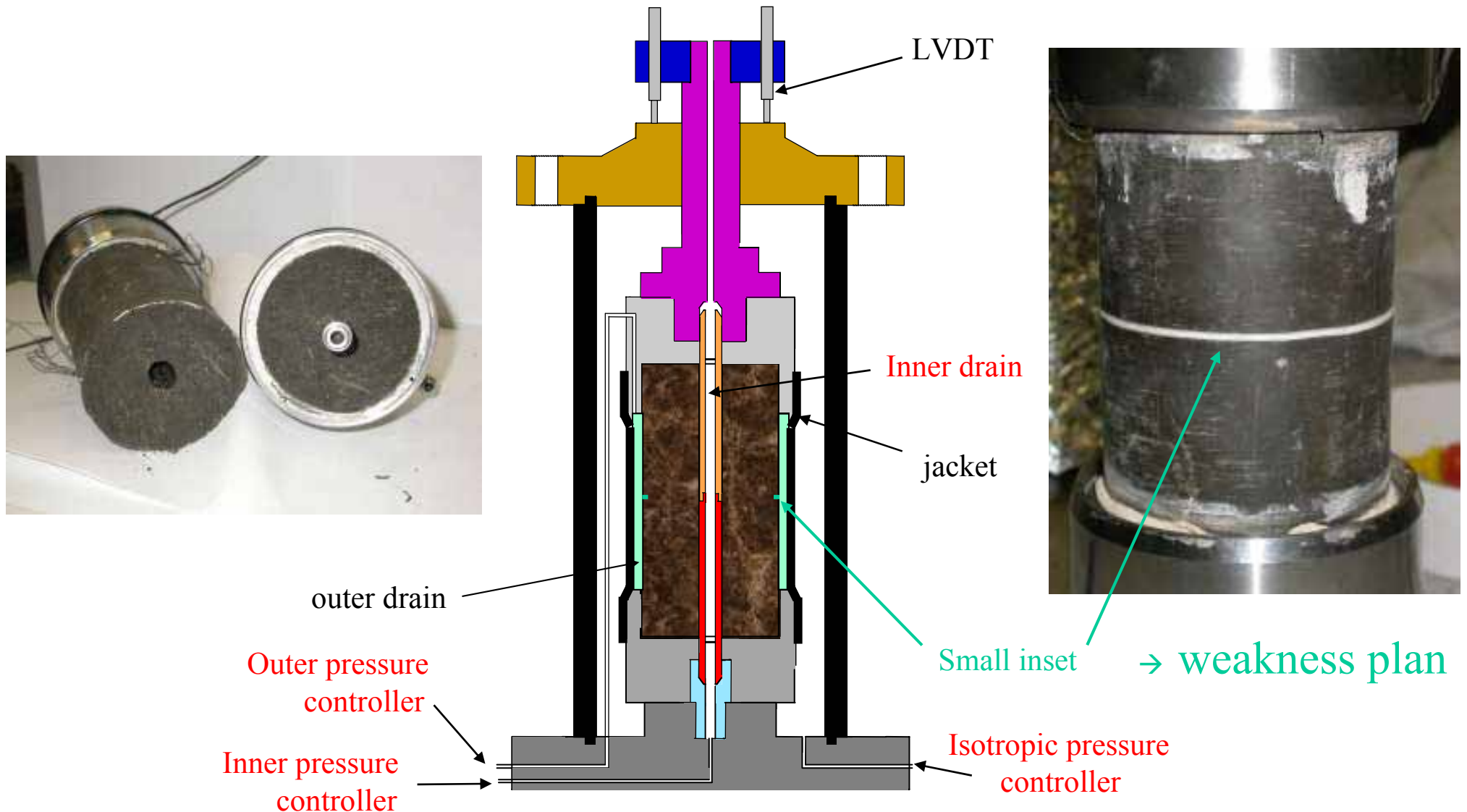
EPFL - LMR

- Outer part of the inner drain consisting of a perforated stainless steel hollow cylinder to avoid the convergence of the clay
- Inner and outer drains composed of geotextile to minimize the clogging of the hydraulic circuits



Use of a **small inset** to initiate the fissure in the central part of the clayey sample

EPFL - LMR



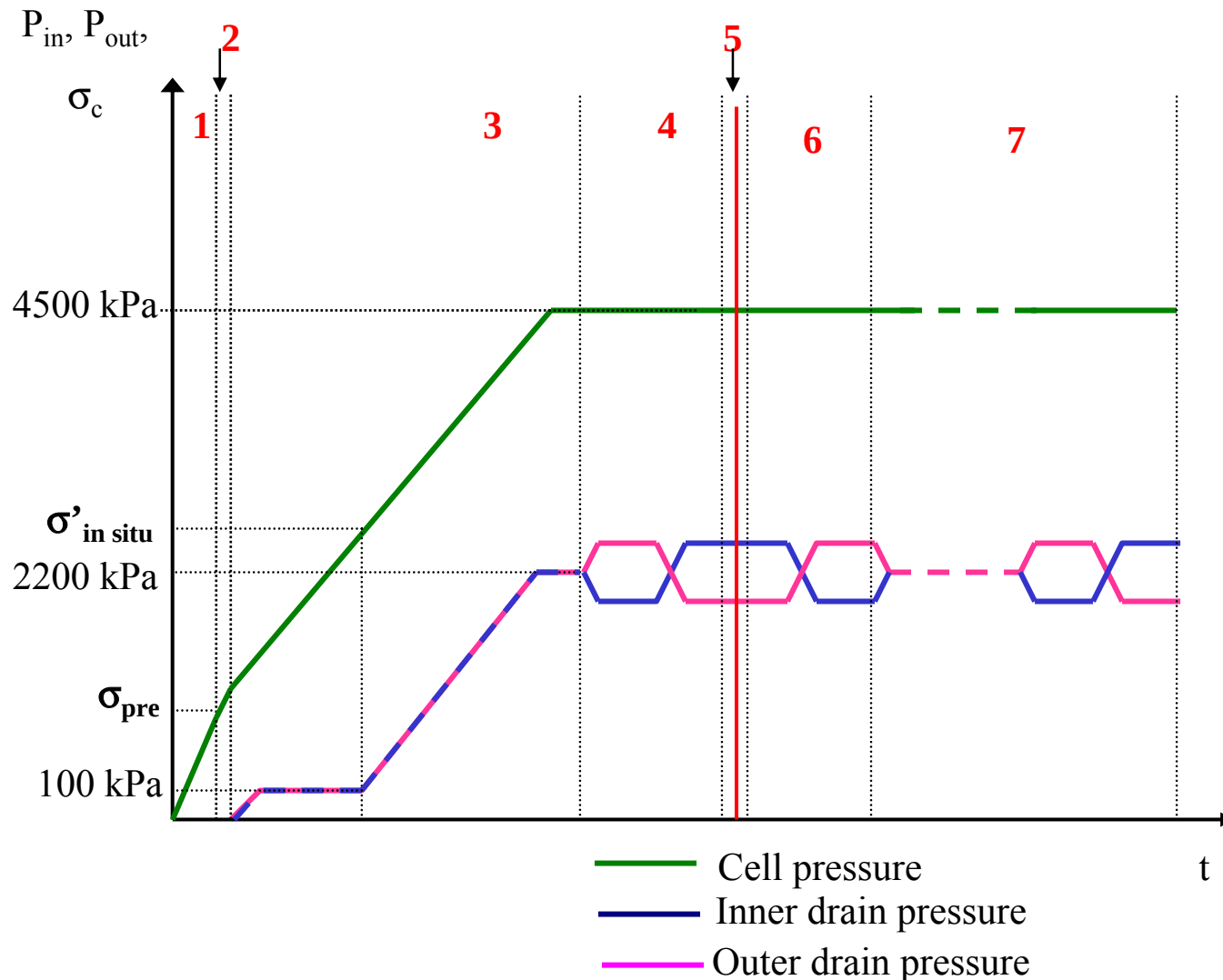
Fracturing and self-sealing in hollow cylinder specimens of Boom Clay and Opalinus Clay

EPFL - LMR

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Experimental procedure

EPFL - LMR



- 1: preloading**
- 2: hydraulic circuits saturation**
- 3: consolidation stage**
($v=500$ kPa/day)
- 4: permeability measurement on the virgin sample**
- 5: fracturing**
- 6: permeability measurement on the fractured sample**
- 7: self-sealing analysis**

Permeability measurement

EPFL - LMR

- when steady state is reached

$$Q_{\text{inner drain}} = Q_{\text{outer drain}}$$

$$K = \frac{Q \cdot \gamma_w}{2 \cdot \pi \cdot h \cdot \Delta P} \cdot \ln \frac{r_1}{r_2}$$

with:

K [$\text{m} \cdot \text{s}^{-1}$]: hydraulic conductivity

Q [$\text{m}^3 \cdot \text{s}^{-1}$]: entering or leaving flow

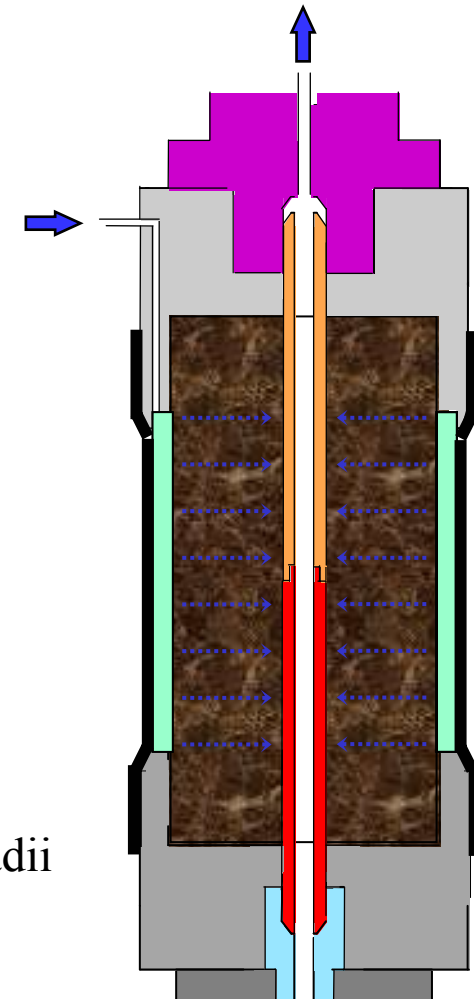
γ_w [$\text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-2}$]: unit weight of the fluid

h [m]: height of drainage

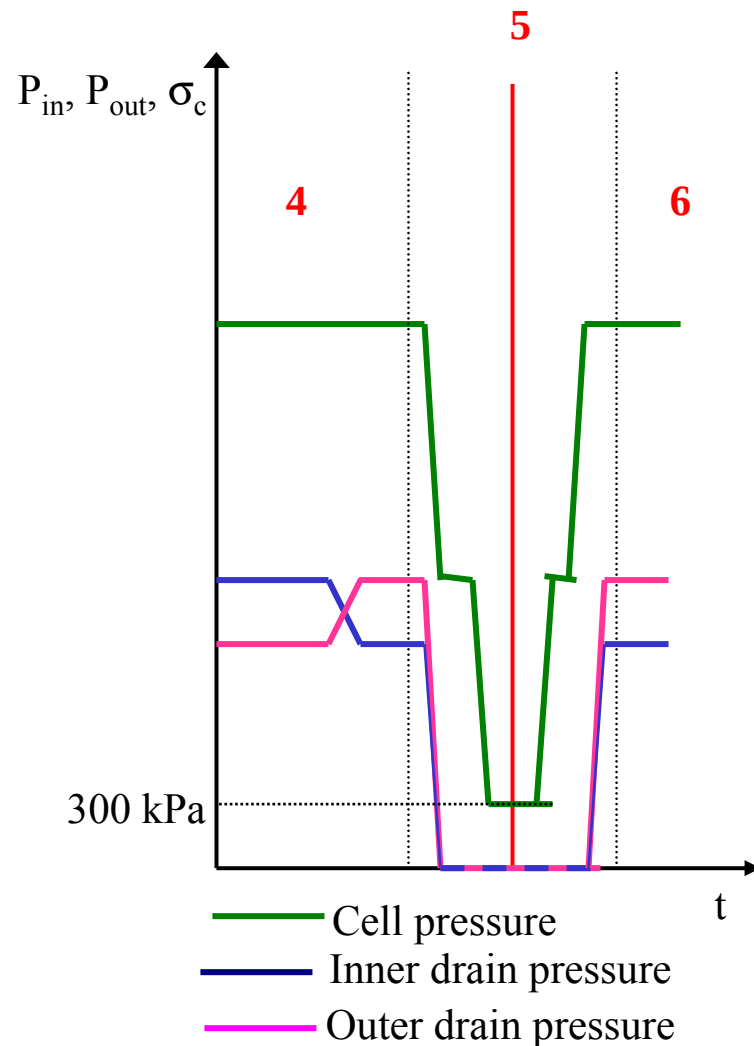
ΔP [Pa]: pressure difference between internal and external radii

r_2 [m]: external radius

r_1 [m]: internal radius



Fracturing



4: permeability measurement on the virgin sample

5: fracturing

6: permeability measurement on the fractured sample

Fracturing and self-sealing in hollow cylinder specimens of Boom Clay and Opalinus Clay

EPFL - LMR

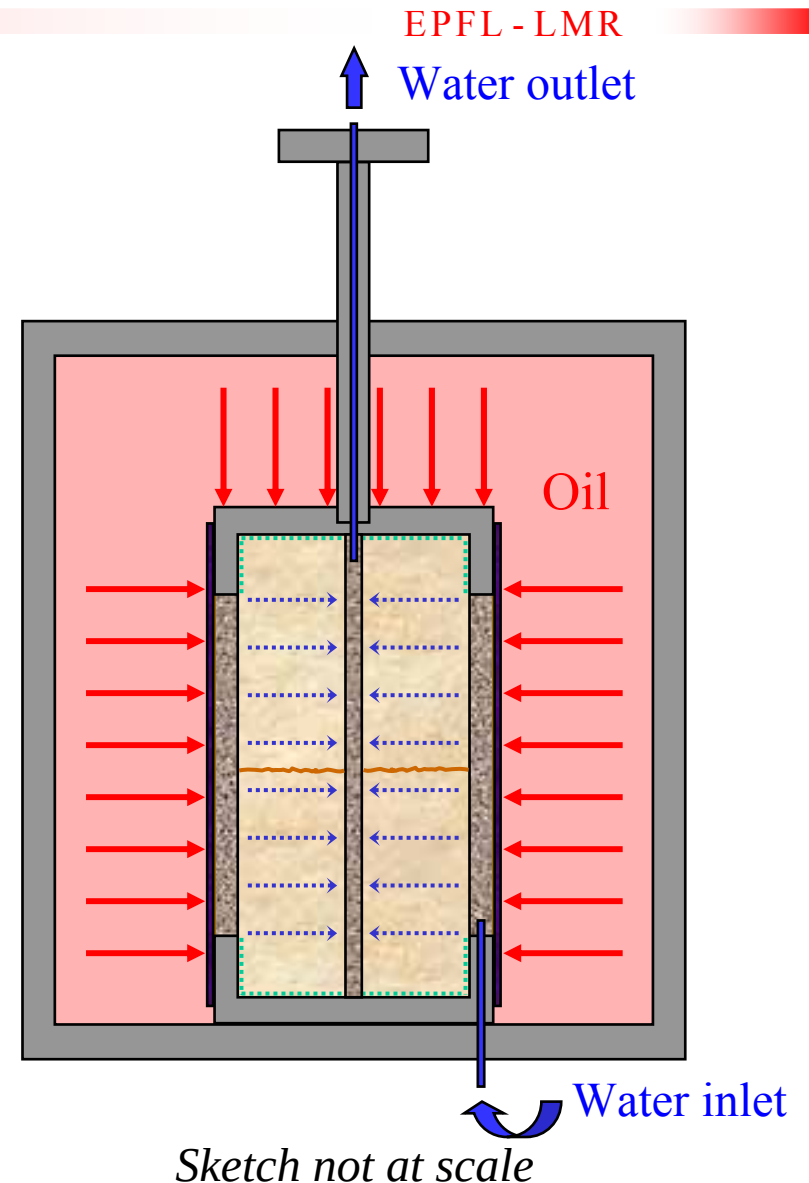
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Results of the trial test on Boom Clay

☺ fissure generated in a horizontal plane, i.e. parallel to the bedding planes

!! Testing conditions not similar to the in situ ones : $\sigma_3 = 5 \text{ MPa}$, $u = 0.5 \text{ MPa} \rightarrow \sigma'_3 = 4.5 \text{ MPa}$

	$k [\cdot 10^{-13} \text{ m/s}]$
virgin sample	8
fracturing	
10 μ	80
40 μ	180
80 μ	16'000
closure of the fissure	
fractured sample	16



Development of shear bands in test 1

EPFL - LMR



**Shear bands observed on
sample 1**

☹ No tensile fracture occurred in the sample even under an extension axial deformation of 10%

...but

☺ no change of permeability observed related to the development of shear bands.

➔ No change in permeability related to diffuse crack proliferation

(in accordance with L3S observations)

Tensile fracture achieved in next tests

EPFL - LMR



Tensile fracture observed on sample 2
(cored parallel to the bedding planes)

☺ fissure orientated horizontally,
perpendicularly to the symmetry
axis and the bedding planes.

After the removal of the sample from the cell

☺ fissure hardly discernable,

☺ small traction required to reopen it

➔ **Some self-healing effect**
(unfortunately not quantifiable)

Summary of the experimental results on Boom clay

EPFL - LMR

Before fracturing

Test	1	2	3	4	5
K_{conv} (m/s)	3.9 E-12	3.4 E-12	3.3 E-12	4.1 E-12	-
K_{div} (m/s)	3.7 E-12	3.2 E-12	3.3 E-12	3.3 E-12	2.3 E-12

After fracturing

K_{conv} (m/s)	-	2.9 E-12	-	4.1 E-12	-
K_{div} (m/s)	-	2.6 E-12	3.4 E-12	4.1 E-12	2.3 E-12

The permeability a few days after fracturing is hardly different from that measured on the virgin sample



Fractures undergo a very fast sealing under an hydrostatic state of stress

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5. Conclusions

Experimental difficulties

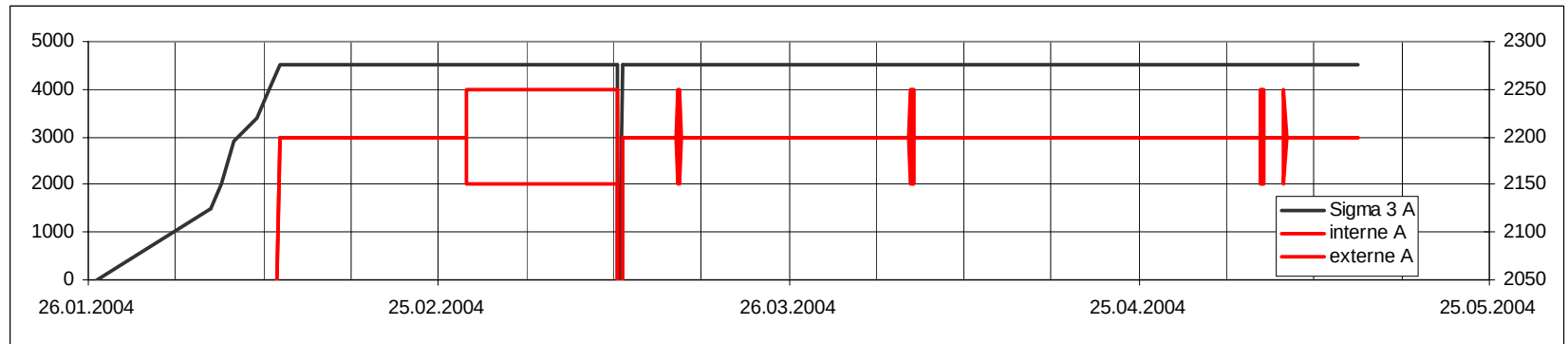
EPFL - LMR

- Very low permeability of the virgin samples
 - Extremely long tests
 - Perfectly steady states are probably not reached (but tests are carried on for pragmatic reasons...)
- Difficult to keep a constant pressure gradient in the fissured samples
 - Clear connection between the inner and outer drains through the induced fissure

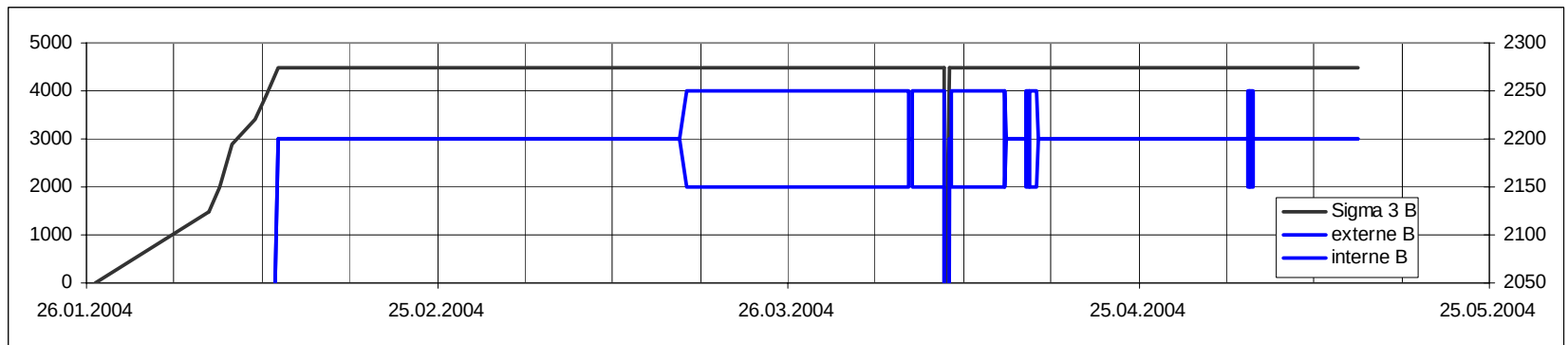
Parallel testing of three samples

EPFL - LMR

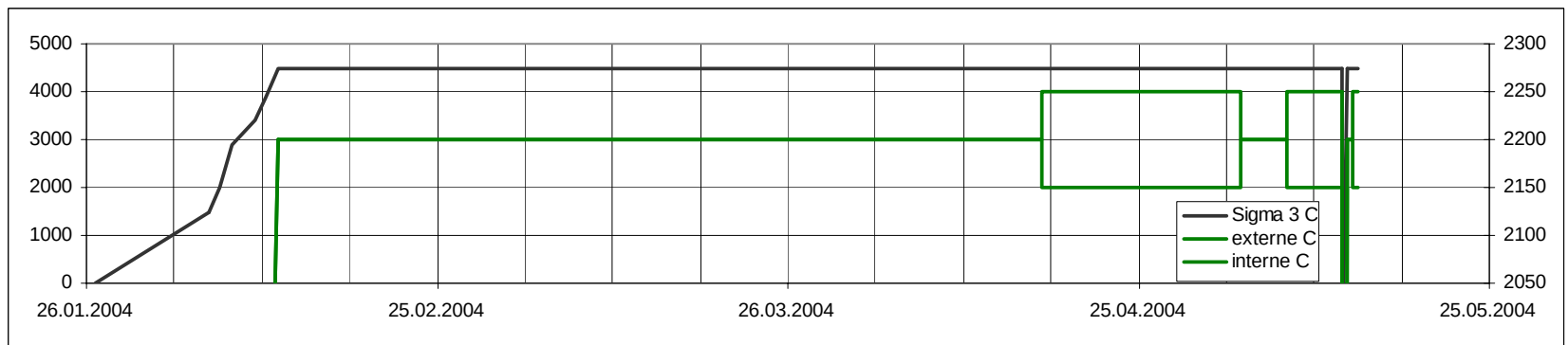
Sample 1



Sample 2

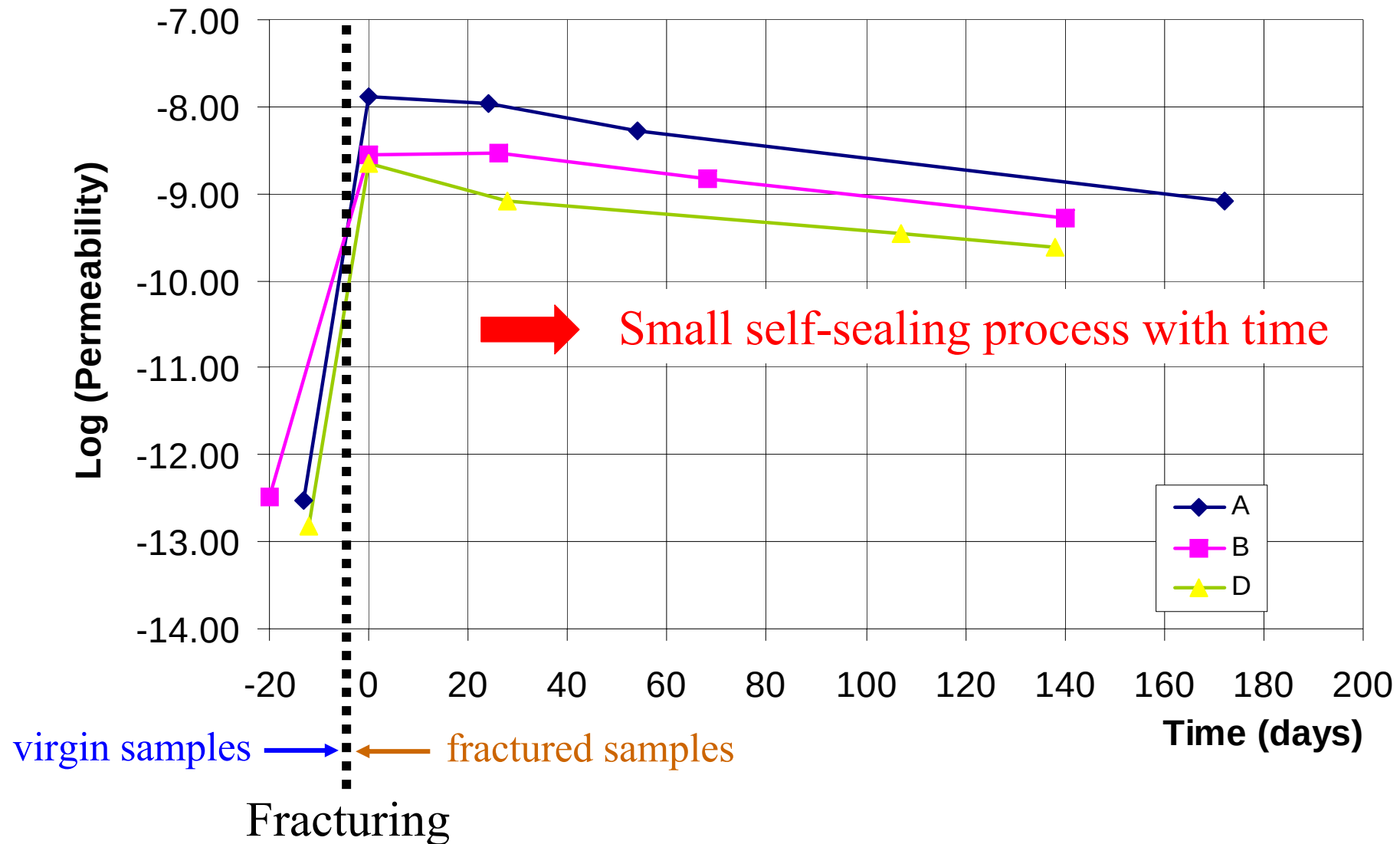


Sample 3



Change in permeability in the Opalinus Clay samples

EPFL - LMR



Current conclusions for Opalinus Clay

EPFL - LMR

- Permeability of the Opalinus Clay **virgin** samples :
 $3 \cdot 10^{-13}$ m/s
- Permeability of the Opalinus Clay **fissured** samples :
4 to 5 orders of magnitude larger
 $1 \cdot 10^{-8}$ to $2 \cdot 10^{-9}$ m/s
- **Small self-sealing with time**
in agreement with the in situ experiment n°1 carried out at Mont Terri, even if the process seems to be slower in laboratory tests

! Valid for localised cracks induced by traction
Conclusions could be different for diffused cracks (e.g. shear bands)

Fracturing and self-sealing in hollow cylinder specimens of Boom Clay and Opalinus Clay

EPFL - LMR

1. Aim of the tests
2. Experimental device and procedure
 - Modified LEGEP cells
 - Testing procedure
3. Results on Boom Clay
4. Current results on Opalinus Clay
5. Conclusions

Fracturing and self-sealing in hollow cylinder specimens of Boom Clay and Opalinus Clay

EPFL - LMR

Boom Clay

- No change in permeability related to diffuse crack proliferation
- Very fast sealing of localised cracks in specimens kept under an hydrostatic state of stress
- Some self-healing effect noticed

Opalinus Clay

- Significant increase of permeability for localised cracks
- Small self-sealing process with time for localised cracks in specimens kept under an hydrostatic state of stress
- Self-healing effect not checked for the moment



Selfrac (SE-MT)

In-situ Experiment Mt. Terri No. 1 + 2

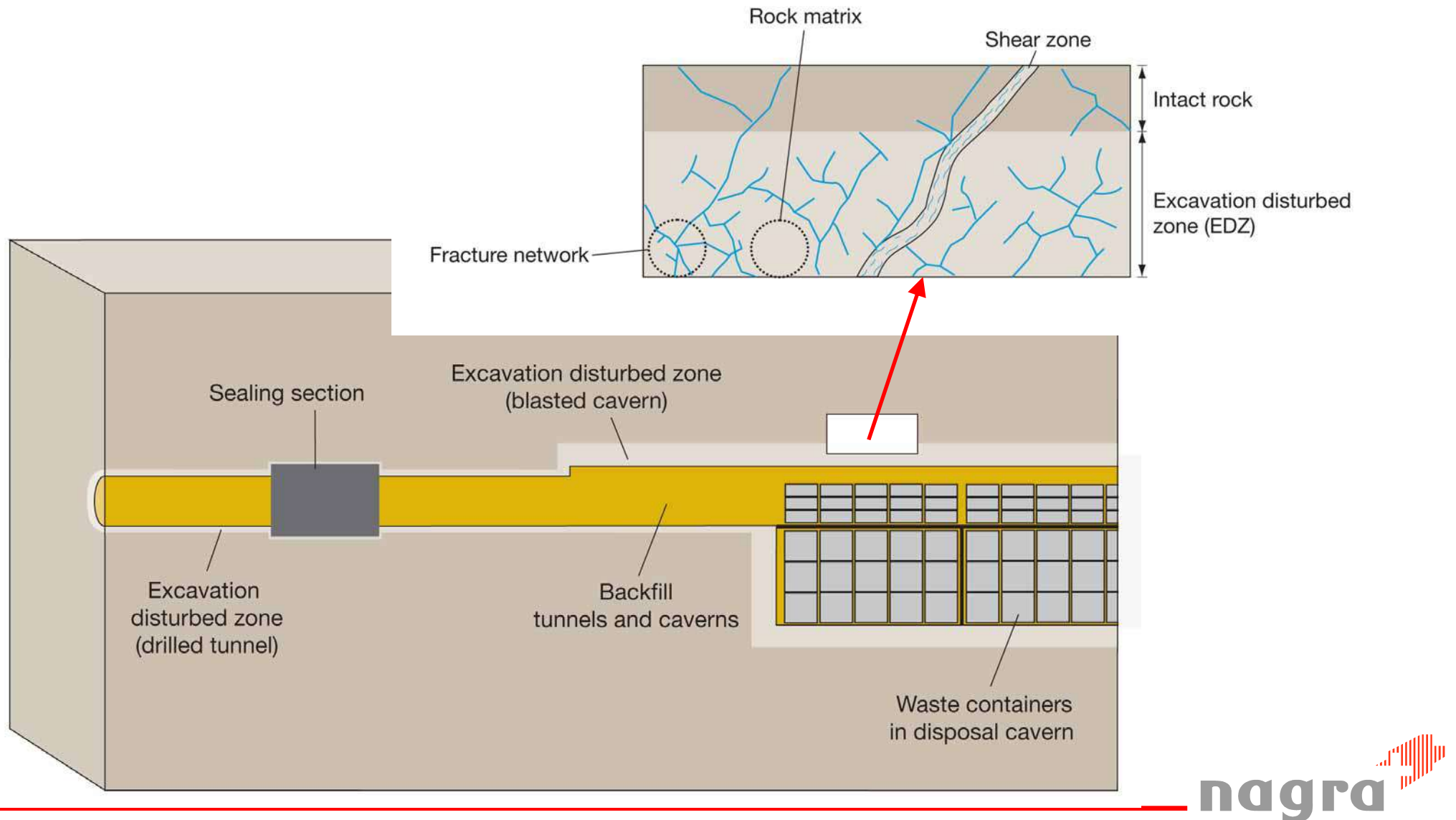


EC-Project



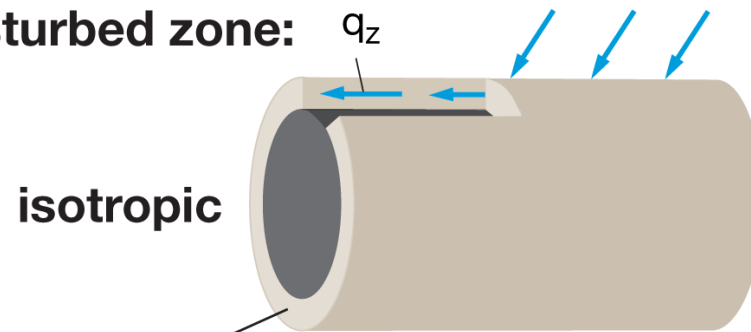
B. Frieg & C. Bühler

EDZ in the direct vicinity of openings (1)



EDZ – isotropic vs anisotropic

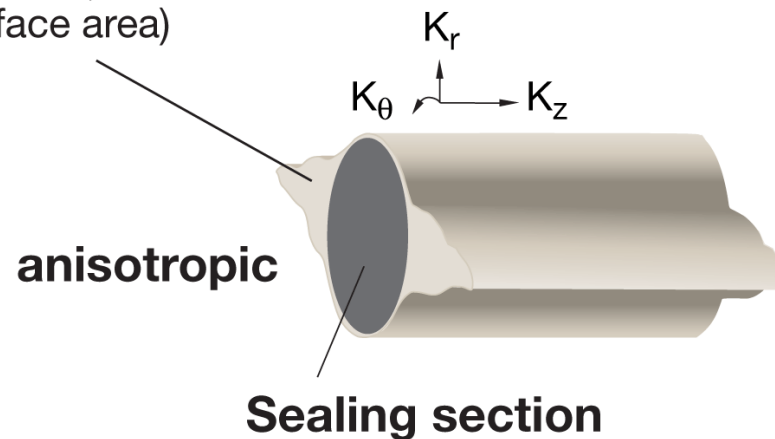
Excavation disturbed zone:



$$q_z = F_{\text{eff}} \cdot K_{z,\text{eff}} \cdot dh/dz; \quad [\text{m}^3/\text{s}]$$

q_z = axial flow
 $K_{z,\text{eff}}$ = effective axial permeability
 dh/dz = hydraulic gradient

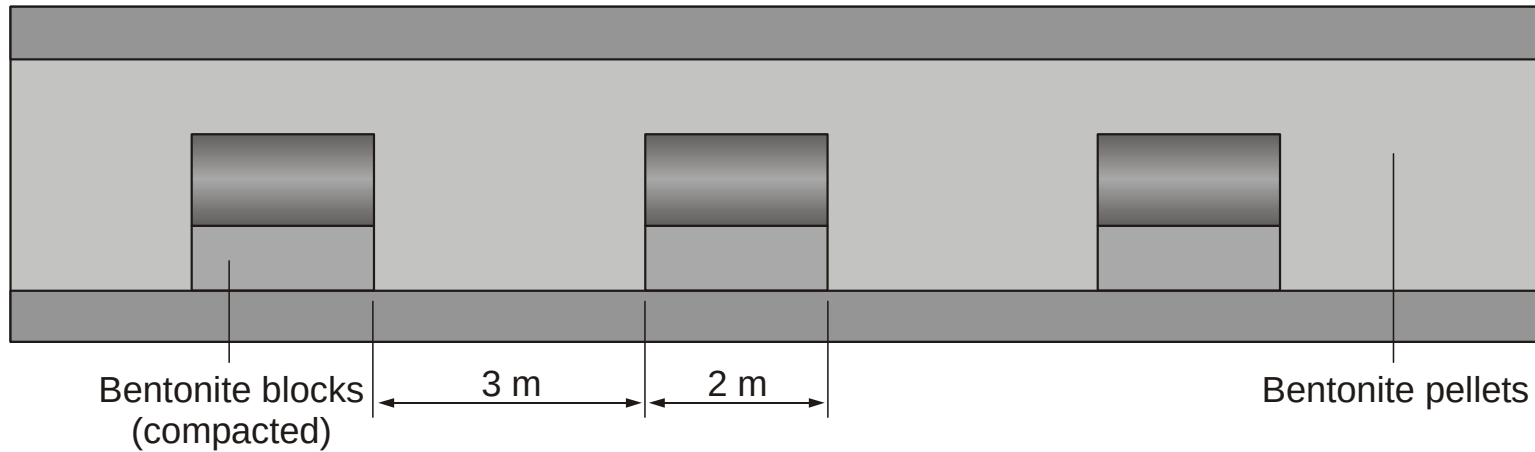
F_{eff} (effective surface area)



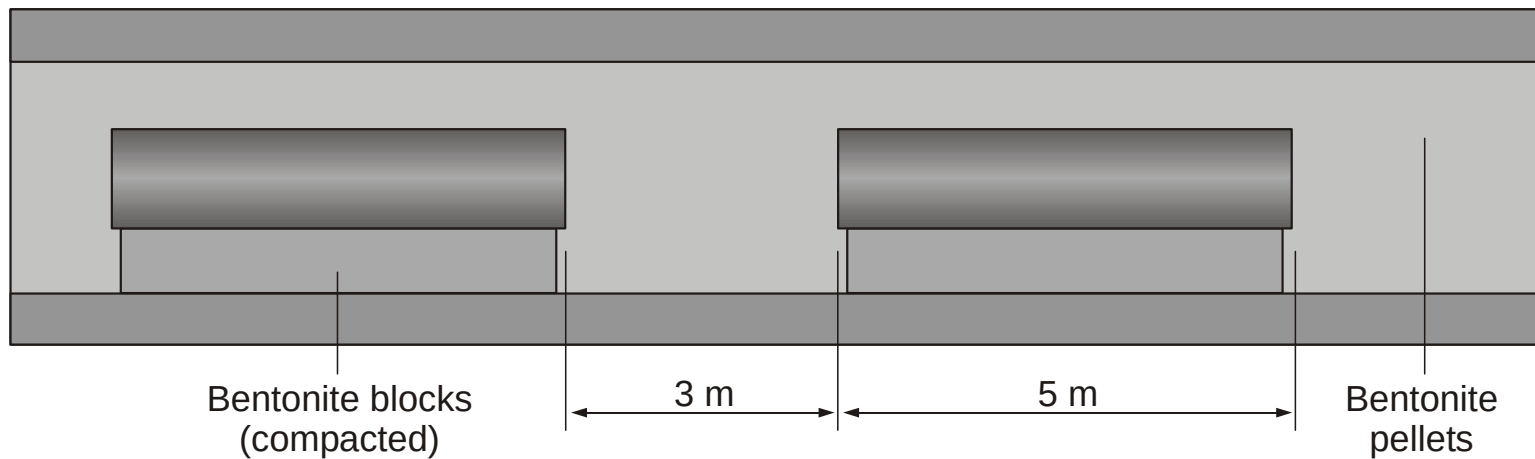
Important parameters

K_r = radial permeability
 K_z = axial permeability
 K_θ = angular permeability

Concept of emplacement of HLW / SF canisters in Opalinus Clay



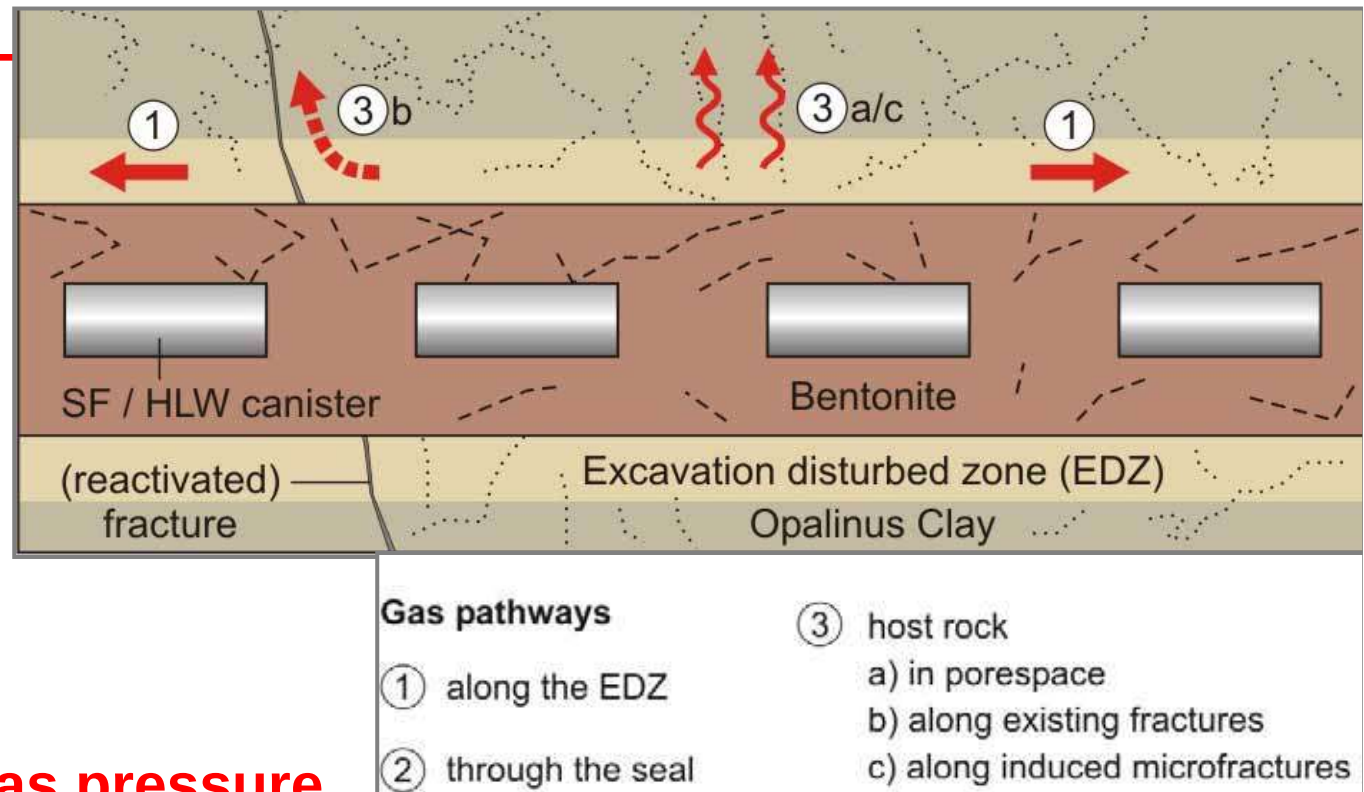
HLW



SF

Relevance of the excavation disturbed zone (EDZ)

e.g. release
of repository
gas



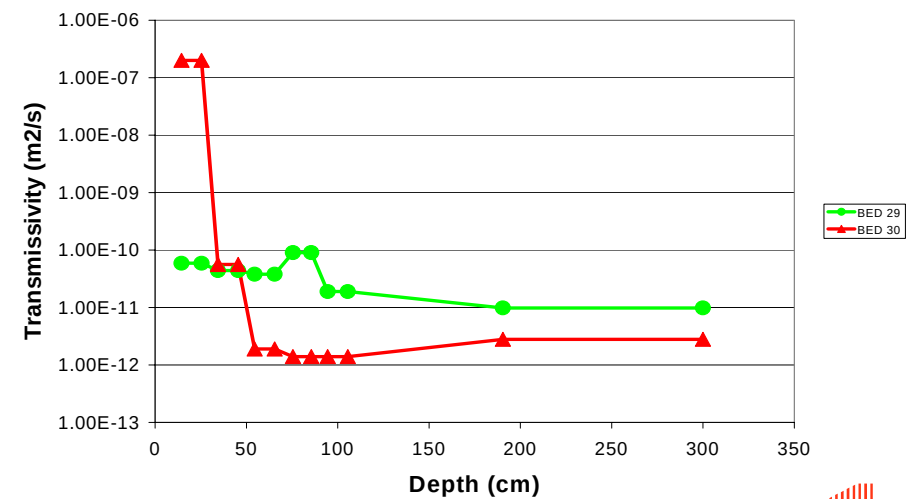
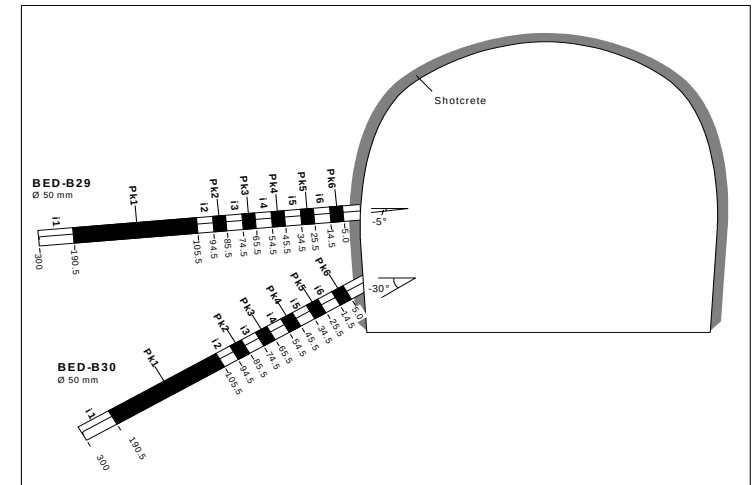
⇒ Build-up of **excess gas pressure**

⇒ Possible impact on **longterm performance** of the disposal concept (engineered / geological barrier system)

⇒ **Driving force for contaminated water** from the disposal area

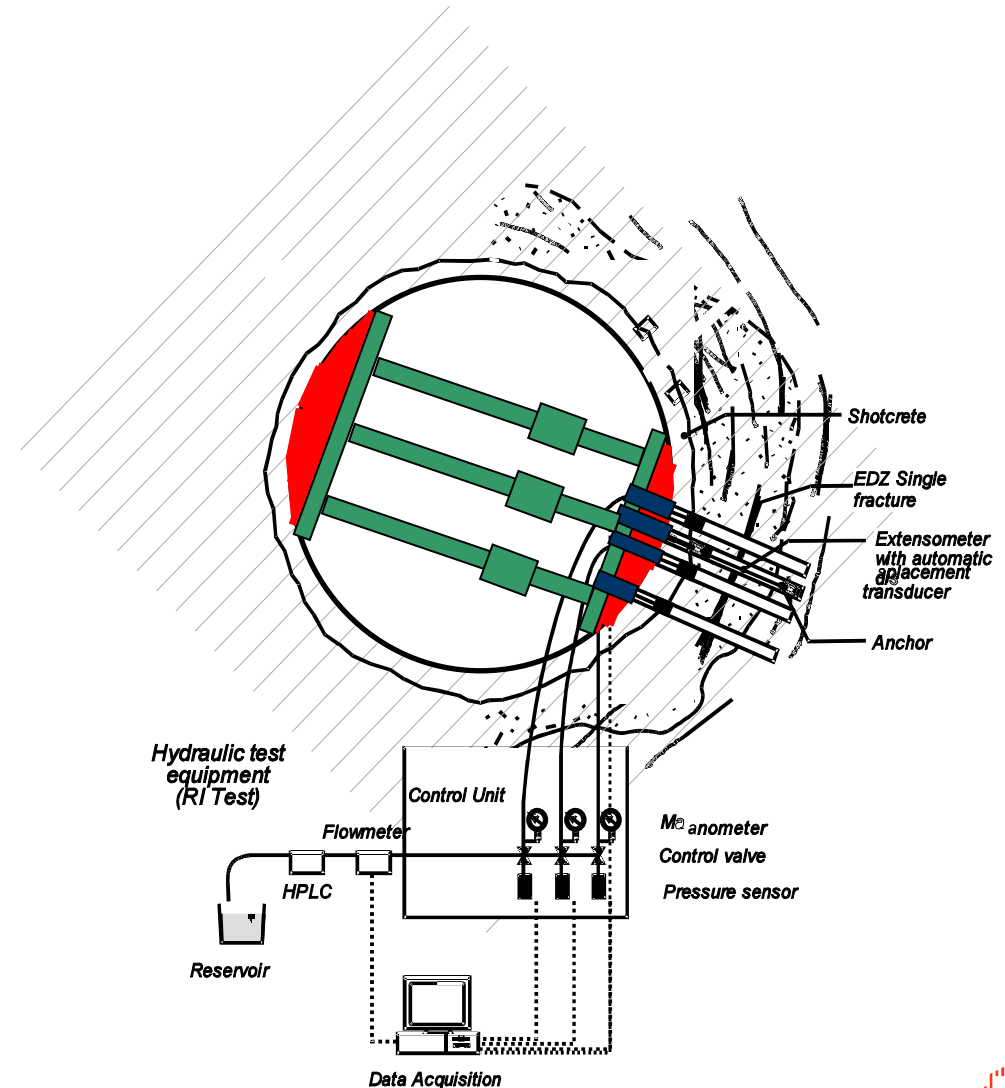
⇒ **Contaminant transport** in gaseous phase

EDZ at Mont Terri - Foto and hydraulic transmissivity

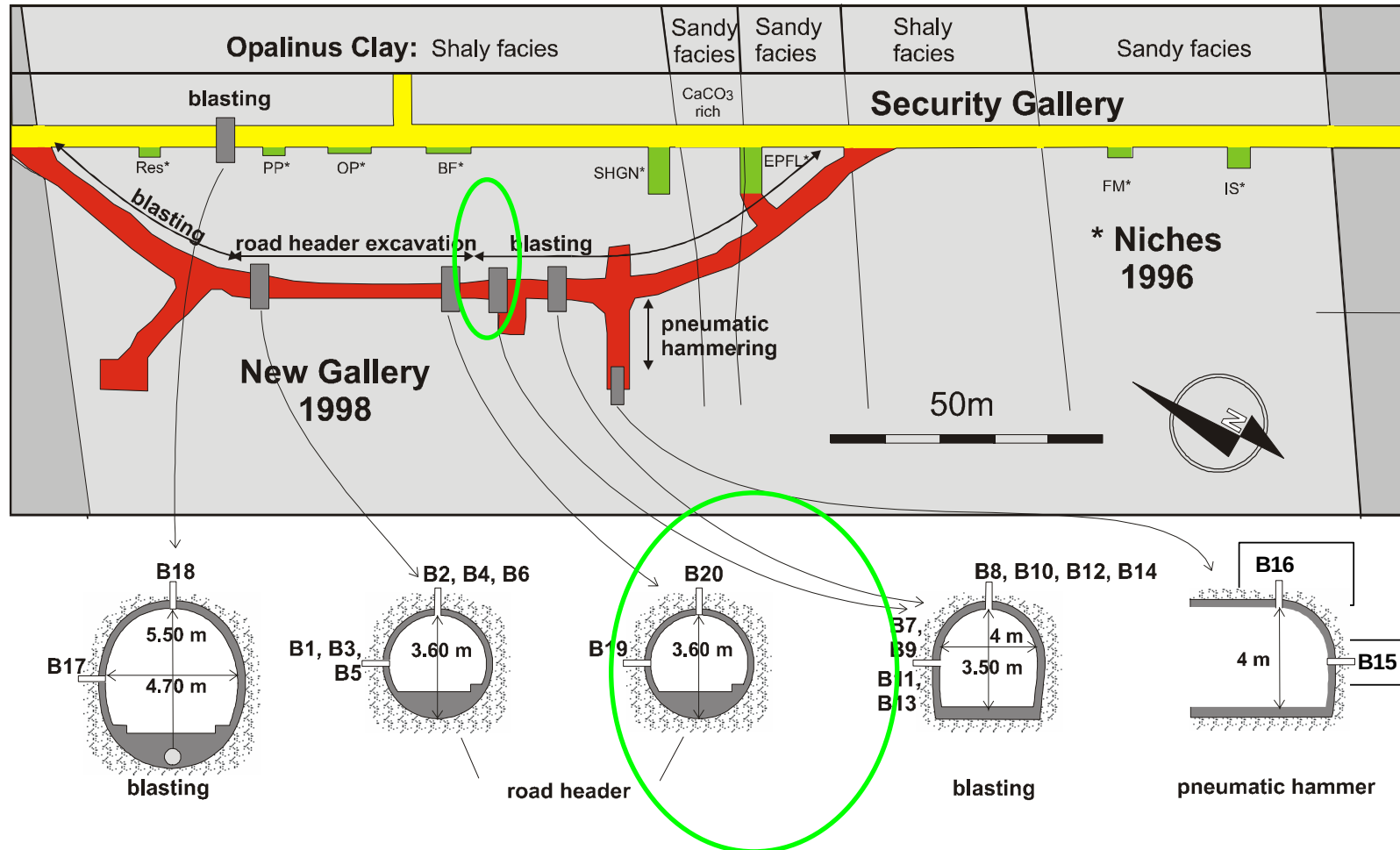


Concept of in-situ Experiment 1 at Mt. Terri

- Testing of the influence of bentonite swelling pressure on the transmissivity of the EDZ. The swelling pressure will be simulated by a load plate equipment
- Question: Will the mechanical self-healing lead to undisturbed conditions or is a permanent increased transmissivity obvious?



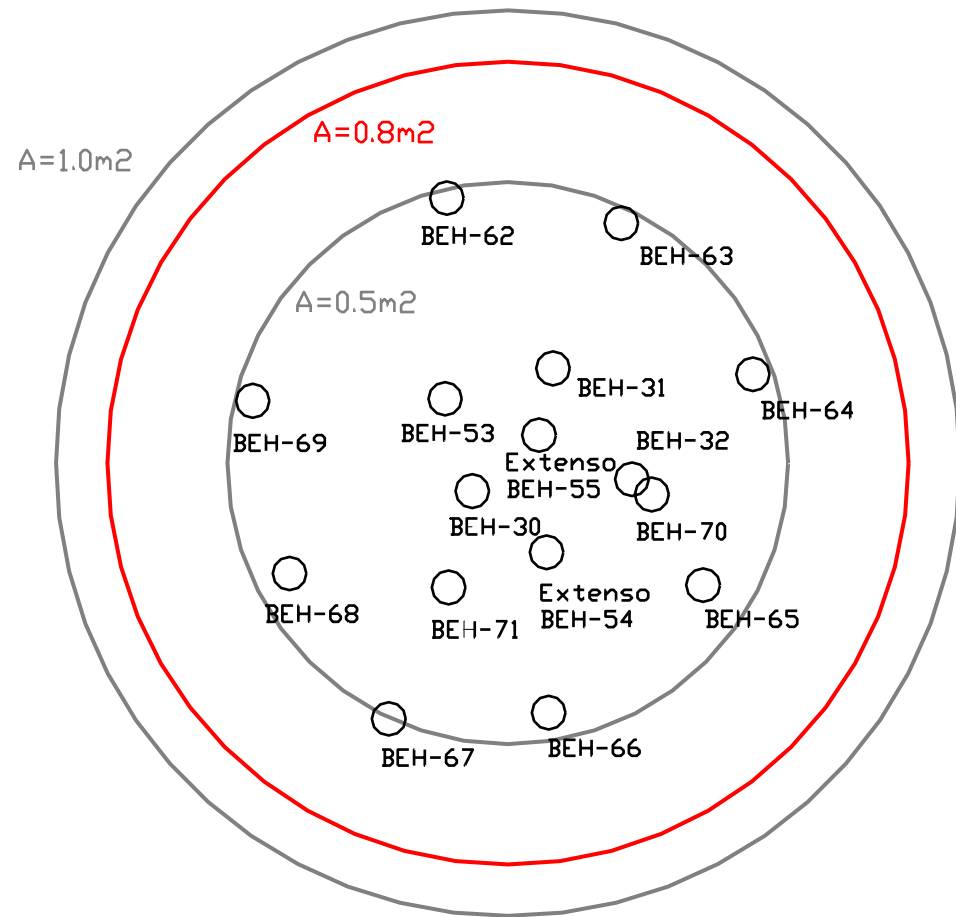
Mt. Terri Test Site EH-1



Design of size for loading plate

Constraints:

- Limited press load
- Cover all boreholes
- Max. load 5 MPa
- Size of loading plate
 $\varnothing 1000 \text{ mm}$
- Area 0.8 m^2



Borehole Configuration of Site EH1

- *Lower Plate*

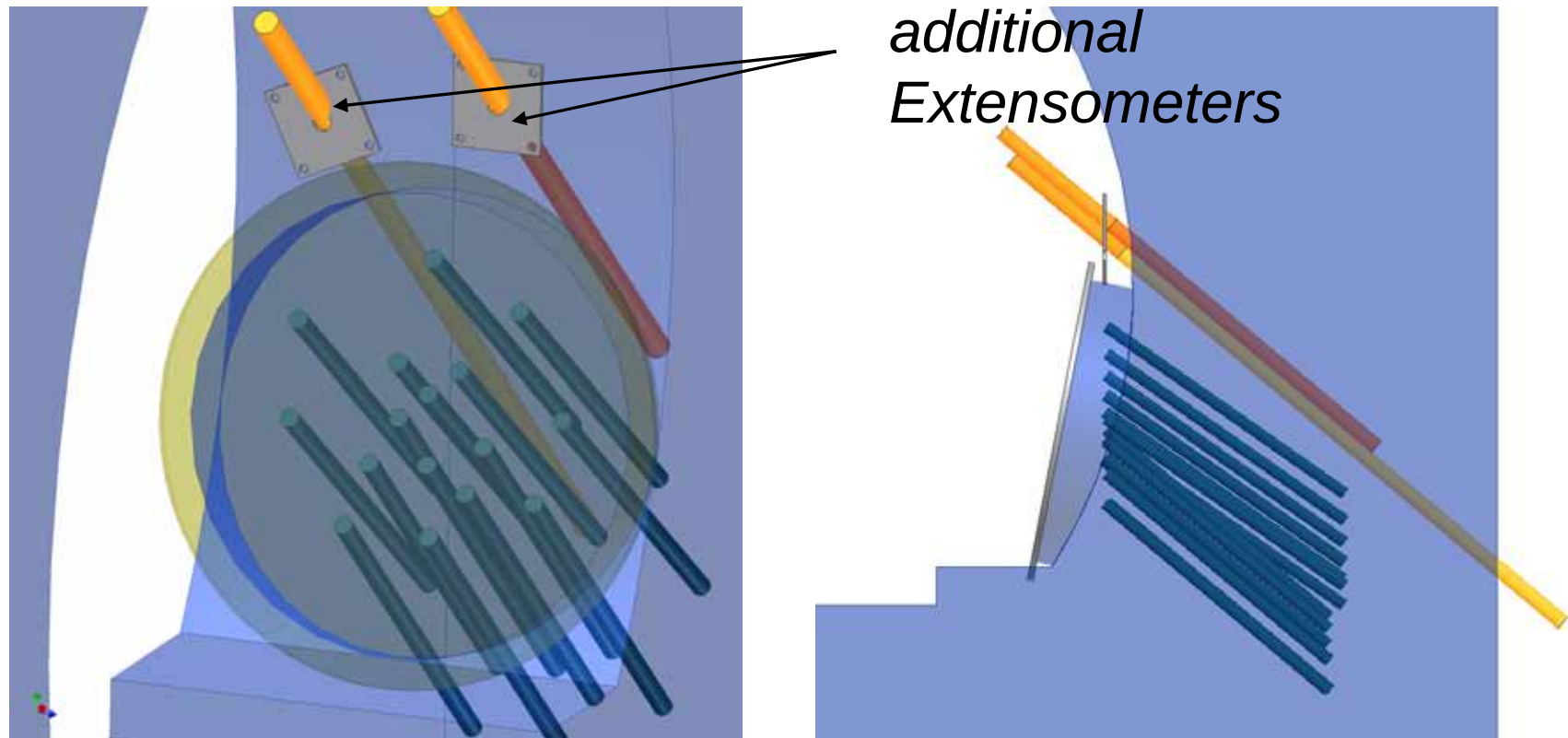


Plate Load equipment ready for transport to Mt. Terri



- *3 hydraulic jacks*



- *Ending plates of plate loading equipment*

Ending plates temporarily attached to wall



● *Upper Plate*



● *Lower Plate*

Loading equipment

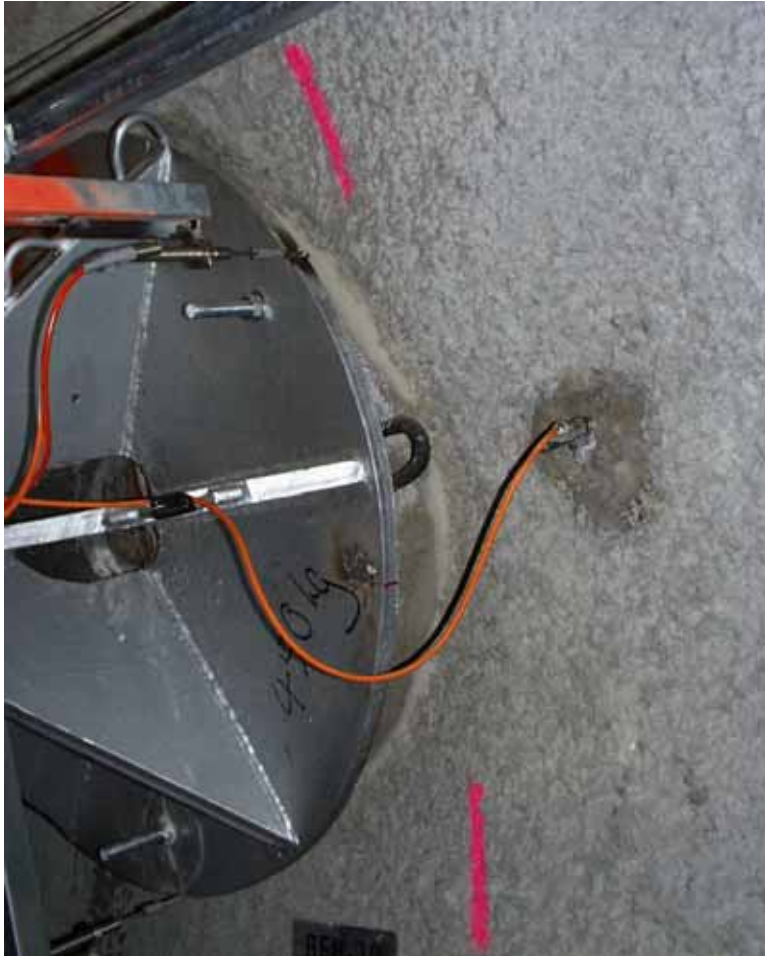


● *Upper Plate*



● *Lower Plate*

Measurement of plate and rock displacement



● *Upper Plate*



● *Lower Plate*

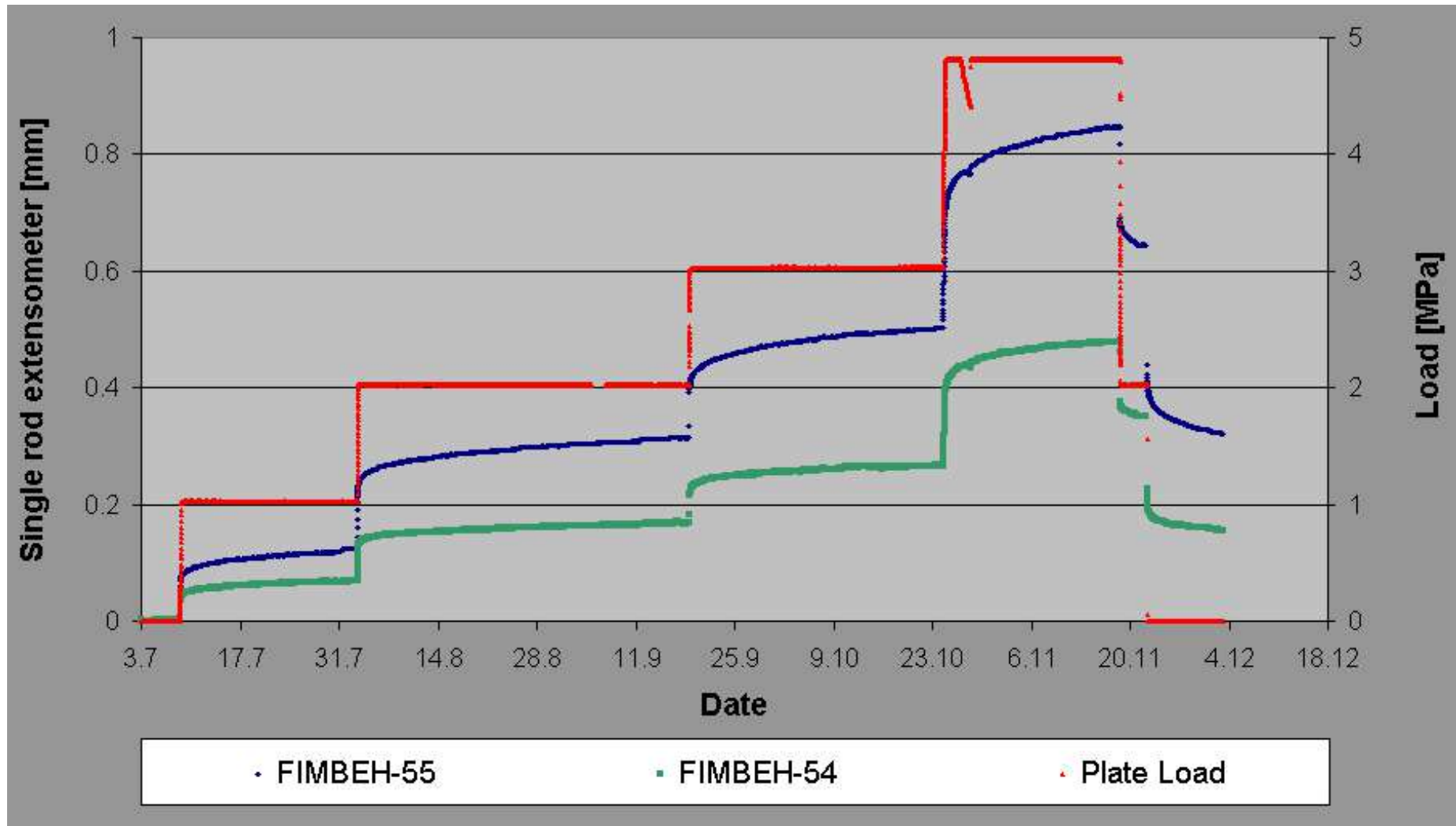
Complete test set-up



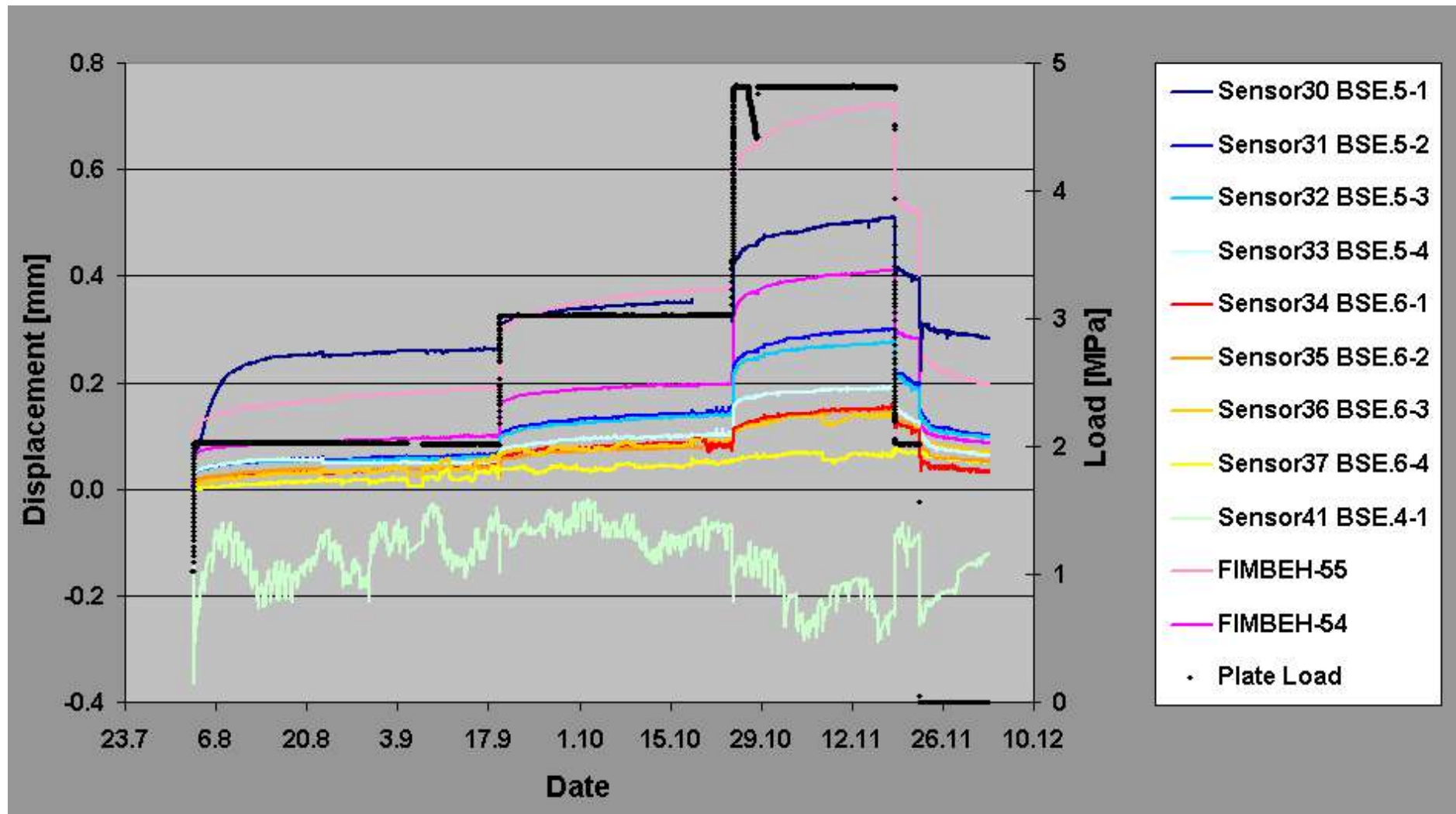
Equipment involved

- Solexperts GeoMonitor data acquisition
- 2 x 4-point extensometers (lower plate / 0 - 2 m)
- 3 x single-point extensometers (lower plate / 0 - 1 m; upper plate / 0 - 2.5 m)
- 6 x displacement transducers (3 per plate)
- Complete loading plate equipment with 3 hydraulic jacks and load control device
- 14 single packers in the observation boreholes equipped with valves and pressure transducers
- Pressure tank for hydraulic test (injection tests)
- High precision flow meter / flow controller (RI-tests)

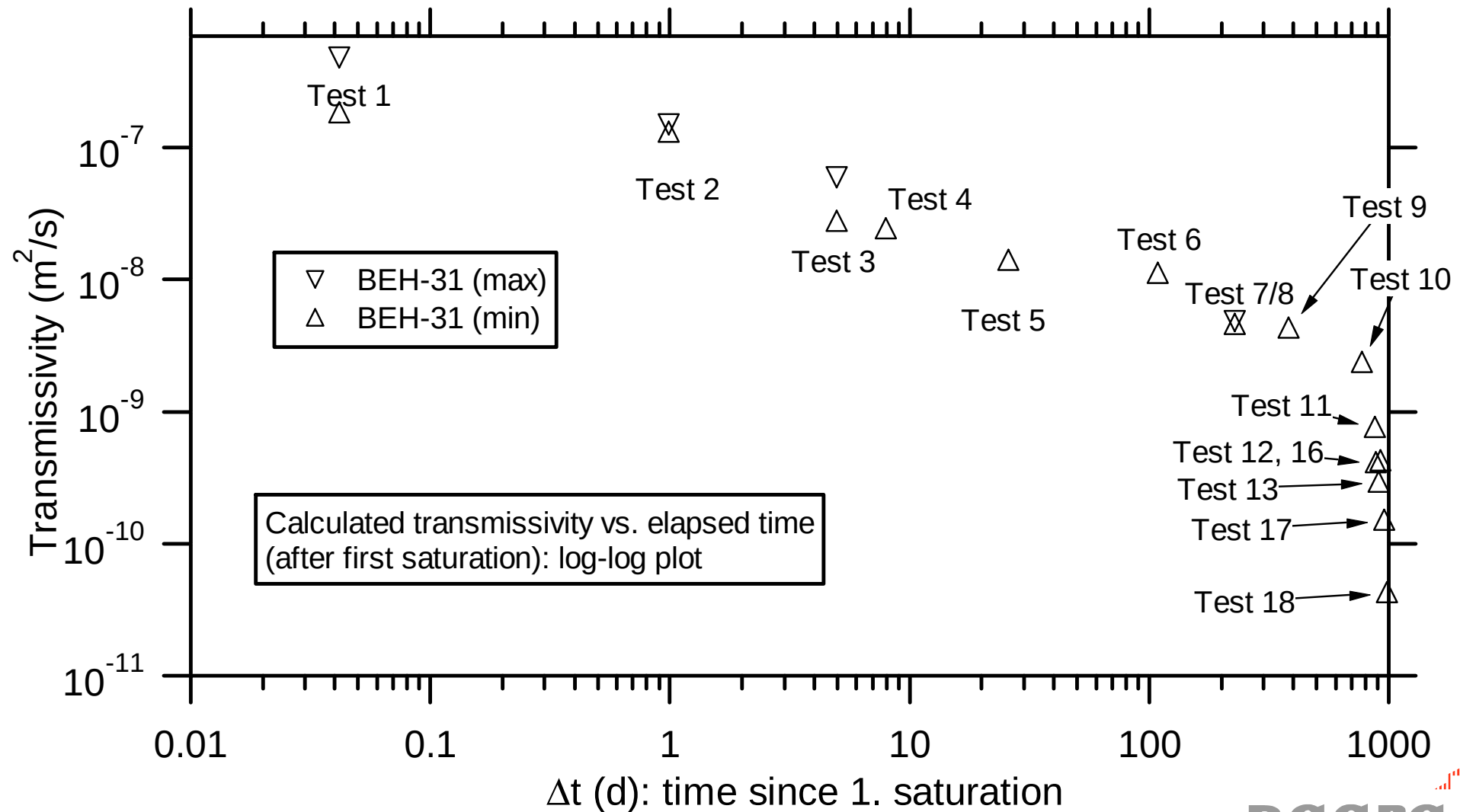
Existing extensometers installed with packers



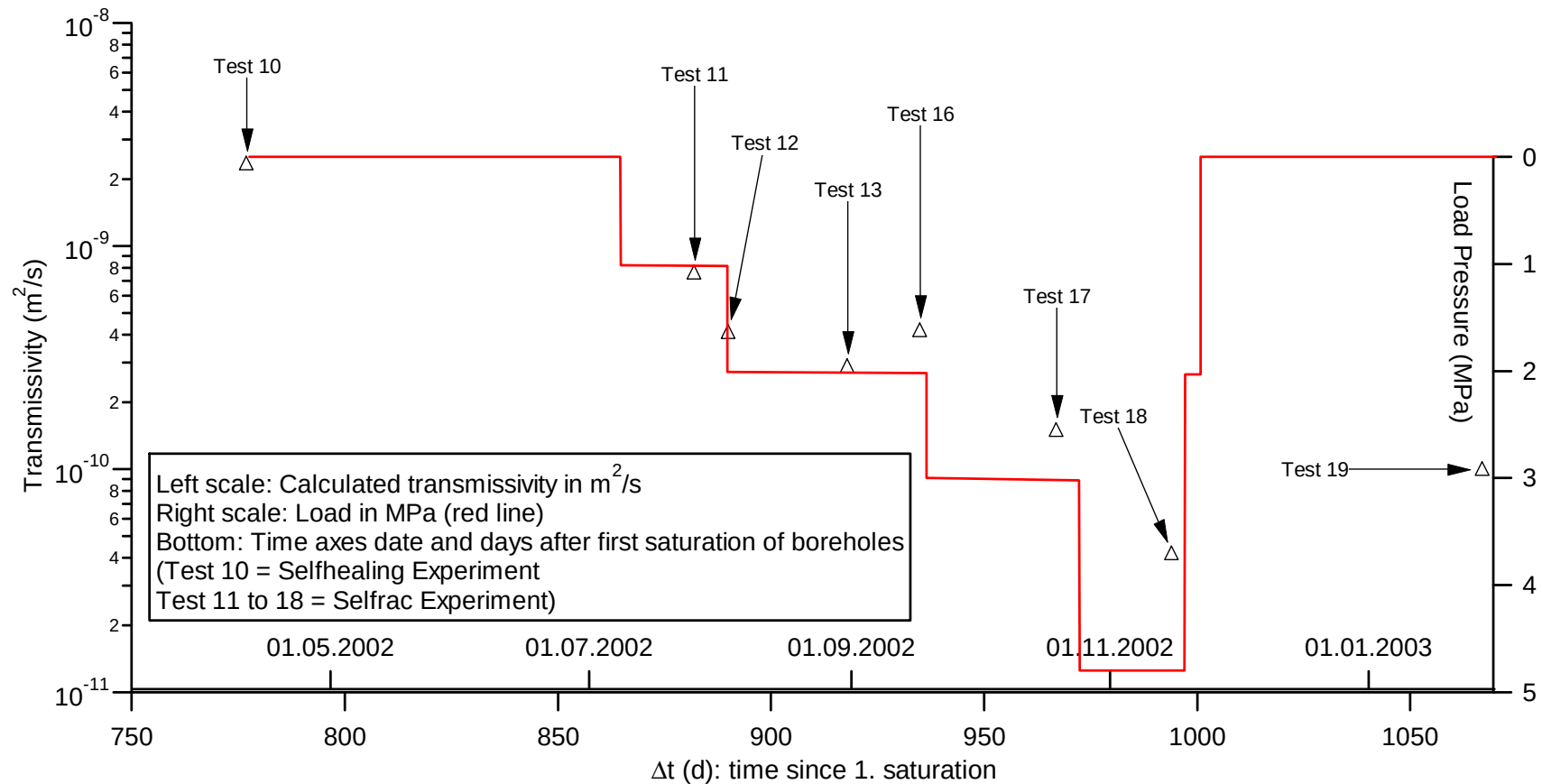
All extensometers



Calculated transmissivity vs. elapsed time (BEH-31)



Result of 1st. in-situ test (Transmissivity and load vs. time (BEH-31))



Result: Decreasing transmissivity in the direct vicinity of the tunnel (EDZ) with increasing load applied to the tunnel wall

Summary field experiment No.1

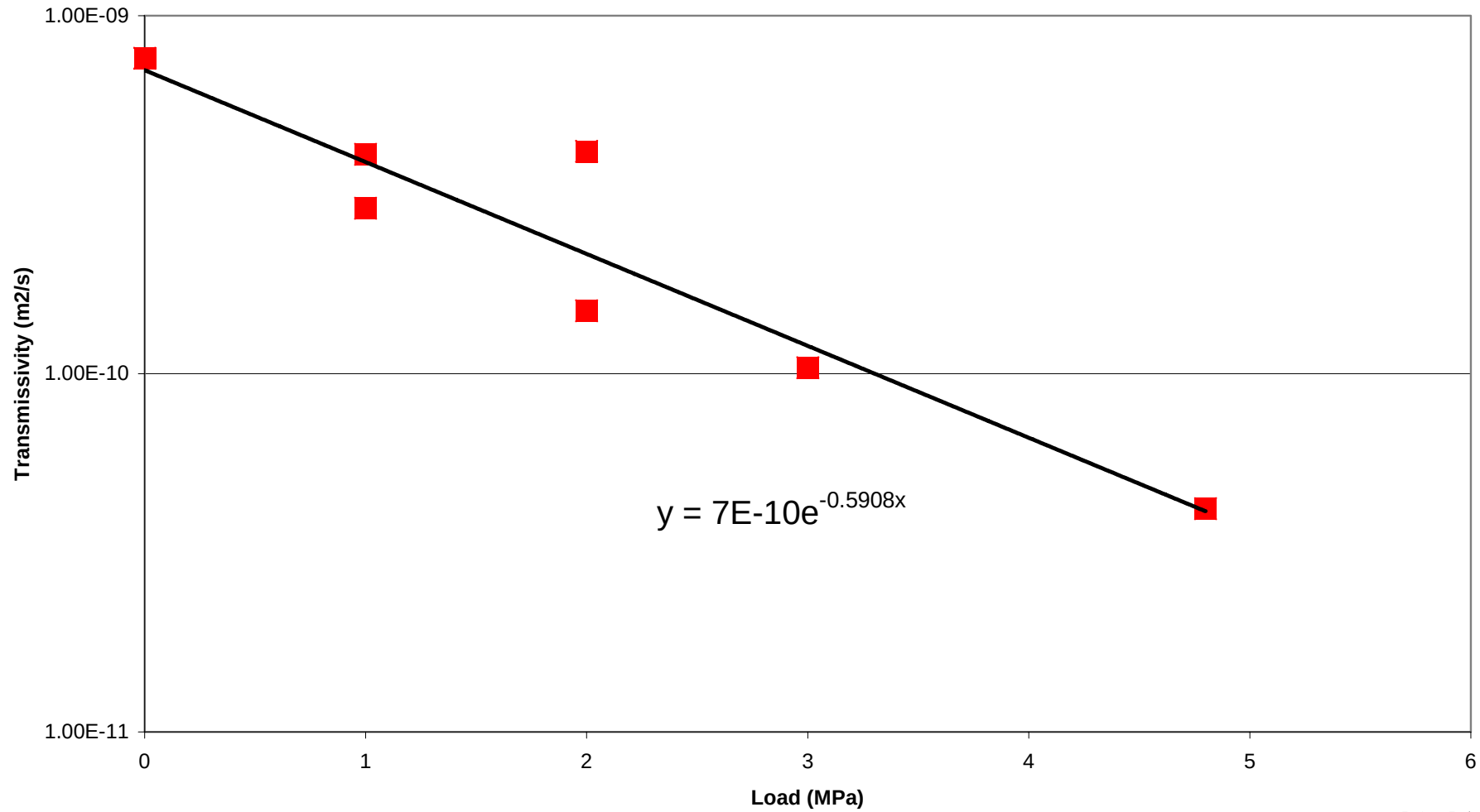
- The field experiment was successfully performed. The data quality is good except from one single-point extensometer (opposite site / upper plate).
- The experiment was extended in the sense of duration and testing programme as well as installed equipment (displacement transducer/plate and extensometer/opposite site) and number of hydrotesting campaigns (singlehole and crosshole testing).
 - Load-steps: 1, 2, 3, and 4.8 MPa
 - Unloading-steps: 2 and 0 MPa
 - Hydrotesting: 1 test before loading and 6 tests (2 designed for crosshole testing) during load test and 1 test at the end under unloading conditions.

Conclusion field experiment No. 1

- It is obvious that the transmissivity shows an significant reduction (nearly two order of magnitude) after the start of the loading test.
 - 2.1 E-9 (Test 10) $\Rightarrow$ 4.2 E-11 / 1.3 E-11 (Test 18)
 - Test 19 (unloading conditions / Jan. 03): 1.0 / 1.5 E-10
- The reduction with time increases in relationship to the previous EH-experiment.
- The reduction is related to the applied load.
- The assumed selfhealing effect/process combined with a significant reduction in transmissivity has been proven with the performed pressure load test.

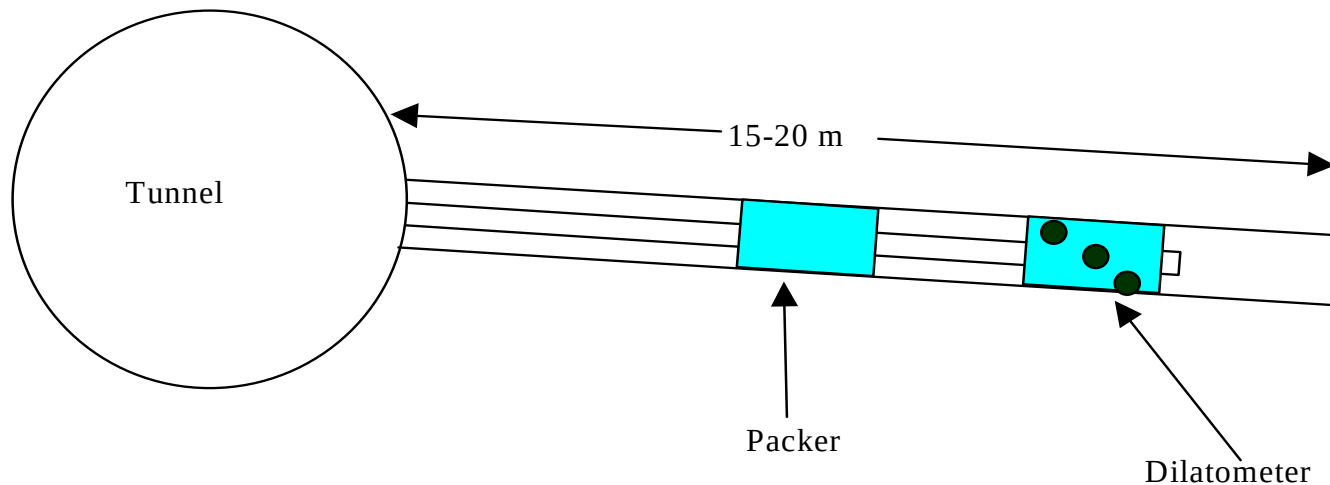
Transmissivity vs. Load

SELFRACT-FIELD EXPERIMENT No. 1



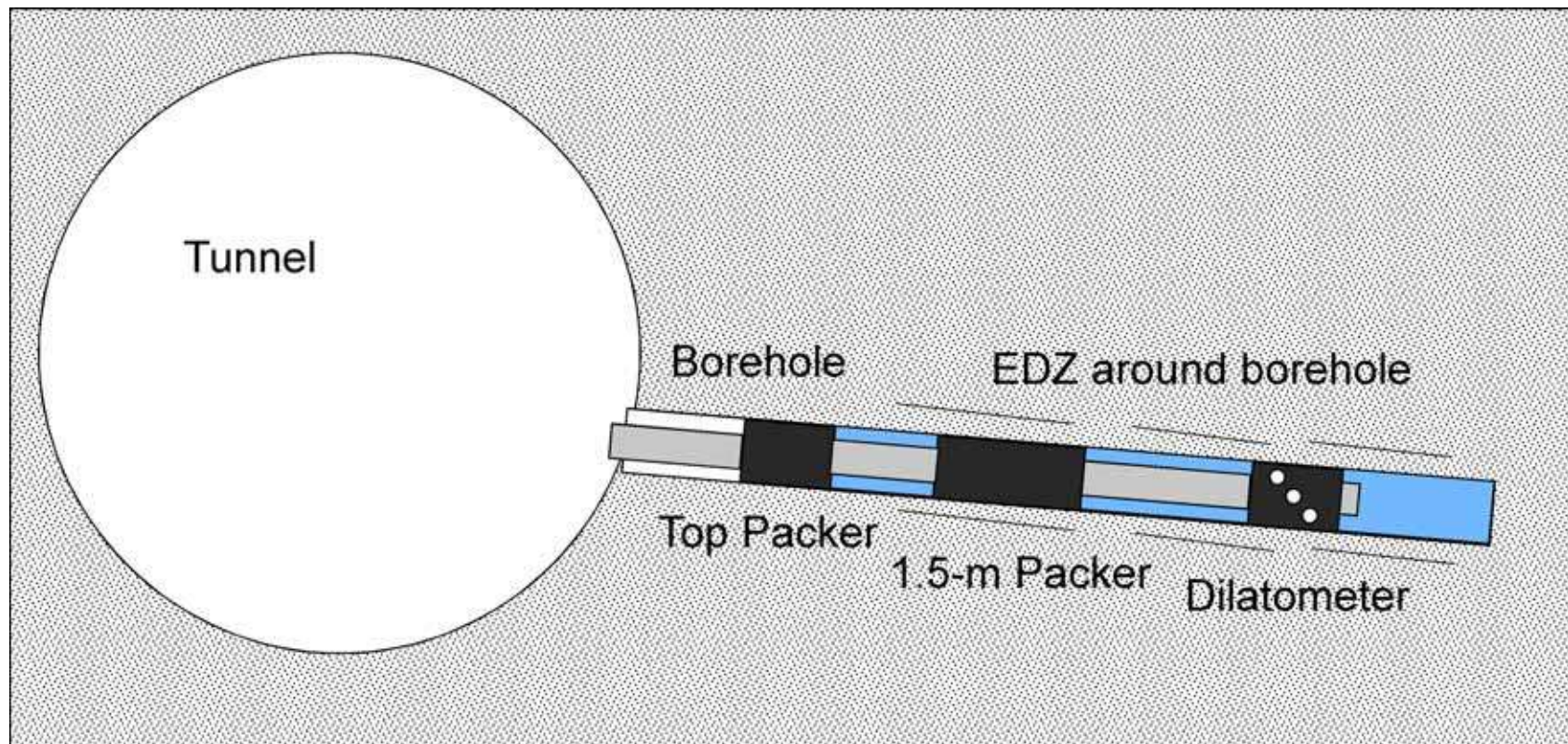
Concept of in-situ Experiment 2 at Mt. Terri

- The proposed work in test 1 shows the change of the local transmissivity and not the more important effective axial transmissivity.
- Test 2 will investigate the effective **axial transmissivity** on a reduced scale (borehole). The swelling pressure and the associated deformation will be simulated by a dilatometer.

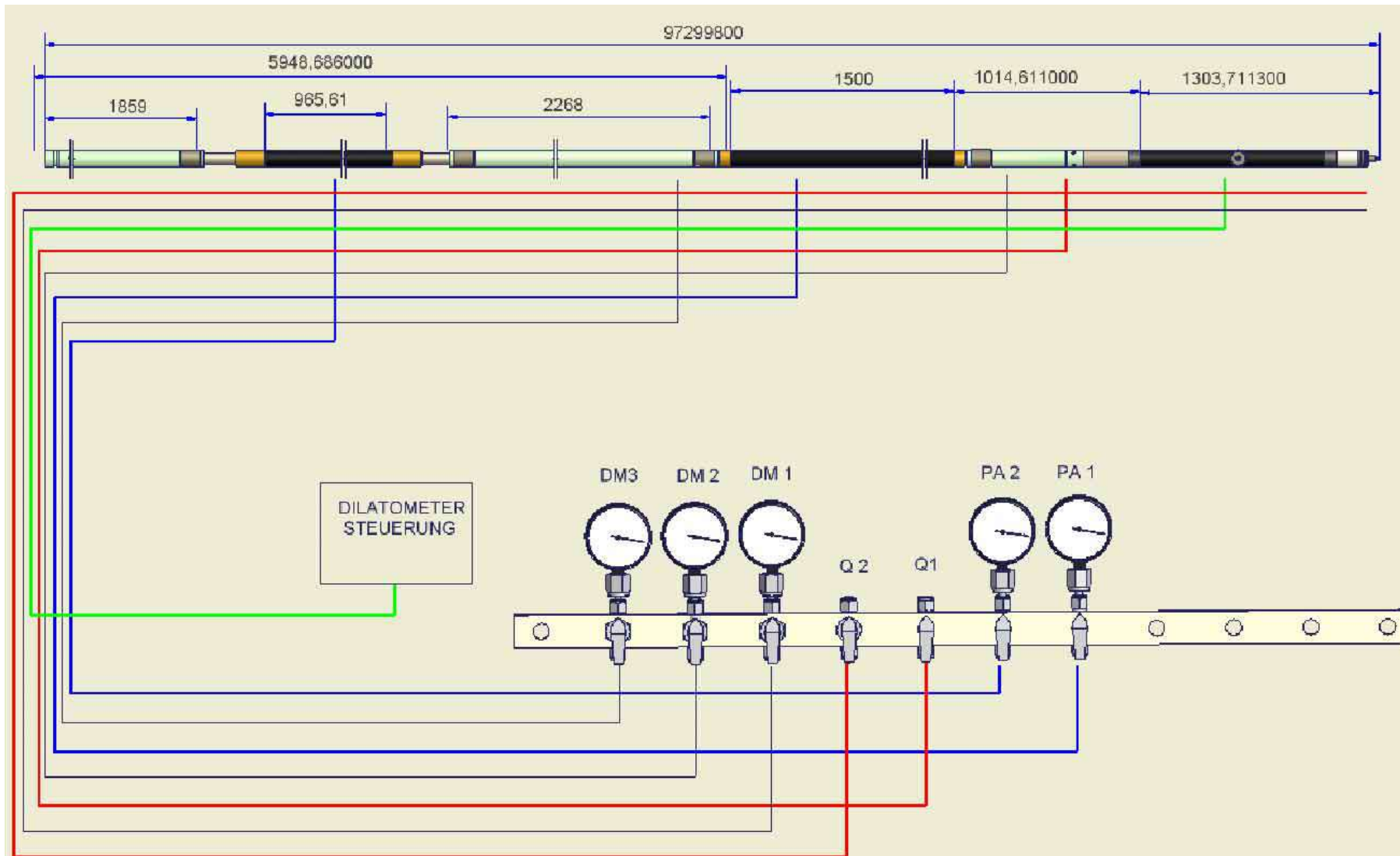


Aims of in-situ Experiment 2 at Mt. Terri

- Study of the EDZ around a borehole (axial transmissivity)
- Monitoring of borehole dilatation and transmissivity as a function of loading



Equipment layout 2nd. in-situ test



Test programme in-situ test 2

- Installation of borehole equipment immediately after drilling
- Filling up of the borehole with artificial formation water
- Expansion of packer 1 and 2
- Expansion of dilatometer 2 – 3 days later
- 1st hydraulic test → pulse test
- Increase of dilatometer pressure in the dilatometer
- 2nd hydraulic test → pulse/flow test with flowmeter
- Increase dilatometer pressure
- Continuation with hydraulic testing (PW/RI/HI) and further stepwise increase of the dilatometer pressure

Installation of dilatometer



Oriented installation of dilatometer



Low volume test interval 2



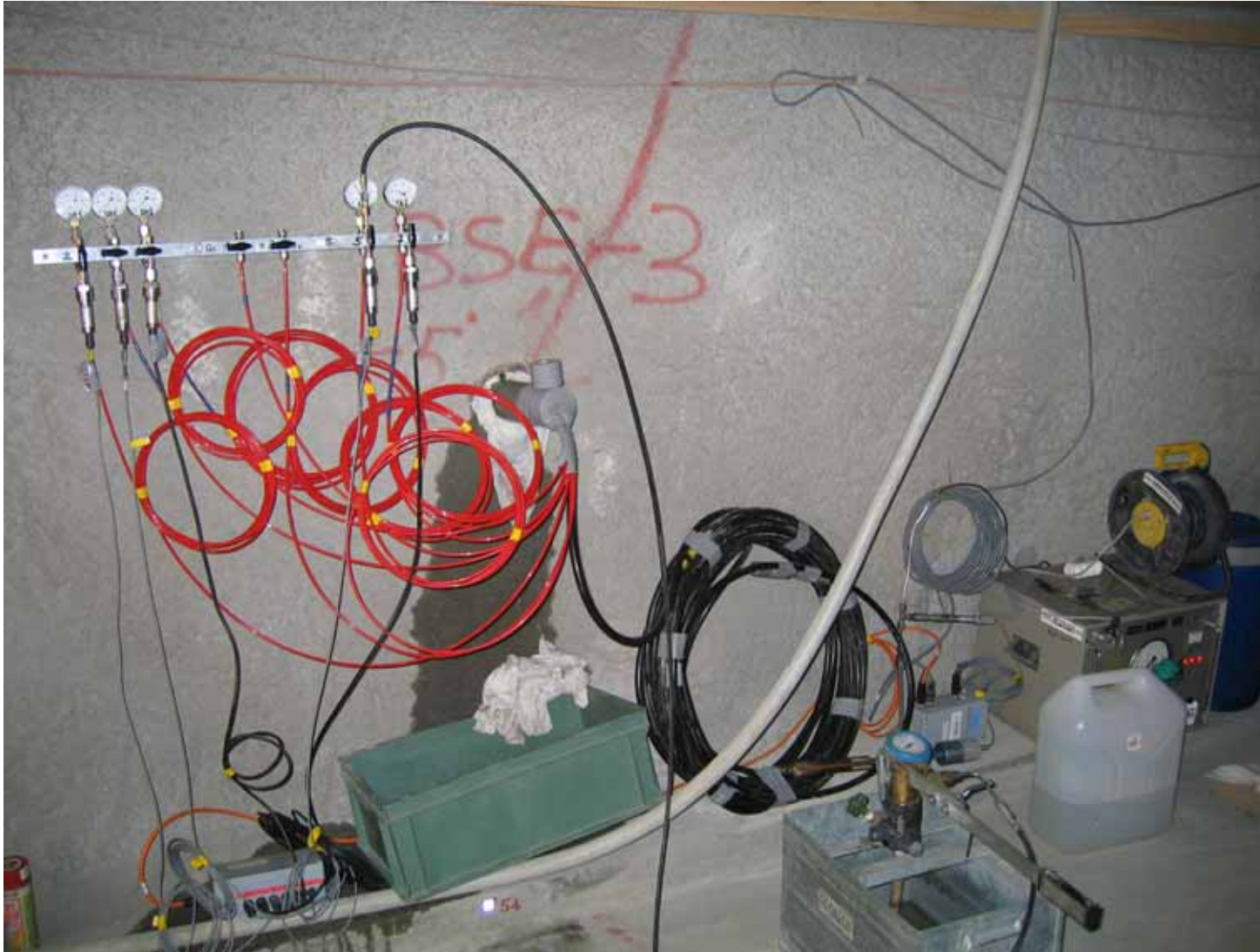
Packer No. 1 (1.5 m length)



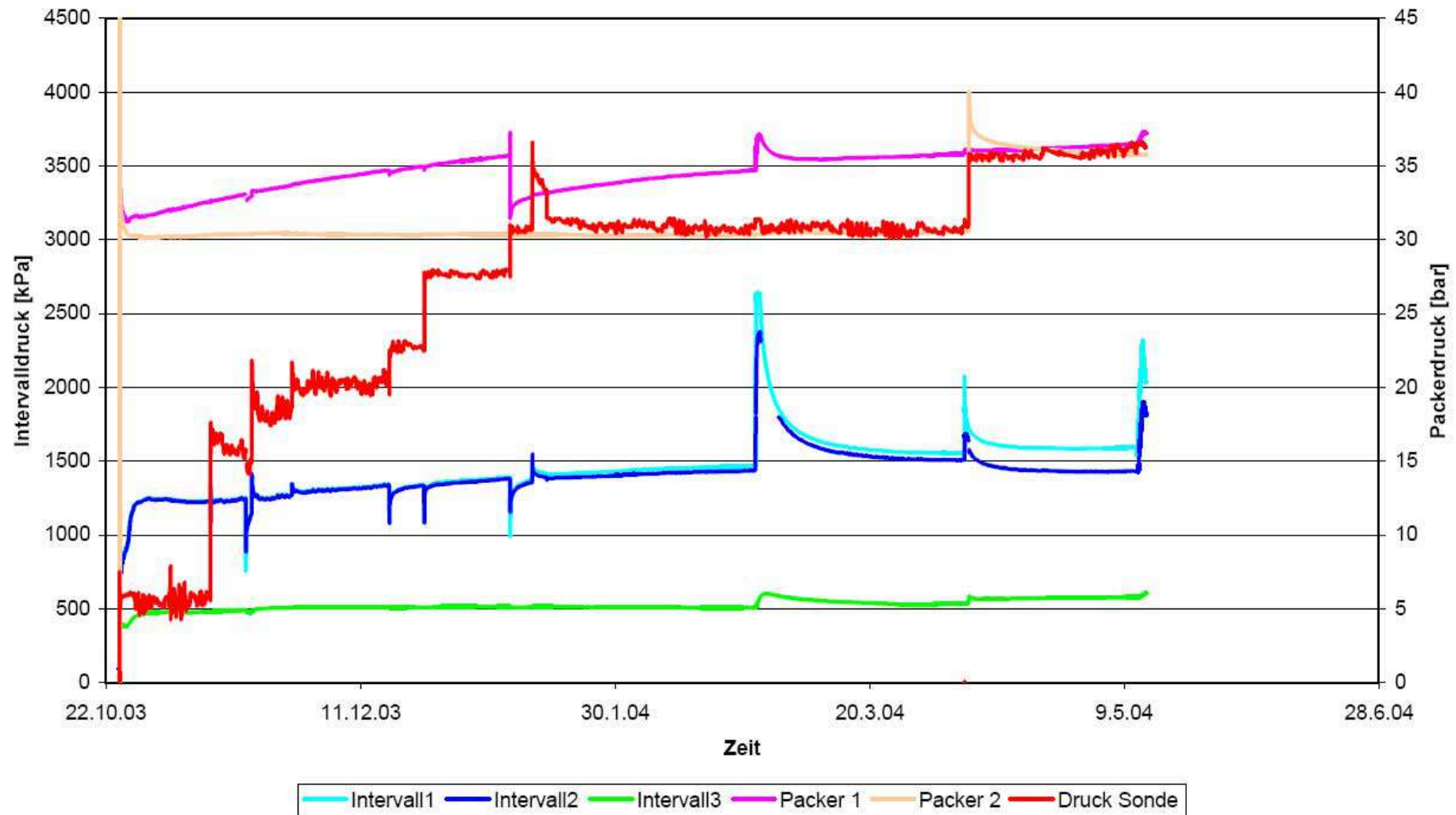
Packer No. 2 (1 m length)



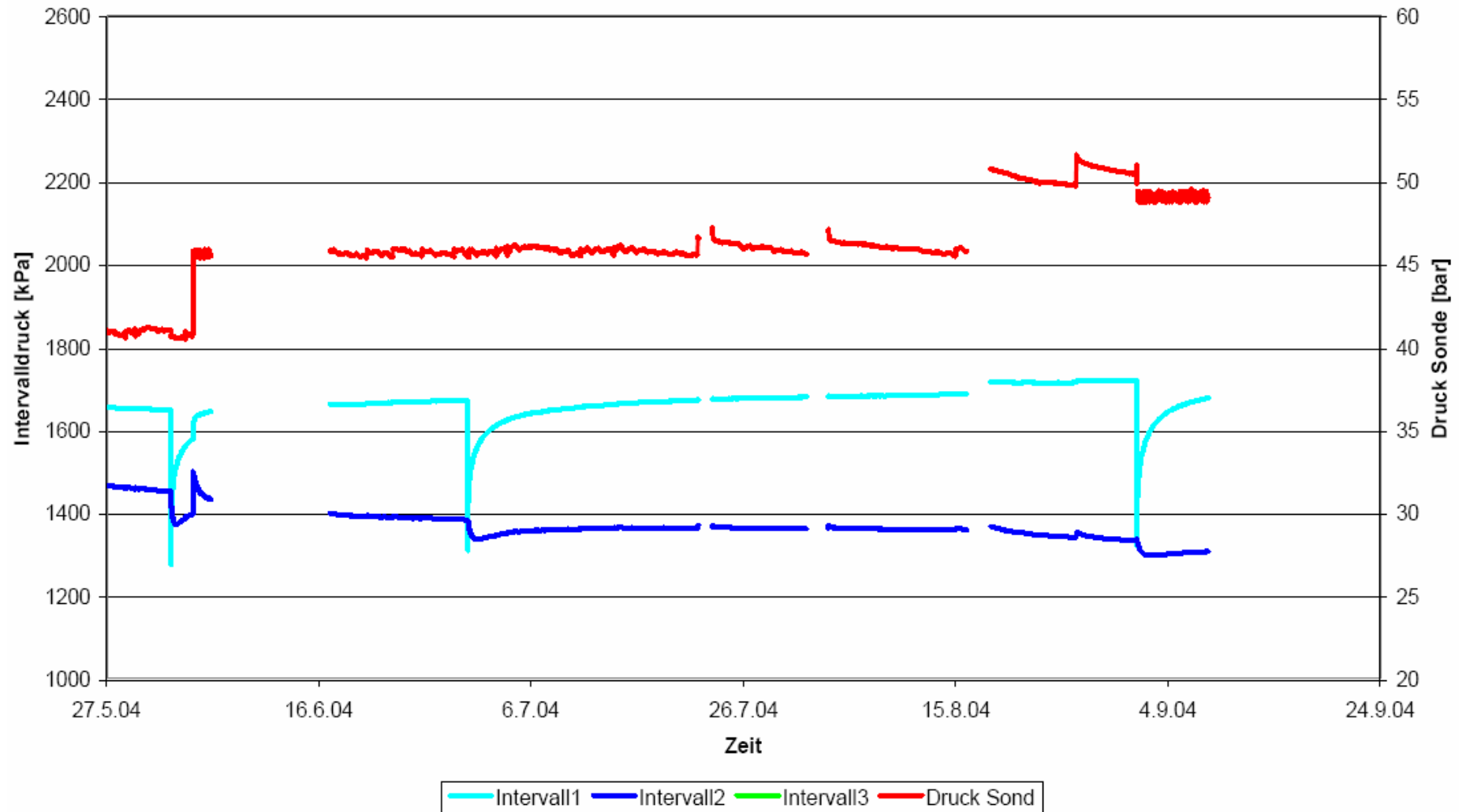
Surface equipment



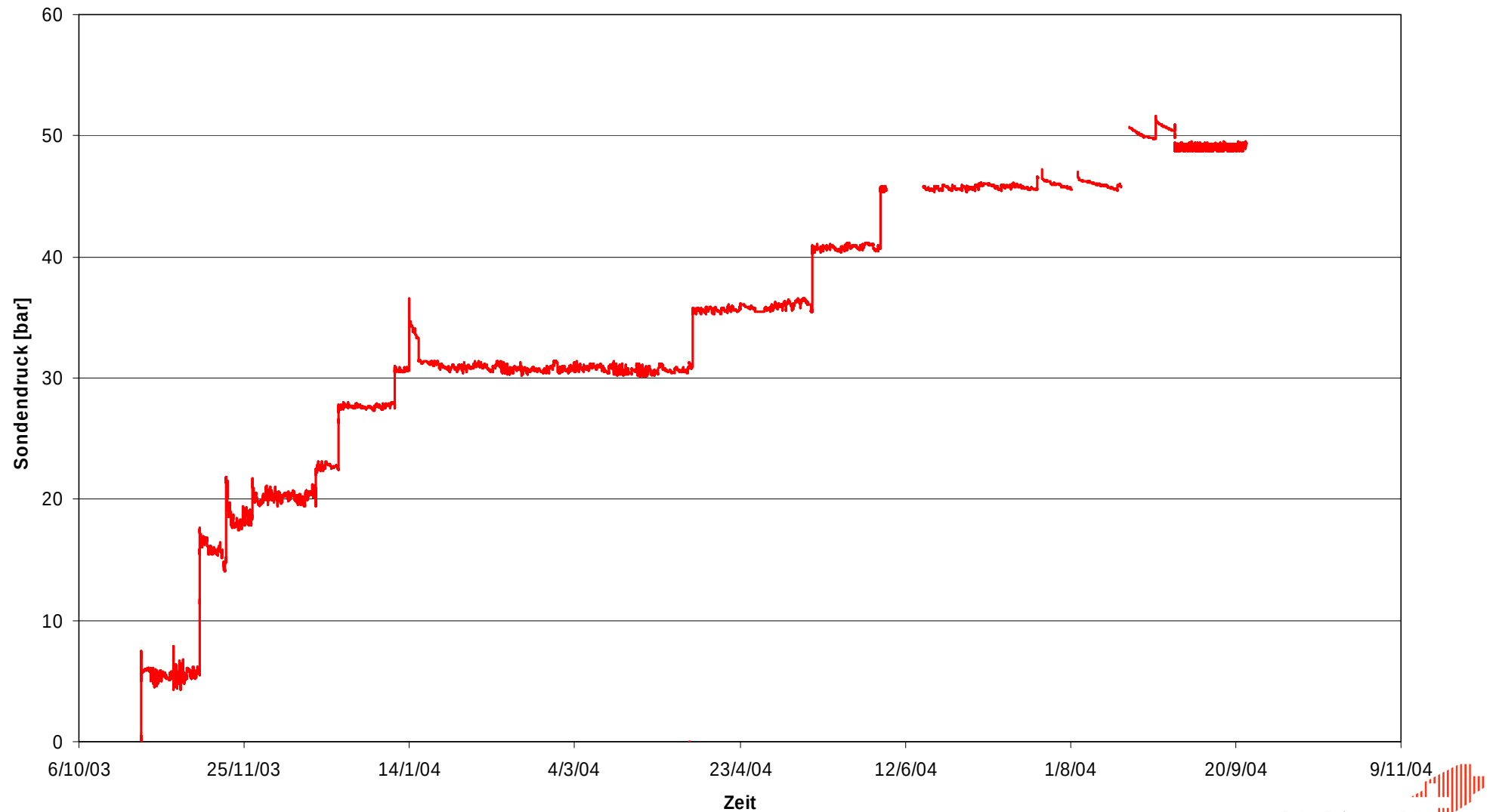
Intervall and packer pressures (Oct. 03 – May 04)



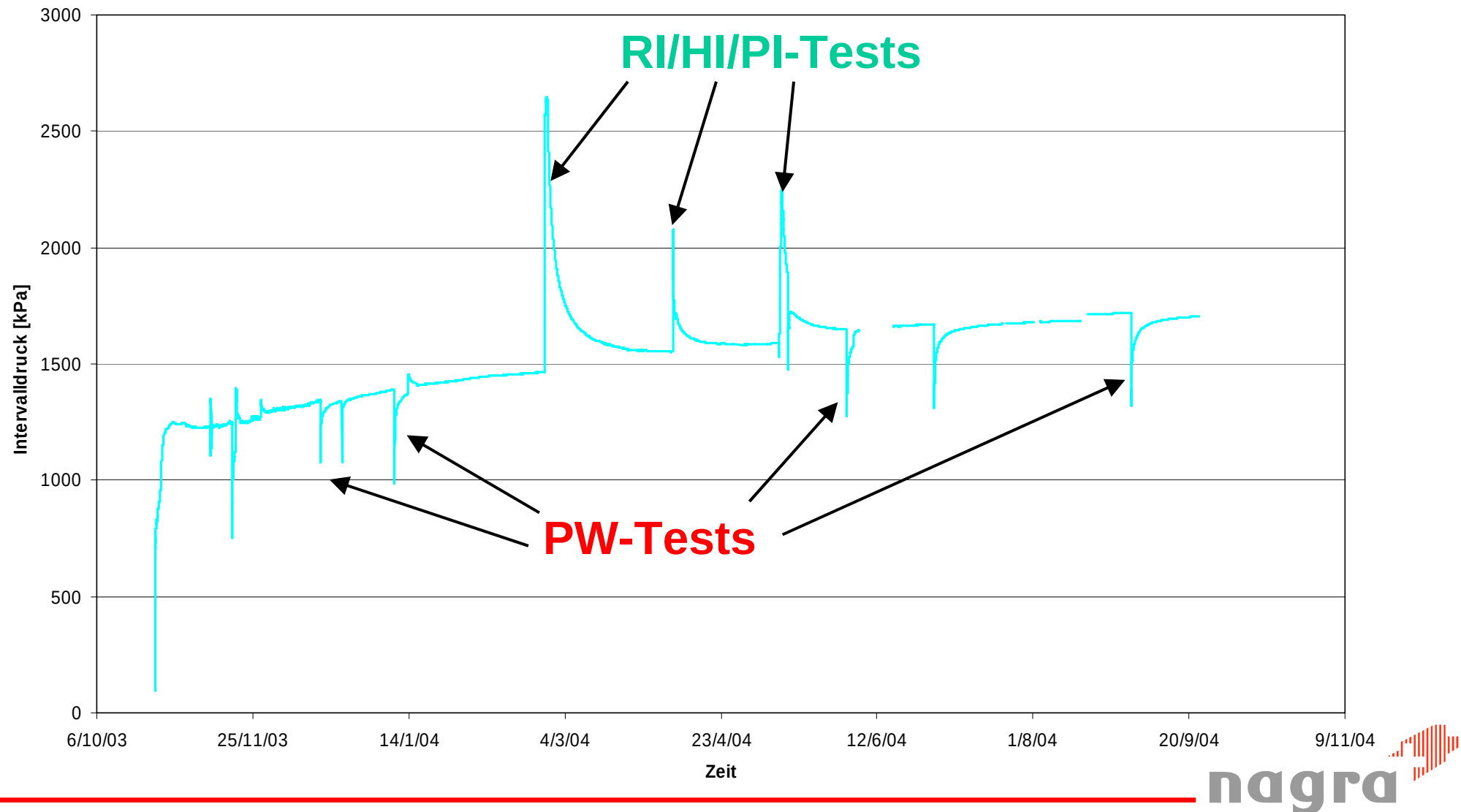
Interval and Dilatometer pressures (May 04 – Sep 04)



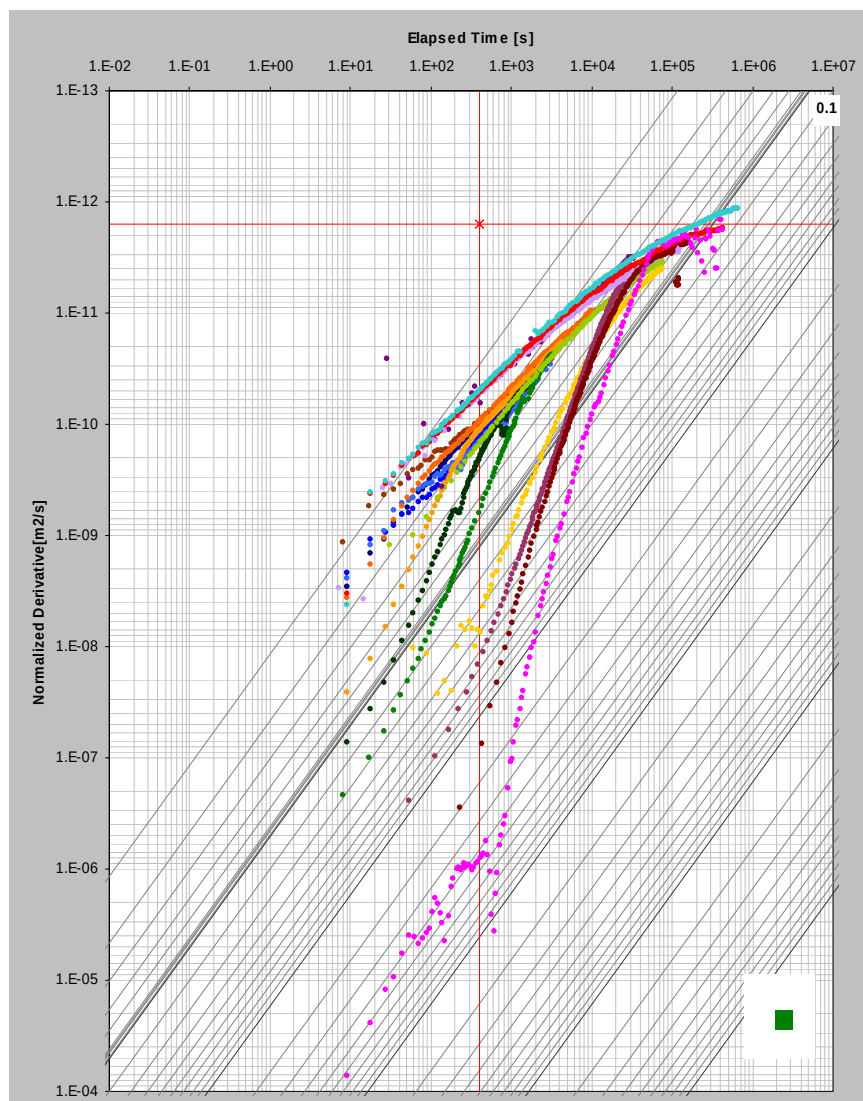
Dilatometer pressure vs. Time



Interval pressure (I1) vs. Time



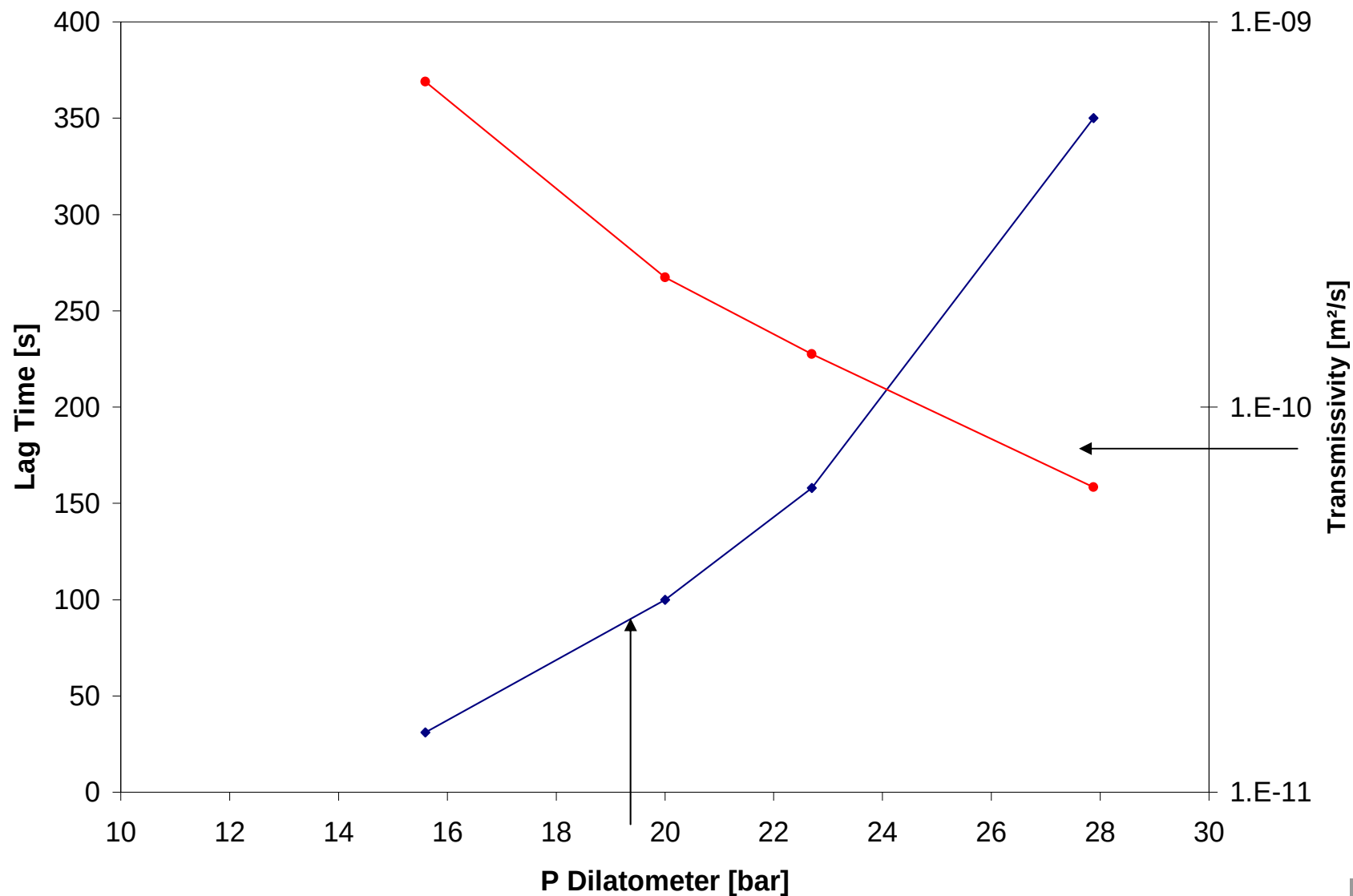
Normalized plots with all hydraulic tests



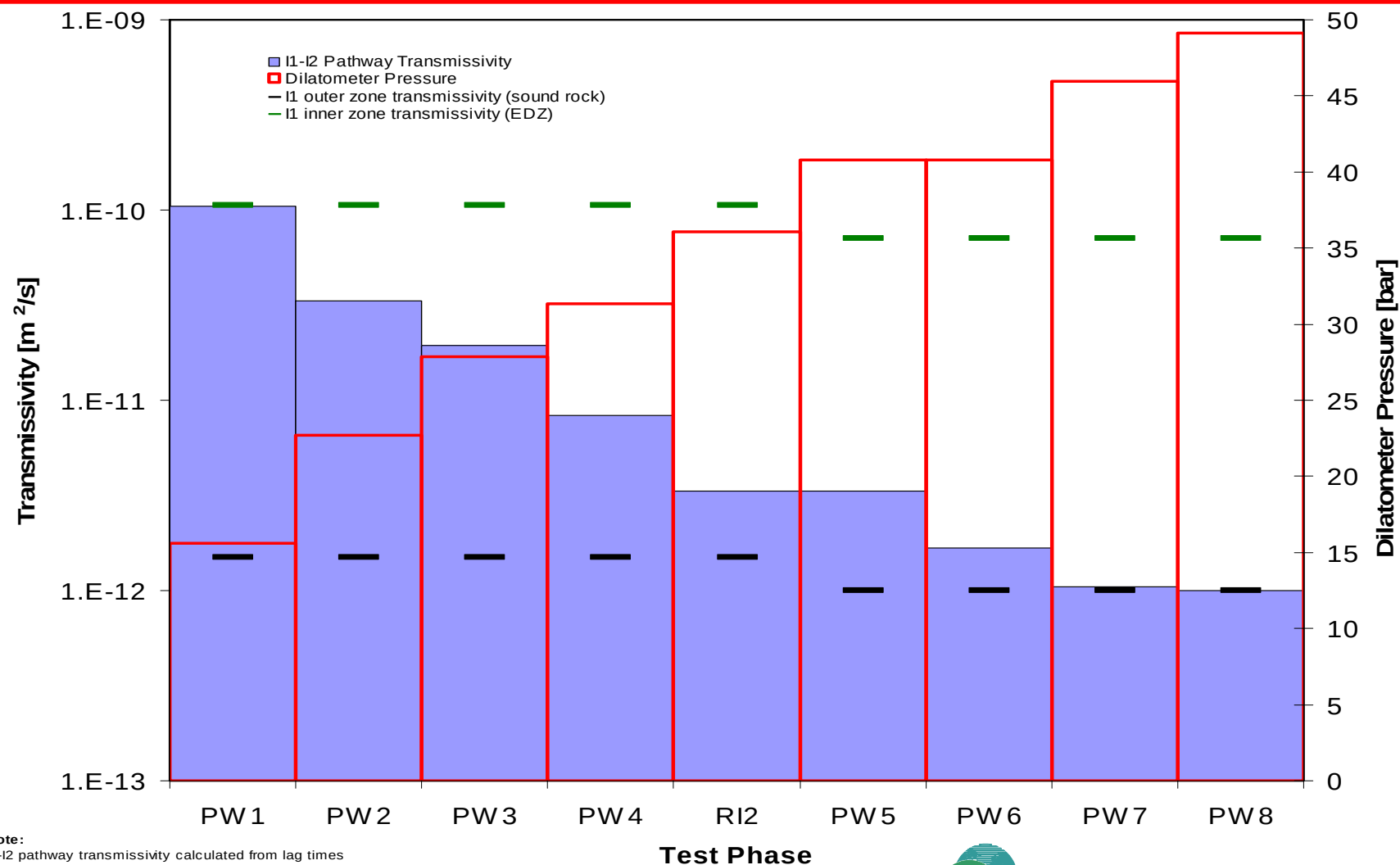
T [m2/s] vs. elapsed time [s]

- On a normalised log-log plot a vertical shift of the derivative indicates a change in the analysed transmissivity.
- A horizontal shift indicates a diffusivity change.
- Changes in the shape of the derivative would indicate alterations of the flow model diagnosed.

Pulse test results from observation interval 2



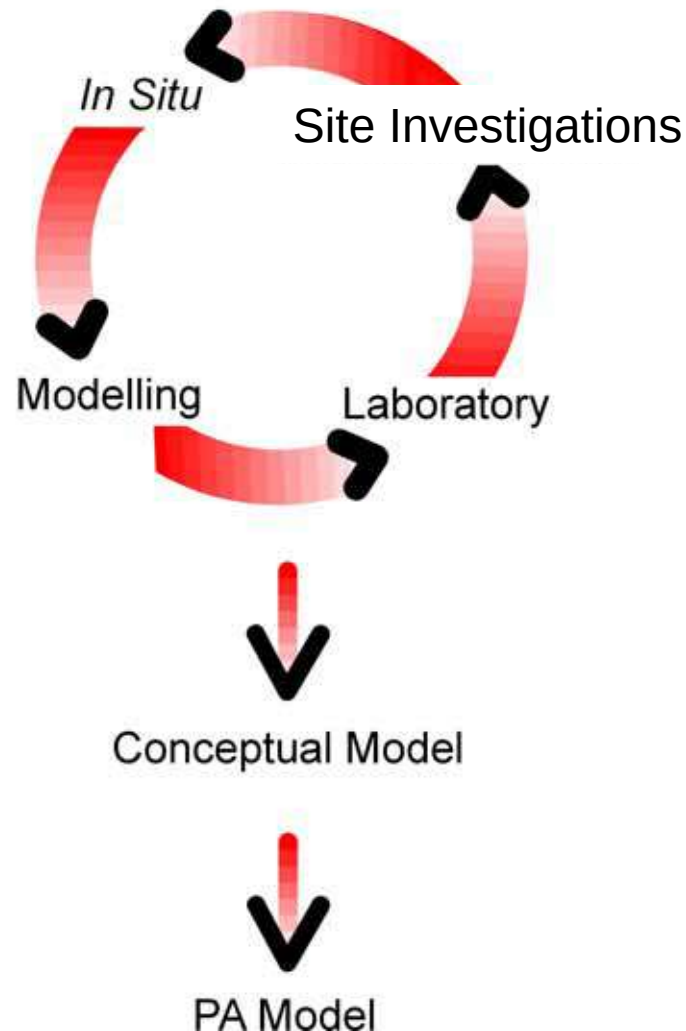
Transmissivity vs. Dilatometer pressure



Conclusion field experiment No. 2

- It is obvious that the transmissivity shows an significant reduction (nearly two order of magnitude) after the start of the dilatometer test.
 - 1.05 E-10 (Test PW 1) $\Rightarrow$ 1.0 E-12 (Test PW 8)
- The reduction with time is comparable with the in-situ test No. 1.
- The reduction is related to the applied dilatometer pressure.
- The assumed selfhealing effect/process combined with a significant reduction in axial transmissivity has been proven with the performed dilatometer test.

Recommendation – Closing the circle



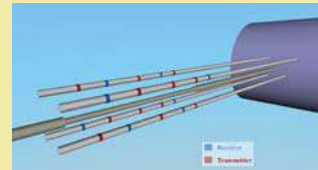
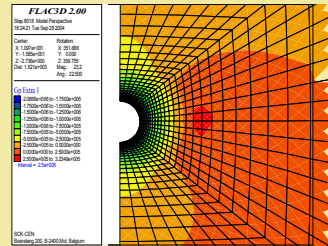
**Integration, comparison
and link between
laboratory, modeling,
in-situ testing and site
investigations**

Looking forward to

- **Workshop**
- **Final report of
the Selffrac experiment**

SELFRACT: in-situ tests and observations at HADES

Wim Bastiaens – Mol – 4th October '04



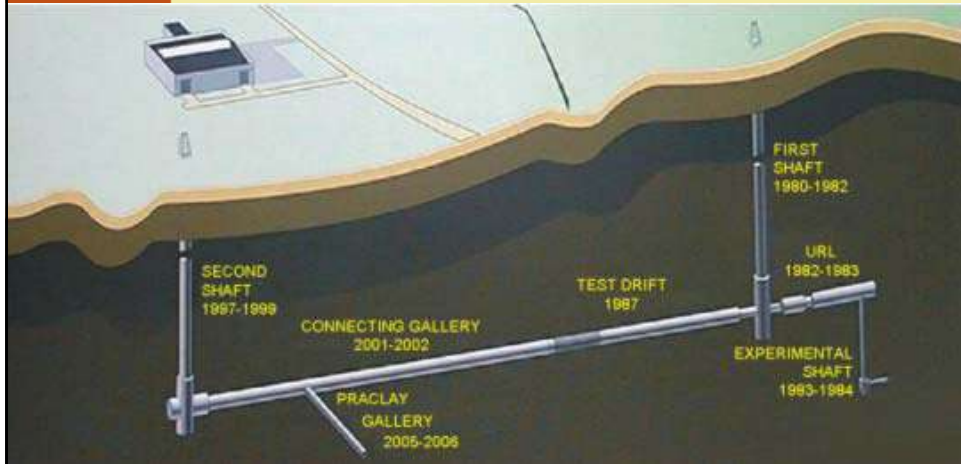
Overview

- Intro
 - HADES
 - Connecting gallery
- EDZ around the CG (in-situ 3)
 - Fractures (observations & cores)
 - Mechanical parameters (SBPT)
 - HDZ (pp & k)
- Seismic & acoustic measurements (in-situ 4)
 - around a collapsing borehole
 - in a re-installed core



Intro: Hades

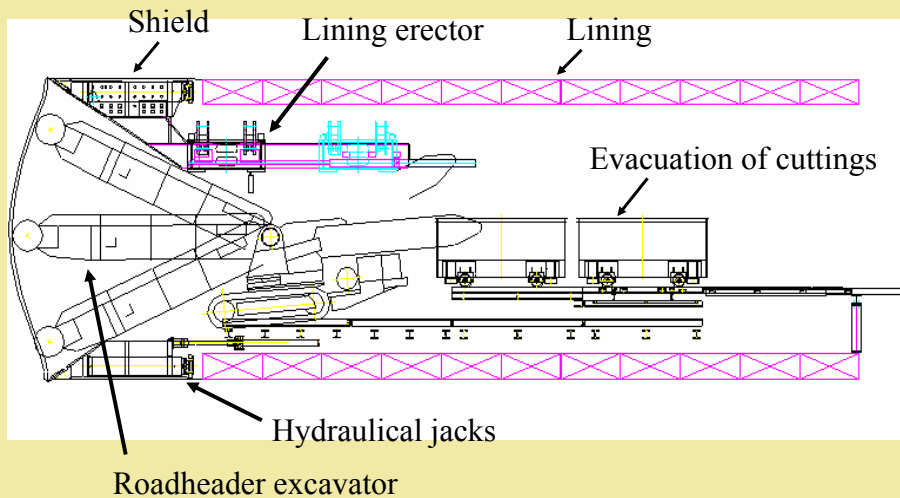
Boom Clay: 180m – 280m * HADES: 223m



Intro: connecting gallery

- External diameter: 4.8m
- Internal diameter: 4.0m
- Length: ~90m
- Depth: -223m
- Duration:
 - Mounting chamber: Aug'01 – Sep'01
 - Connecting gallery: Jan'02 – Mar'02
- Limit convergence (9 cm, < 4%)

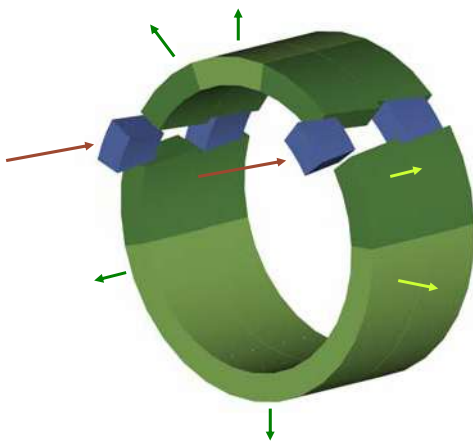
Intro: connecting gallery



Intro: connecting gallery



Intro: connecting gallery



SCK·CEN

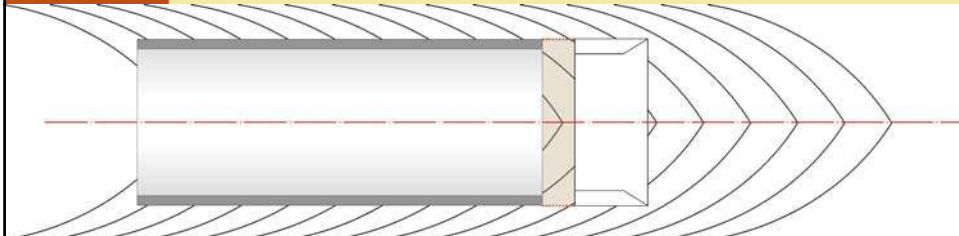
EDZ around CG: fractures

- Fracture observation:
 - Front
 - Sidewalls (unsupported zone)
 - Consistent fracture pattern
 - Except begin (shaft) and end (Test Drift)
 - No pre-existing fractures observed



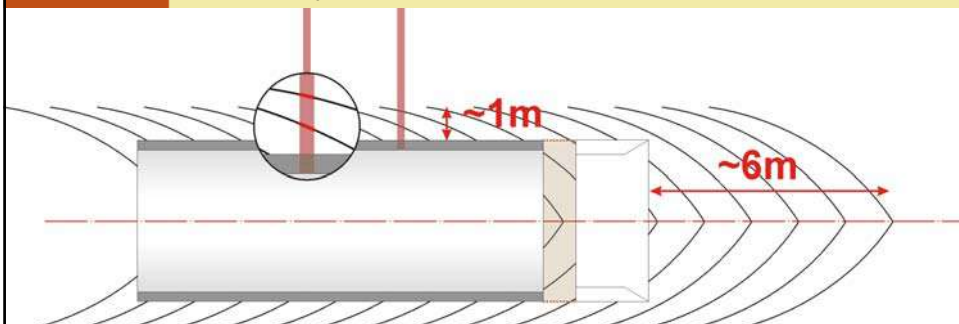
EDZ around CG: fractures

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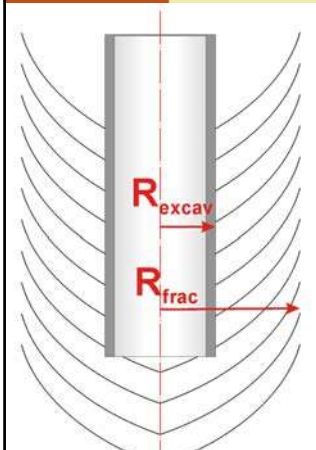
EDZ around CG: fractures

- EXTENT
 - Radial: ~1 m
 - cored boreholes (some local “healing”)
 - Axial: ~6 m
 - Observations (near Test Drift) & modelling
- SHAPE
 - $K_0 < 1$



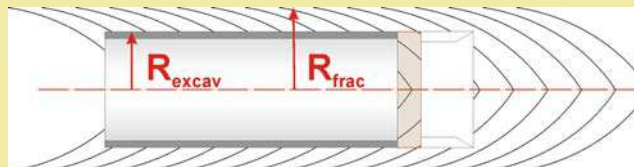
EDZ around CG: fractures

- Extent = f (convergence)
- CG vs. second shaft:
 - Similar shape (not same)
 - Different extent (cf. convergence)



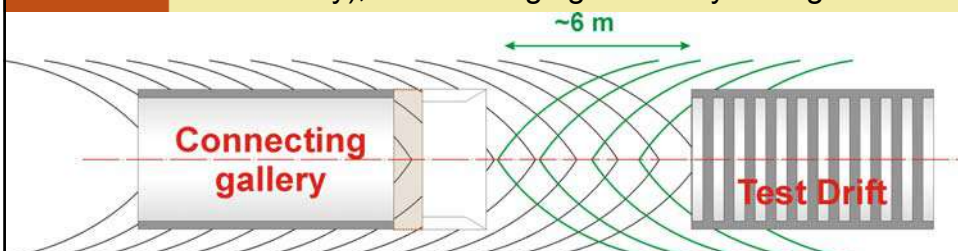
$$\text{2nd shaft: } \frac{R_{frac}}{R_{excav}} = 2.4$$

$$\text{Connecting gallery: } \frac{R_{frac}}{R_{excav}} = 1.4$$



EDZ around CG: fractures

- Connecting gallery vs. Test Drift:
 - Similar pattern: mirror
 - ~6 metres
 - Oxidation only in last metre:
 - Sealing
 - Re-activation => only partial healing (if any); but converging and dehydrating front



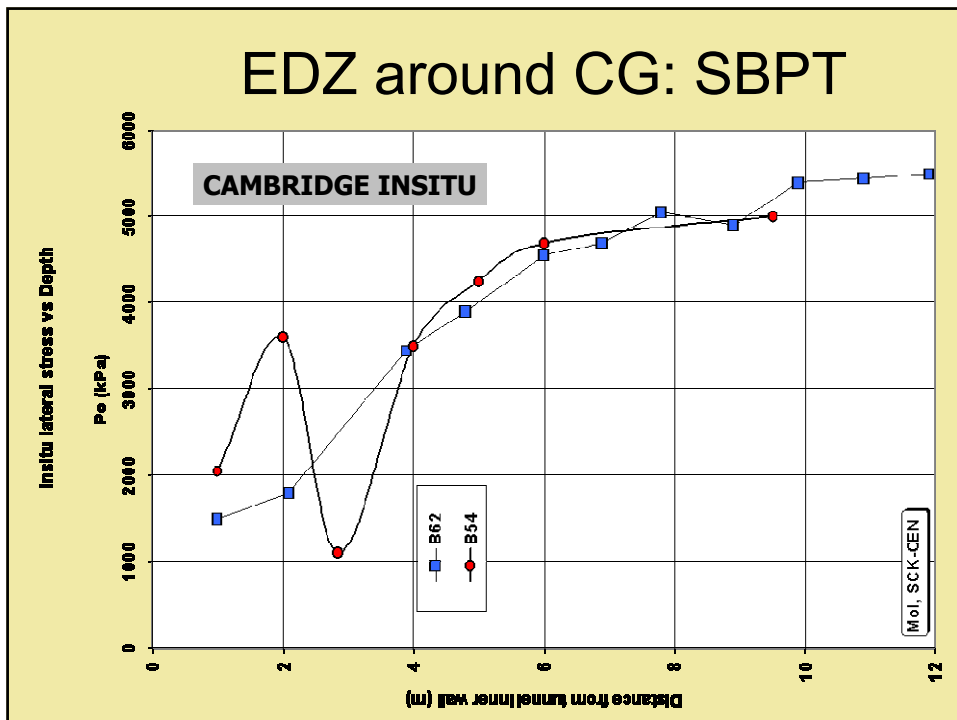


EDZ around CG: SBPT



EDZ around CG: SBPT

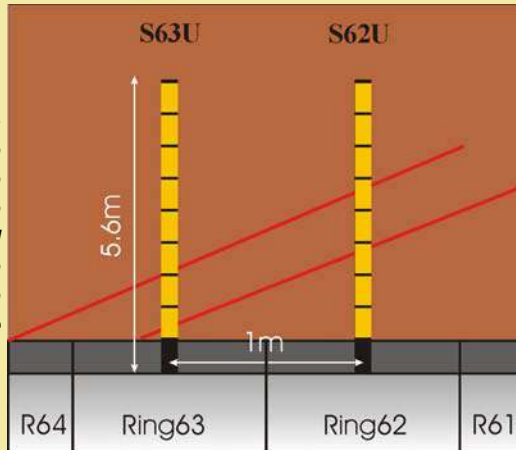
- 2 tests (by Cambridge insitu, UK)
 - April 2002 (CG finished March 2002)
 - August 2004 (T3: ??)
 - Both eastward, ~20m distance
 - Same test procedure, same analysis
- Conclusions: cf. comparison 2 tests
 - In-situ stress has risen in first meters
 - Other parameters (shear strength, shear modulus, ...) appear to be unchanged: high repeatability
 - $K_0 \sim 0.9$ (caution...)
 - EDZ/EdZ (M) ~ 6-8 m (roughly)



EDZ around CG: HDZ, pp

- Piezometers
 - Several locations, lengths, orientations
 - Example:

Diameter: 60mm
Drilling diameter: 75mm
Length: 5.6m
Distance: 1.0m
Vertically upward
Test interaction
Test inter-connection
Small intervals: fracture

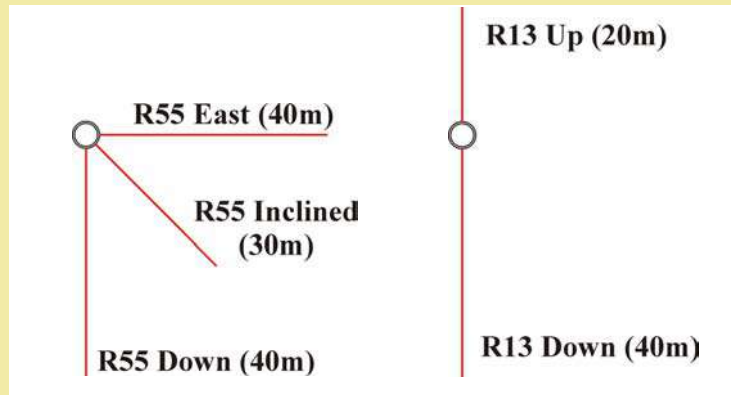


EDZ around CG: HDZ, pp

- Results:
 - Interaction:
 - Strong HM coupling (cf. EC CLIPEX, ...):
 - pore pressure change at one filter influences other filters
 - Inter-connection:
 - No evidence of connected fracture network:
 - gradual influence
 - piezometers “sealed off” from atmosphere from 60cm into host rock (cf. later)

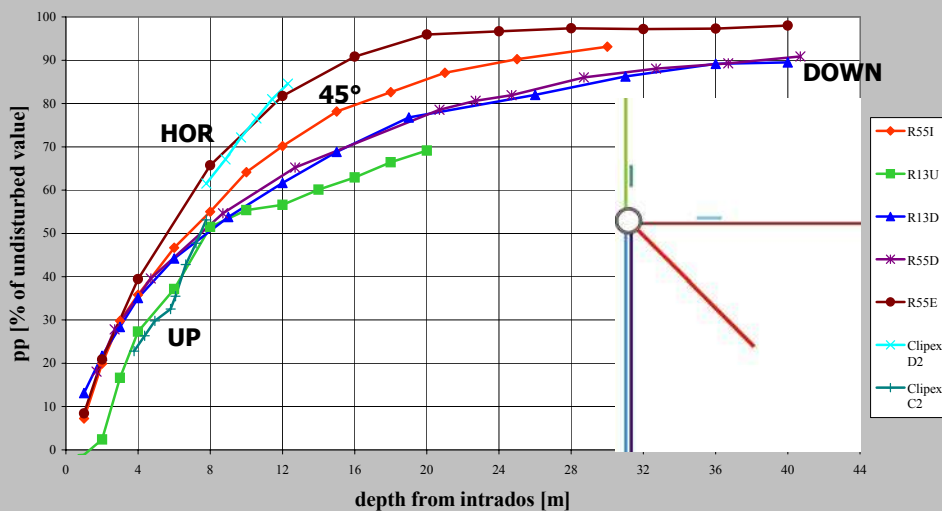
EDZ around CG: HDZ, pp

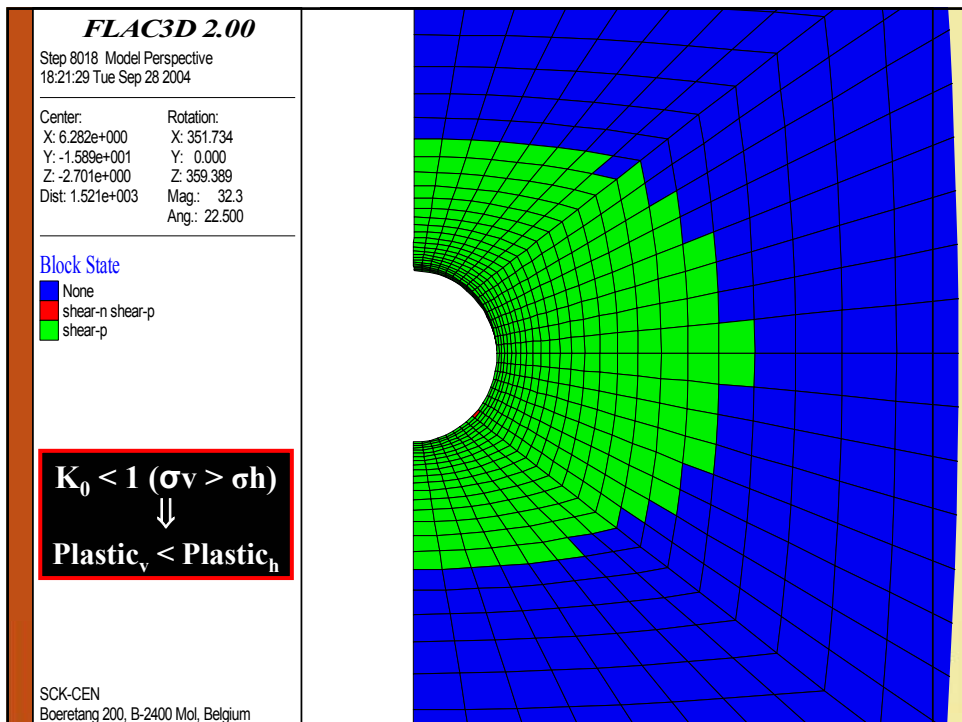
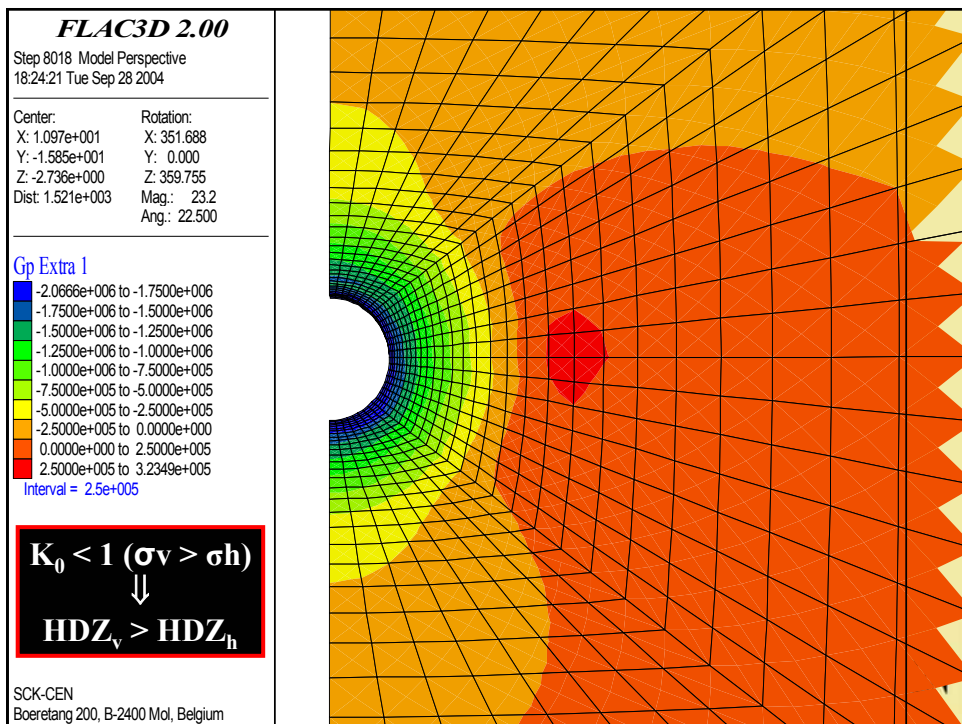
- Pore water pressures



EDZ around CG: HDZ, pp

pp profiles 15-sep-04 (in-situ @ filter)

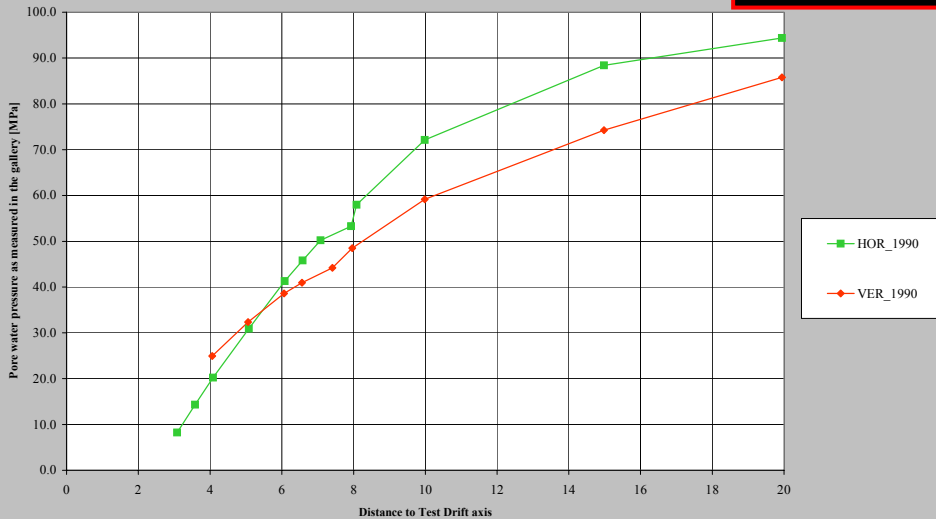




EDZ around CG: HDZ, pp

Comparison pp ring 41&48 TD: Horizontal vs. vertical

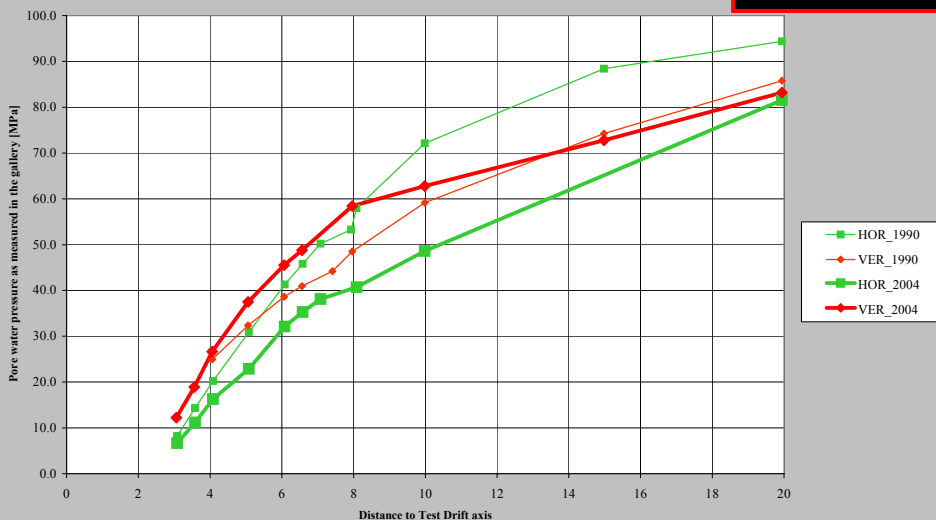
**Test Drift
Excavated: 1987**



EDZ around CG: HDZ, pp

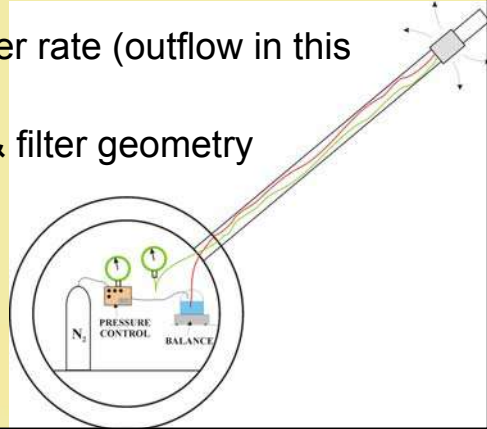
Comparison pp ring 41&48 TD: Horizontal vs. vertical

**Test Drift
Excavated: 1987**



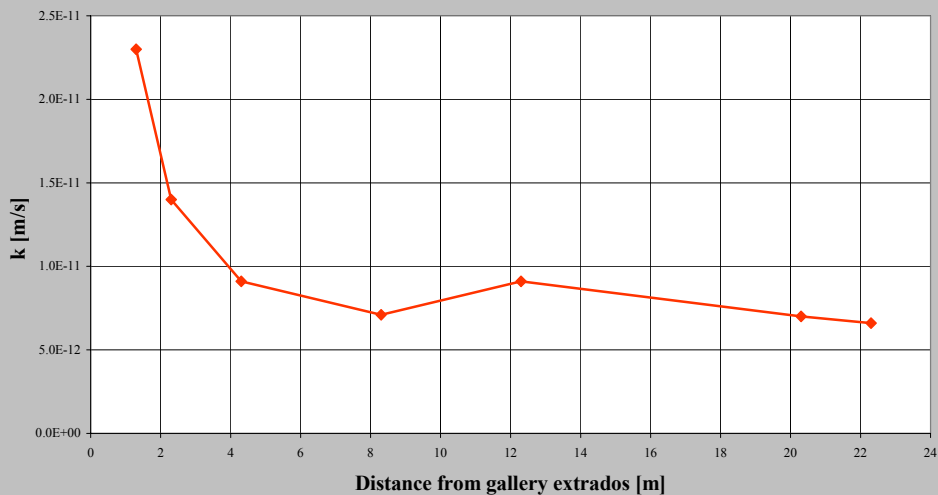
EDZ around CG: HDZ, k

- Steady state k-measurements
 - Apply constant pressure at piezometric filter
 - Measure water rate (outflow in this case)
 - Darcy's law & filter geometry
 - k-value [m/s]



EDZ around CG: HDZ, k

Hydraulic Conductivity measured at R55Down



EDZ around CG: HDZ

- Pore water pressures:
 - ANISOTROPY
 - $\sigma_v > \sigma_h$
 - HDZ is larger in a vertical cross section
 - » Measurements
 - » Model
 - » Analytical (elastic model)
 - Plastic zone is larger in a horizontal cross section
 - » Model
 - » Analytical (elastic model)
 - $k_h > k_v$
 - HDZ-shape “inverts” on long term (~5 à 10 y)
 - Pressure build up from 60cm into host rock
 - Strong coupling/interaction
 - Hydraulic conductivity
 - Influenced zone ~6 m (cf. stress state, decompression)
 - Undisturbed value (k_H) $\sim 6 \cdot 10^{-12}$ m/s



Seismic and acoustic

- Performed by GMuG (D)
- Monitoring of uncased central borehole using seismic and acoustic emission measurements.
- Later on, the acoustic properties should recover due to reconsolidation of the host rock around the collapsed borehole.
- Long-term seismic cross-hole and down-hole measurements
- Monitoring acoustic properties of re-installed clay core

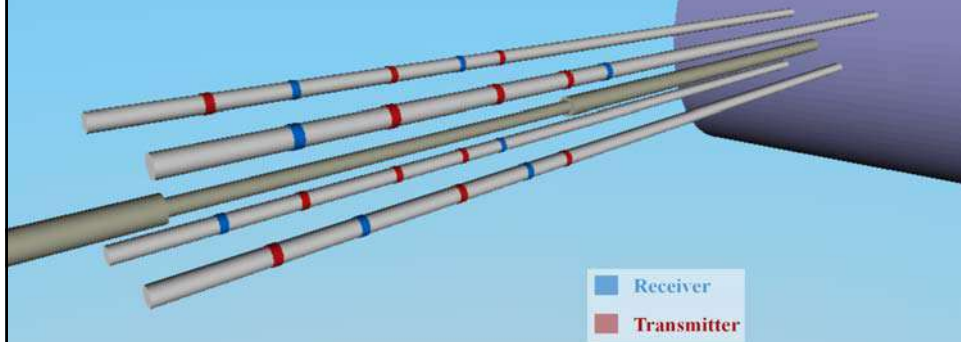


Seismic and acoustic

COLLAPSING BOREHOLE

Phase 1: instrumented boreholes (Dec '03)

Phase 2: central borehole (June '04)

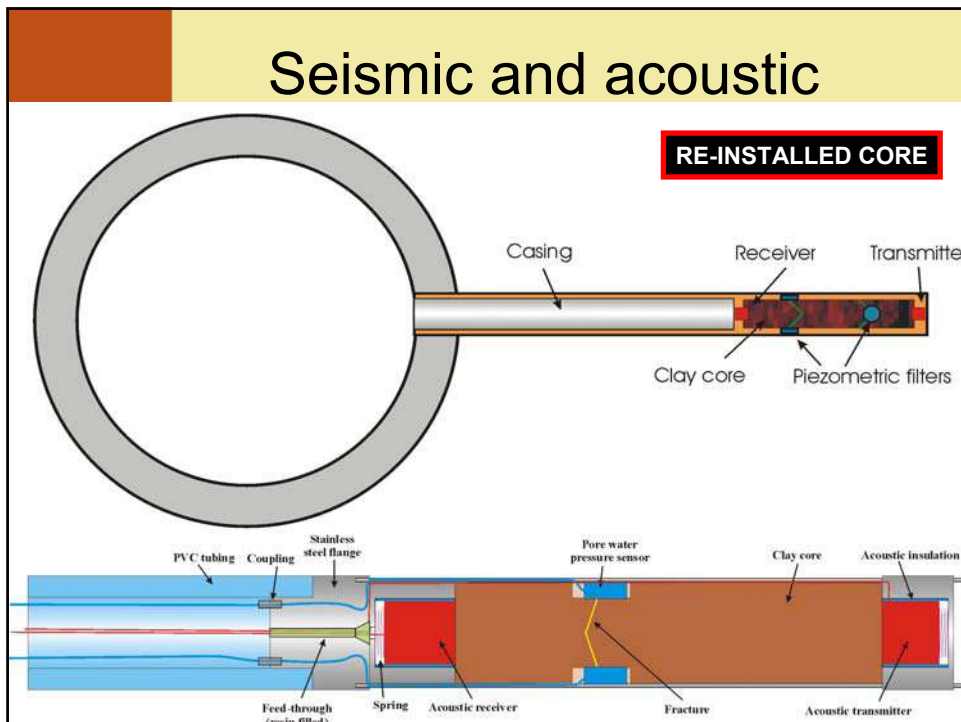
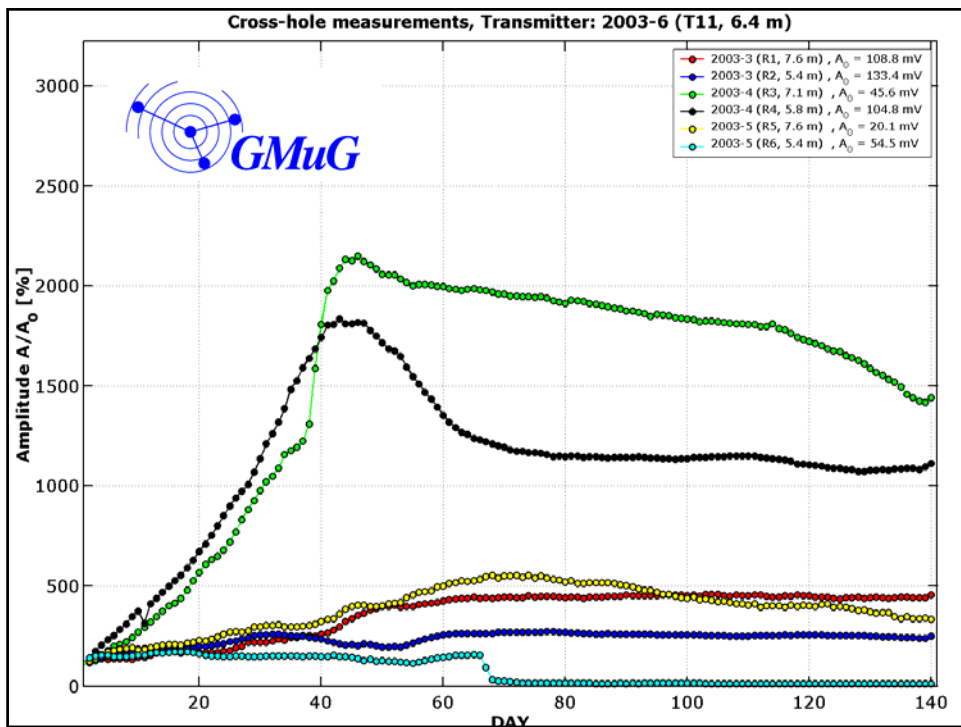


Seismic and acoustic

RESULTS

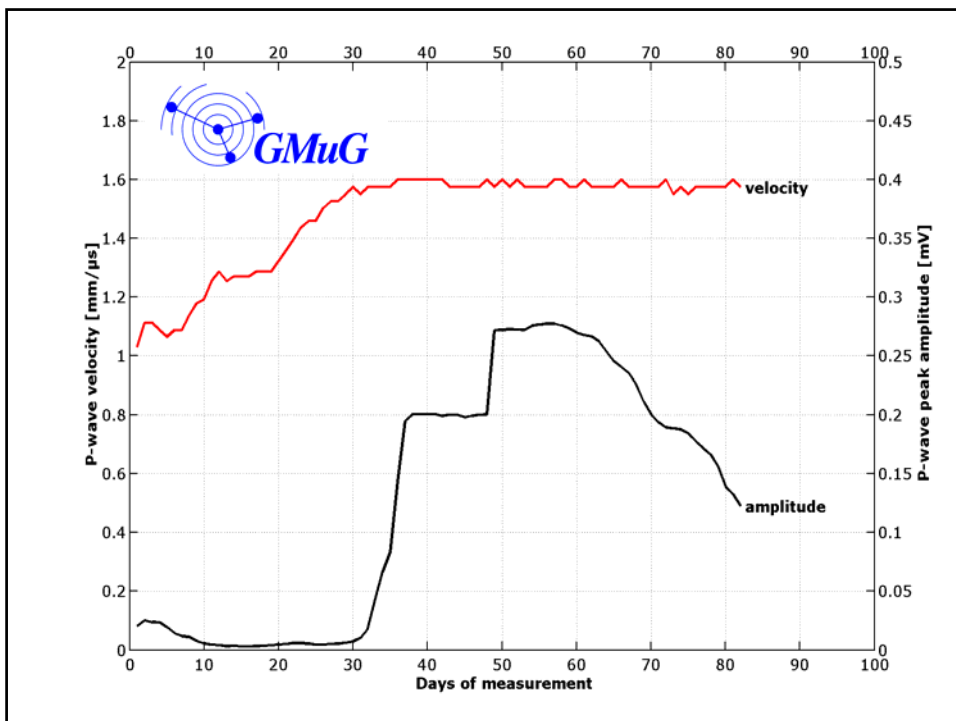
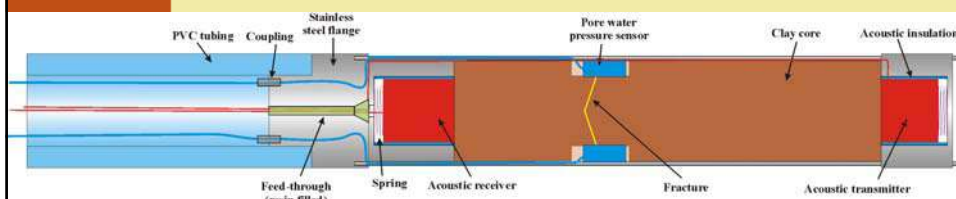
- Phase 1:
 - Seismic measurements:
 - Seismic velocity ~ constant (from 1.7 to 2.0 m/ms)
 - Increase of seismic amplitudes during first seven weeks
 - Sudden changes of amplitudes were observed: may indicate crack growth in the neighborhood of these sensors (site effect; local).
 - Acoustic emission measurements
 - Strong events where all channels were hit were located
 - Many low-frequency events: artificial ?
 - Few high-frequency events: cracks ?
- Phase 2:
 - In progress





Seismic and acoustic

RE-INSTALLED CORE



CONCLUSIONS (1/2)

- Acoustic & seismic measurements
 - Seismic velocity 1.7 – 2.0 m/ms
 - “Stabilisation” period: restoration of acoustic properties
 - Amplitudes increase (main test)
 - Velocity/amplitudes increase (core test)
 - Some features remain un-explained:
 - e.g. decreasing amplitudes
 - AE events:
 - Many “artificial”
 - Some cracks ?
 - Interpretation is ongoing



CONCLUSIONS (2/2)

- EDZ around the CG
 - Fractures extent ~1m (radially)
 - Mechanical EdZ/EDZ: ~6-8m, “stable” after some months
 - HDZ
 - Large HDZ, up to 40m
 - Anisotropy of σ en k !!!
 - Initially: HDZ VERT = MAX
 - Over time: HDZ HOR = MAX
 - Hydraulic conductivity
 - Influenced zone ~6m
 - $k_H \sim 6 \cdot 10^{-12}$ m/s
- $K_0 < 1$
 - SBPT
 - fracture shape
 - HDZ (in-situ, model, analytical)





SELFRACT Project

Laboratory tests to characterize Sealing/Healing process

Chanchole S., De Greef V., Hamza R.,
Malinsky L.



Plan

- Overview of the experimental programm
- Experimental results
- Constitutive modelling



Overview of the experimental programm

- Characterization of Initial permeability (pulse tests)
- Tensile test (healing)
- Long-term permeability tests on hollow cylinders (in finalization)
- Mock-up test (hollow cylinder) (in progress)



Initial Permeability Pulse tests

- Confinement 4.5MPa P_{inj} 2Mpa
- Mol $k = 2 \times 10^{-19} \text{ m}^2$
- Mont Terri

$4-6 \times 10^{-20} \text{ m}^2$ $\perp$ to the bedding plane

$1-5 \times 10^{-19} \text{ m}^2$ $//$ to the bedding plane

(anisotropy /material heterogeneity ?)



Tensile Test

- Boom sample 60x120mm
- Tensile failure stress 0.2MPa
- a 0.5MPa normal stress applied during 10 days on the wetted fracture plane
- No cohesion recovery

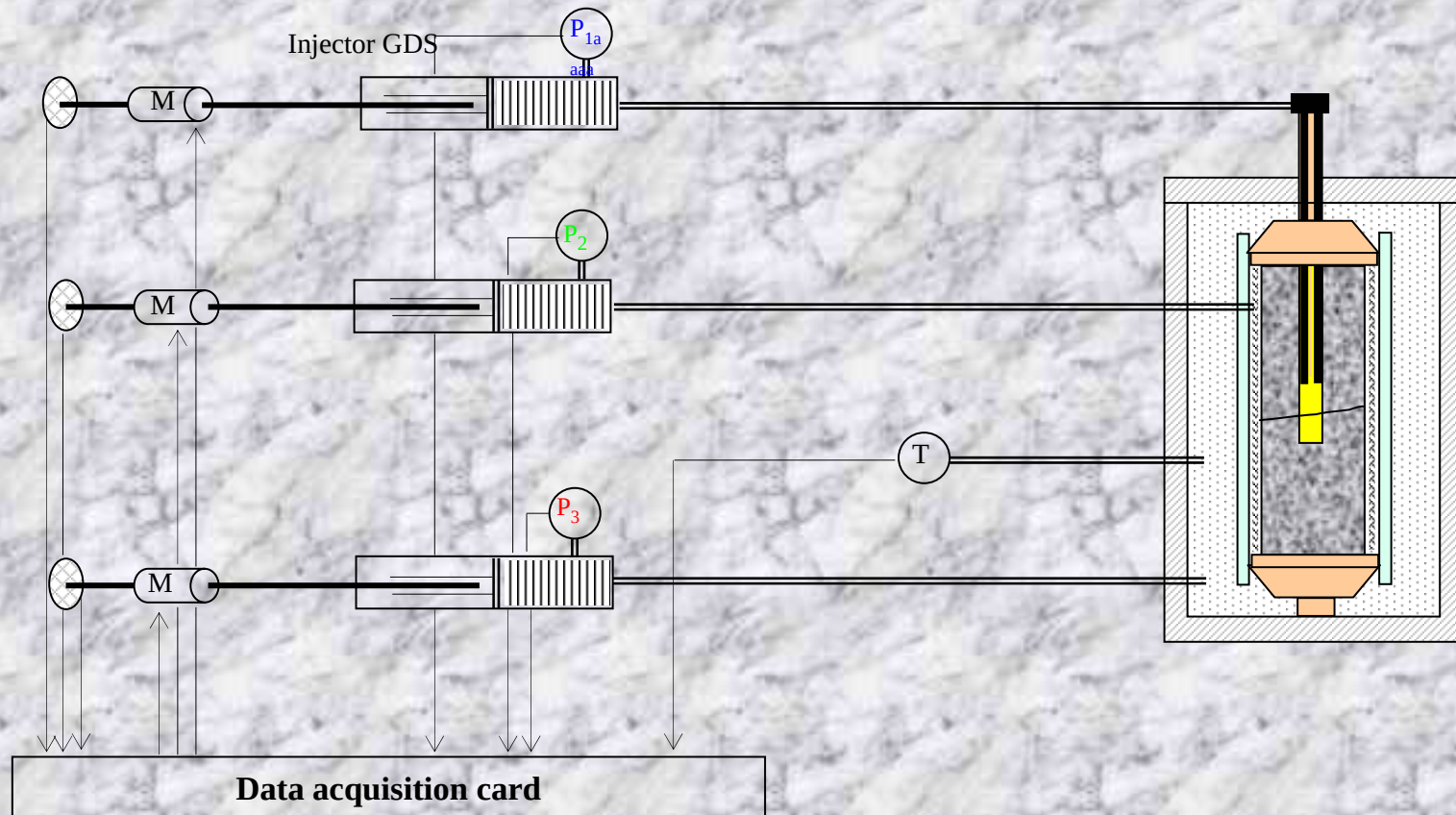


Permeability test on hollow cylinder

- 50x100mm, cavity radius 2-4mm
- Steady state flow
- Longs duration (up to 9 months)
- Various hydromechanical paths (confinement pressure, inner and outer pore pressure, deviatoric stress)

Permeability tests on hollow cylinders

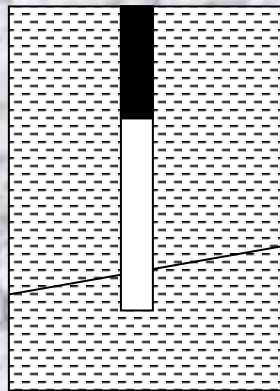
Experimental set-up



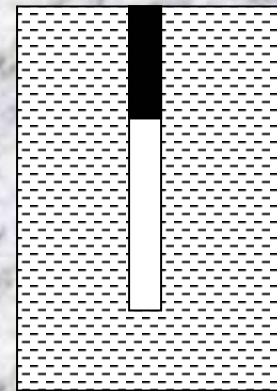


Permeability tests on hollow cylinders

2 types of tests in order to evaluate the effect of one discontinuity and the sealing/healing process



Sample with an initial radial fracture



Intact Sample



Permeability computation

Homogeneous sample



Steady state flow assumption

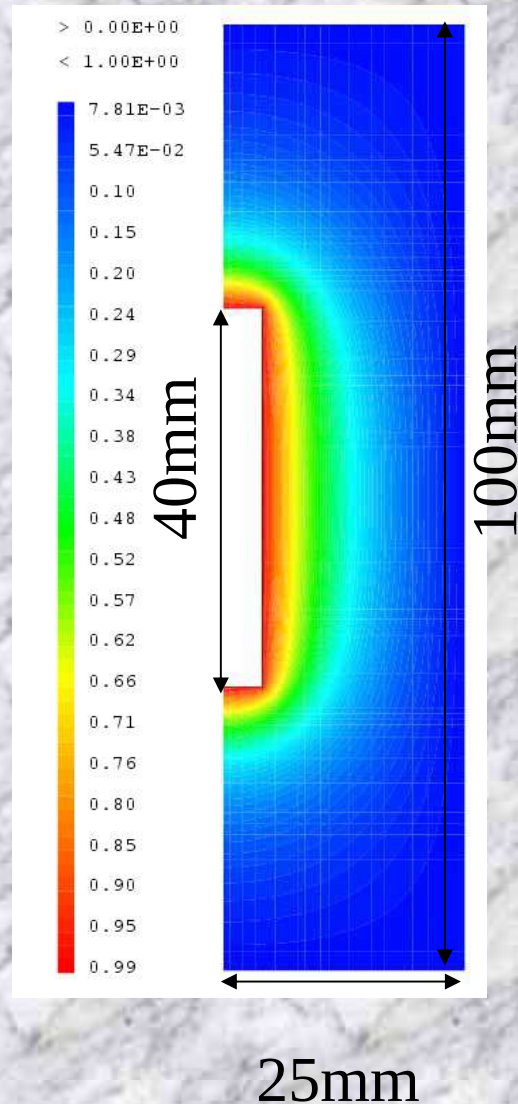
$$Q = k \frac{\Delta P}{\eta} L$$

Q : total flow rate

k : intrinsic permeability of
an homogeneous rock

L : characteristic length
numerically computed

ΔP : pore pressure difference





Permeability computation

Sample with a radial fracture



rock flow + fracture flow

$$Q = Q_r + Q_f$$

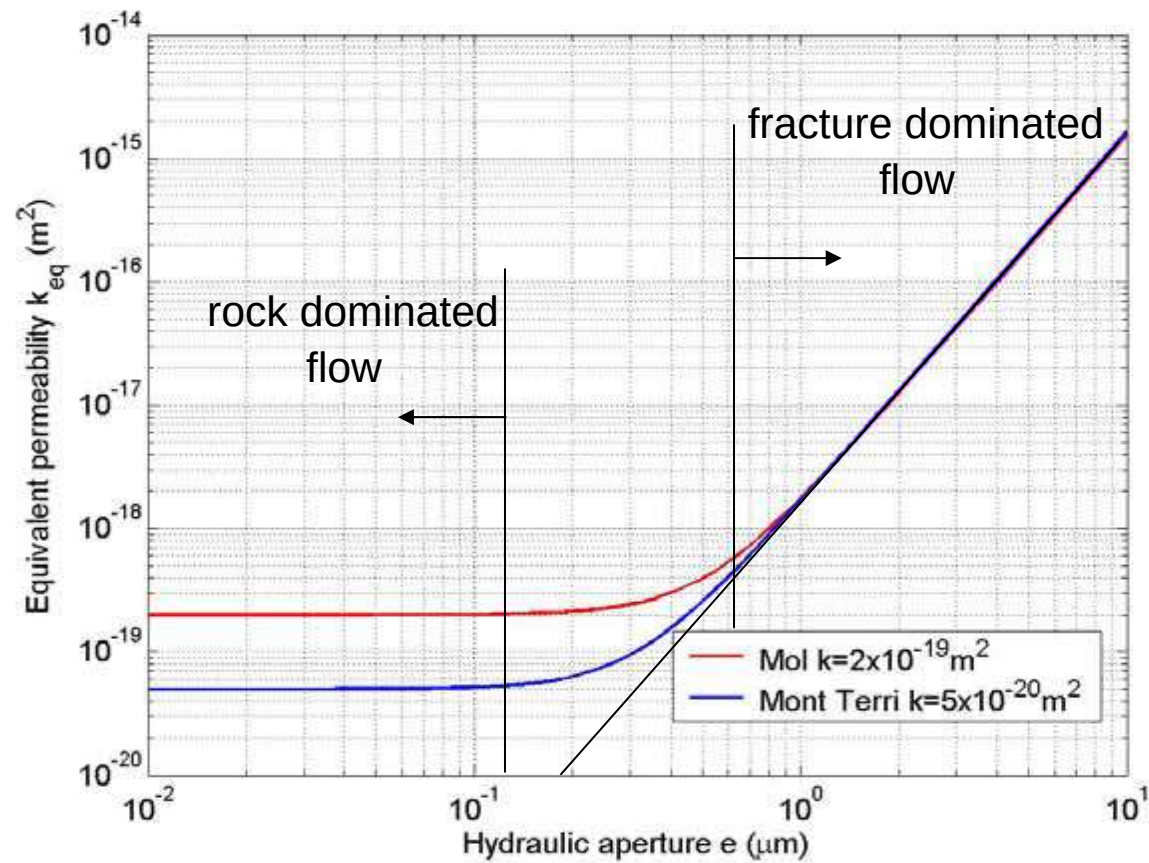
$$= \frac{\Delta P}{\eta} k L + \frac{\Delta P}{\eta} \frac{\pi}{6 \log\left(\frac{r_e}{r_i}\right)} e^3$$

$$= \frac{\Delta P}{\eta} k_{eq} L \quad \text{measured equivalent permeability}$$



Permeability computation

sample with a radial fracture





Permeability tests on hollow cylinders

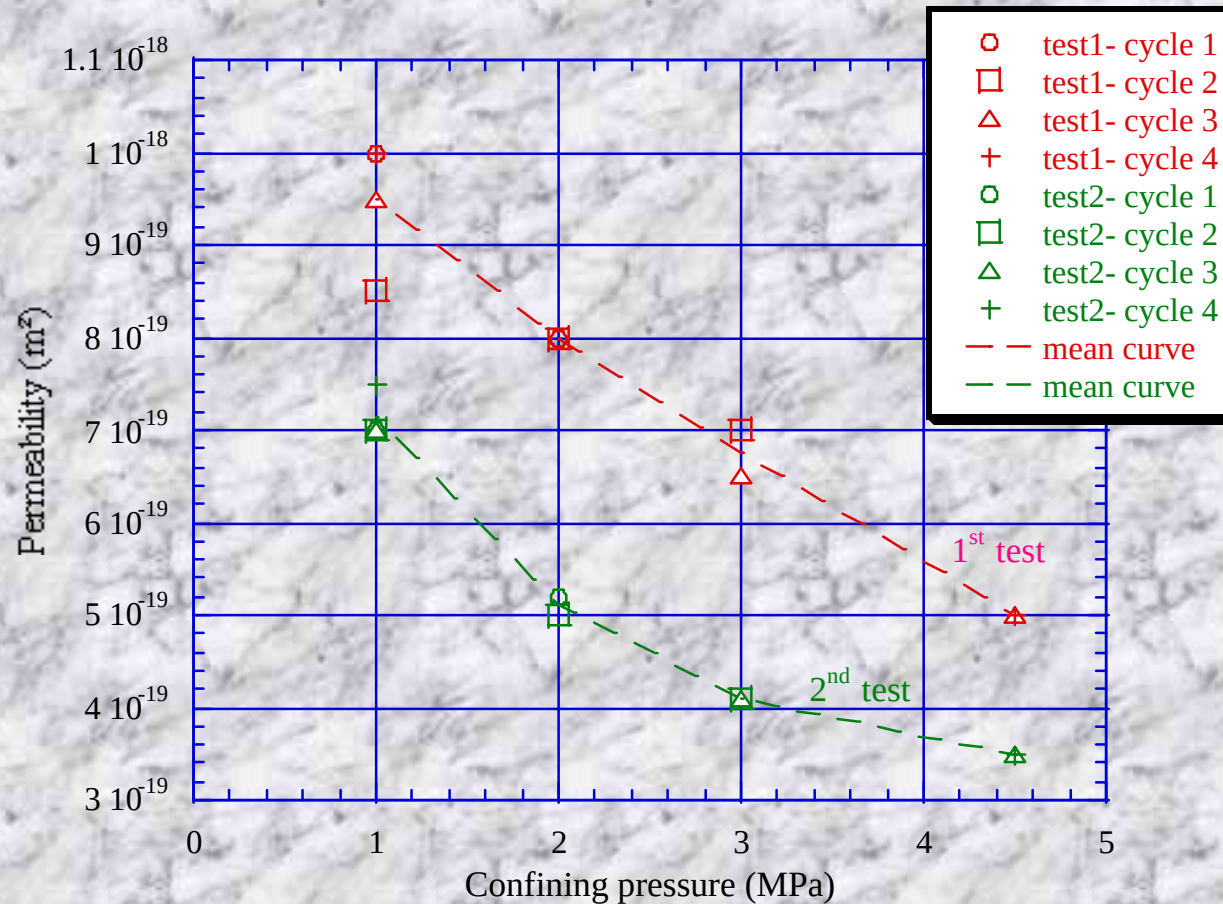
Results - Mol clay

- reversible/irreversible (contractancy) effect of effective pressure on permeability
- no irreversible permeability increase after hydraulic fracturation : evidence of self-sealing. (see also MEGAS experiment Ortiz and al.1995)



Permeability tests on hollow cylinders

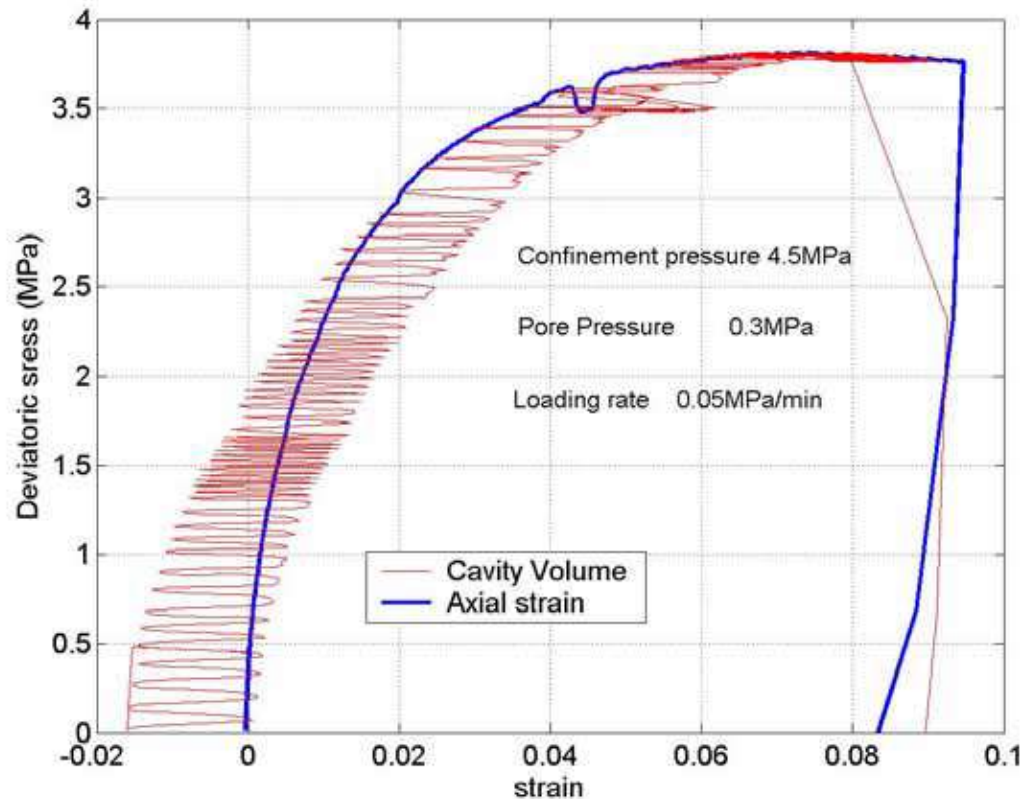
Mol



Reversible effect of confing pressure

Permeability tests on hollow cylinders

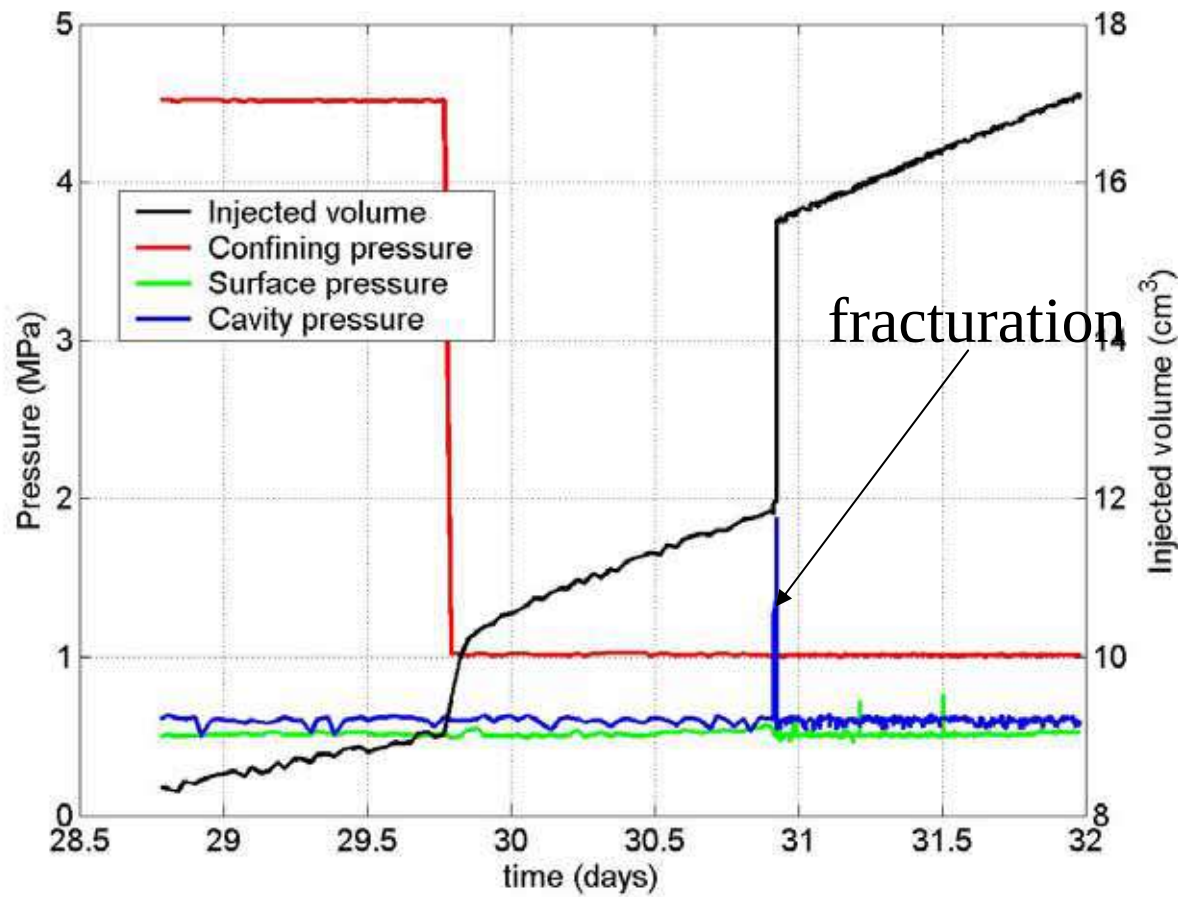
Mol – shearing stage (contractant behavior)



⇒ irreversible decrease of permeability
($k=2 \times 10^{-19} \text{m}^2$ during 20 days)

Permeability tests on hollow cylinders

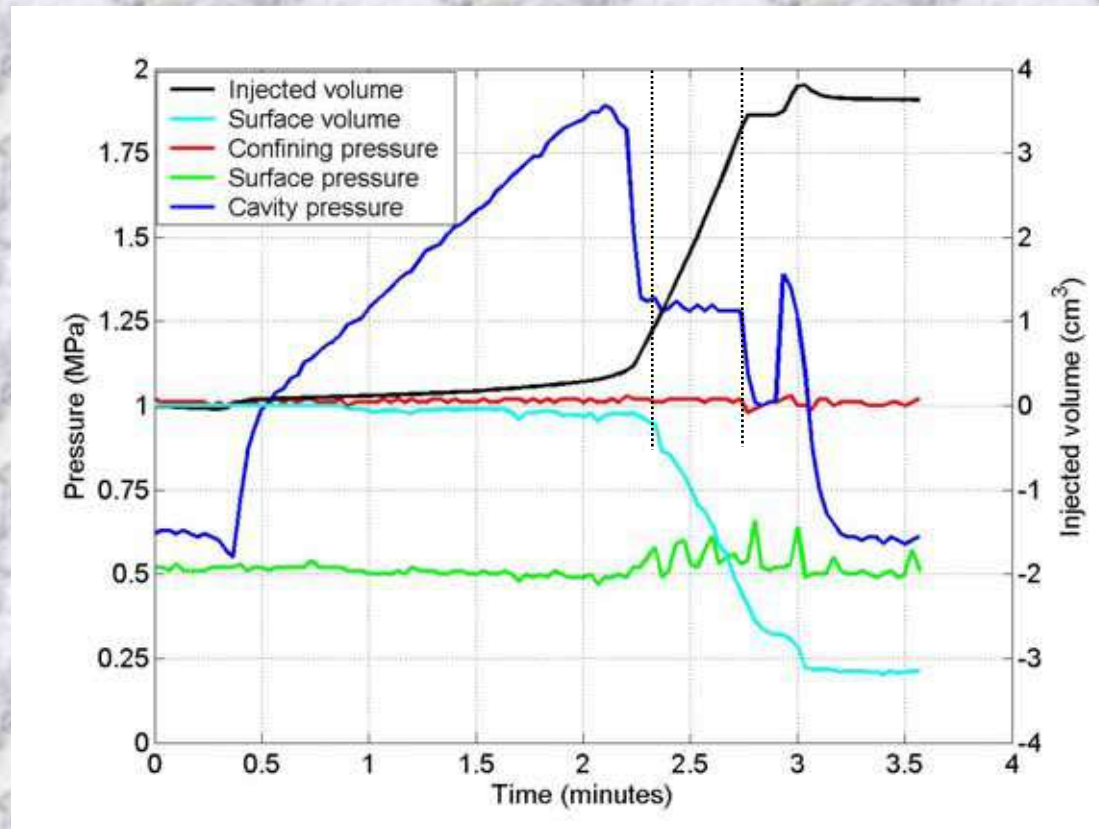
Mol





Permeability tests on hollow cylinders

Mol – Hydraulic fracturation stage



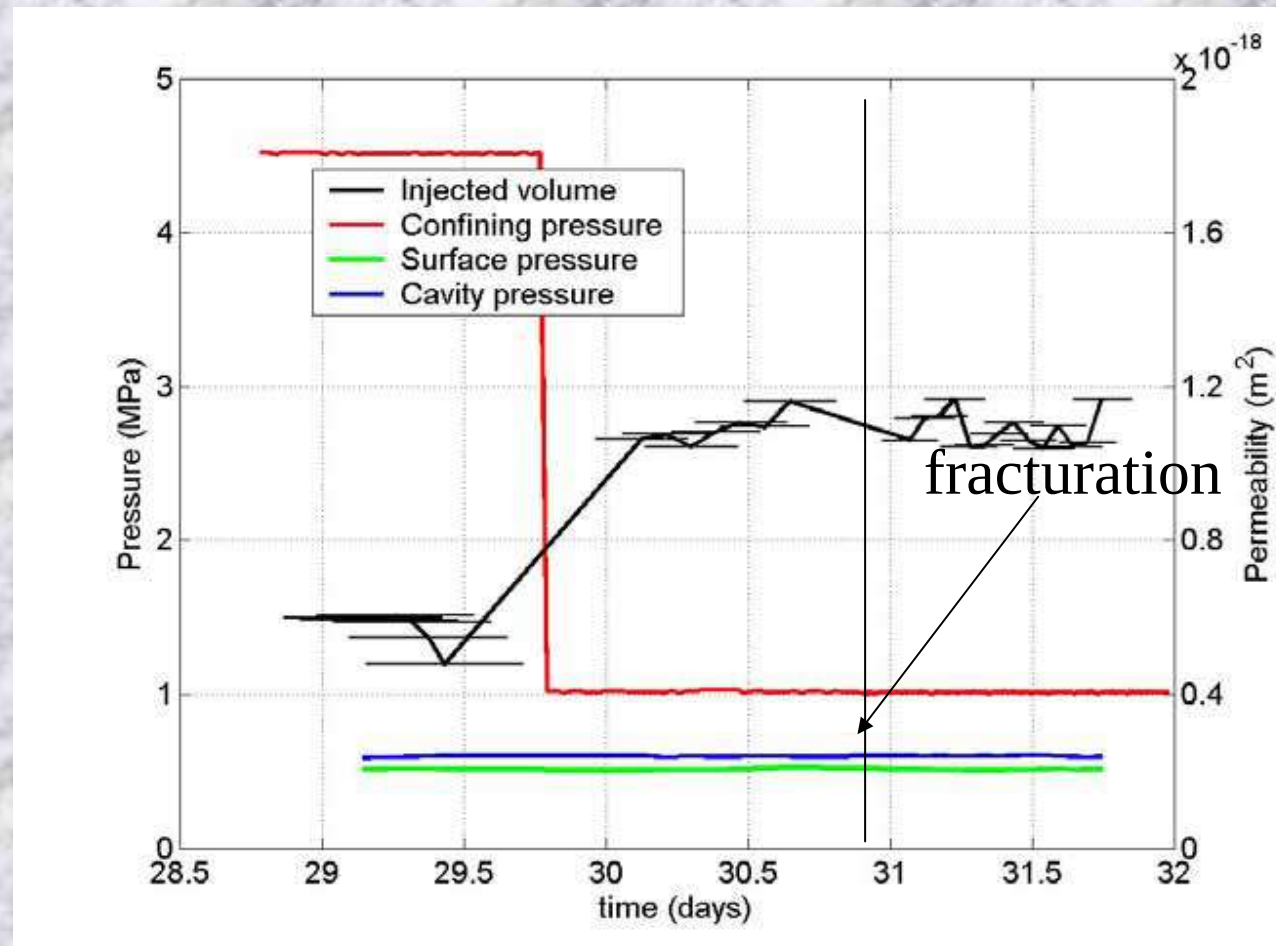
Steady state flow after fracturation

$$k_{eq} = 7 \times 10^{-16} \text{ m}^2 \quad e = 8 \mu\text{m}$$



Permeability tests on hollow cylinders

Mol – Hydraulic fracturation stage



no irreversible effect of fracturation on permeability (self-sealing)



Permeability tests on hollow cylinders

Mol clay sample after dismantling





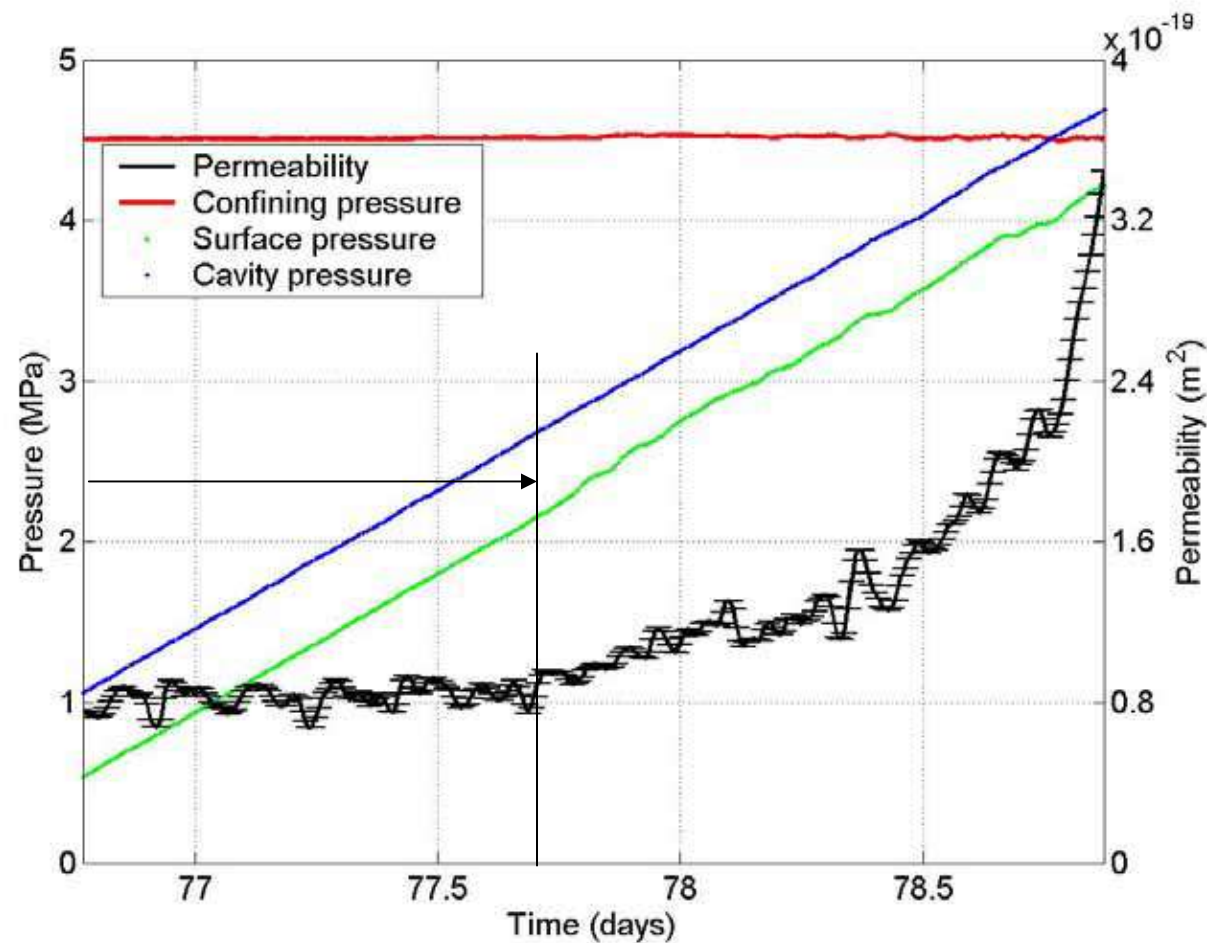
Permeability tests on hollow cylinders

Results – Mont Terri clay

- in finalization
- Tests performed on samples with a radial fracture
- $k_{eq} = 5 \times 10^{-20} \text{ m}^2 \rightarrow 5 \times 10^{-19} \text{ m}^2$ ($e=0 \rightarrow 0.7 \mu\text{m}$ if $k=5 \times 10^{-20}$ is assumed. transition from rock dominated flow to fracture dominated flow?)
- decrease of permeability according to time by a factor 5 in 95 days (fracture self-sealing?)
- Self-healing ? (to confirm after dismantling)
- A test on an intact sample is planned in order to confirm these results

Permeability tests on hollow cylinders

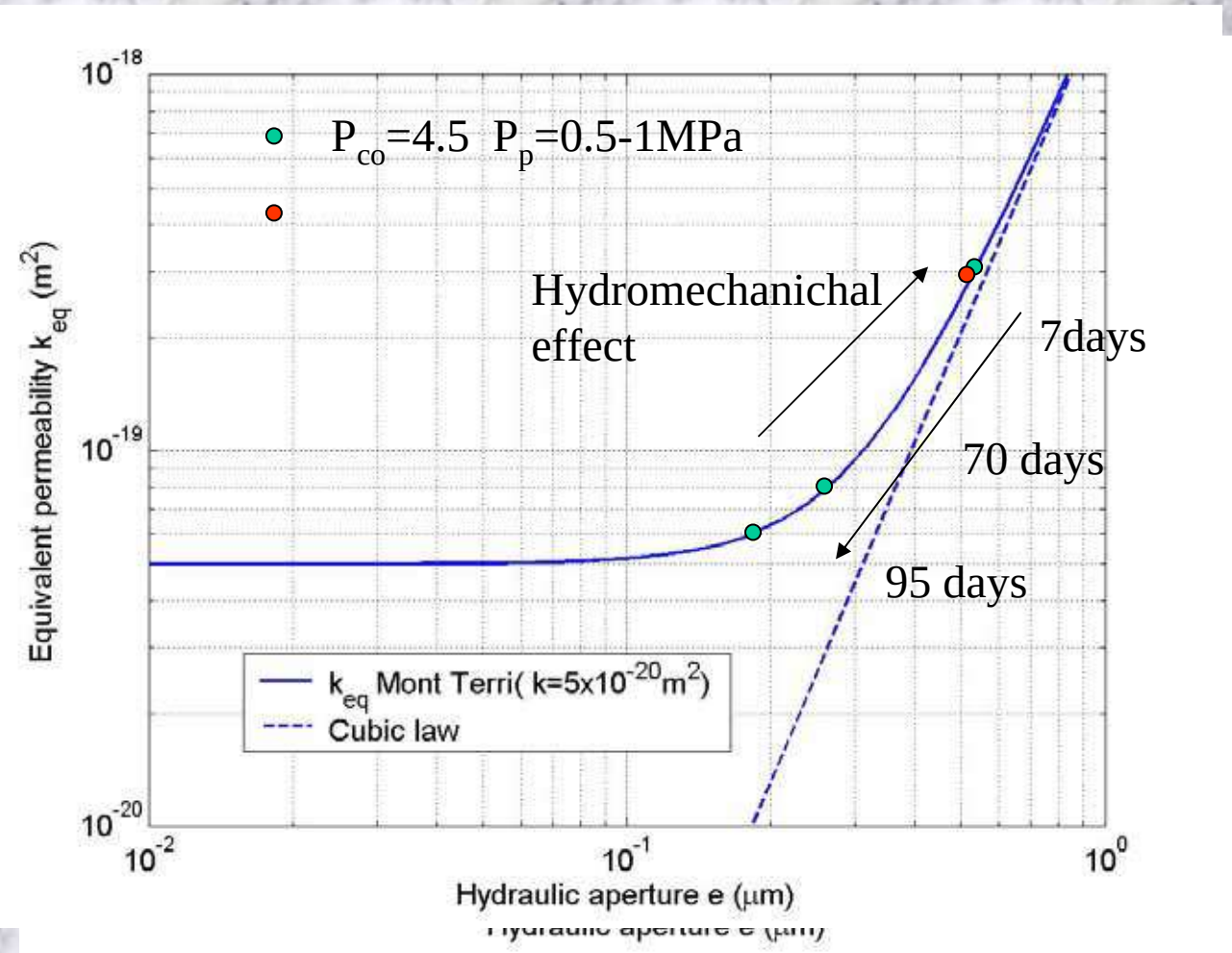
Results – Mont Terri clay



Hydromechanical effect

Permeability tests on hollow cylinders

Results – Mont Terri clay





Constitutive modelling

identified mechanism	model
• Consolidation • time effect • swelling • Dissolution/cristallization	x x (x) indirect



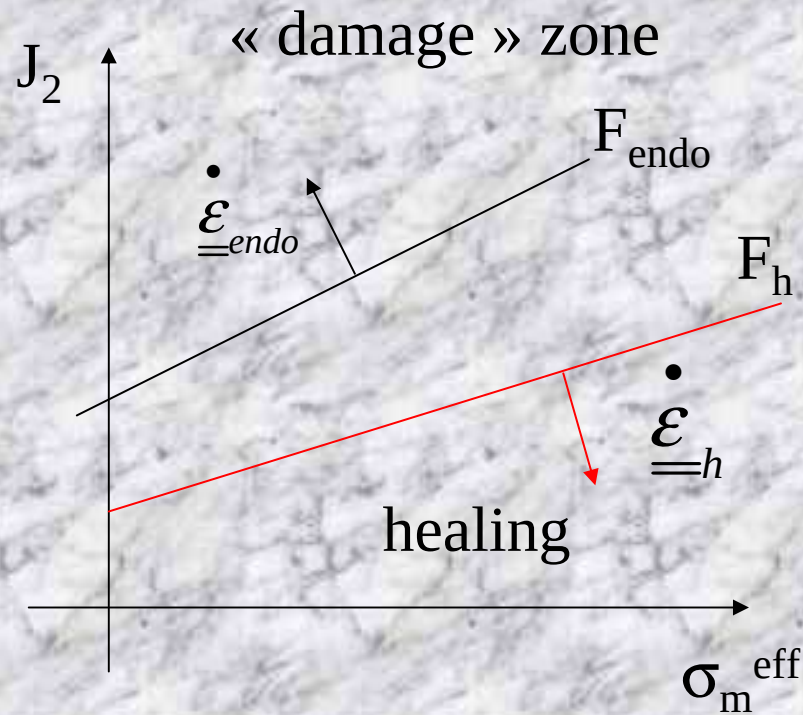
Constitutive modelling



modelling assumption

- Continuous porous medium
- Effective stress
- Introduction of a « healing strain »
- Strain/permeability coupling

Constitutive modelling



$$\underline{\underline{\epsilon}}_{=irr} = \underline{\underline{\epsilon}}_{=p} + \underline{\underline{\epsilon}}_{=vp} + \underline{\underline{\epsilon}}_{=h}$$

damage mechanisms

healing strain

$$\dot{\underline{\underline{\epsilon}}}_{=h} = -\frac{1}{\eta} \langle -F_h \rangle^n |\underline{\underline{\epsilon}}_{=irr}|^p \cdot \frac{\partial F_h}{\partial \underline{\underline{\sigma}}^{eff}}$$

$$k(\underline{\underline{\epsilon}}_{=irr}, \underline{\underline{\epsilon}}_{=e})$$



Laboratory tests to characterise the fracturation processes and Modelling

Part I: Conclusions on the experimental program

C. Coll, J. Desrues, C. Viggiani, P. Bésuelle

Acknowledgements: S. Marello & P. Charrier



Outline

- Experimental results (Cécile Coll)
 - Boom Clay
 - Opalinus Clay

- Modelling (J. Desrues)

- Conclusions & Perspectives

Experimental devices



Biaxial Cell



Triaxial Cell



Control of temperature

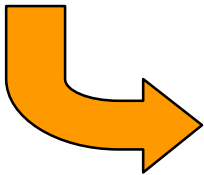


Local strain measurements



Overview of tests on Boom Clay

- Uniaxial compression tests + Triaxial compression tests
- Isotropic Compression
- Triaxial extension test
- *Tests with constant deviatoric load*
- Biaxial (plane strain compression) tests



- Volumetric behaviour under isotropic and deviatoric conditions
- Behaviour at failure
- Characterisation of fracturation (cracks type, propagation)
- Permeability evolution

Triaxial tests on Boom Clay (1)

□ *Isotropic conditions*

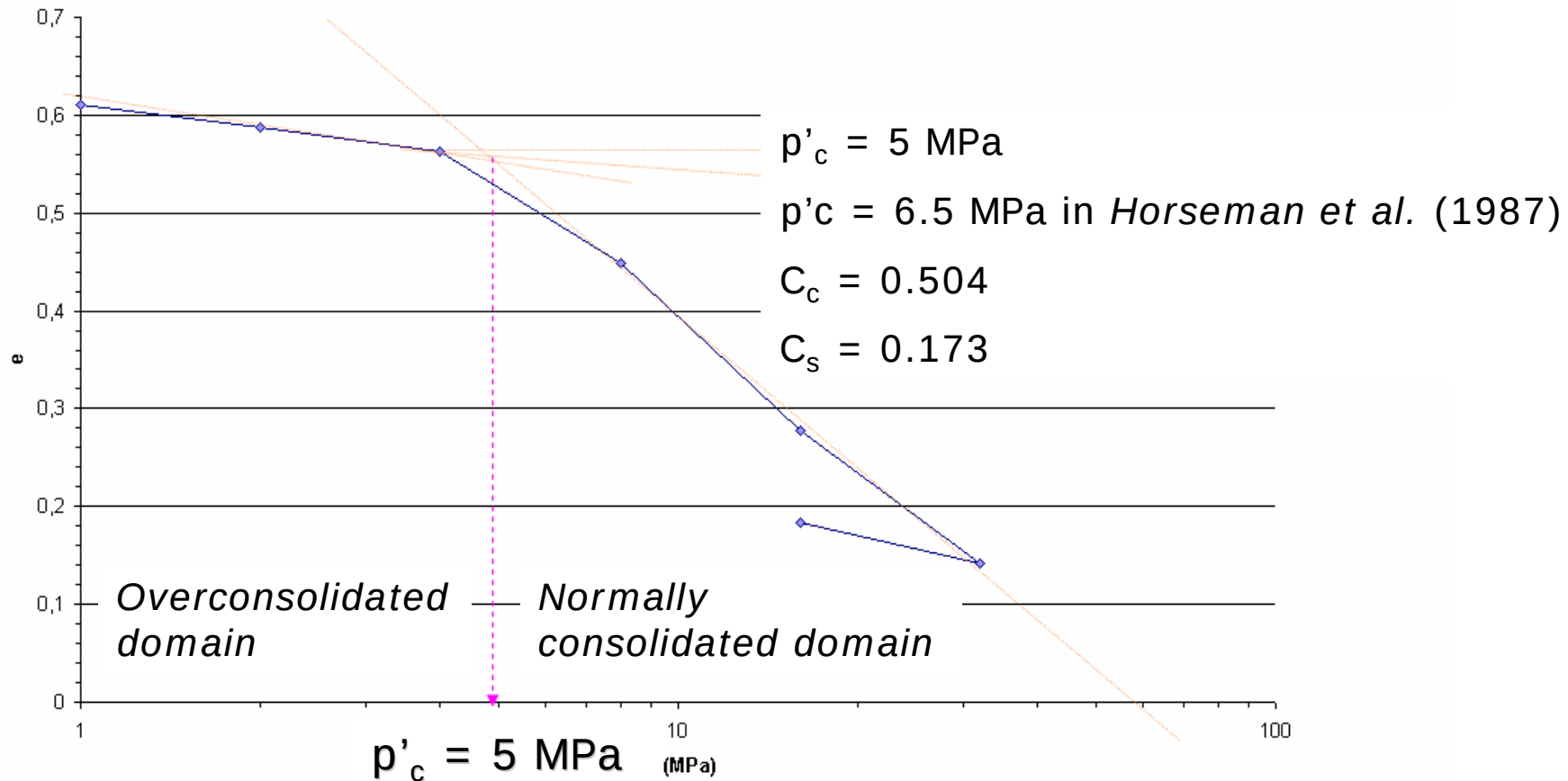
- Under constant mean effective stress (less than 3 MPa), BC *swells*
- *Non isotropic* behaviour ($e_a \neq e_r$)
- *Permeability decreases when p' increases (reduction of pore space)*
- *Characterisation of OC/NC domain ($p'_c \sim 5$ MPa)*

Behaviour under isotropic conditions

Isotropic test : preconsolidation pressure



$$0.144 < e < 0.557 (e_0)$$

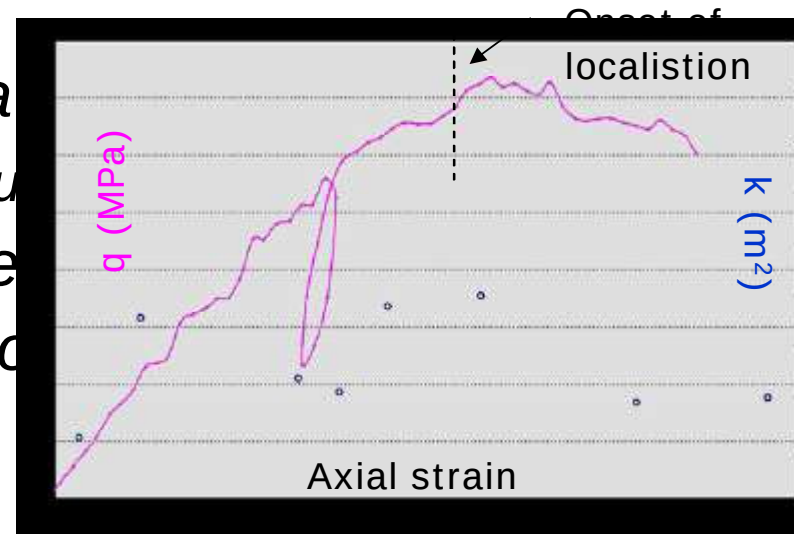


Triaxial tests on Boom Clay (2)

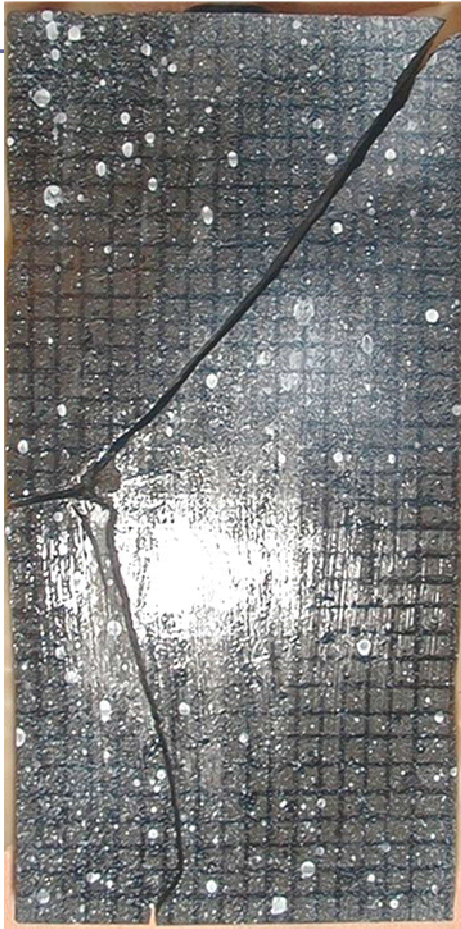
□ Deviatoric conditions



- Brittle-dilatant behaviour at low p' with q -peak + *shear banding*
- Ductile-contractant behaviour
- Strain rate effect (to be further investigated)
- Onset of localisation : behaviour change
- No significant evolution of k with deviator stress

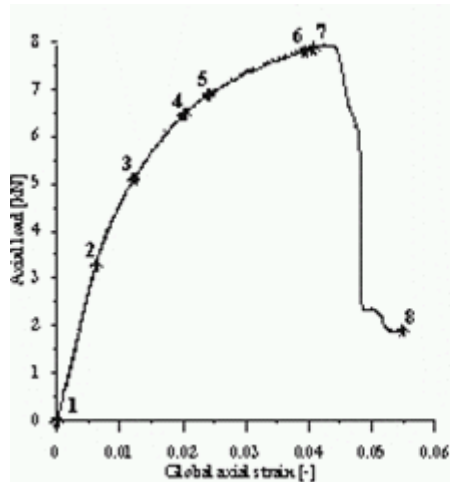


Biaxial tests on Boom Clay (1)



test BCSM04 on Boom Clay

Biaxial tests on Boom Clay (2)



01-02



02-03



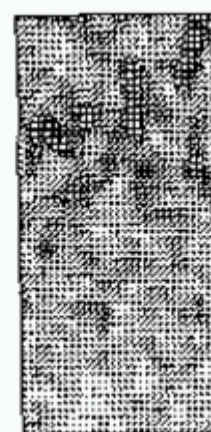
03-04



04-05



05-06



06-07

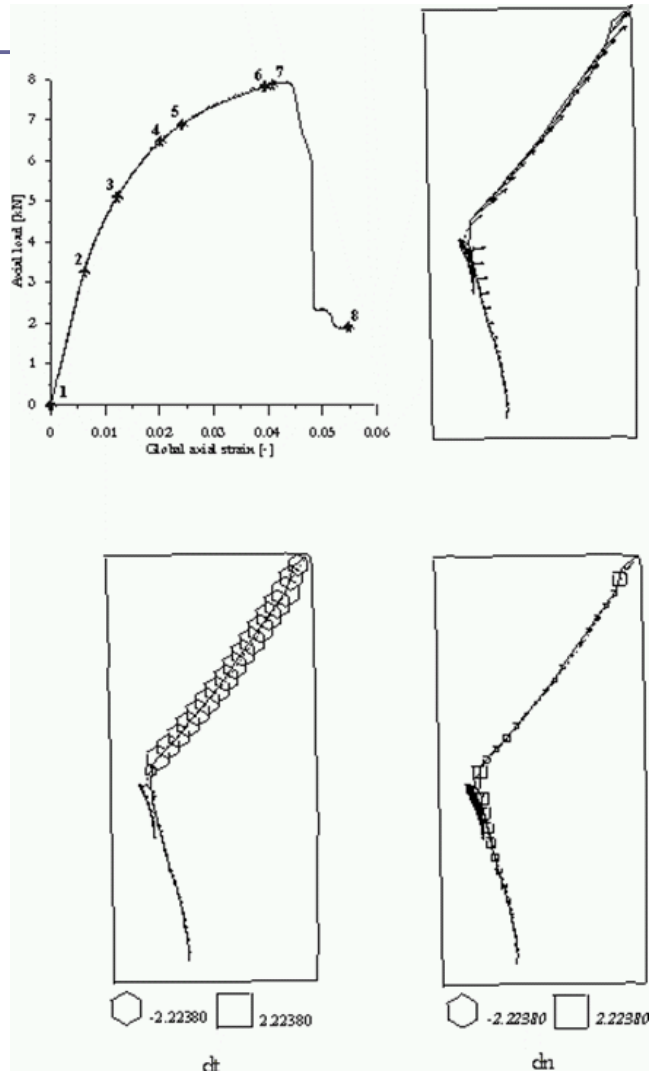


07-08

FRS-based shear strain field
test BCSM04

Biaxial tests on Boom Clay (3)

FRS-based discontinuity displacements
test BCSM04



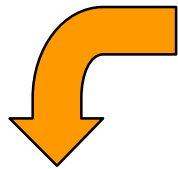


Conclusions for Boom Clay

- Fracturation processes characterized
 - Cracks and Shear Bands

- Effects on permeability
 - Global permeability not affected by strain localisation

Overview of tests on Opalinus Clay



- Triaxial compression tests (*undrained tests*)
 $p_0 = 2.6, 4.5, 7.2$ MPa (and $u_0 = 2.2$ MPa at both ends of the specimen)
- Uniaxial compression tests
- Biaxial tests (uu tests)

- High influence of water content
- Multiple fissures
- $q_{failure} \nearrow$ when $p' \nearrow$
- Drop of excess pore pressure at failure
- No evolution of the permeability for the tests at $p_0 = 4.5$ and 7.2 MPa
- Post peak increase of k (3 to 4 orders of magnitude) for the test at $p_0 = 2.6$ MPa



2.6 MPa



4.5 MPa

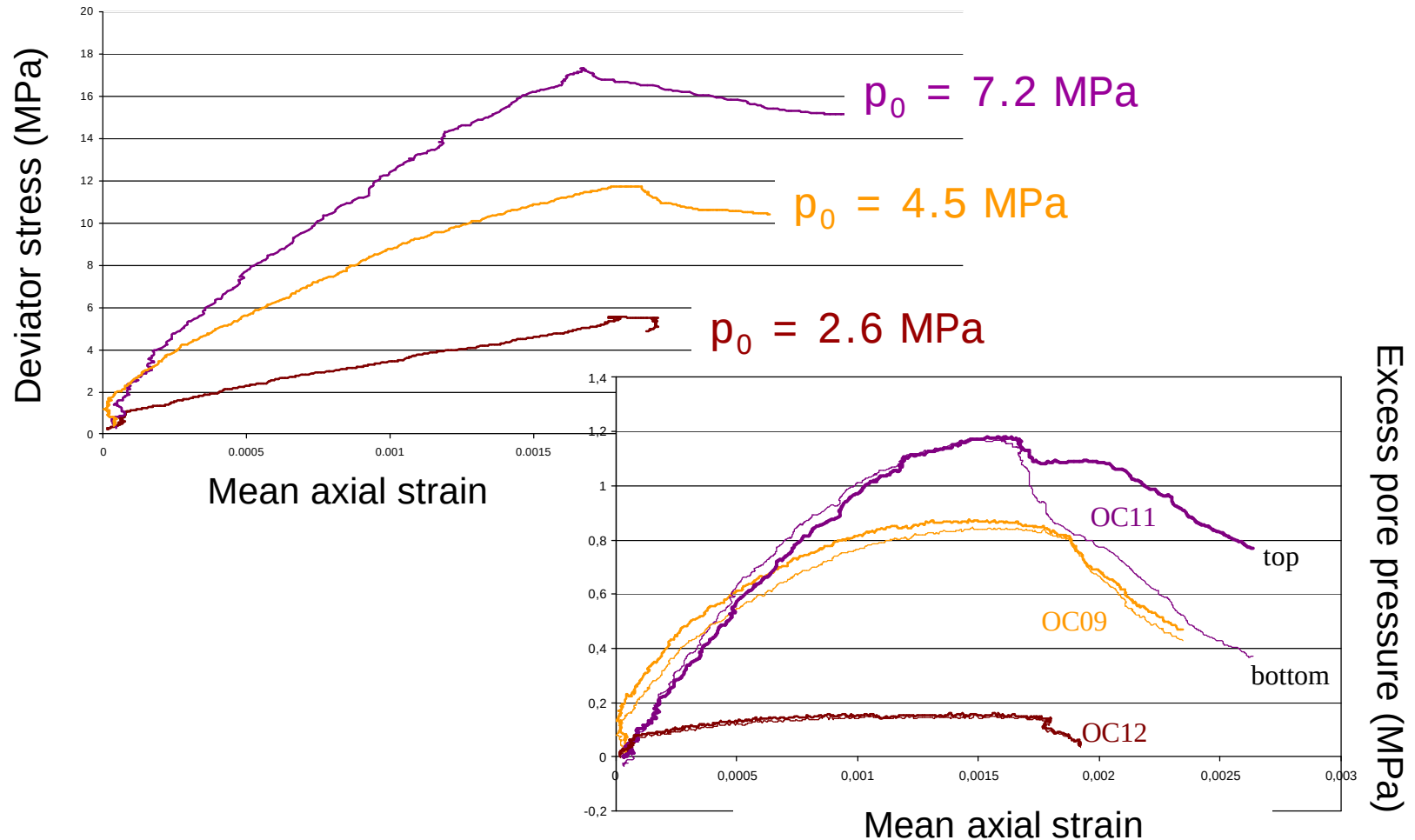


7.2 MPa

Less fissures

Triaxial tests on Opalinus Clay

Stress-Strain behaviour



Biaxial tests on Opalinus Clay

test OCSM03 on Opalinus Clay

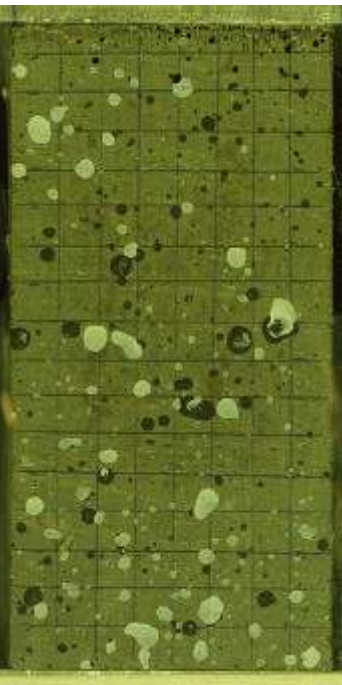


Photo 1

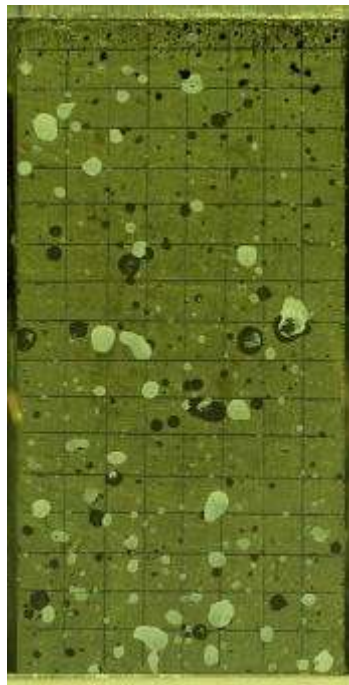


Photo 4

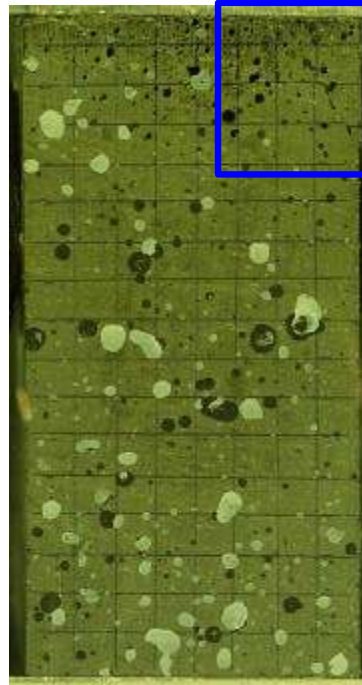
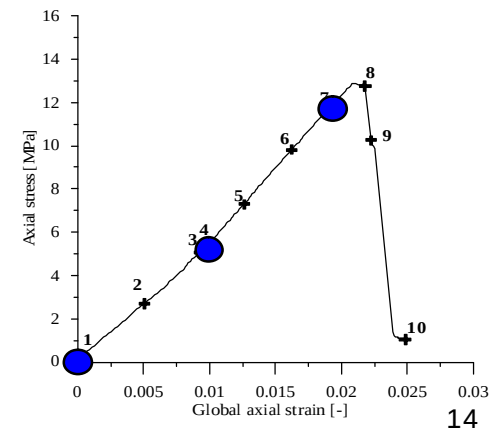
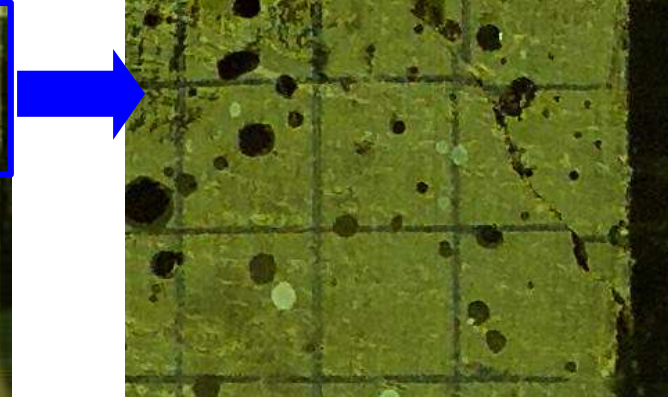
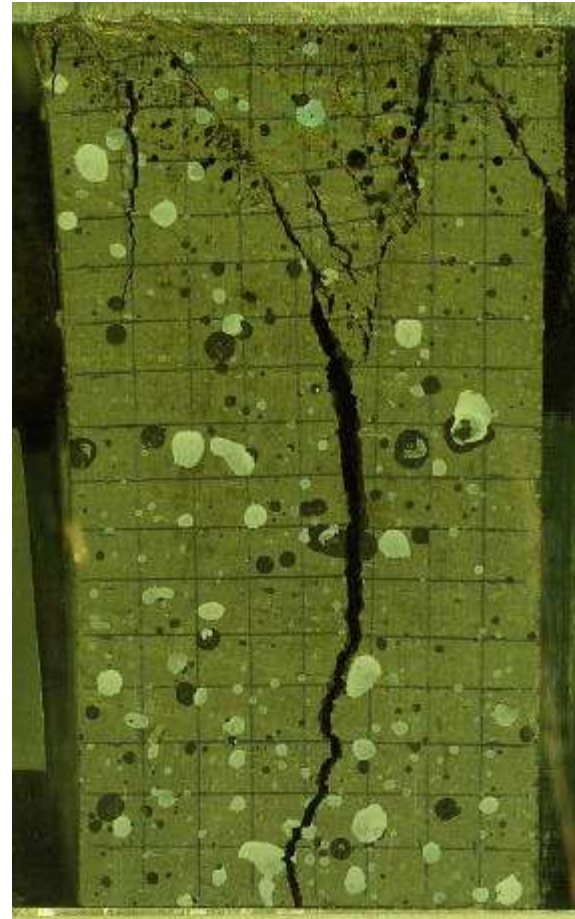
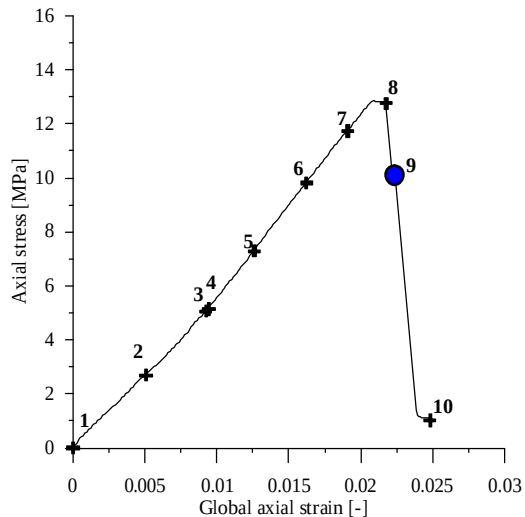


Photo 7



Biaxial tests on Opalinus Clay

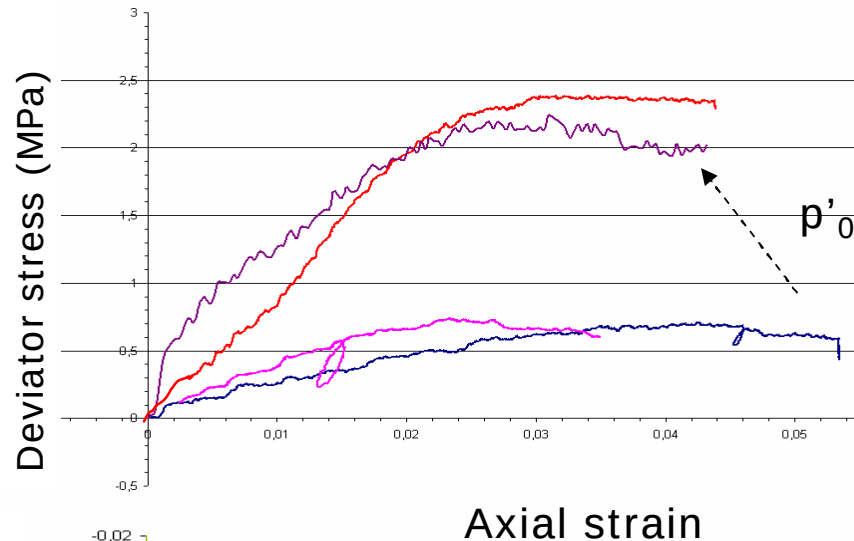
test OCSM03 on Opalinus Clay



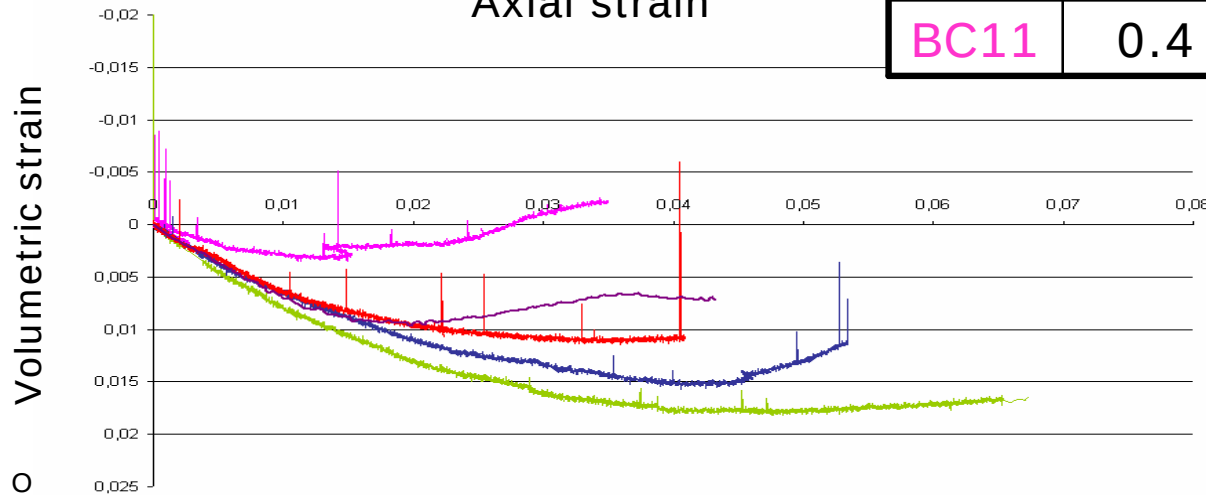
Conclusions on Opalinus Clay

- Observation of **fissures** rather than shear bands in triaxial and biaxial tests
- Density of fissures ↘ when p' ↗
- Fissures aperture (and permeability?) depends on mean effective stress

Stress-Strain behaviour of BC



Test	p'_0 (MPa)	OCR	V ($\mu\text{m}/\text{min}$)
BC09	5	1	0.25
BC12	2.3	2.17	25
BC07	2.3	2.17	0.25
BC08	0.4	12.5	0.25
BC11	0.4	12.5	0.25



BC12



Future experimental work

□ Further TX tests

- Boom clay (back up a few tests)
- Opalinus clay (microscale HM testing, double porosity approach)
- In-situ X-ray micro tomography → fracture network characterization in view of permeability (flow model)

□ Further stress paths

- More relevant to excavation problems ($p' \searrow$ and $q \nearrow$)

□ Further techniques

- X-ray micro tomography, ultrasonic tomography



Modelling Hydromechanical Coupling and Localization in Porous Media

Jacques Desrues, René Chambon, Pierre Bésuelle

Grenoble SELFRAC Team

*A part of this work performed in collaboration
with R. Charlier and co-workers
during JD stay in ULg - autumn 2002*

Modelling fracturation process : Constitutive / Numerical



- ❑ Constitutive : CLoE model calibration including shear band analysis
- ❑ Constitutive & numerical : HM coupling efficiency assessment : global response and localisation prediction
- ❑ Constitutive & numerical : bifurcation prediction in FEM computations (biaxial test, borehole)
- ❑ Theoretical & numerical : second gradient model for POST-localisation modelling
- ❑ HM coupled 2nd gradient model
- ❑ Further research needed

CLoE model

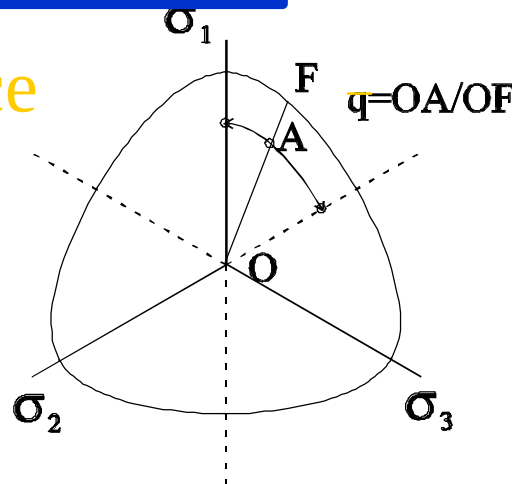
3S

C constance

LoE explicit localisation

$$\underline{\dot{\sigma}} = \underline{\underline{A}} : \underline{\dot{\epsilon}} + \underline{b} \|\underline{\dot{\epsilon}}\|$$

Limit surface



$$\underline{\underline{A}} = \begin{bmatrix} a & f' & e' \\ f & b & d' \\ e & d & c \end{bmatrix} \quad \underline{\underline{A}} = \begin{bmatrix} a & e' & e' \\ e & b & d \\ e & d & b \end{bmatrix}$$

$$\underline{b}' = [k \ l \ m \ 0 \ 0 \ 0]^T$$

general
stress state

$$\underline{b}' = [k \ l \ l \ 0 \ 0 \ 0]^T$$

axisymmetric
stress state



Explicit Bifurcation Criterion for CLoE

Shear Band Equations :

$$\dot{\mathbf{F}}^1 = \dot{\mathbf{F}}^0 + \bar{\mathbf{g}} \otimes \bar{\mathbf{n}}$$

$$\bar{\mathbf{n}} \cdot \dot{\mathbf{s}}^1 = \bar{\mathbf{n}} \cdot \dot{\mathbf{s}}^0$$

$$\dot{\mathbf{s}} = \mathbf{f}(\dot{\mathbf{F}})$$

- Incrementally Linear (ized) case :

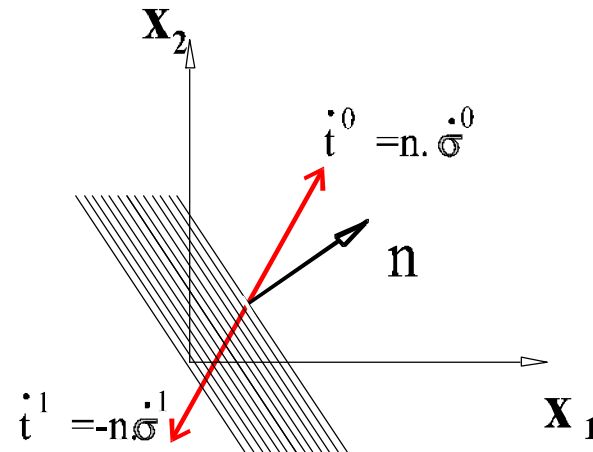
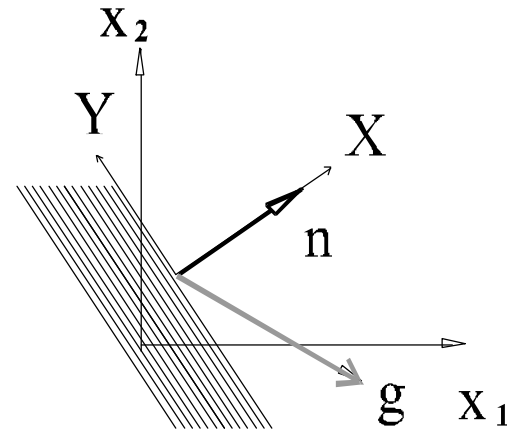
$$\det(\bar{\mathbf{n}} \cdot \underline{\underline{L}} \cdot \bar{\mathbf{n}}) = 0$$

- General case :

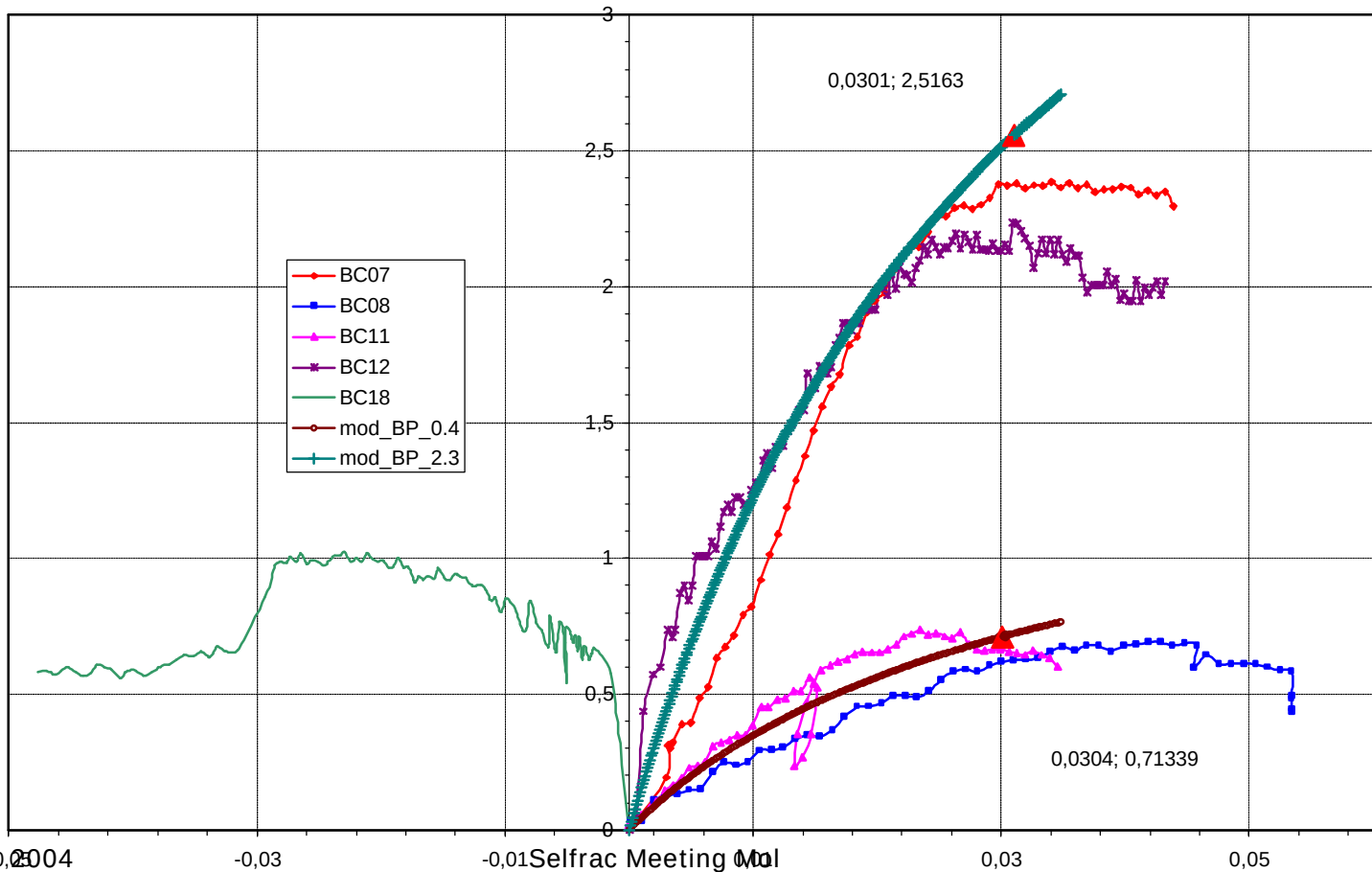
$$\bar{\mathbf{n}} \cdot \mathbf{f}(\dot{\mathbf{F}}^0 + \bar{\mathbf{g}} \otimes \bar{\mathbf{n}}) = \bar{\mathbf{n}} \cdot \mathbf{f}(\dot{\mathbf{F}}^0)$$

- CLoE : general (no linearization)

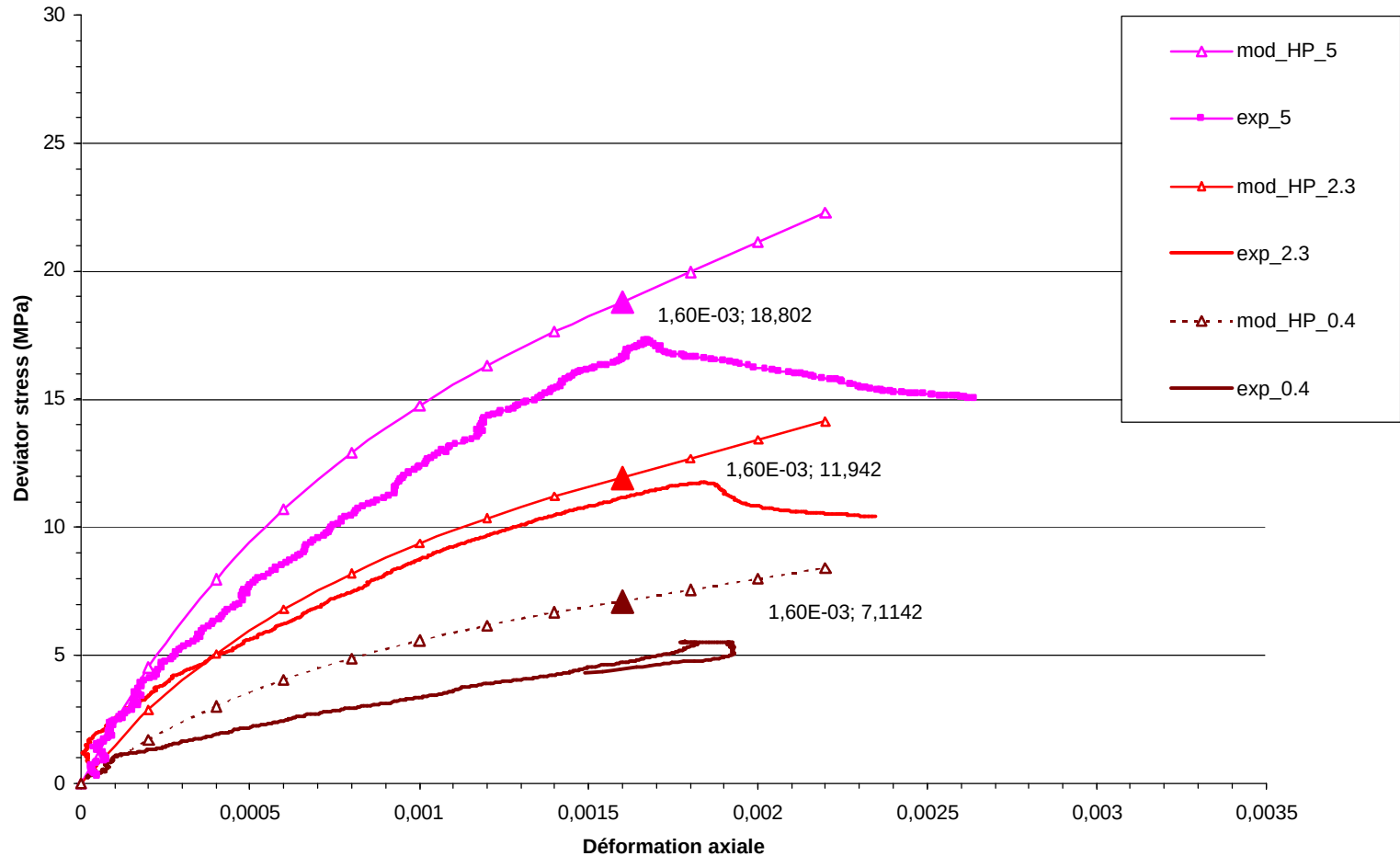
$$C = \left\| P_{il}^{-1} b_{lk} n_k n_j + P_{jl}^{-1} b_{lk} n_k n_i \right\| - 2 = 0$$



Model calibration : Boom Clay

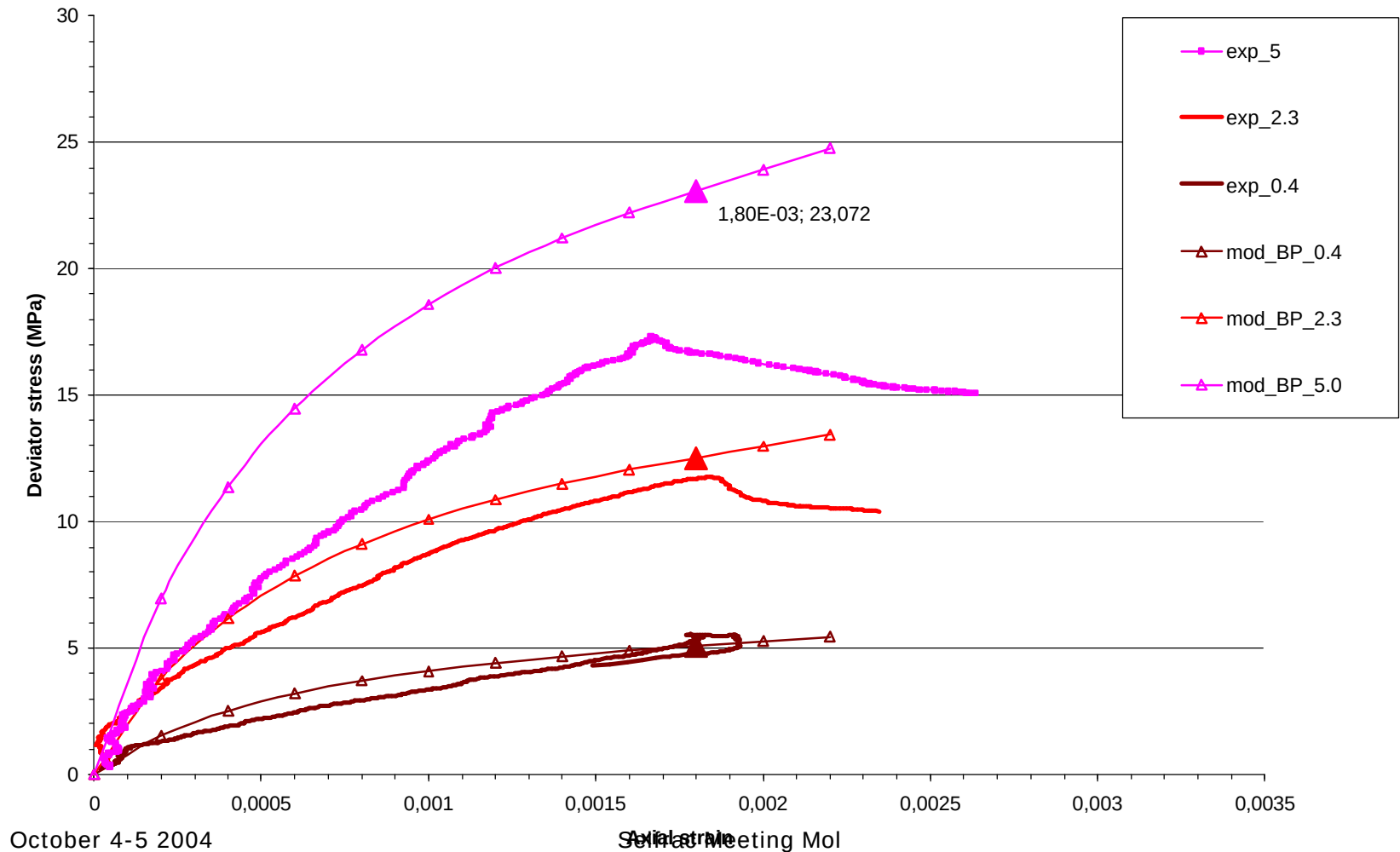


Model calibration (High Mean Stress) : Opalinus Clay





Model calibration (Low Mean Stress) : Opalinus Clay





HM Coupling & Localization

- ✓ Comparison :
Meca Only (dry) *versus* HM drained
- ✓ Comparison : Open Drainage,
Slow – Fast – Very Fast
- ✓ Closed Drainage Slow – Fast
- ✓ Delayed Drainage
- ✓ Injection



HM Coupling & Localization

- ✓ Comparison :
→ Meca Only (dry) *versus* HM drained
- ✓ Comparison : Open Drainage
Slow – Fast – Very Fast
- ✓ Close Drainage Slow – Fast
- ✓ Delayed Drainage
- ✓ Injection

Numerical tests :

HM sand
(with

(Hostun Sand)



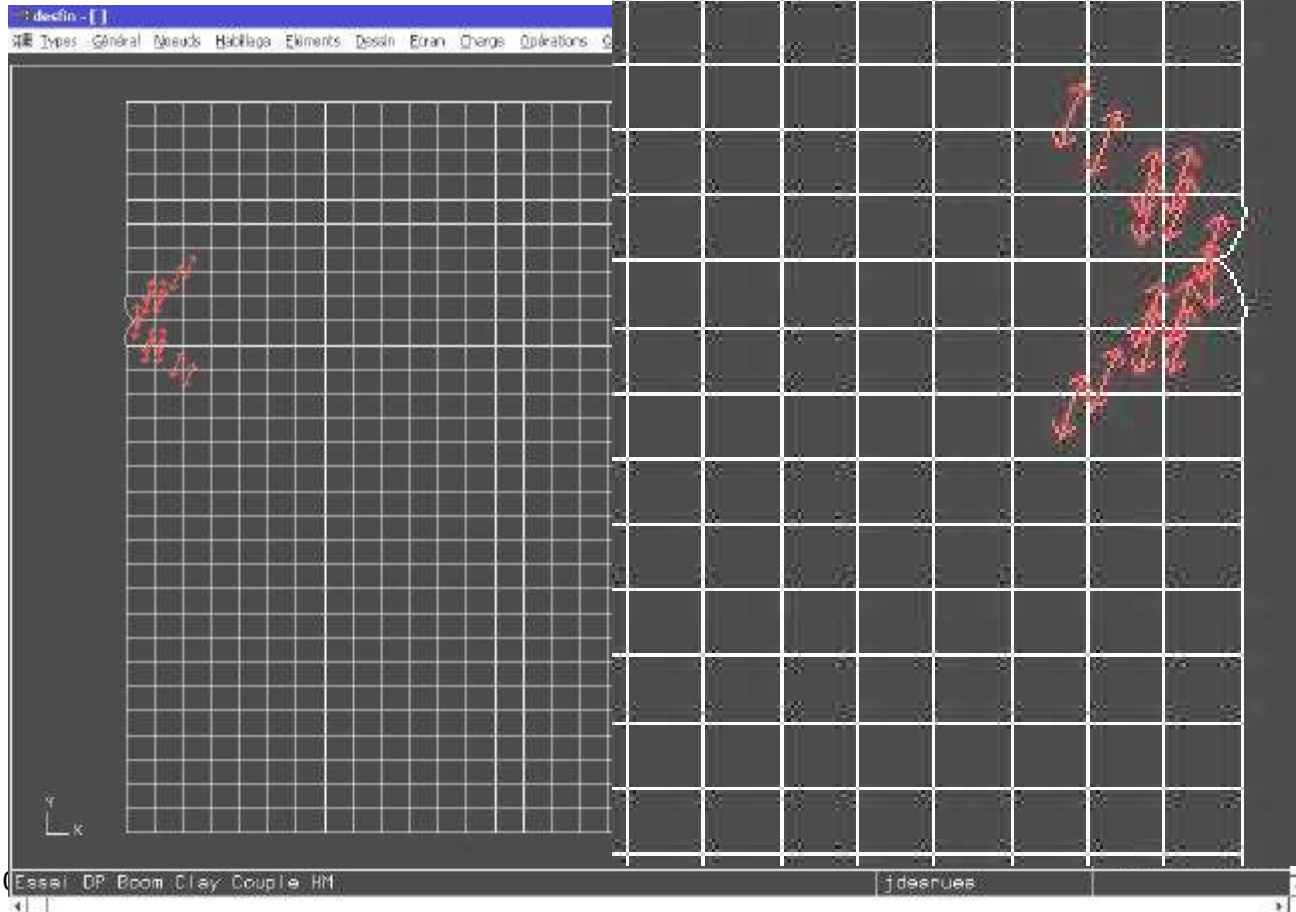


Boom Clay

- Modelling biaxial test with Boom Clay parameters determined from the model calibration

Boom Clay

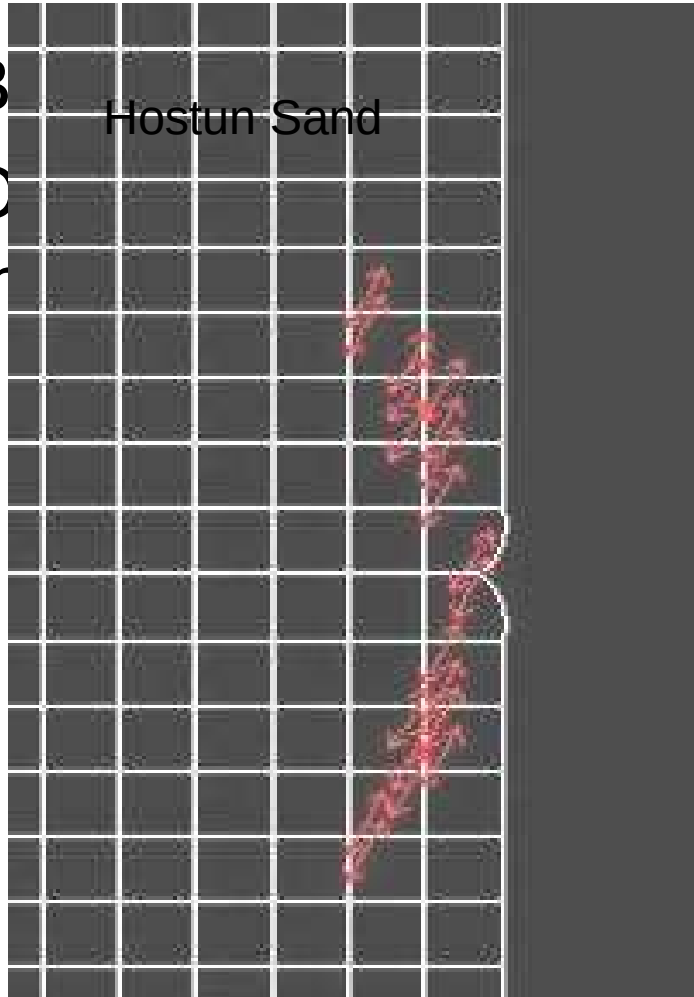
□ Bifurcation detection



Boom Clay

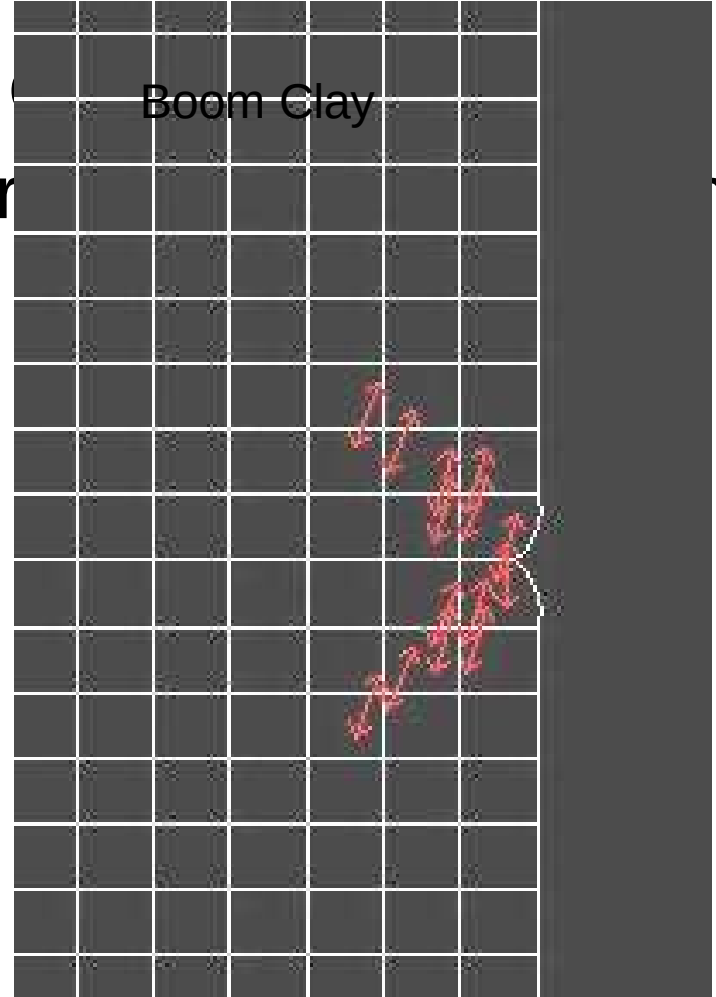
- B
- C
- in

Hostun Sand

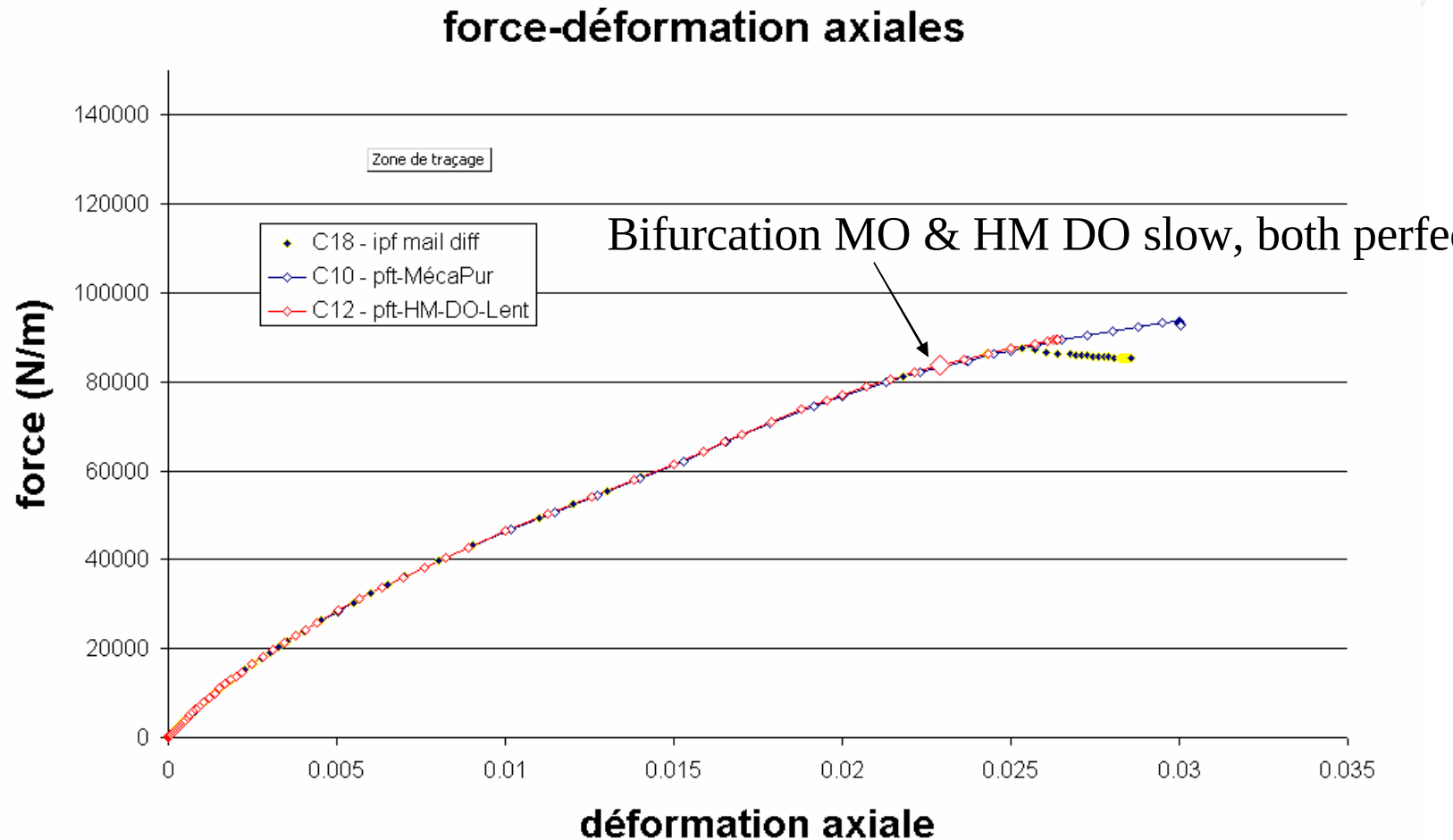


n (l
y fr
e

Boom Clay



Comparison axial Load- Strain





HM Coupling & Localization

Comparison Meca Only – HM drained

- ➡ Hydro Mechanical coupling ok in the drained limit
- ➡ Localization criterion in effective stress ok



HM Coupling & Localization

- ✓ Comparison Meca Only – HM drained

- ➔ ✓ Comparison Open Drainage
Slow – Fast – Very Fast

- ➔ ✓ Close Drainage Slow – Fast

- ✓ Delayed Drainage

- ✓ Injection



HM Coupling & Localization

□ Comparison Meca Only – HM drained

□ Comparison Open Drainage

Slow : 1,2 mm/min ...

0,012 min⁻¹

Fast : x 1000

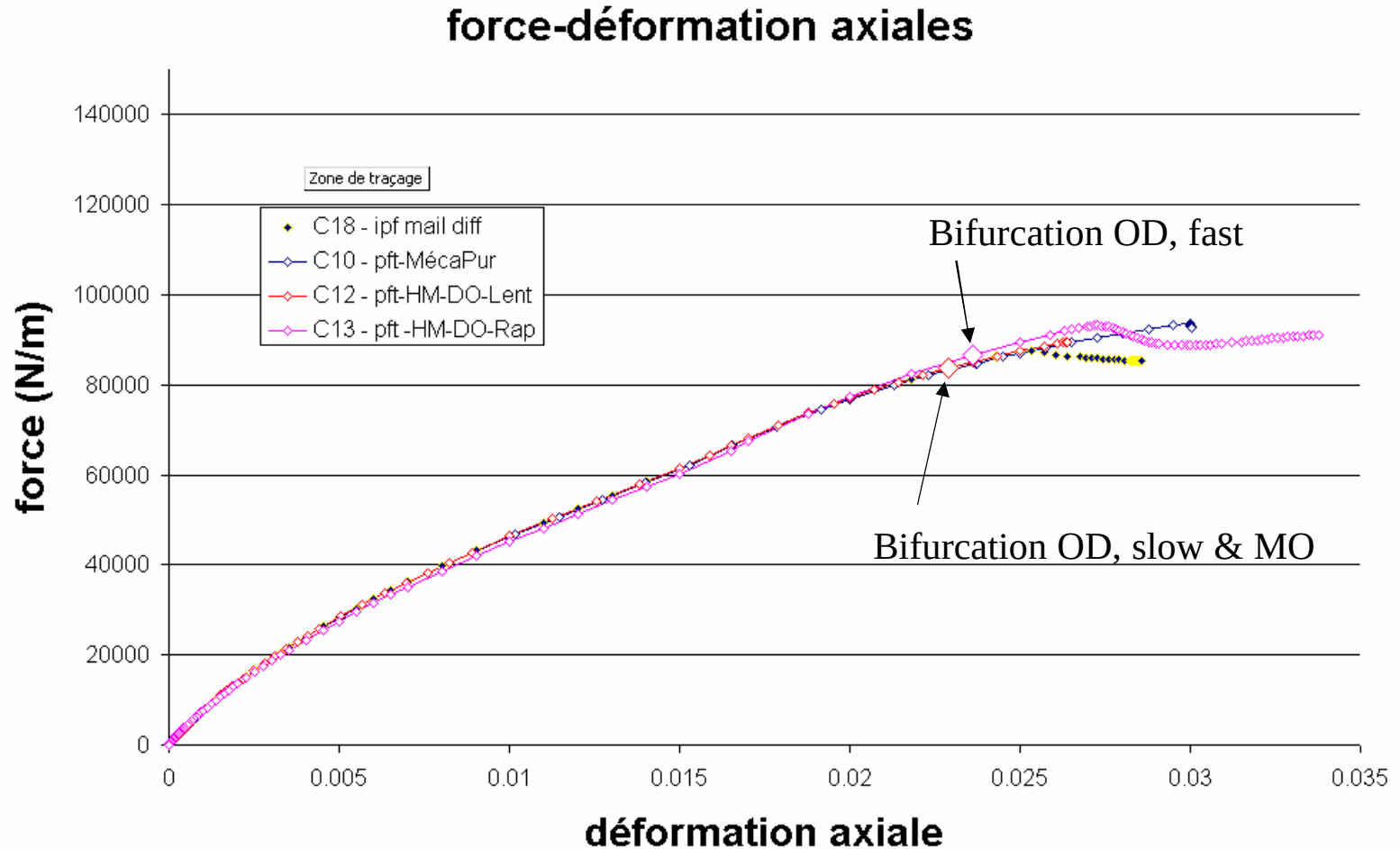
12 min⁻¹

→ Very Fast : x 1000 000

12 000 min⁻¹

(soit 1,2 km/min !)

Comparison axial Load- Strain



HM Coupling & Localization

Comparison Meca Only – HM drained

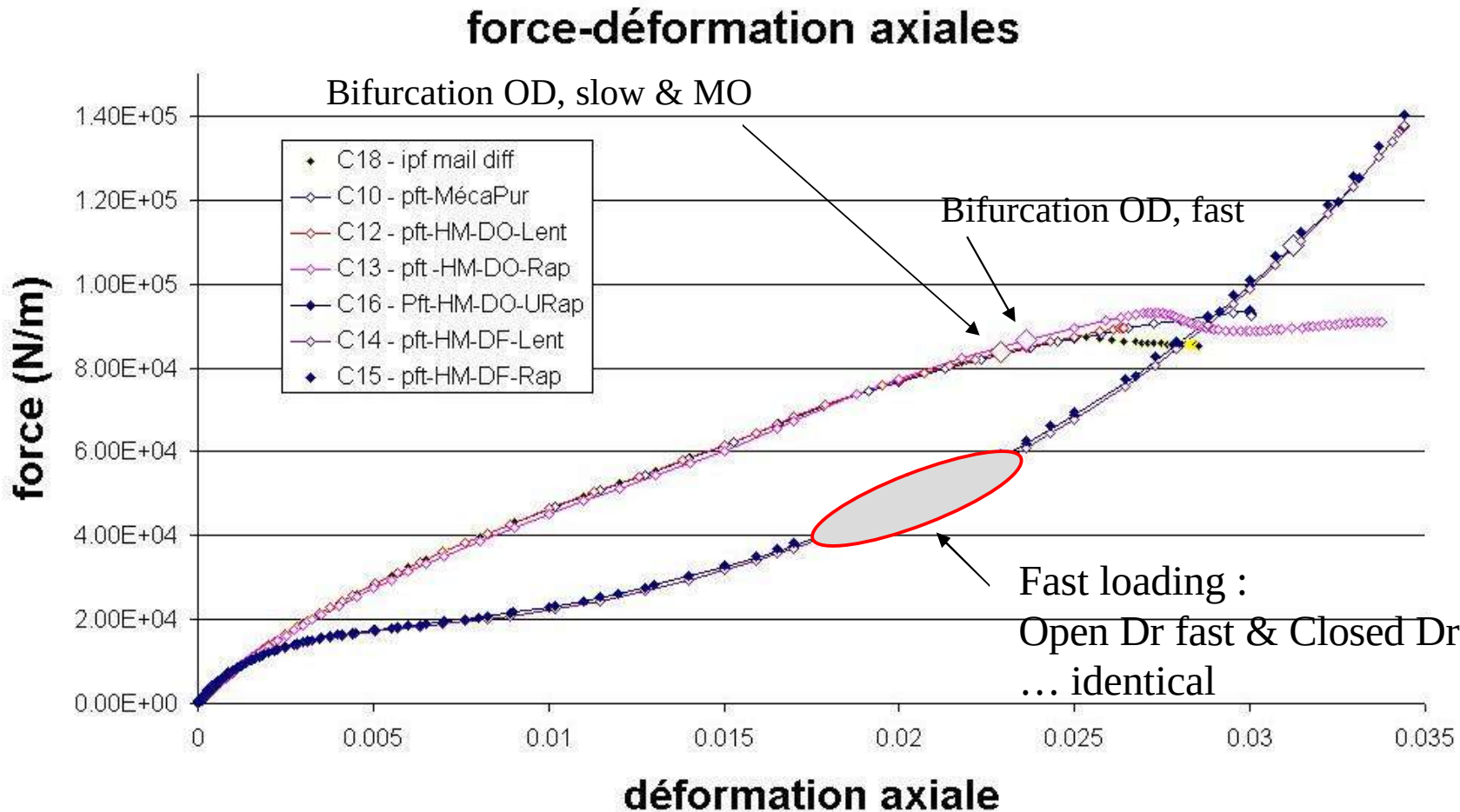
Comparison Open Drainage

Slow : 1,2 mm/min ...	0,012 min ⁻¹
Fast : x 1000	12 min ⁻¹
Very Fast : x 1000 000	12 000 min ⁻¹
(i.e. 1,2 km/min !)	



- results : numerical « spontaneous » localization does not develop, bifurcation is detected in a few elements in a very limited upper layer, axial load increases very fast ... load-strain curve departs completely from the drained tests ... but it coincides with the undrained test response (Closed Drainage)

Comparison axial Load- Strain





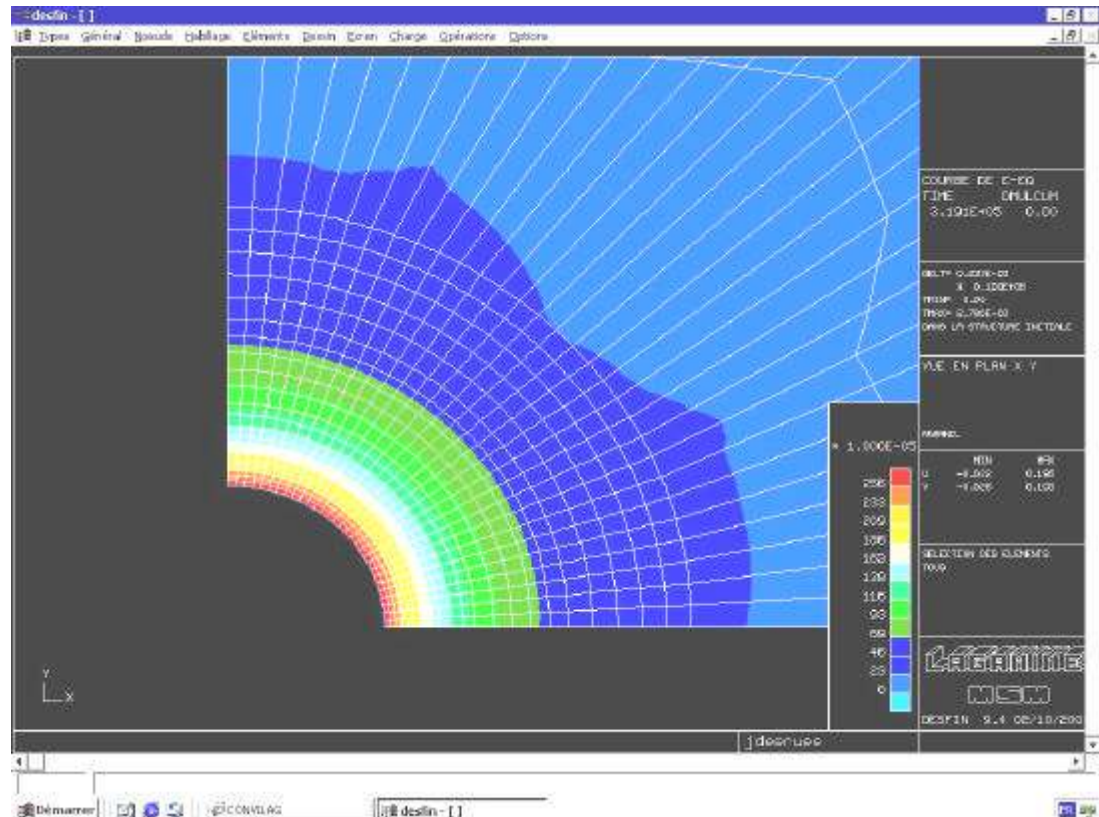
HM Coupling & Localization

Drainage & Rate effect

- ➡ Hydro Mechanical coupling ok in the undrained limit : indeed, open drainage with very high rate is equivalent to closed drainage.
- ➡ Localization criterion in effective stress ok in the undrained limit : no bifurcation predicted (as long as cavitation in the pore fluid does not occur)

Borehole stability modelling

- CLoE model with Boom Clay parameters
- Cumulated deviatoric strain

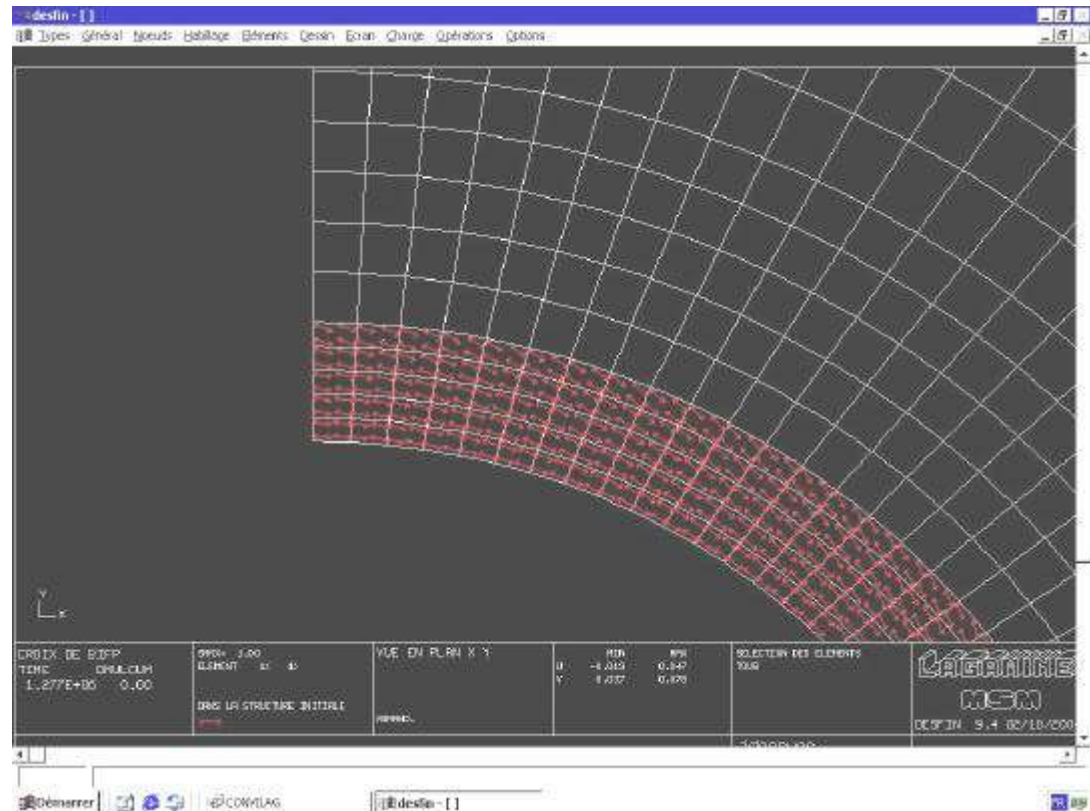


- CLoE model with Boom Clay parameters
- Cumulated volumetric strain



Borehole stability modelling

- CLoE model with Boom Clay parameters
- Bifurcation crosses





Post-localisation strategy :

Bifurcation detection ok... *then what ?*

Modelling material degradation in localized zones calls for introducing softening in the model;

Softening induces severe problems in numerical simulations : loss of uniqueness, mesh dependency...

→ It is necessary to *regularize* the problem.



Post-localisation strategy :

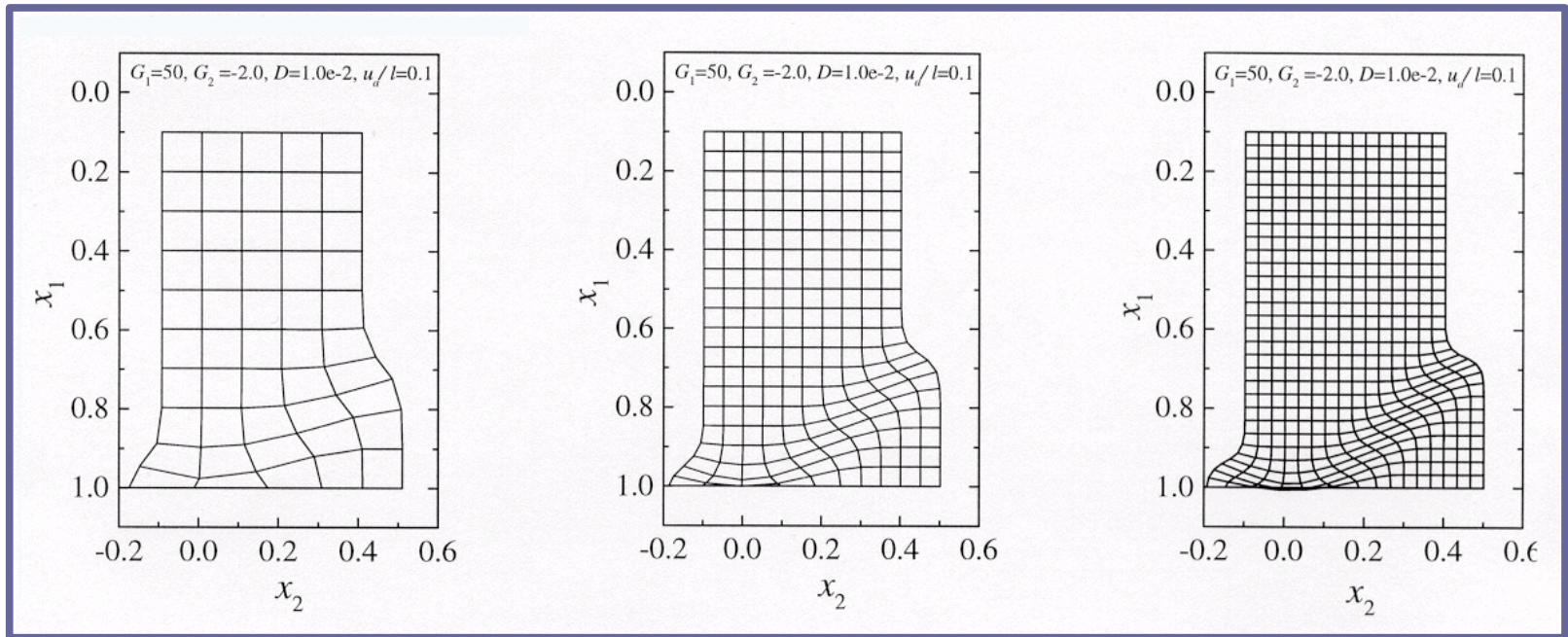
Developed in the framework of the SELFRAC project :

Enriched continuum : second gradient (local)

▣ Virtual work principle (1D illustration)

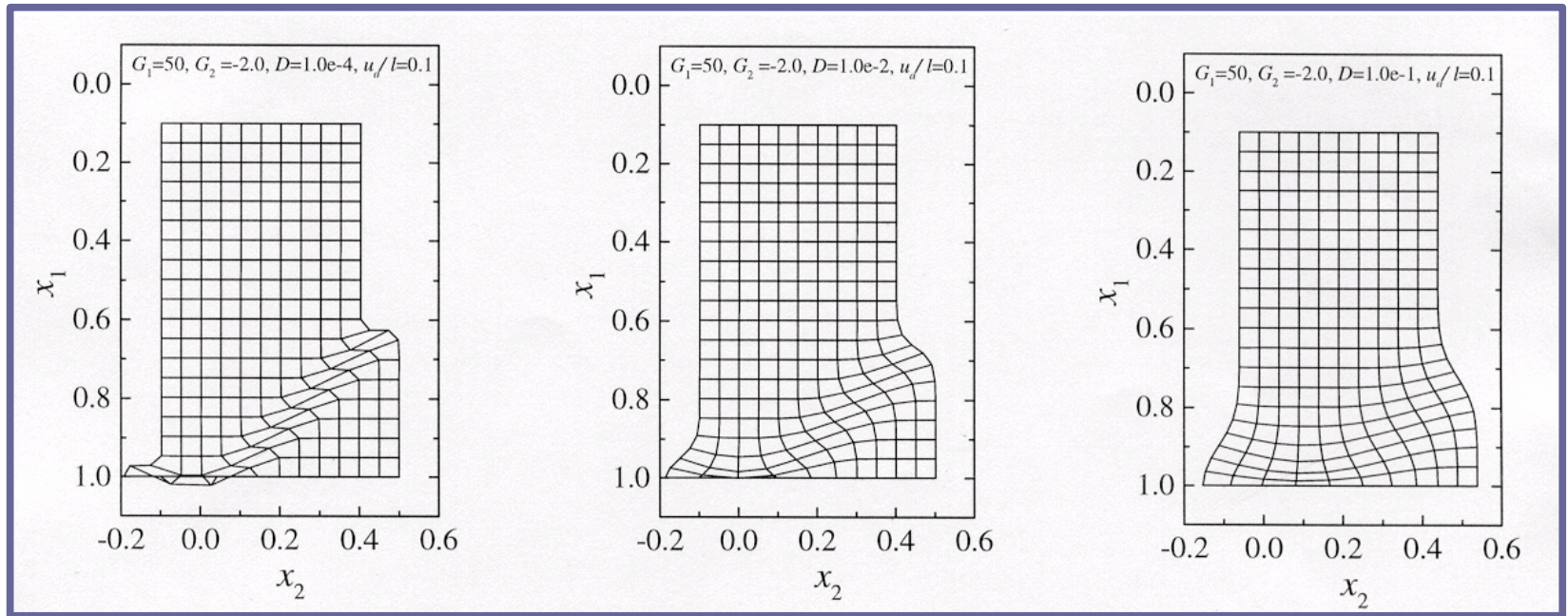
$$\forall u^* : \int_{a(t)}^{b(t)} (Nu^{*'} + Mu^{*''}) dx = P_e^*$$

Second gradient restores mesh independency



Same material (same internal length),
different meshes : *same bandwidth*

Second gradient restores mesh independency

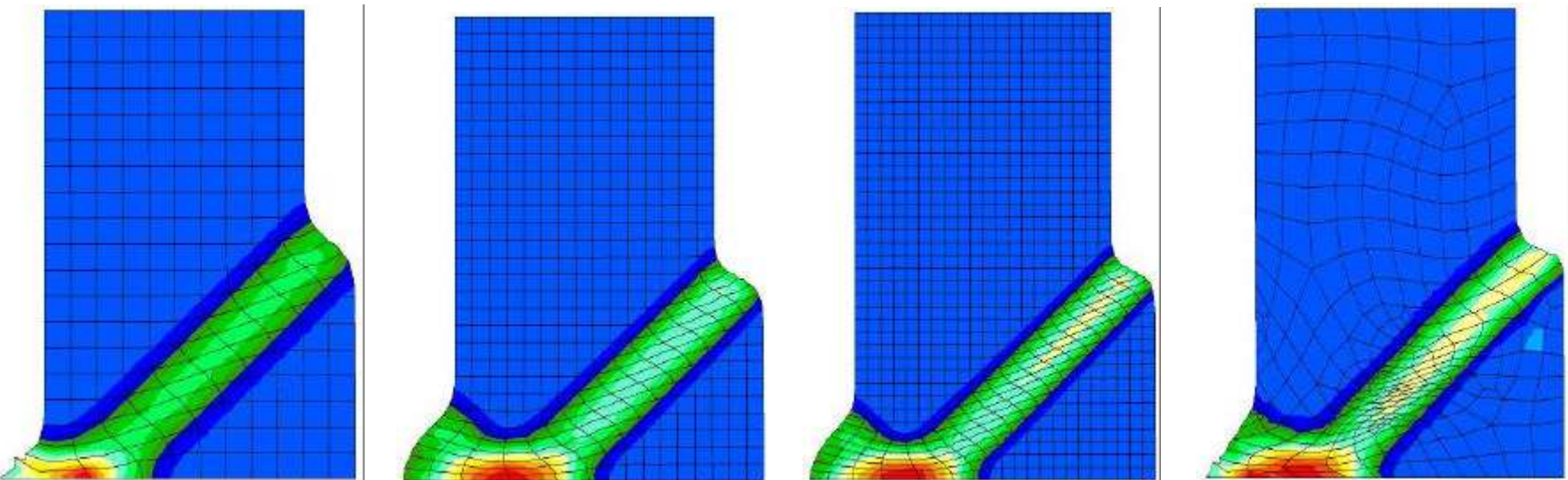


different internal length,
same mesh :
bandwidth changes

*The response is clearly
governed by the material,
NOT by the mesh*



Second gradient restores mesh independency



Second gradient local model
implemented in FEM code Lagamine – Ulg



Post-localisation strategy :

Second gradient theory and implementation OK...
But what about HM coupling in this framework ?

Another outcome of the SELFRAC project :

Enriched continuum : second gradient local
+ **Hydro-Mechanical coupling**

Future theoretical and numerical work

- In situ test computations (in progress)
- Further computations
 - Extending the modelling framework to unsaturated media (and other relevant multi-physics coupling)
- Further theoretical developments
 - Softening branch for CLoE-like model in the framework of enriched continua
 - From shear band to cracks : interaction & propagation
- Further numerical developments
 - 3D implementation
 - From shear band to cracks : XFEM, ...

SEALING/HEALING in Argillaceous Media: Laboratory Tests Results

Lorenzo ORTIZ

CEN•SCK

Experimental Programme (1): Permeameter cell tests

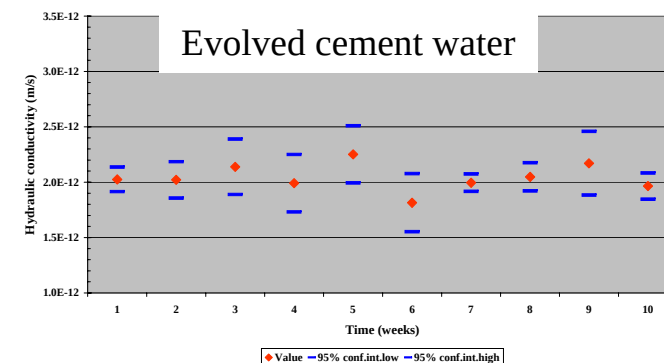
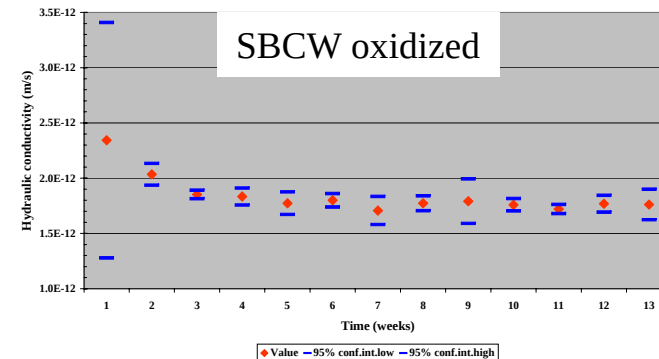
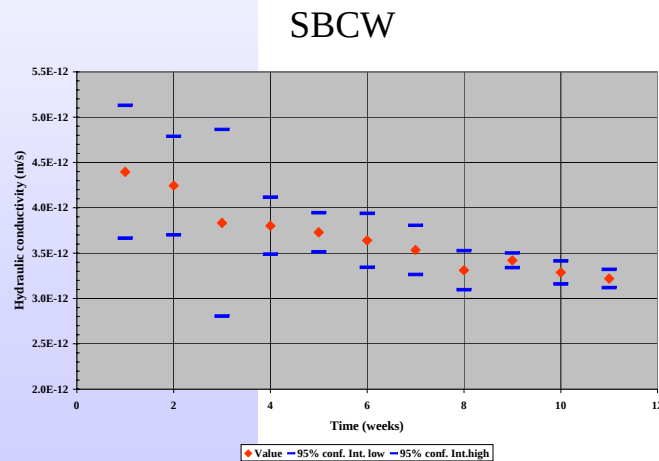
- Artificial planar fracture through the sample
- Testing of the chemical component in the self-healing (self-sealing) process using different injection fluid compositions in constant volume conditions en monitoring K evolution
 - Boom Clay (soft plastic clay)
 - Synthetic Boom Clay Water (SBCW)
 - Idem in oxidized conditions
 - Evolved cement water
 - Opalinus Clay from Mont Terri (indurated clay)
 - Low saline Pearson water
 - High saline Pearson water (still running)
 - Low saline evolved cement water
- μ CT scans taken at regular intervals to visualize the sealing process

Experimental Programme (2): Isostatic cell tests

- Testing of the combined chemical and mechanical components in the self-healing process using controlled isostatic and effective stress conditions
 - Two tests per clay type (Boom Clay and Opalinus Clay)
 - Drilling of a hole through the axis of the cylindrical sample
 - Boom Clay: 60 and 120 mm diameter
 - Opalinus Clay: 2.5 (still running) and 4 mm diameter
 - Monitoring of the permeability evolution

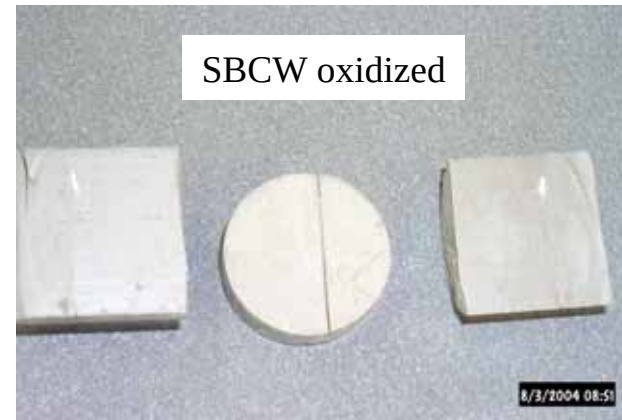
Permeameter Cell Tests: Boom Clay (1)

- A slow self-sealing is observed when SBCW in normal and oxidized condition is injected
- A fast self-sealing is observed when evolved cement water is injected



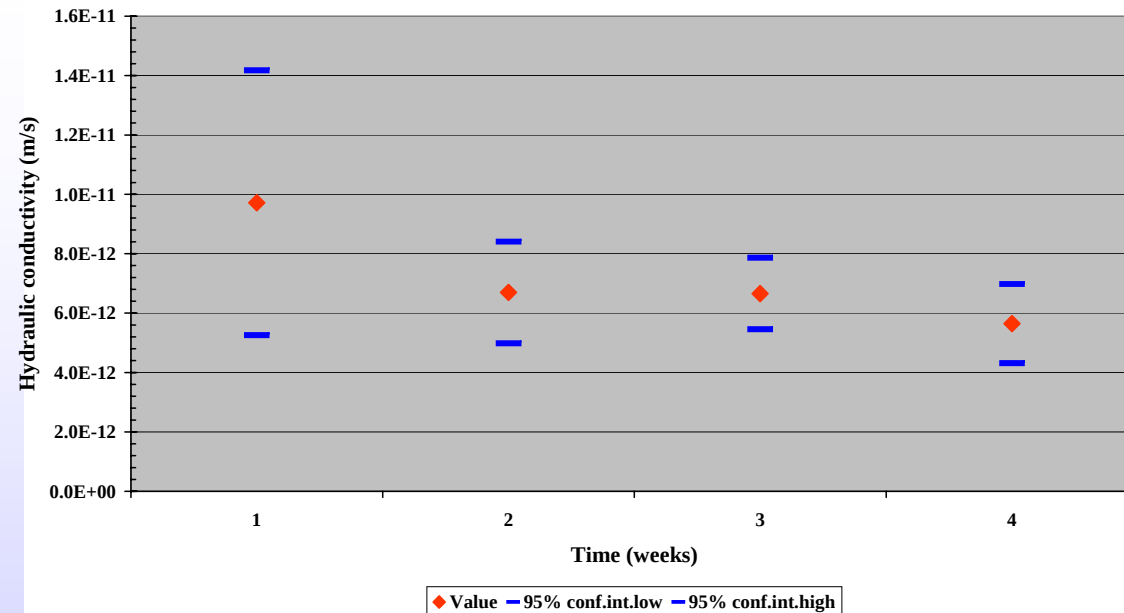
Permeameter Cell Tests: Boom Clay (2)

- Though the hydraulic properties seem to be restored, the mechanical properties are not. The best cohesion is obtained with the injection of evolved cement water. SEM micrographs show only clay minerals present in the original fracture: no cementation (cf presentation M. Van Geet together with μ CT scans)



Permeameter Cell Tests: Opalinus Clay Mont Terri (1)

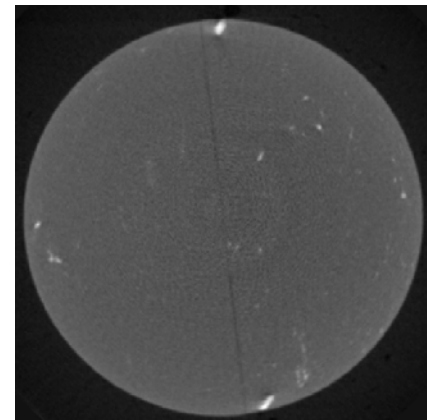
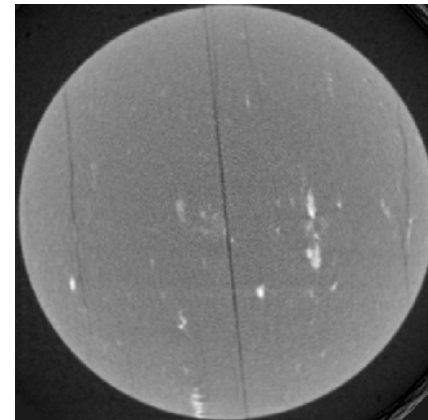
Opalinus Clay sample with evolved cement low saline Pearson water (A3)



- A very moderate self-sealing (although not statistically significant) could be observed for the Opalinus Clay at the timescale of the lab test (1 month)

Permeameter Cell Tests: Opalinus Clay Mont Terri (2)

- The main fissure is still present, the peripheral faults could not anymore be detected with the μ CT

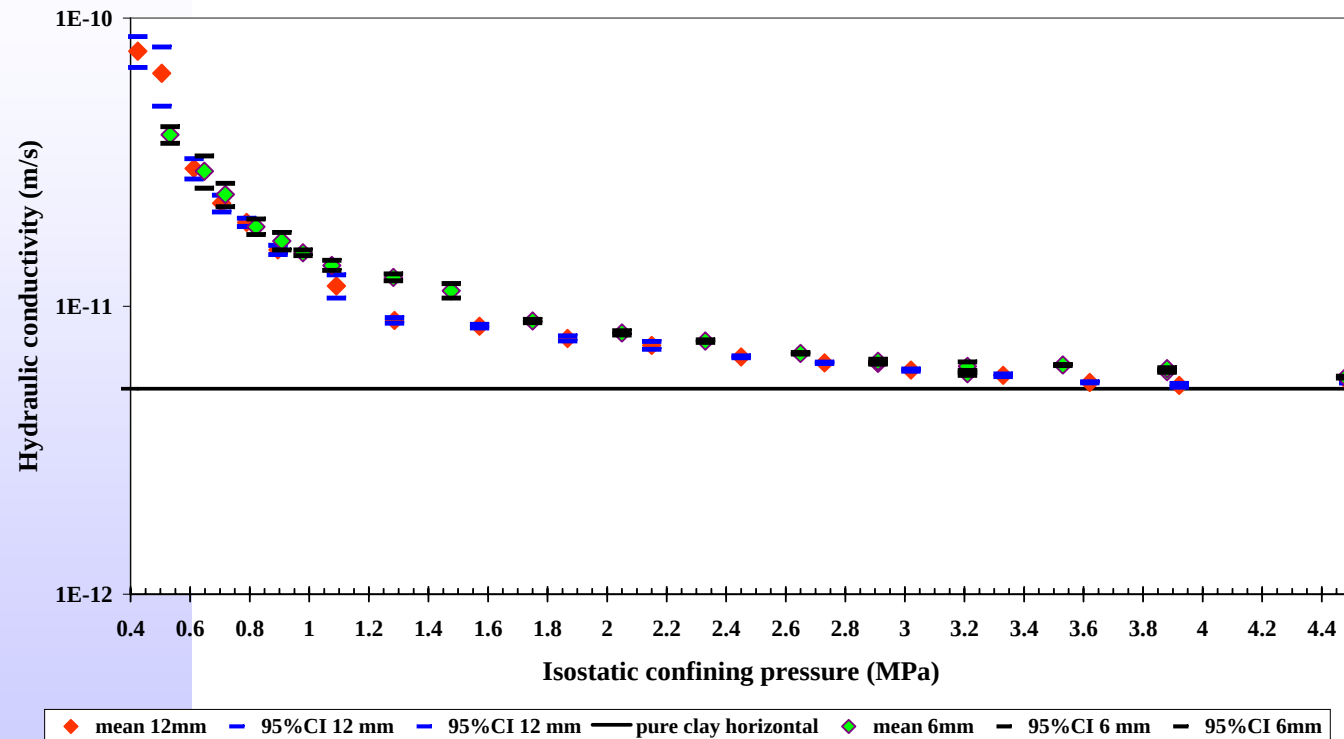


Isostatic Cell Tests: Boom Clay

- Two tests have been carried out on Boom Clay samples
 - Same original core
 - 6 and 12 mm centered drillhole at the installation
 - SBCW injected through the bottom of the sample (flow parallel to the orientation of the bedding plane)
 - The confining pressure is progressively incremented (starting at 0.1 MPa g) up to a final value of 4.5 MPa while the mean effective stress and mean pore water pressure are kept equivalent
 - The evolution of the hydraulic conductivity and of the consolidation are monitored

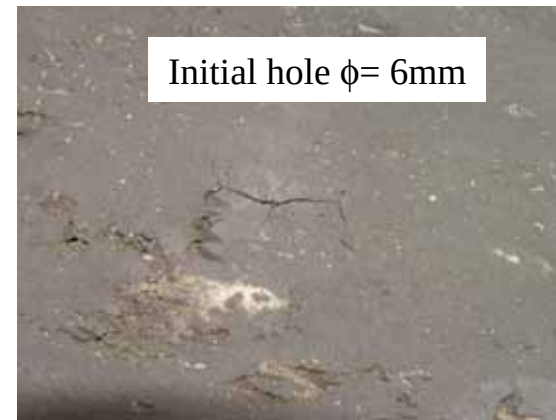
Hydraulic Conductivity Evolution of the Boom Clay Samples is similar

Evolution of the hydraulic conductivity in BC sample



Pictures of the Samples Taken after the Dismantling Operation

- The decompression of the samples during the dismantling operation provoked the formation of a fissure throughout the sample in its centre en oriented in a // direction vs. The bedding plane
- Fissure dimension correlated with the initial hole dimension
- Discharge rate sample with initial 6mm hole: 5 hours
- Discharge rate sample with initial 12mm hole: 1 week



Isostatic Cell Tests: Opalinus Clay

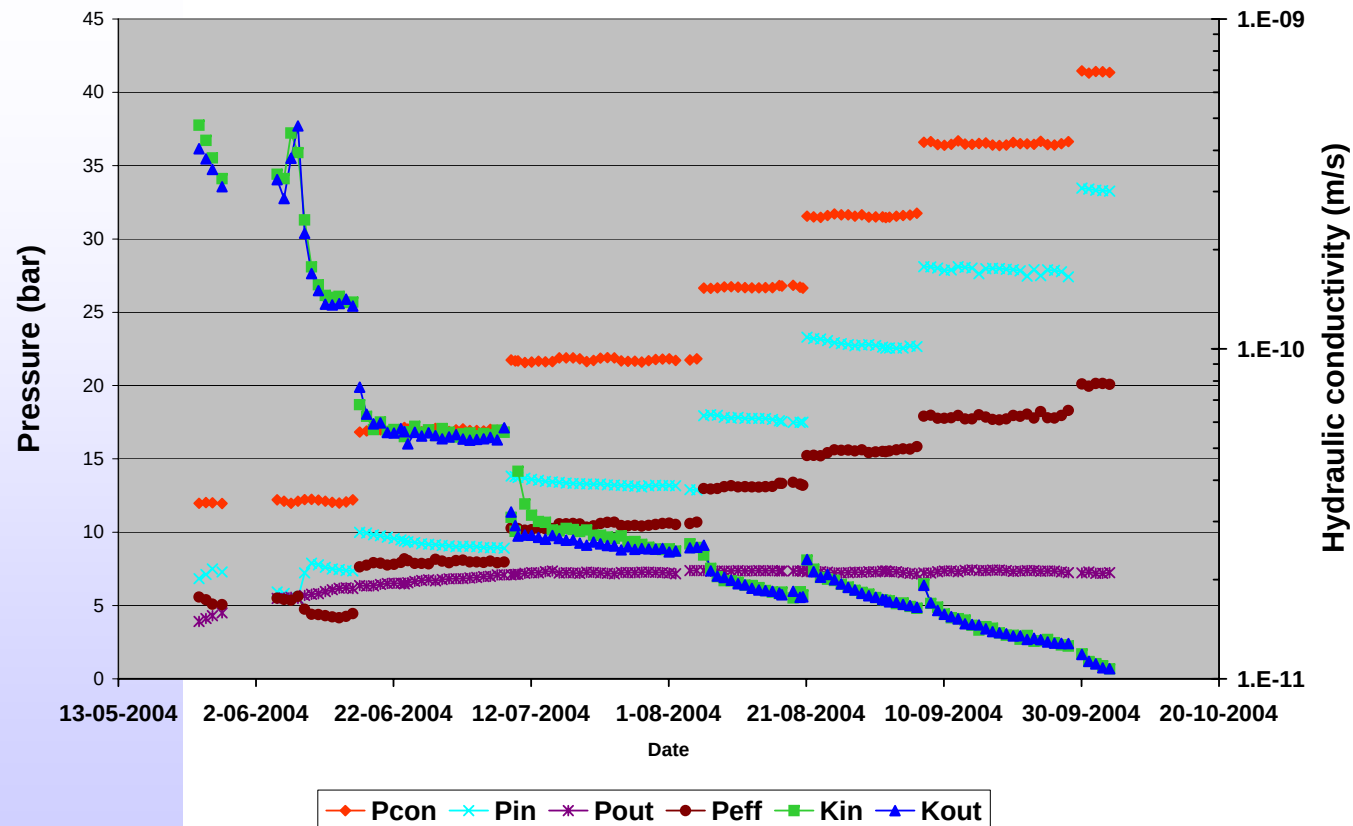
- Two tests have been carried out on Opalinus Clay samples
 - Same original core
 - 2.5 and 4 mm centered drillhole at the installation
 - Low saline Pearson water injected through the bottom of the sample (flow parallel to the orientation of the bedding plane)
 - The confining pressure is progressively incremented (starting at 0.1 MPa g) up to a final value of 4.5 MPa while the mean effective stress and mean pore water pressure are kept equivalent
 - The evolution of the hydraulic conductivity and of the consolidation are monitored

No sealing observed for the sample with the larger hole diameter (4mm)

- The hole was still present when the sample was dismantled with similar dimensions as when installed. A direct connection between the sample boundaries could be established by permeability pulse tests and confirmed visually and by μ CT scans



A Moderate Sealing Process could be Detected for the Sample with the Smaller Hole Diameter (2.5mm)



Conclusions

- No perfect self-healing (restoration of hydraulic AND mechanical properties) could be detected for both argillaceous materials tested
- Lower density detected with μ CT at the original hole location for Boom Clay
- The hydraulic properties were fully restored for Boom Clay (self-sealing)
- The effect of the chemical composition on the sealing of the clay samples could up to now only be detected when evolved cement water was injected through Boom Clay. The cohesion was increased though no cementation was observed.
- A very moderate self-sealing (chemical and mechanical) is observed for Opalinus Clay

Recommendations

- The permeameter cell experiments testing the chemical component of the self-healing seem to be dependent on the experimental procedure (constant head/constant flow, “natural”/artificial fracture, boundary effects, ...). A sensitivity study could complete the experimental data
- For these tests, the small fracture aperture (order of 100µm) implies at least three orders of magnitude difference in permeability to be detected on the integrated surface: tracer tests might give a better idea of the fault conductivity

SELFRAC Exchange Meeting
October 4 2004



**STUDY OF THE SEALING/HEALING PROCESSES
BY ACOUSTIC EMISSION MEASUREMENTS**

A.Vervoort, J.Verstraelen and B.Debecker
K.U.Leuven, Research Unit Mining

Aim of research

**Around excavations in clay formations:
Micro- and macro-fractures occur**

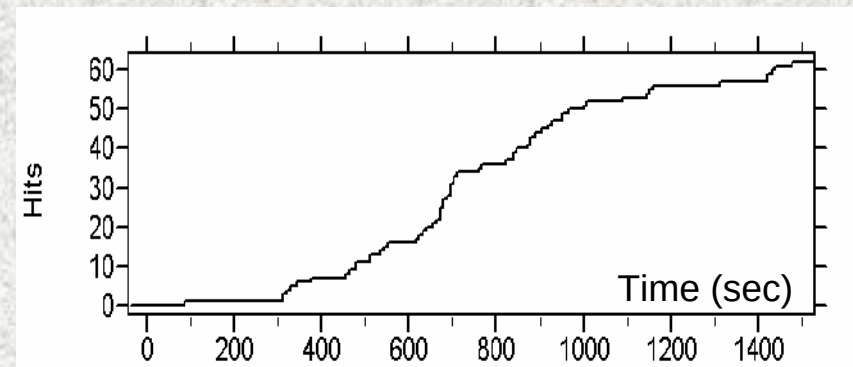
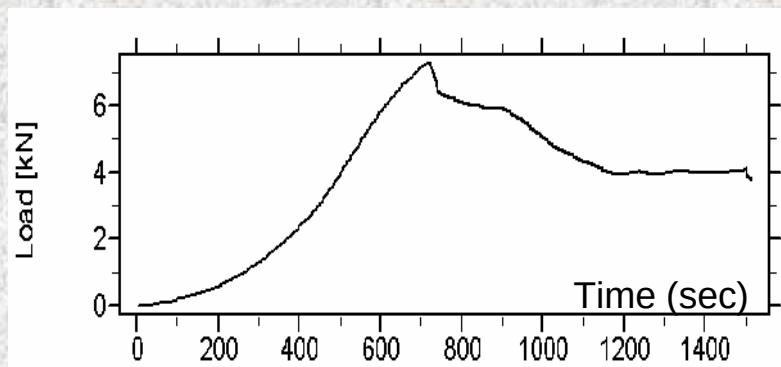


What happens with time ?

1. Acoustic Emission (AE) method was applied
2. Memory or Kaiser effect (KE) was analysed

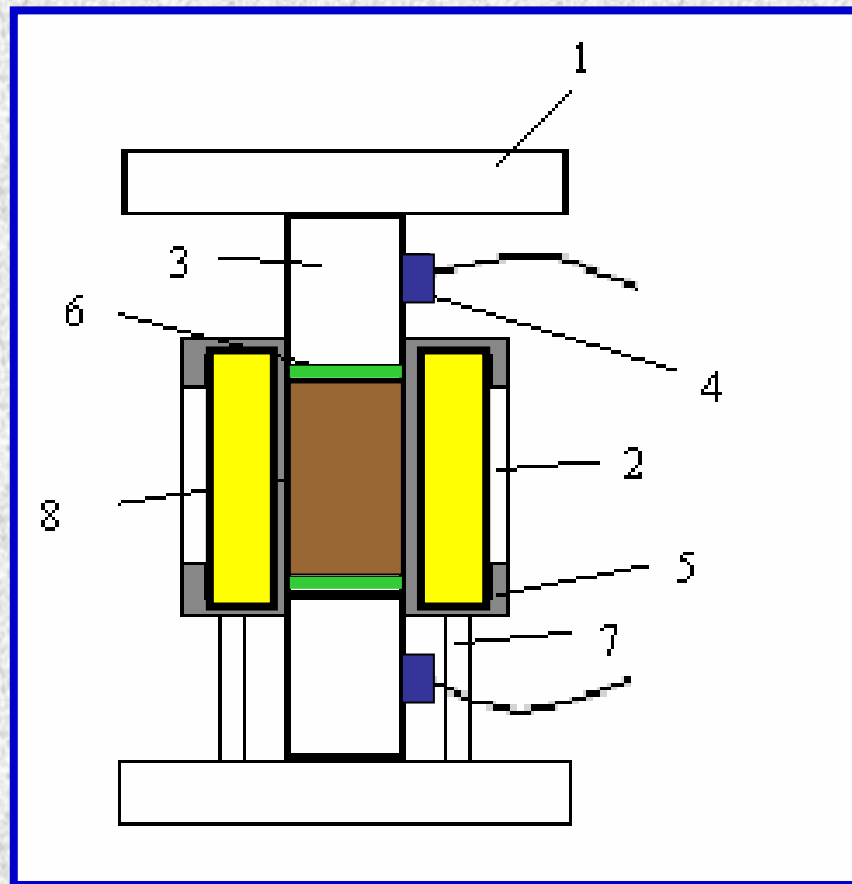
Acoustic Emission (AE)

During ‘micro-fracturing’, energy strain wave is released and can be recorded.



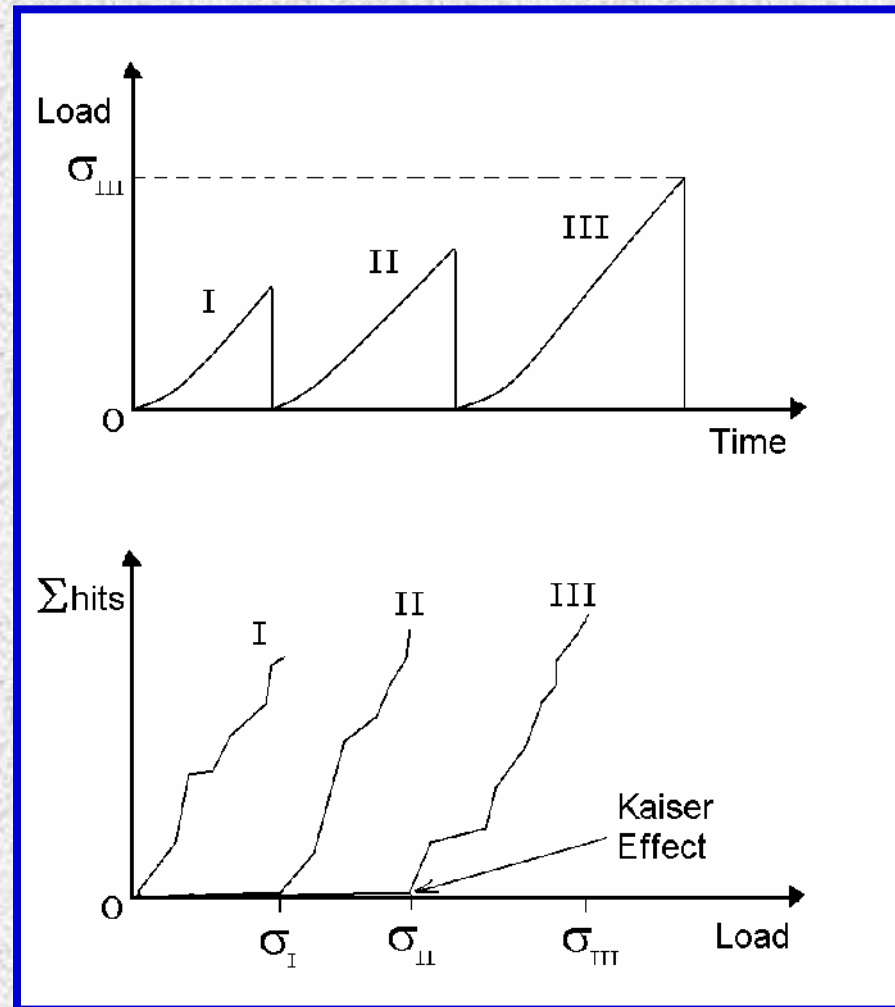
Acoustic Emission (AE)

Experimental set-up



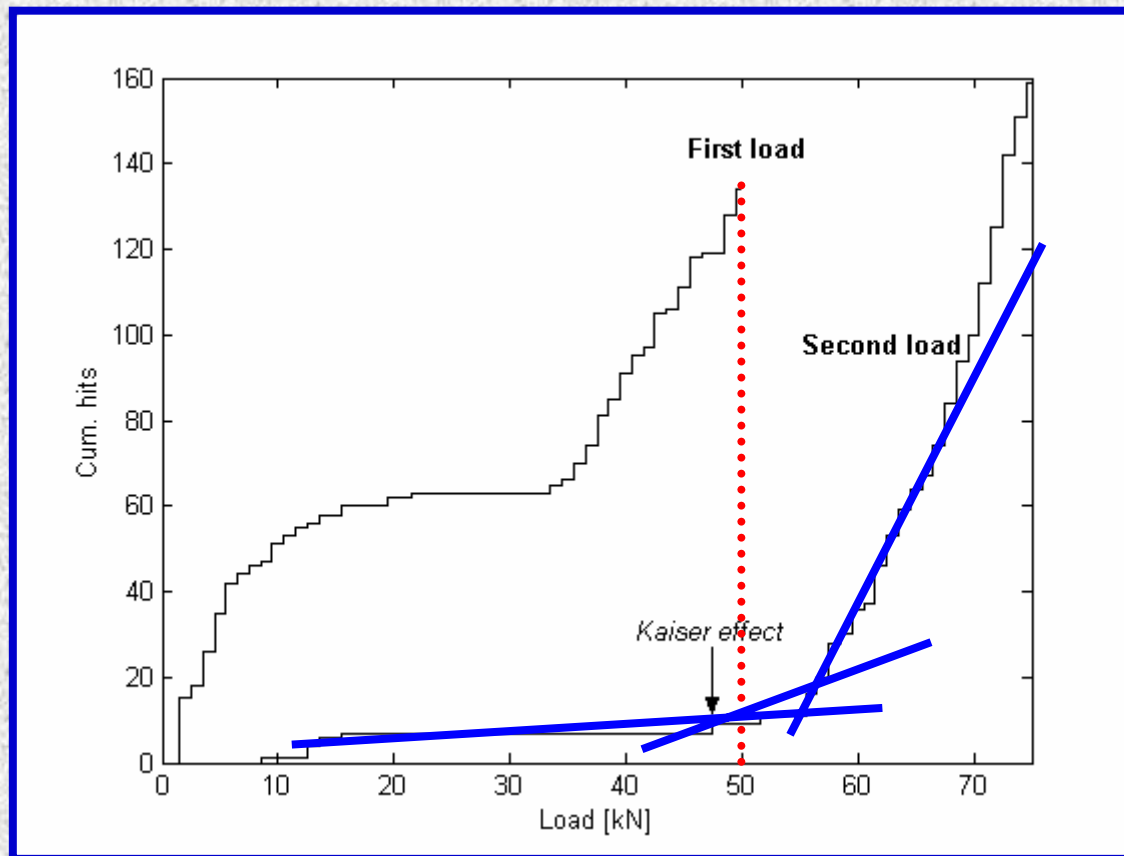
Memory or Kaiser effect (KE)

If rock under stress is unloaded and reloaded, it is generally observed that the AE activity remains low till the previous maximum load level is reached.



Memory or Kaiser effect (KE)

Kaiser effect in shales (uni-axial loading)



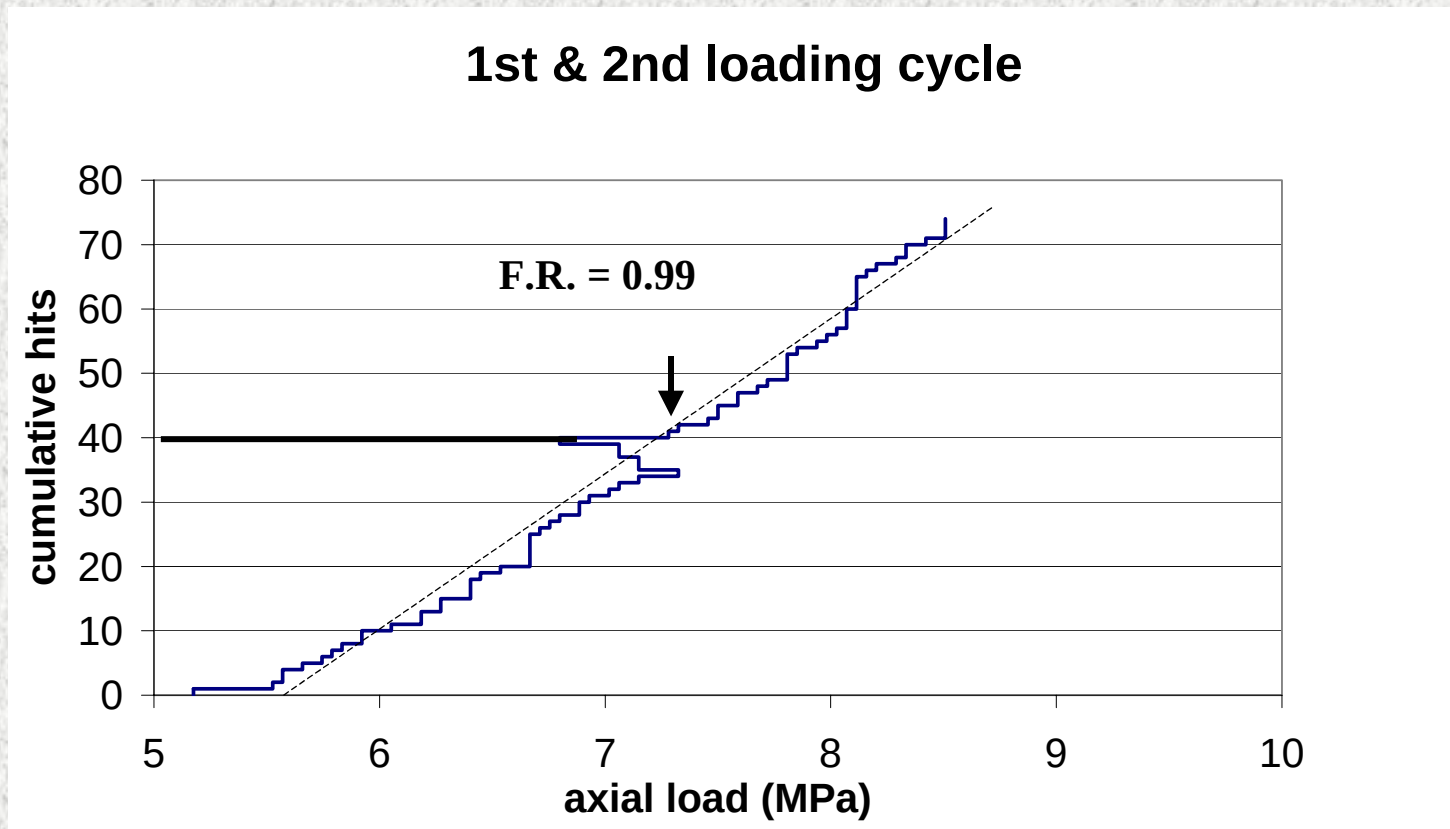
Memory or Kaiser effect (KE)

Kaiser effect in Opalinus Clay (tri-axial loading)

1. Isotropic tri-axial load of 5 MPa & pore pressure of 0.5 MPa (minimum of 48 hours)
2. Circumferential load and pore pressure remain constant, while axial load increases (e.g. to 7.5 MPa)
3. Axial load decreases, followed by a new increase (e.g. till failure)

Memory or Kaiser effect (KE)

Kaiser effect in Opalinus Clay (tri-axial loading)



Evolution with time

Healing of induced micro-fractures

What happens with the Kaiser effect as a function of time ?

What happens with the micro-fractures as a function of time ?

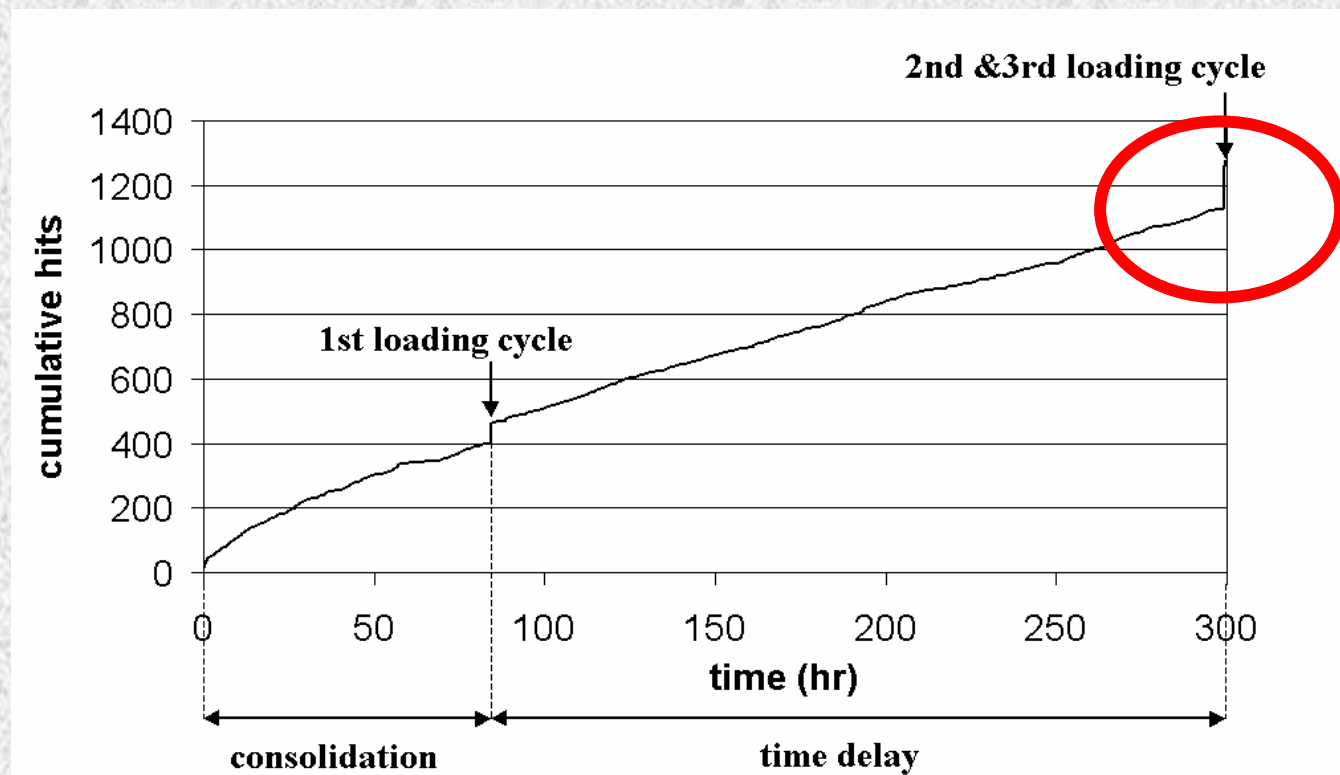
Between 1st and 2nd cycle: interval of 1 to 30 days

Isotropic stress state of 5 MPa

Pore pressure of 0.5 MPa

Evolution with time

Boom Clay: Entire test

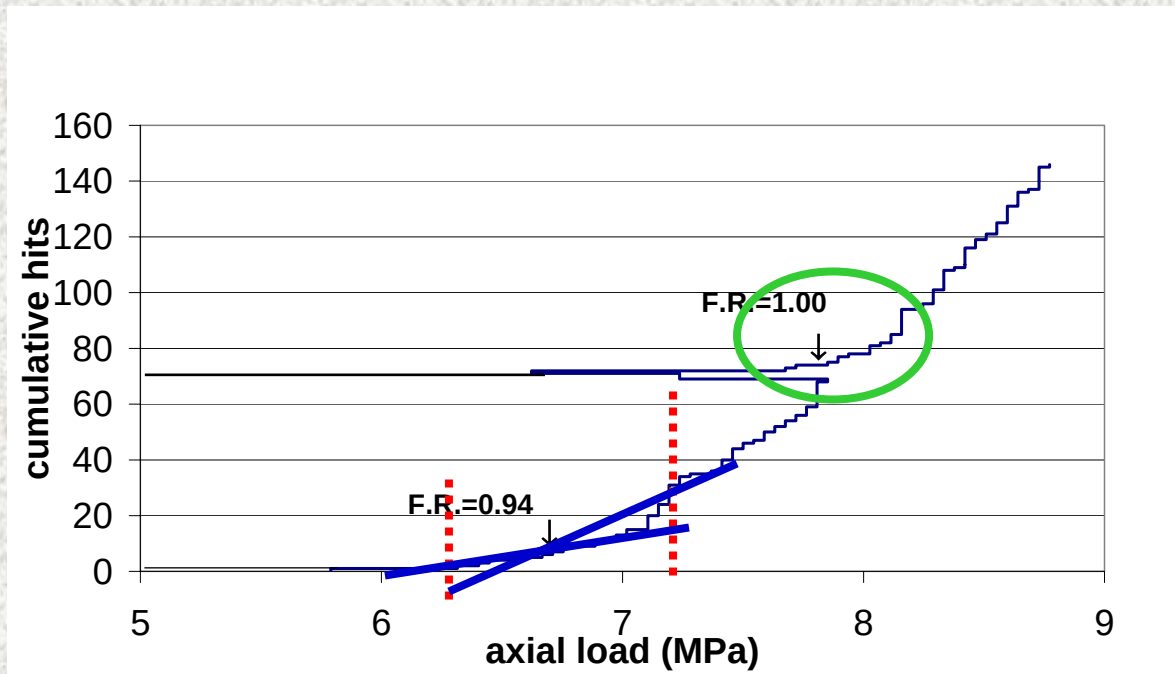


3 hits/hour

9 days delay

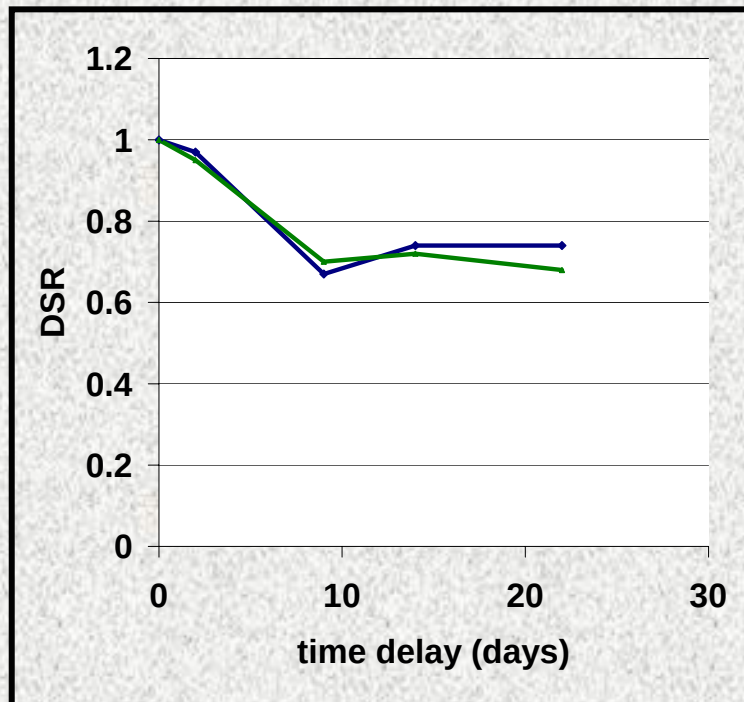
Evolution with time

Boom Clay: 2nd (9 days delay) and 3rd cycle (immediately)



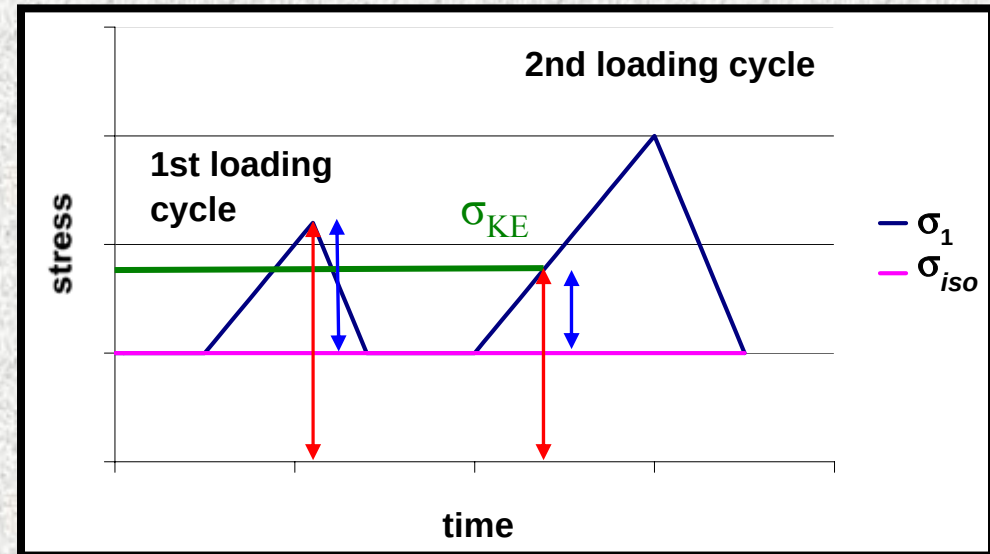
Evolution with time

Overview of all results



Boom clay

Opalinus clay



$$Fr = \frac{\sigma_{1K.E.}^{II}}{\sigma_{1max}^I}$$

$$DSR = \frac{(\sigma_1 - \sigma_{ISO})_{K.E.}^{II}}{(\sigma_1 - \sigma_{ISO})_{max}^I}$$

Discussion

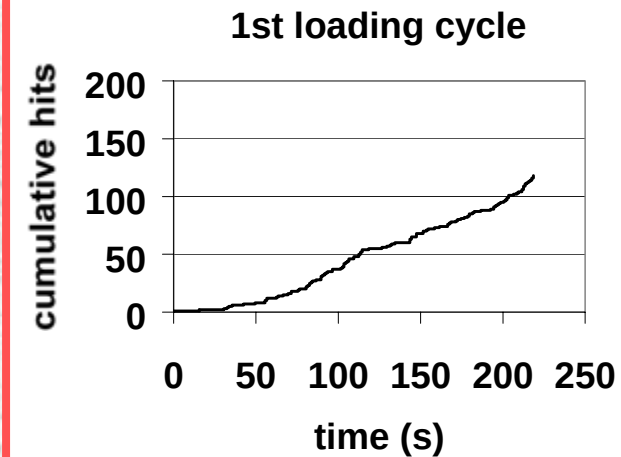
Laboratory

Loading of sample



Damage induced

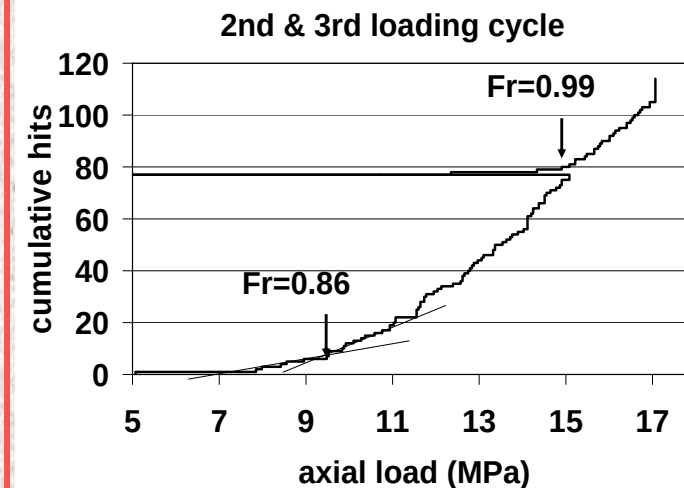
Characterised by AE



Partial unloading, **time delay**, reloading



KE is less (decrease in Fr and in DSR)



Discussion

Laboratory

Loading of sample



Damage induced

Characterised by AE

Partial unloading, **time delay**, reloading



KE is less (decrease in Fr and in DSR)

In situ

Stress re-distribution during excavation



Damage induced
(micro- and **macro**-fractures)

=

Loss of cohesion

Increase of cohesion with time ?
= Healing

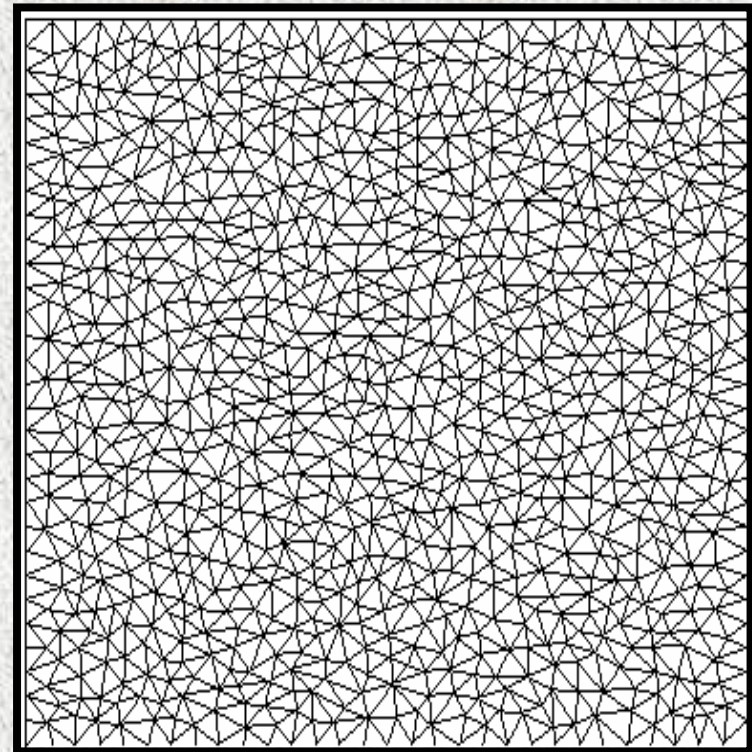
Numerical simulations

Boundary element code DIGS:

Pre-defined mesh of elements

Different properties given to elements (e.g. flaws, intact elements, ...)

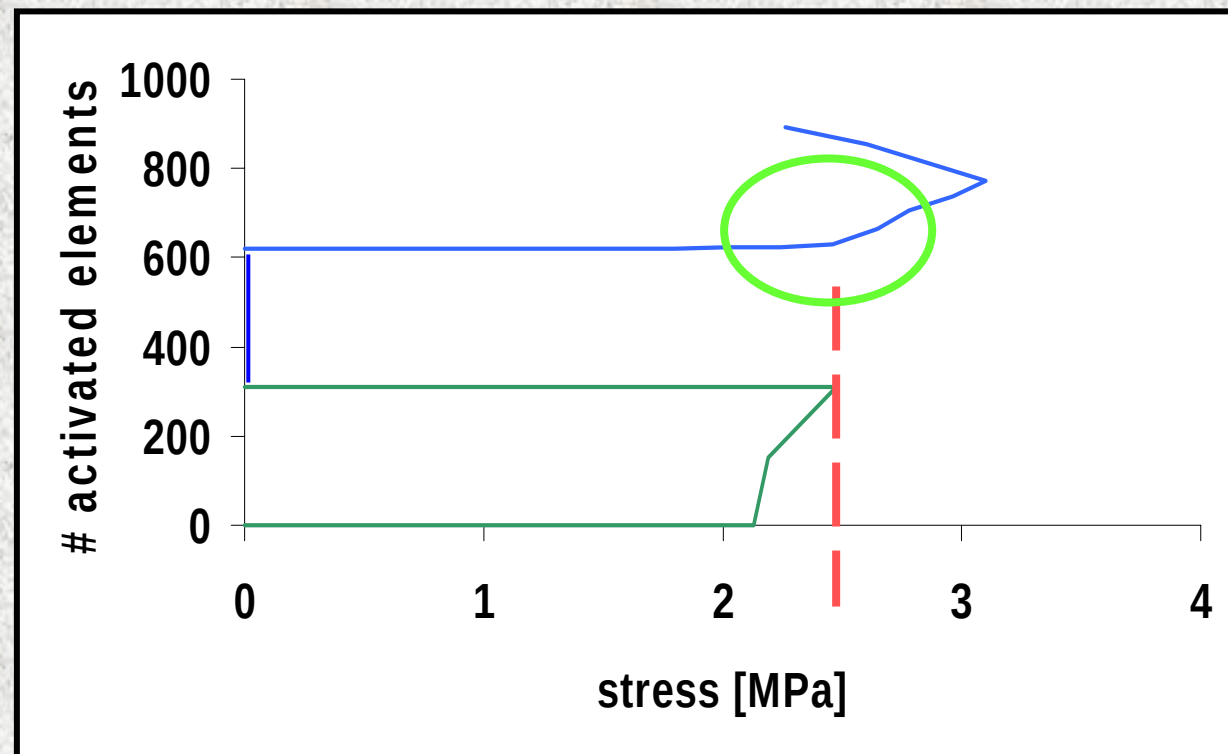
Different initial and residual properties



Simulation of closing of activated elements and
of an increase of their strength

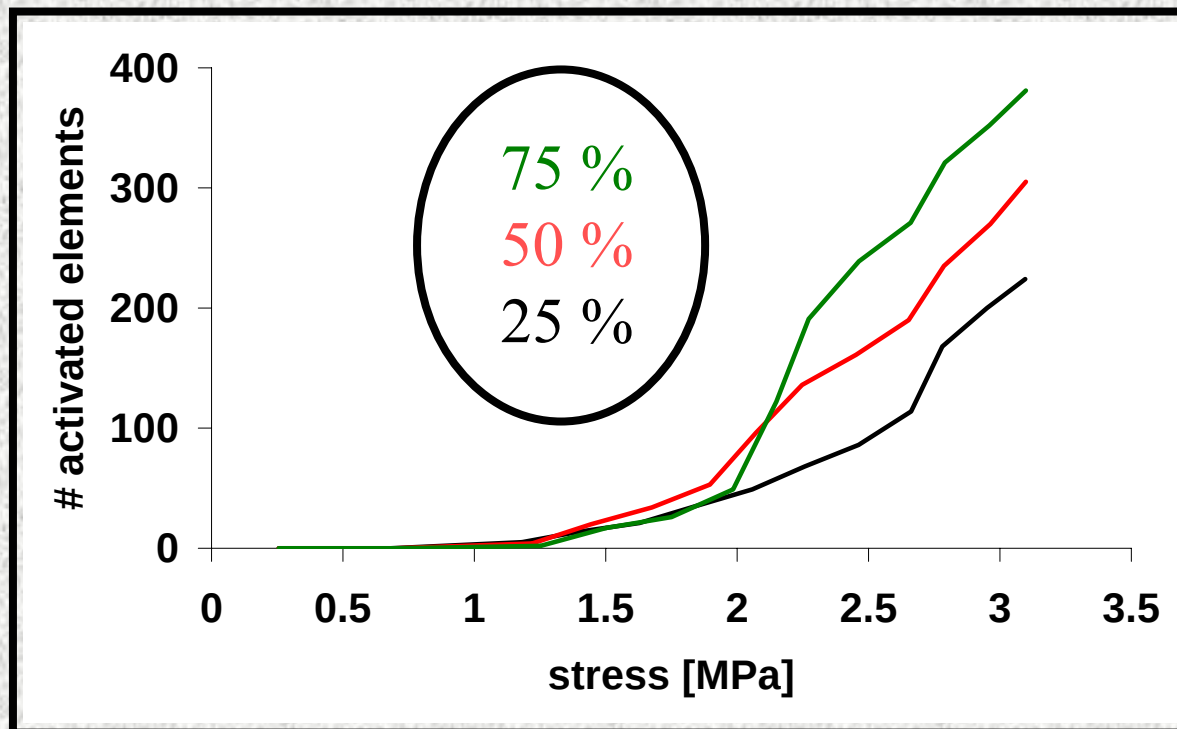
Numerical simulations

1. Loading of sample to 2.5 MPa, followed by unloading
2. All residual displacements of activated elements are put equal to zero (normal and shear displacement) → SEALING
3. Reloading: inflection point is clearly visible at 2.5 MPa



Numerical simulations

1. Loading of sample to 2.5 MPa, followed by unloading
2. All residual displacements of activated elements are put equal to zero (normal and shear displacement) + % activated elements is given initial (strong) properties back → HEALING
3. Reloading



Conclusion

Are we able to characterise and quantify the sealing/healing processes ?

It has been shown that ‘something’ is happening at micro-scale.

Link with other laboratory experiments (micro- and macro-scale) and with in situ situation (micro- and macro-scale) ?

Link with change in cohesion ?



More fundamental research required

