

EXCHANGE MEETING HADES 40 PROGRAM

Date : Friday 09-12-2022

40 years of research on geological disposal of radioactive waste at the HADES URL: Wrap-up of results and the role of HADES in an international context.

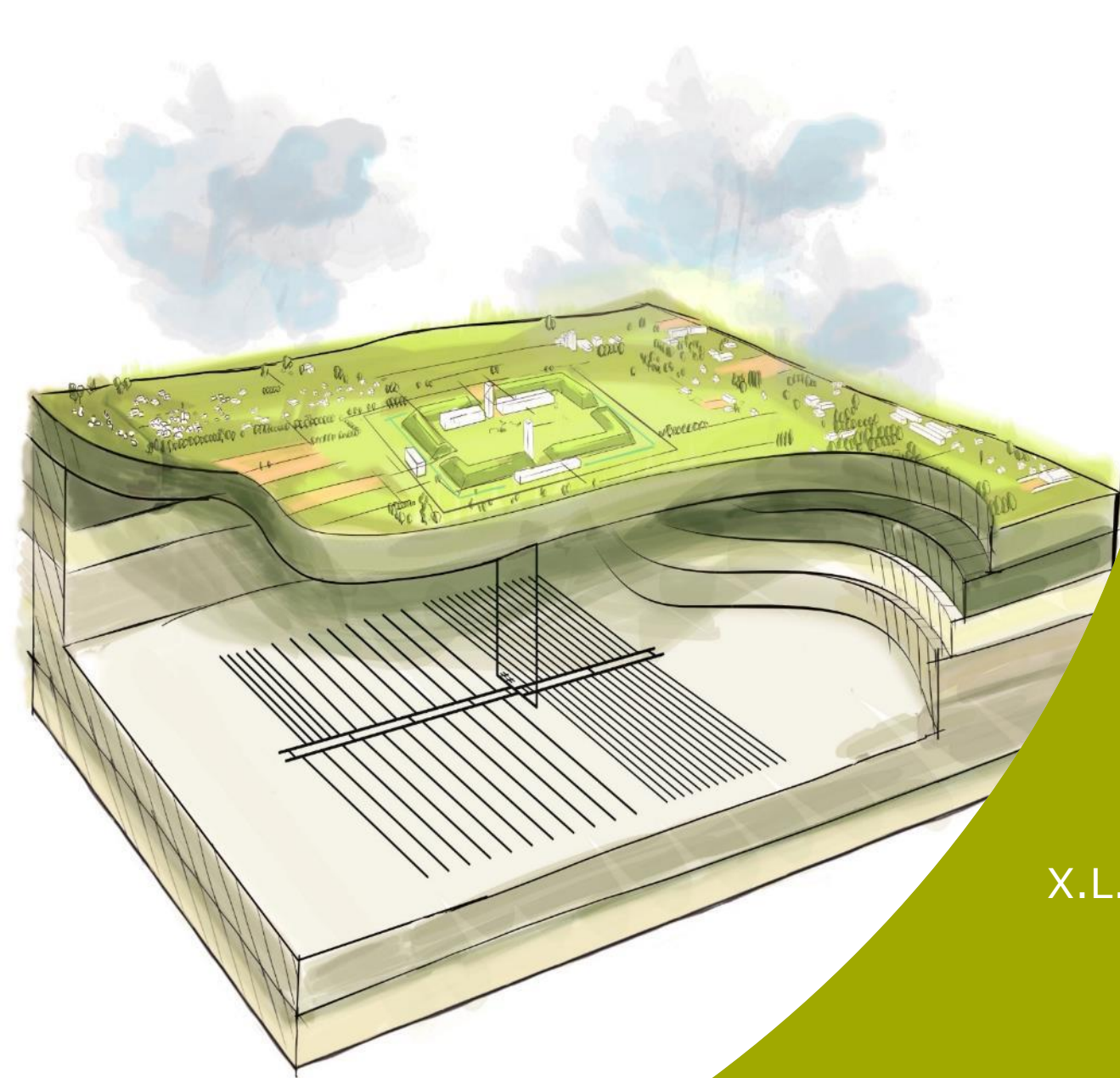
09h00 - 12h30		
Concise overview of key results (25' for each topic, including Q&A)		
08h30 – 09h00	Welcome Coffee	
09h00 – 09h05	Welcome	Peter De Preter director EIG EURIDICE
09h05 – 09h30	The construction of the HADES Underground Research Laboratory and its role in the development of the Belgian concept for a deep geological repository <i>X.L. Li (EIG EURIDICE), B. Neerdael (SCK CEN, now retired) , D. Raymaekers (ONDRAF/NIRAS), X. Sillen (ONDRAF/NIRAS)</i>	Xavier Sillen ONDRAF/NIRAS
09h30 – 09h55	40 years of investigation of the thermo-hydromechanical (THM) behaviour of Boom Clay in the HADES URL <i>X.L. Li (EIG EURIDICE), A. Dizier (EIG EURIDICE), G.J. Chen (EIG EURIDICE), J. Verstricht (EIG EURIDICE), S. Levasseur (ONDRAF/NIRAS)</i>	Xiangling Li EIG EURIDICE
09h55 – 10h20	Characterization of Boom Clay anisotropic THM behaviour based on the small scale ATLAS Heater Test and the large scale PRACLAY Heater Test in the HADES URL <i>G.J. Chen (EIG EURIDICE), X.L. Li (EIG EURIDICE), A. Dizier (EIG EURIDICE), J. Verstricht (EIG EURIDICE), X. Sillen (ONDRAF/NIRAS), S. Levasseur (ONDRAF/NIRAS)</i>	Guangjing J. Chen EIG EURIDICE
10h20 – 10h50	Coffee break	
10h50 – 11h15	Stability analysis and long term behaviour of deep tunnels in clay formation <i>A. Dizier (EIG EURIDICE), M. Scibetta (SCK CEN), G. Armand (ANDRA), J. Zghondi (ANDRA), T. Georgieva (EIG EURIDICE), G. Chen (EIG EURIDICE), J. Verstricht (EIG EURIDICE), X. Li (EIG EURIDICE), D. Léonard (ONDRAF/NIRAS) and S. Levasseur (ONDRAF/NIRAS)</i>	Arnaud Dizier EIG EURIDICE
11h15 – 11h40	Coupled flow and transport modelling of a large-scale in-situ migration experiment with 14C-labelled natural organic matter colloids in Boom Clay. <i>J. Govaerts (SCK CEN), N. Maes (SCK CEN), D. Durce (SCK CEN), M. Aertsens (SCK CEN) , S. Brassinnes (ONDRAF/NIRAS)</i>	Norbert Maes SCK CEN
11h40 – 12h05	Gas transport in Boom Clay: The role of the HADES URL in process understanding <i>E. Jacops (SCK CEN), Li Yu (SCK CEN), G.J. Chen (SCK CEN), S. Levasseur (ONDRAF/NIRAS)</i>	Séverine Levasseur ONDRAF/NIRAS
12h05 – 12h30	The role of the HADES URL in the better understanding of the Boom Clay pore water geochemistry <i>M. De Craen (SCK CEN), H. Moors (SCK CEN), M. Honty (SCK CEN), M. Van Geet (ONDRAF/NIRAS)</i>	Mieke De Craen EIG EURIDICE

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40 years of research on geological disposal of radioactive waste at the HADES URL: Wrap-up of results and the role of HADES in an international context.

12h30 – 13h30	Sandwich Lunch	
13h30 – 15h00		
Role of HADES in an international context (20' for each contribution, including Q&A)		
13h30 – 13h50	45 years of joint research programmes on geological disposal of radioactive waste and the pioneering role of the HADES Underground Research Laboratory <i>S. Ben Hadj Hassine (EC) , C. Davies(EC), R. Garbil (EC)</i>	Seif Ben Hadj Hassine European Commission
13h50 – 14h10	Contribution of HADES URL to the development of the Cigéo project, French industrial centre for geological disposal of high-level and intermediate long-lived radwaste in a deep clay formation <i>G. Armand (ANDRA), F. Plas (ANDRA), J. Talandier (ANDRA), A. Dizier (EIG EURIDICE) , X.L Li (EIG EURIDICE), S. Levasseur (ONDRAF/NIRAS)</i>	Gilles Armand ANDRA (France)
14h10 – 14h30	25 years of cross-fertilization between HADES and Mont Terri rock laboratories <i>Nussbaum Christophe (Swisstopo), F. Bernier (AFCN/FANC), N. Bleyen (SCK CEN), P. Bossart (Swisstopo, now retired), Ch. Bruggeman (SCK CEN), P. De Cannière (AFCN/FANC), Th. Fierz (Solexperts), D. Jaeggi (Swisstopo), B. Neerdael (SCK CEN, now retired), E. Valcke (SCK CEN), G. Volckaert (AFCN/FANC)</i>	Nele Bleyen SCK CEN
14h30 – 14h50	Underground Research Laboratories, an Important Support to the Belgian Regulatory Body's Research and Development Programme and the Management of Uncertainties <i>F. Bernier (AFCN/FANC), V. Detilleux (BEL V), F. Lemy (BEL V), G. Pochet (AFCN/FANC), M. Surkova (AFCN/FANC), G. Volckaert (AFCN/FANC), C. Mommaert (BEL V)</i>	Frédéric Bernier AFCN/FANC
15h00 – 17h00	Closure drink & optional visit Expoo Tabloo	



HADES 40

Construction of the HADES URL
& its role in the development
of the Belgian concept for a
deep geological repository

X.L. Li (EIG Euridice), B. Neerdael (SCK CEN, retired)
D. Raymaekers & X. Sillen (ONDRAF/NIRAS)

EURIDICE Exchange meeting, 2022-12-09

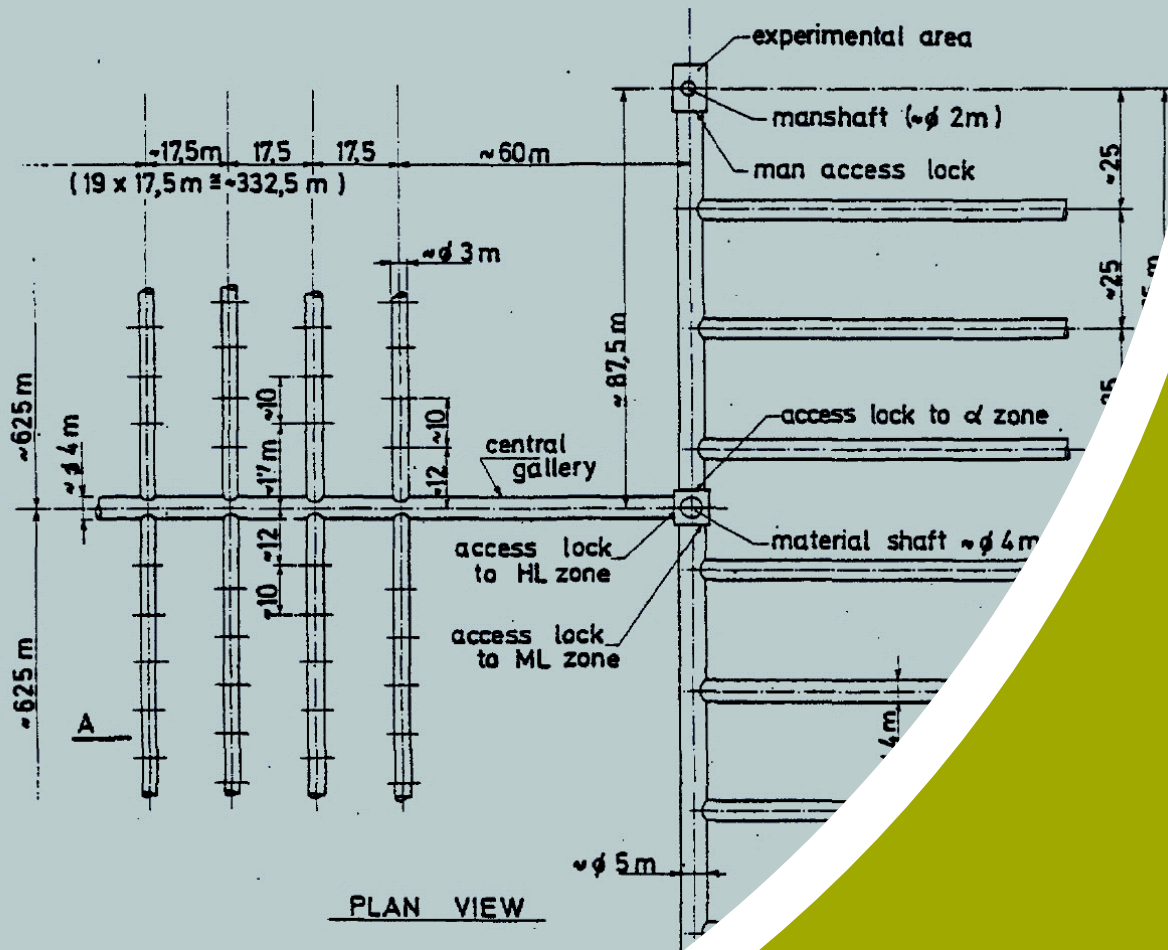
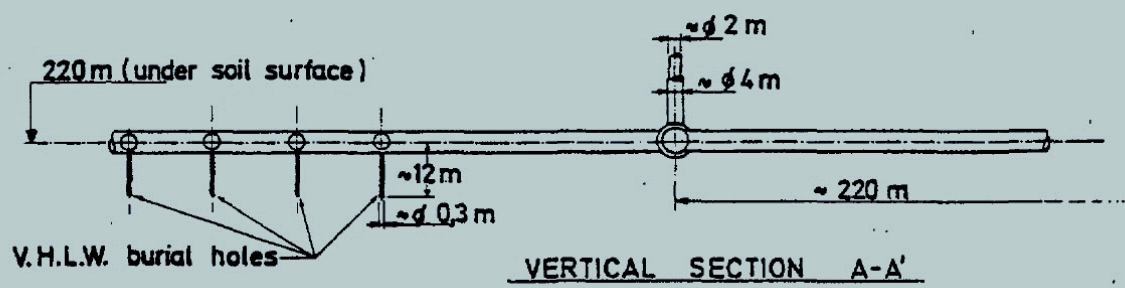


FIG. 6 PROJECT OF NUCLEAR WASTE
THE BOOM CLAY AT MOL

Genesis ~(1974 – 1984)

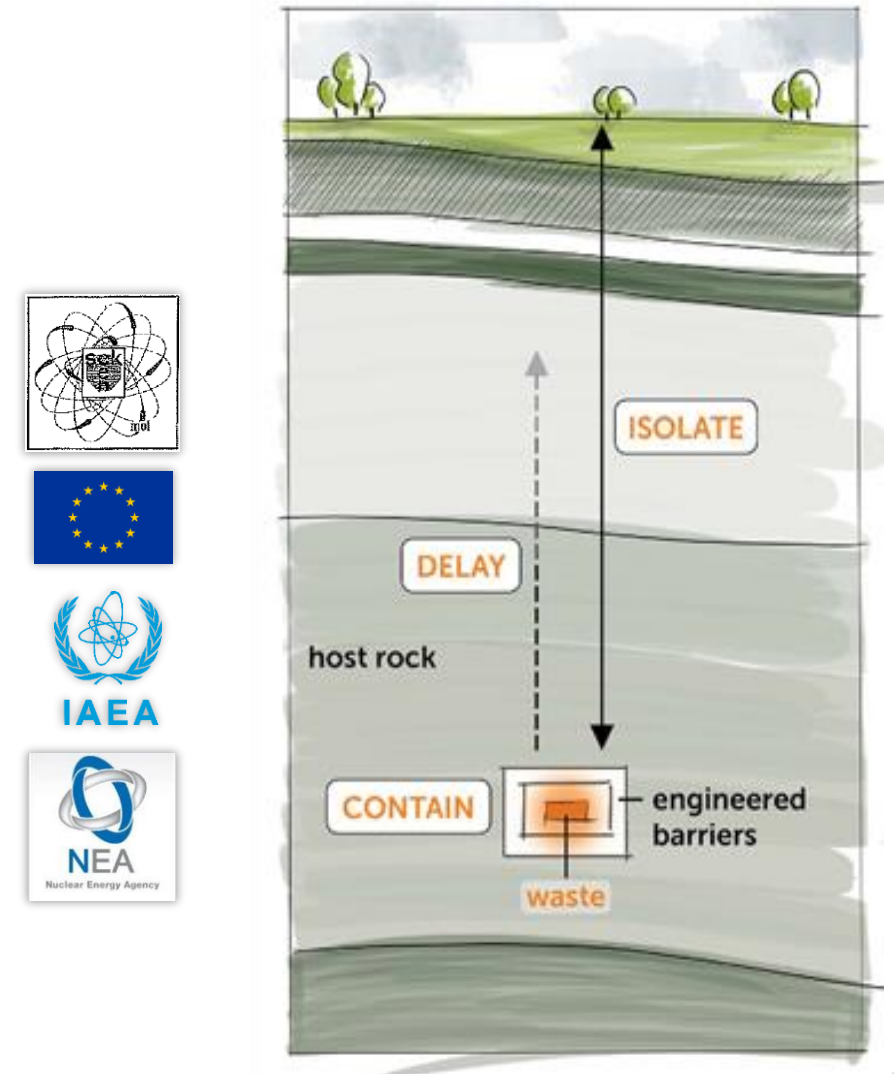
*And God said, "Let there be light." And there was light.
There was still nothing, but you could see it a lot better – Woody Allen*

Illustration: De Beer, Carpentier, Manfroy and Heremans (1977)
Preliminary Studies of an Underground Facility for
Nuclear Waste Burial in a Tertiary Clay Formation

Genesis (mid 70's to mid 80's)

- 7 NPP's built during the period 1969 - 1985
 - ◆ 4 PWR @ Doel, 3 @ Tihange
 - ◆ Built by EBES & INTERCOM (now ELECTRABEL)
- Start of R&D for waste disposal in 1974
 - ◆ Originally led by **SCK CEN**
 - ◆ Has been supported since 1976 by the **EC**
- And They followed international practice and They said 'let there be a deep repository' and They set out to show this could be both a
 - ◆ **FEASIBLE**
 - ◆ **SAFE**solution in Belgium.

Generic geological disposal concept & safety functions

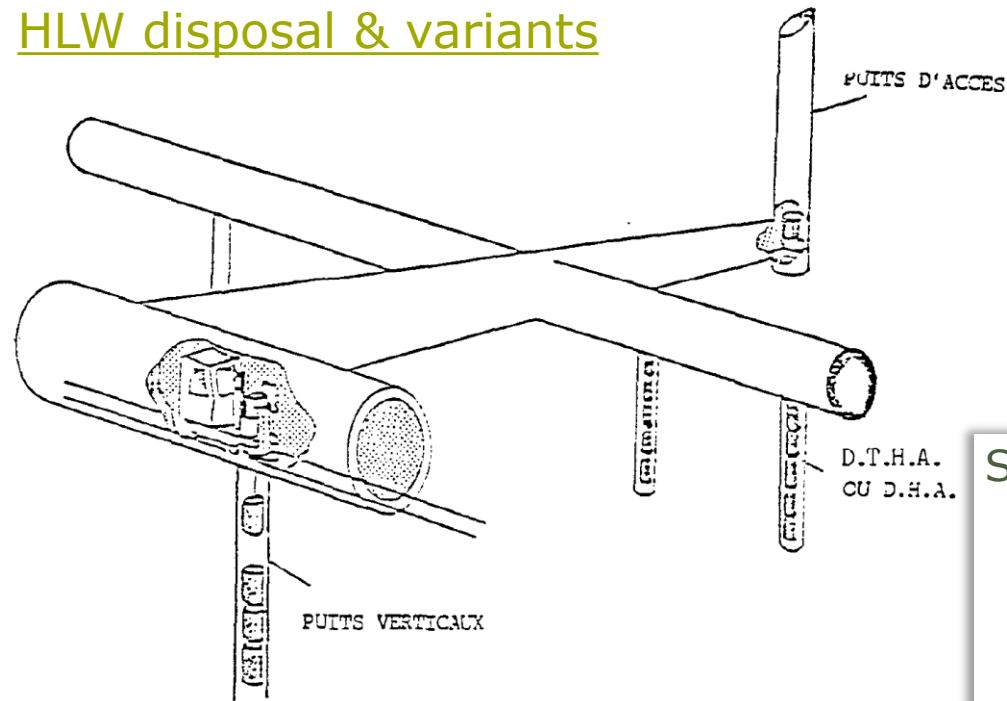


The (quick) search for a suitable host rock

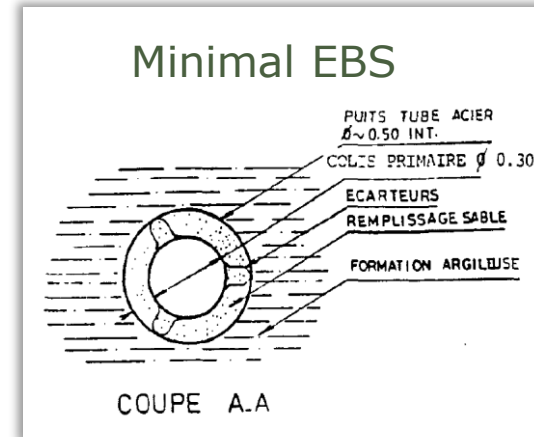
- SCK CEN opted early on to study **Boom Clay**
 - ◆ Found at convenient depth & thickness below SCK CEN
 - ✓ Characteristics that are a priori **suitable for a long term barrier**
 - ⚠ Tunneling at that 220+ meter depth: expected to be **difficult**
- ➔ Demonstrate that construction is **feasible**, with an **URL** as
 - ◆ A demonstrator of the repository concept
 - ◆ An opportunity to study host rock properties & behaviour *in situ*
- ➔ URL and repository development treated as **a single project**

“HADES” disposal concept (mid 70’s to mid 80’s)

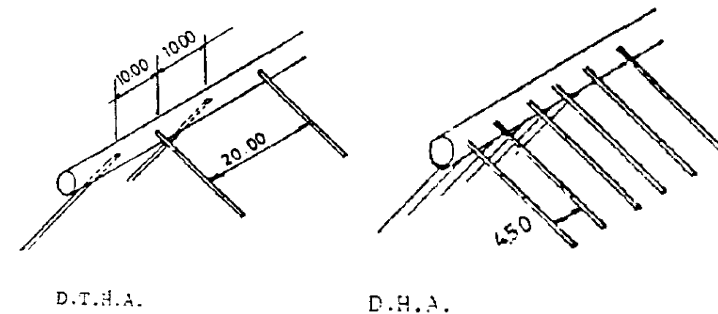
HLW disposal & variants



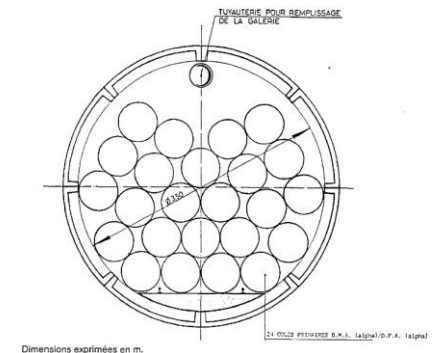
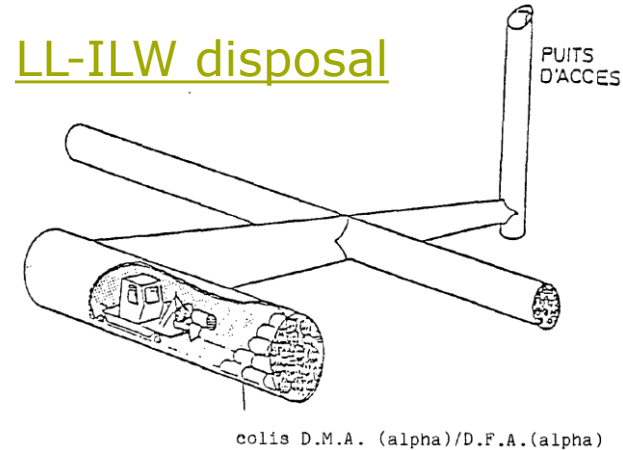
Illustrations: SAFIR (1989)



Spacing depends on heat output

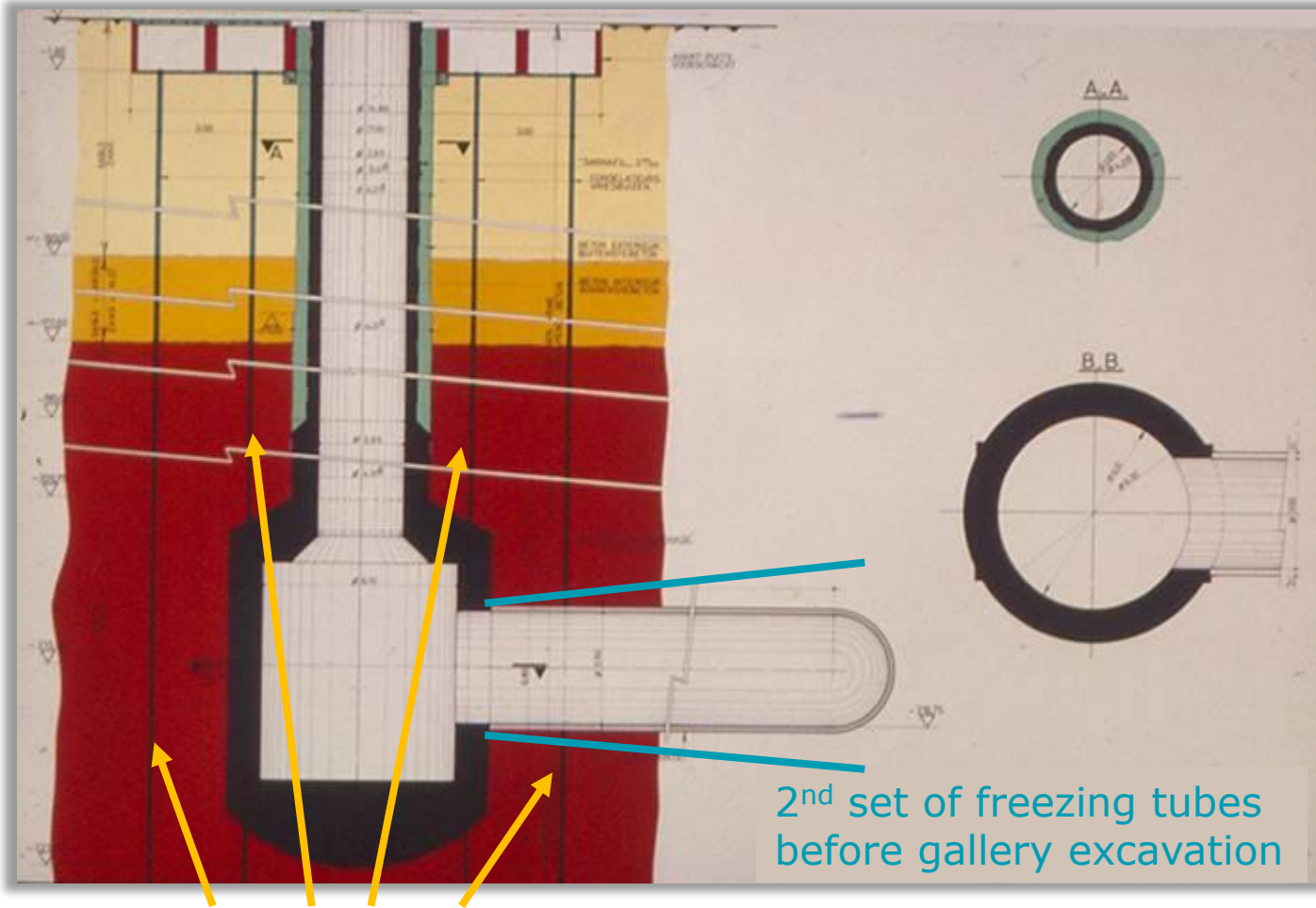


LL-ILW disposal



- ♦ “**H**igh **A**ctivity **D**isposal **E**xperimental **S**ite”
- ♦ Excavation to be made in frozen clay, cast iron lining
- ♦ HLW: in tubes pushed down into clay *below* access galleries
- ♦ EBS reduced to bare essentials (canister and disposal tube)

Getting down there: the 1st shaft (1980-1982)



Note: freezing tubes going all the way in the Boom Clay down to the bottom of the shaft



The original URL gallery (1983)

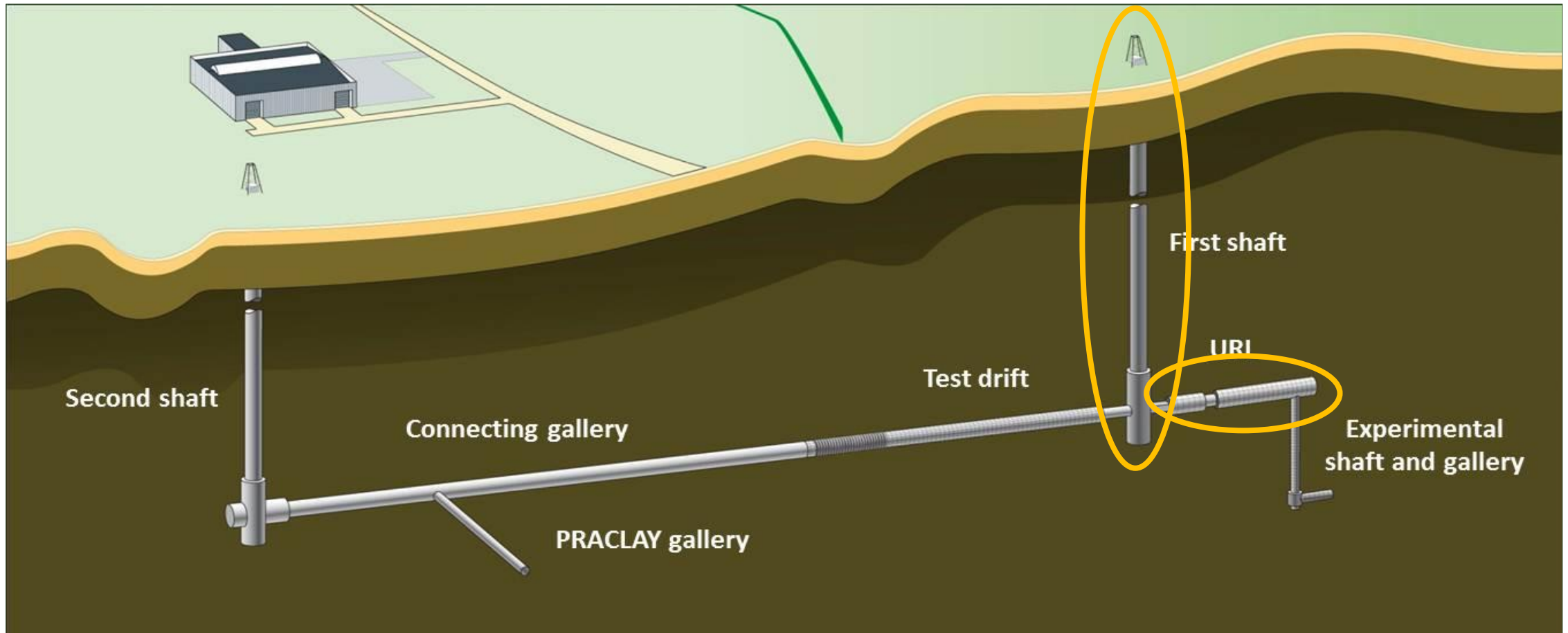
Semi-manual excavation in frozen clay



Prefabricated cast iron lining



HADES at the end of 1983

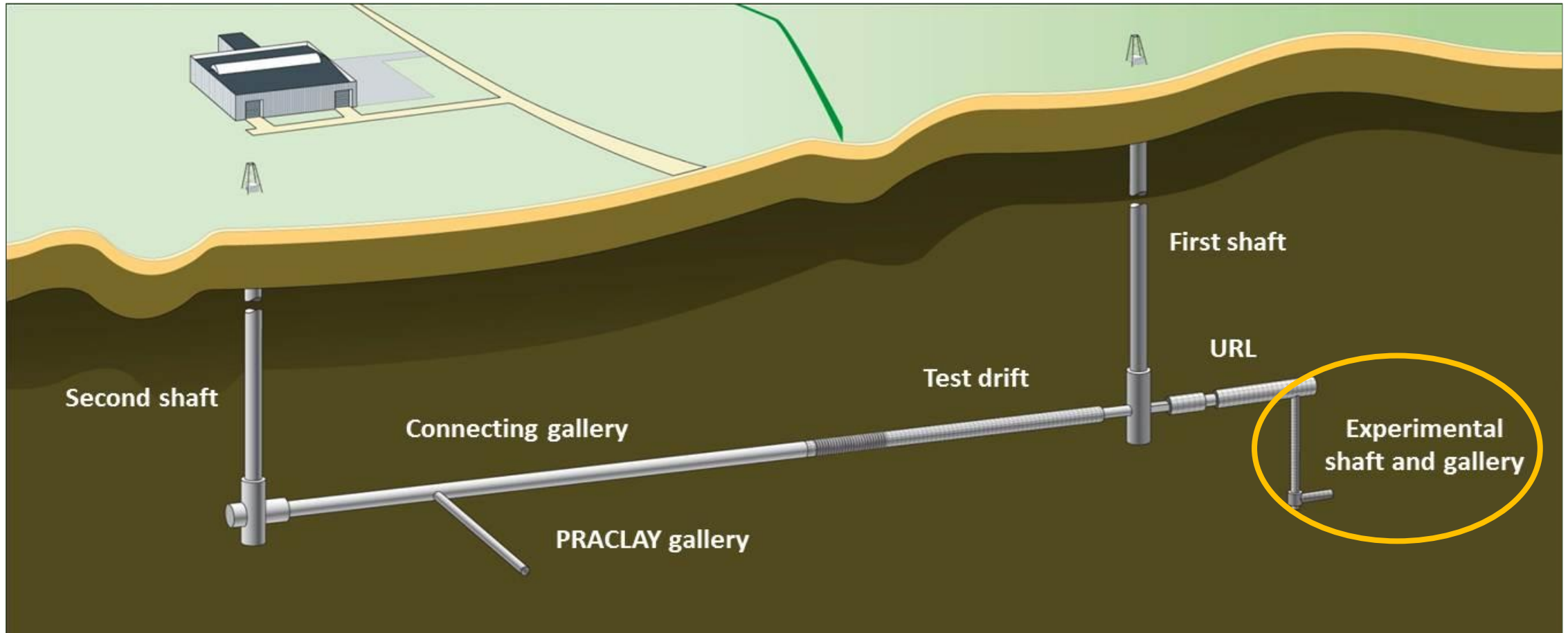




1st return of experience &
subsequent evolution
in the early stage
~(1984-1989)

Illustration: Sliding Ribs section
at the end of the Test Drift
("Toll Pay" section)

Experimental shaft & gallery (1984)

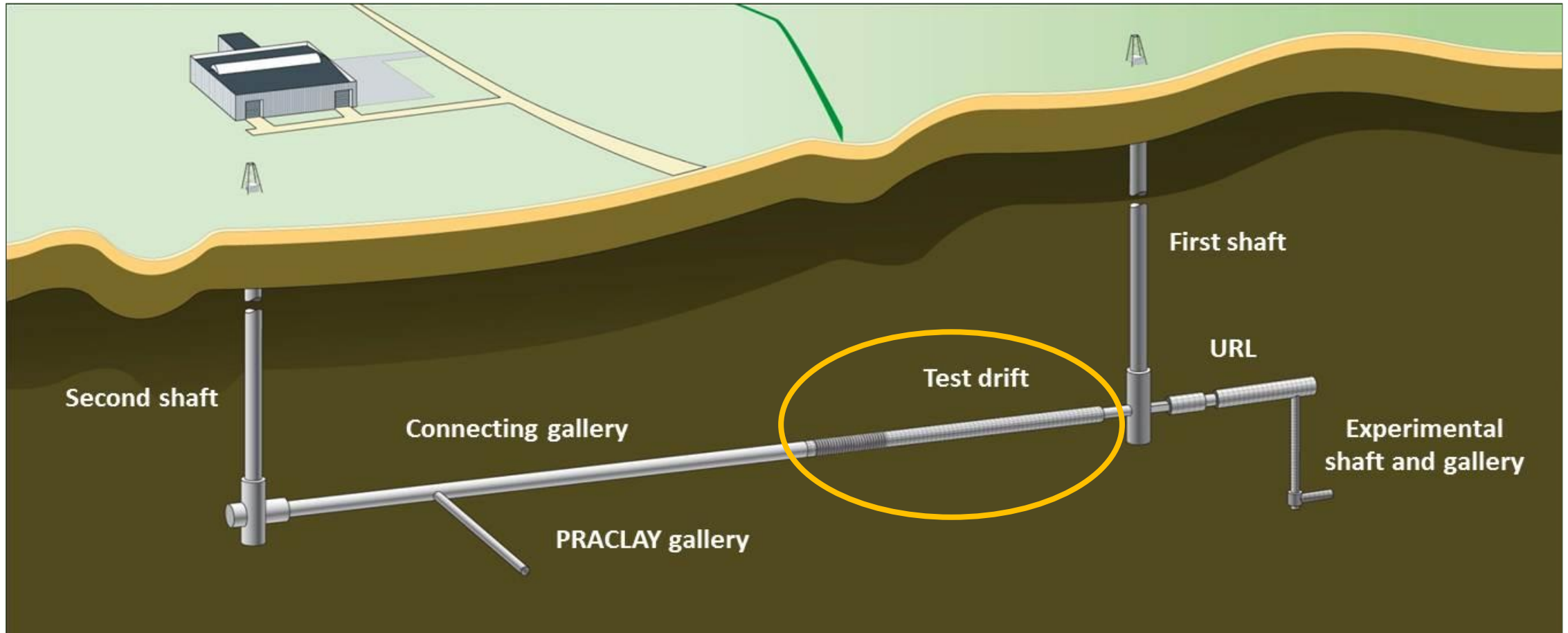


Experimental shaft & gallery (1984)

- Technological limits encountered during excavation of first shaft and URL gallery
 - ◆ Large displacements (near shaft base)
 - ◆ Unfrozen clay at end of URL, but found to be “less plastic than anticipated”
- Experimental shaft & gallery demonstrating capability of excavating and building in unfrozen clay at that depth
 - ◆ Successful
 - ◆ Lining made of concrete blocks
- To be confirmed at larger scale: “Test Drift”



Test Drift (1987)



The Test Drift (1987)

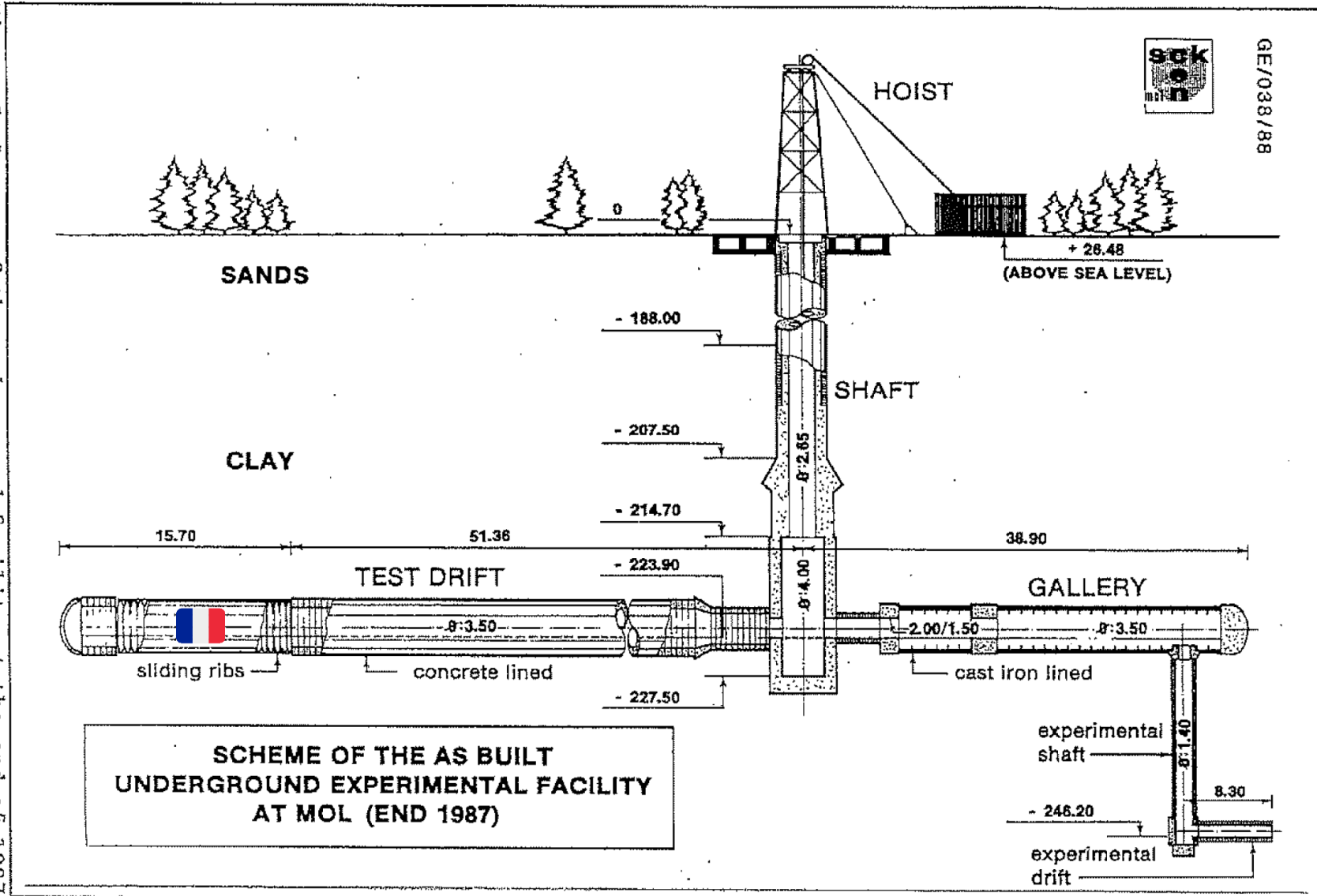
Front: (semi-)manual excavation



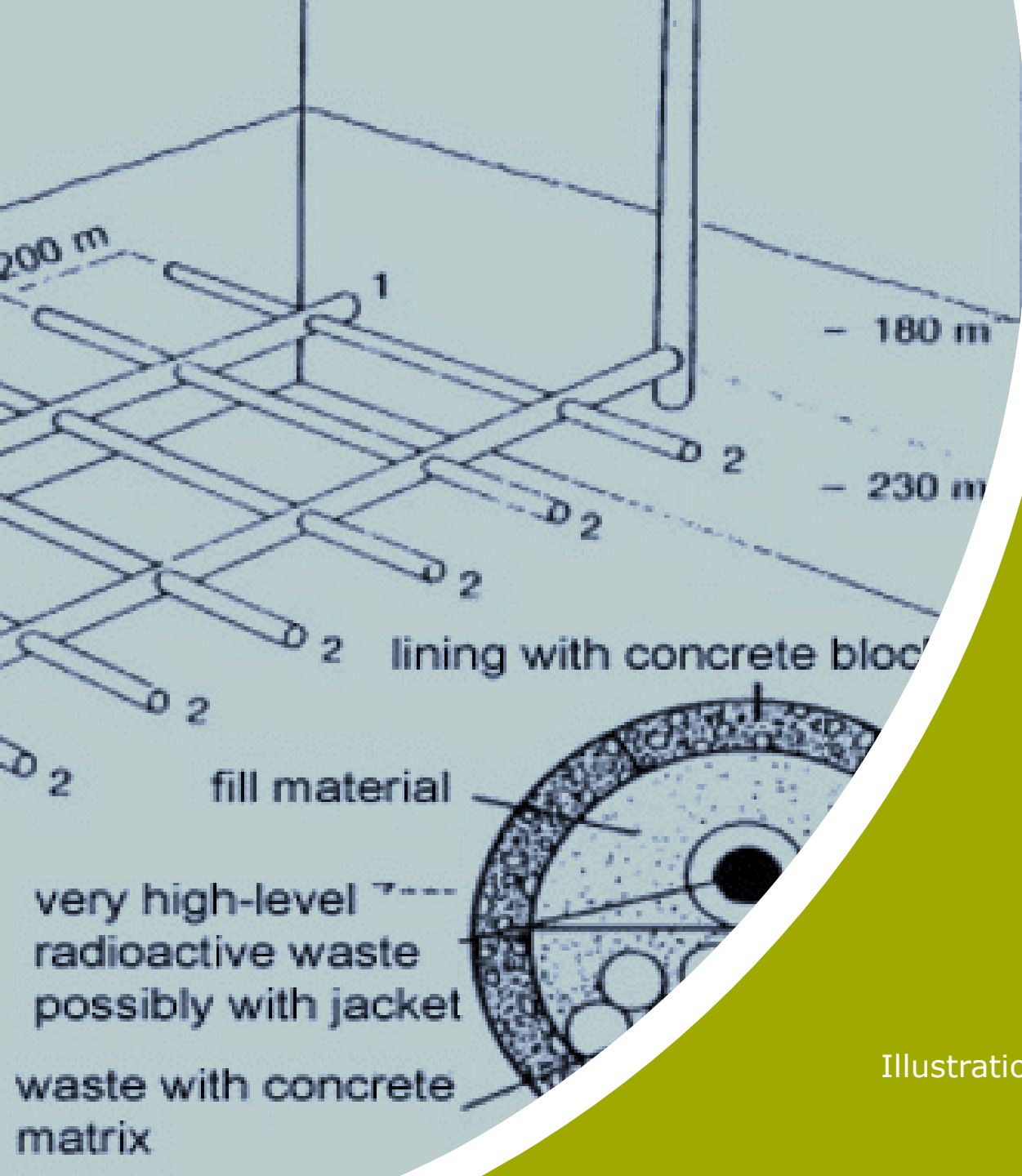
Lining: concrete blocks & wood plates



Figure 5: Layout of the underground facility at the end of 1987



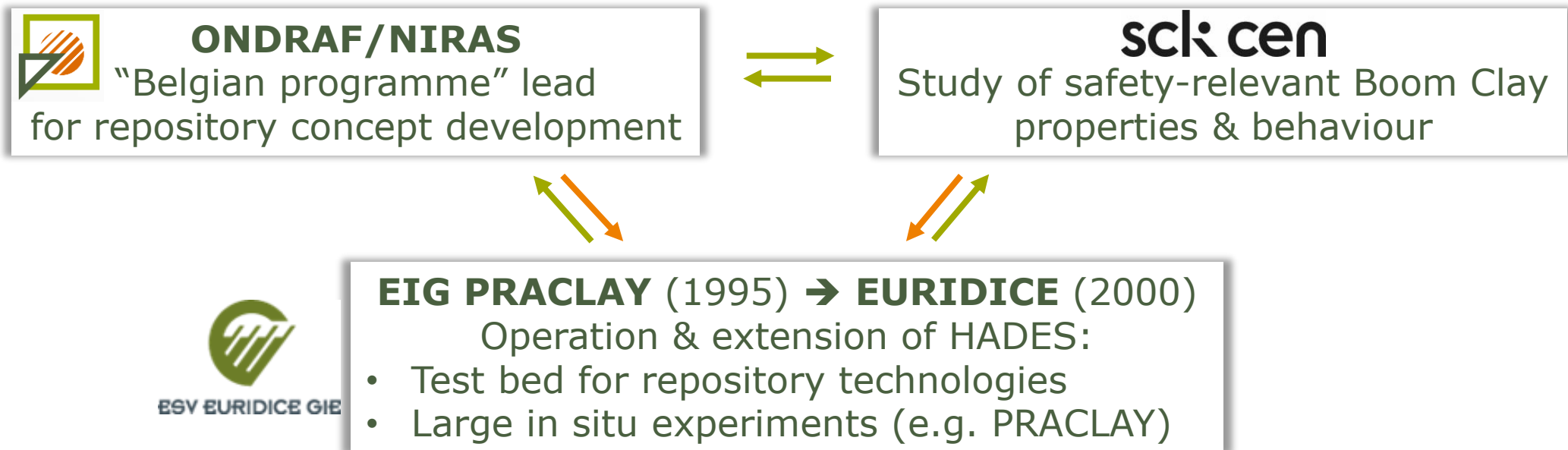
presented at the International Conference on
Civil Engineering in the Nuclear Industry,
Windermere, UK, 20-22 March, 1991

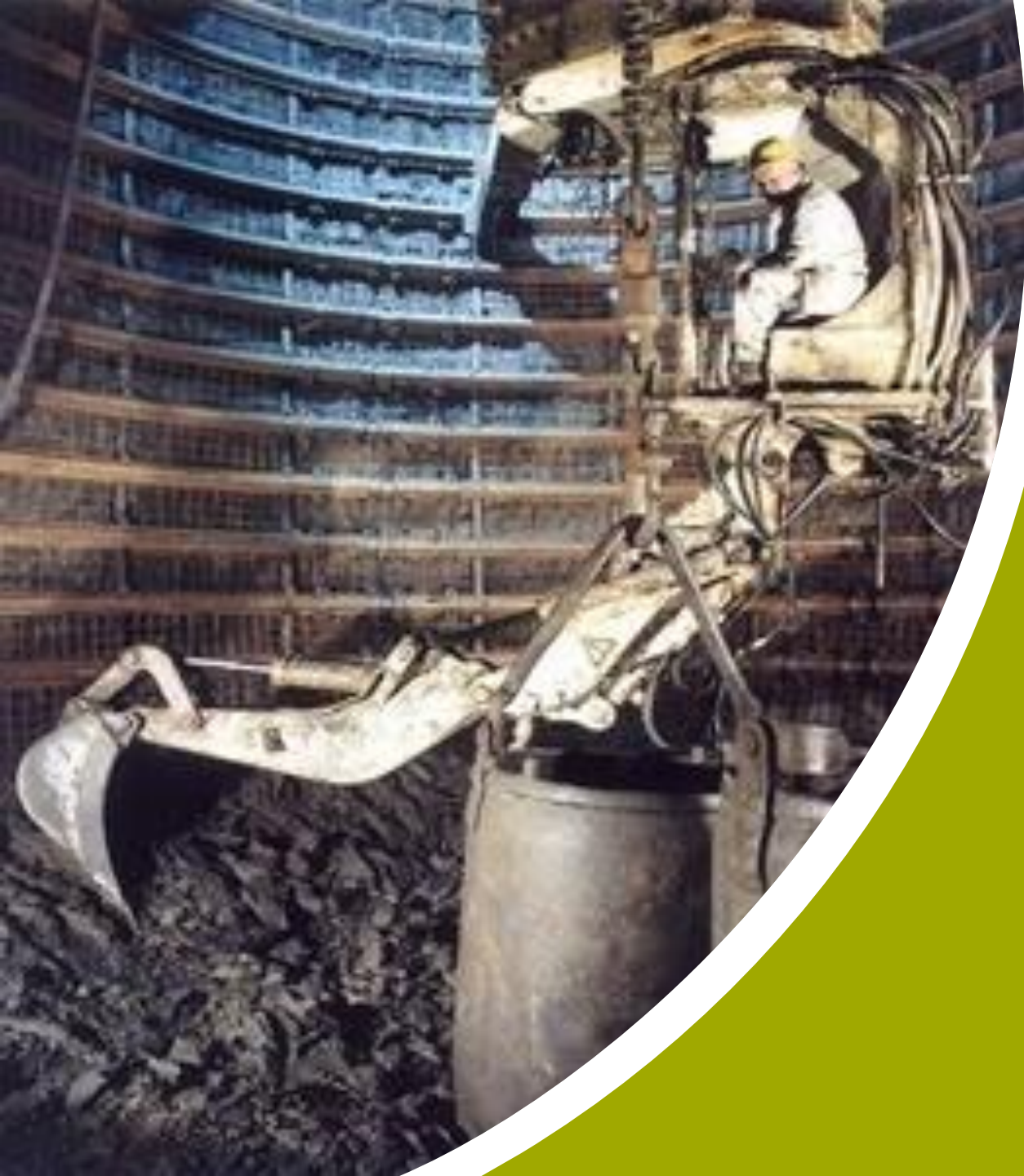


The nineties: from project to programme

90's: from a project to a programme

- Feasibility in principle of building infrastructures in Boom Clay had been demonstrated
- From that point on, development of “Belgian concept” and of HADES took parallel routes

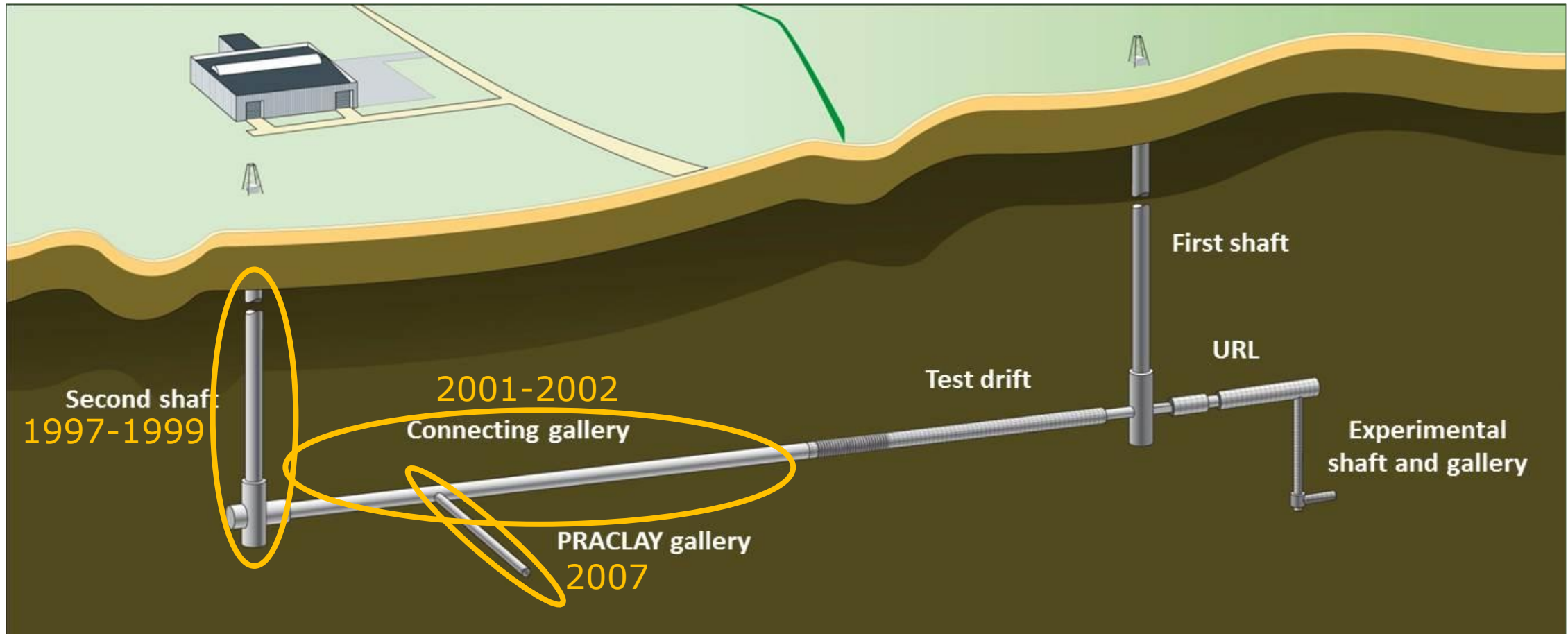




Demonstration of industrial techniques

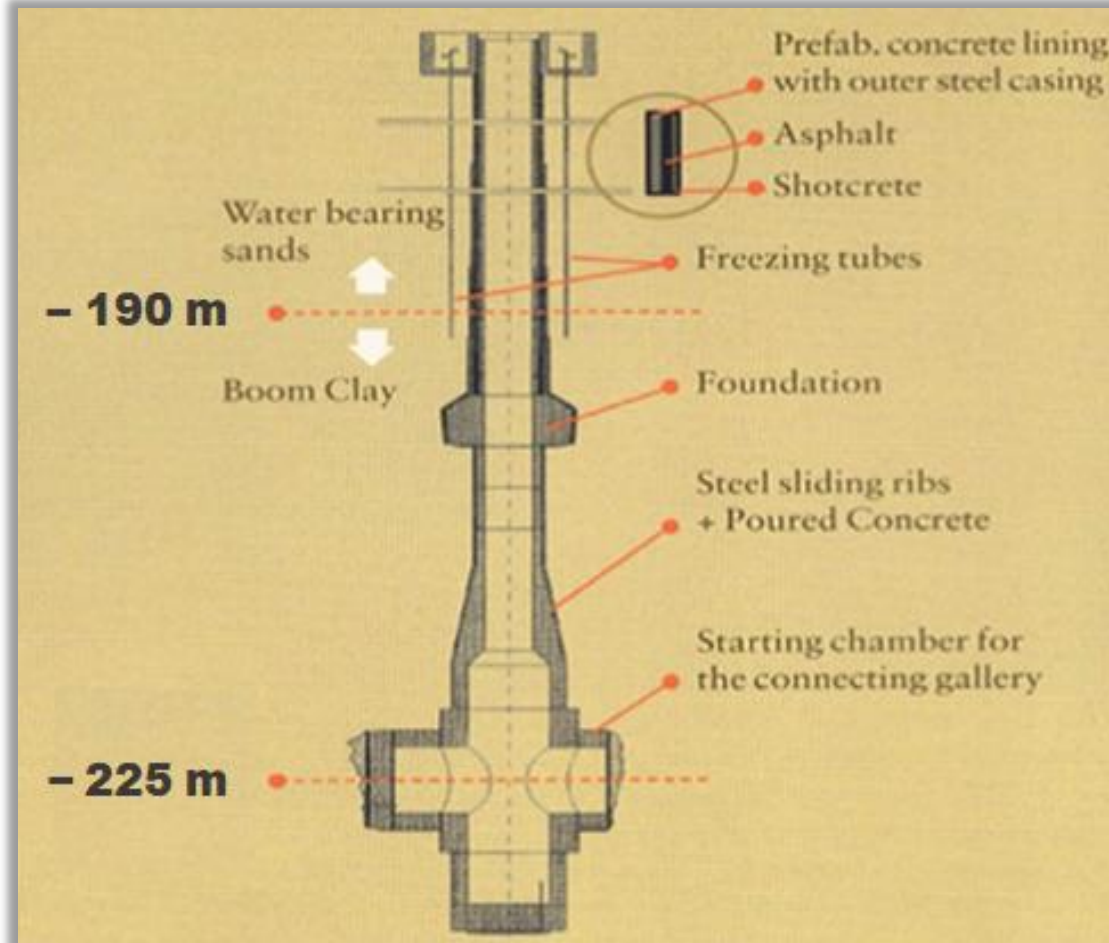
Illustration: mechanized excavation of the second shaft
(1997-1998)

HADES extensions (1997-2007)



Second shaft (1997-1999)

Shaft cross-section
(note: freezing only up to top of clay)



Prefabricated concrete rings
(with outer steel casing)

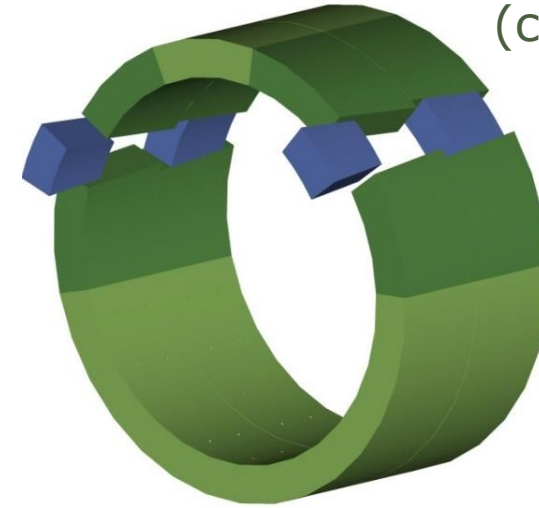


Connecting Gallery (2001-2002)

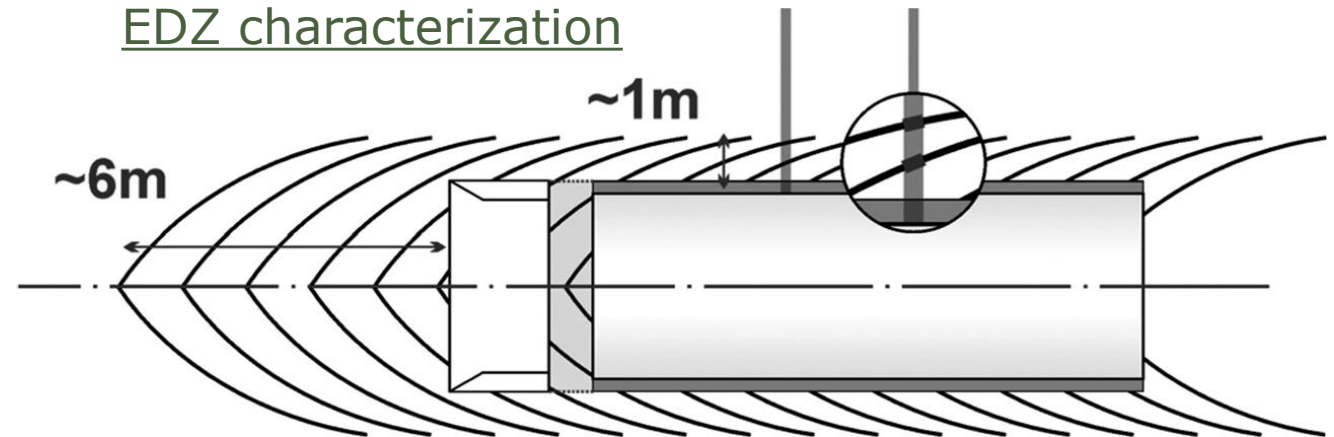


Tunnelling machine

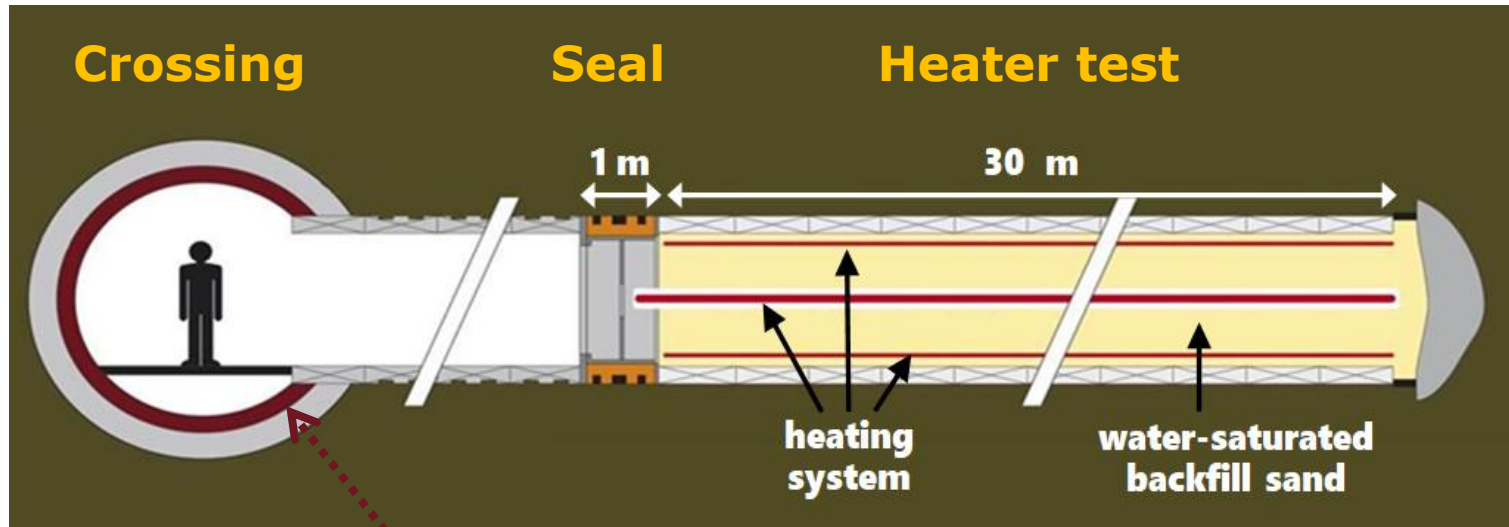
Concrete segments & wedge blocks (conical keys)



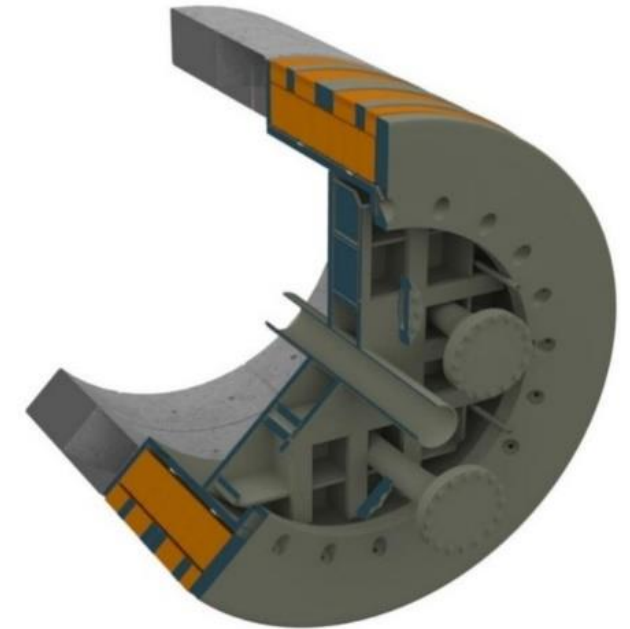
EDZ characterization



PRACLAY gallery (& experiment setup)



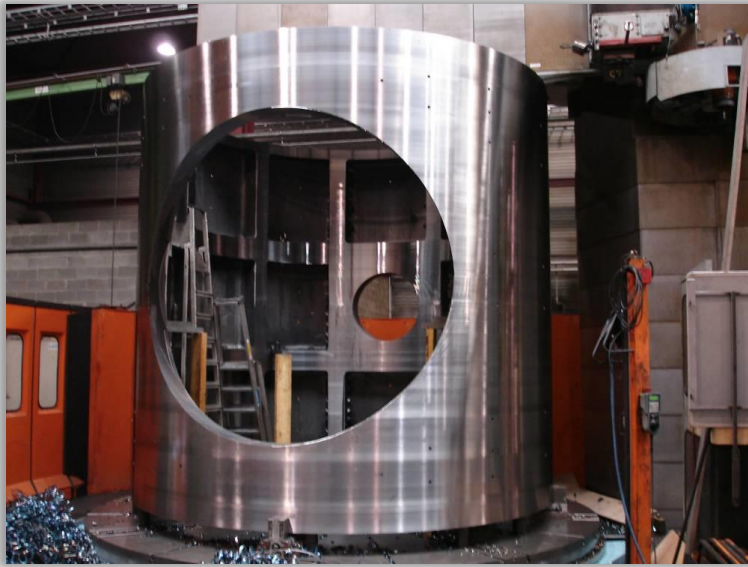
Seal detail



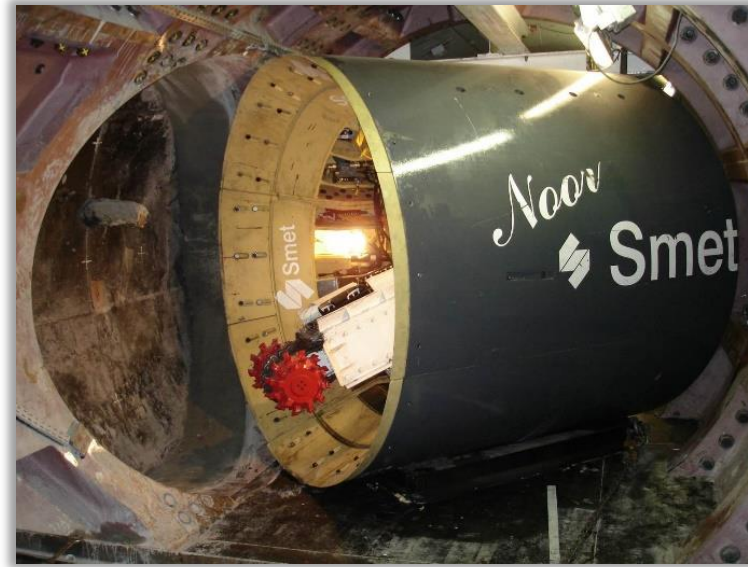
- ◆ Crossing, with reinforcement ring
- ◆ Stop-restart test
- ◆ Seal for the purposes of the heater experiment ($\neq$ from repository seal)

PRACLAY gallery (2007)

1. reinforcement ring for crossing



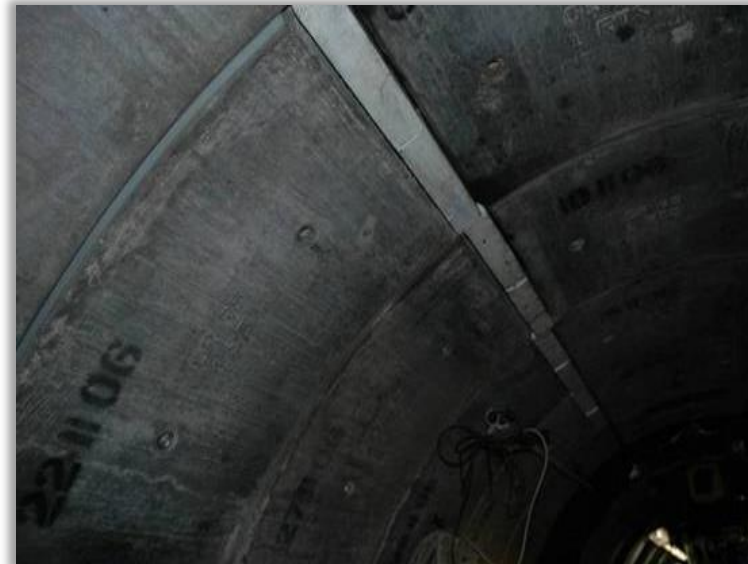
2. Tunneling machine

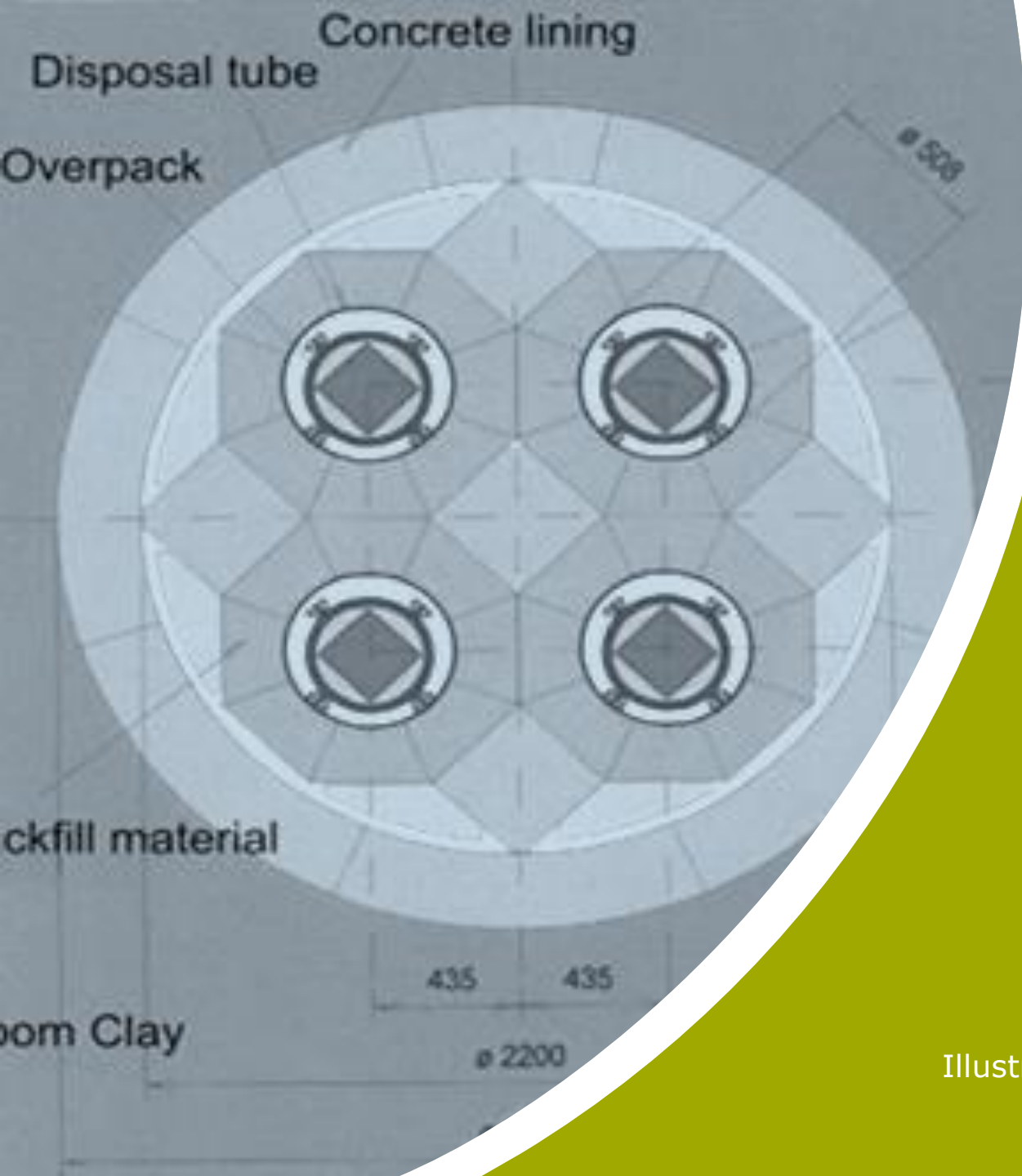


3. Gallery lining emplacement



4. Compressible elements





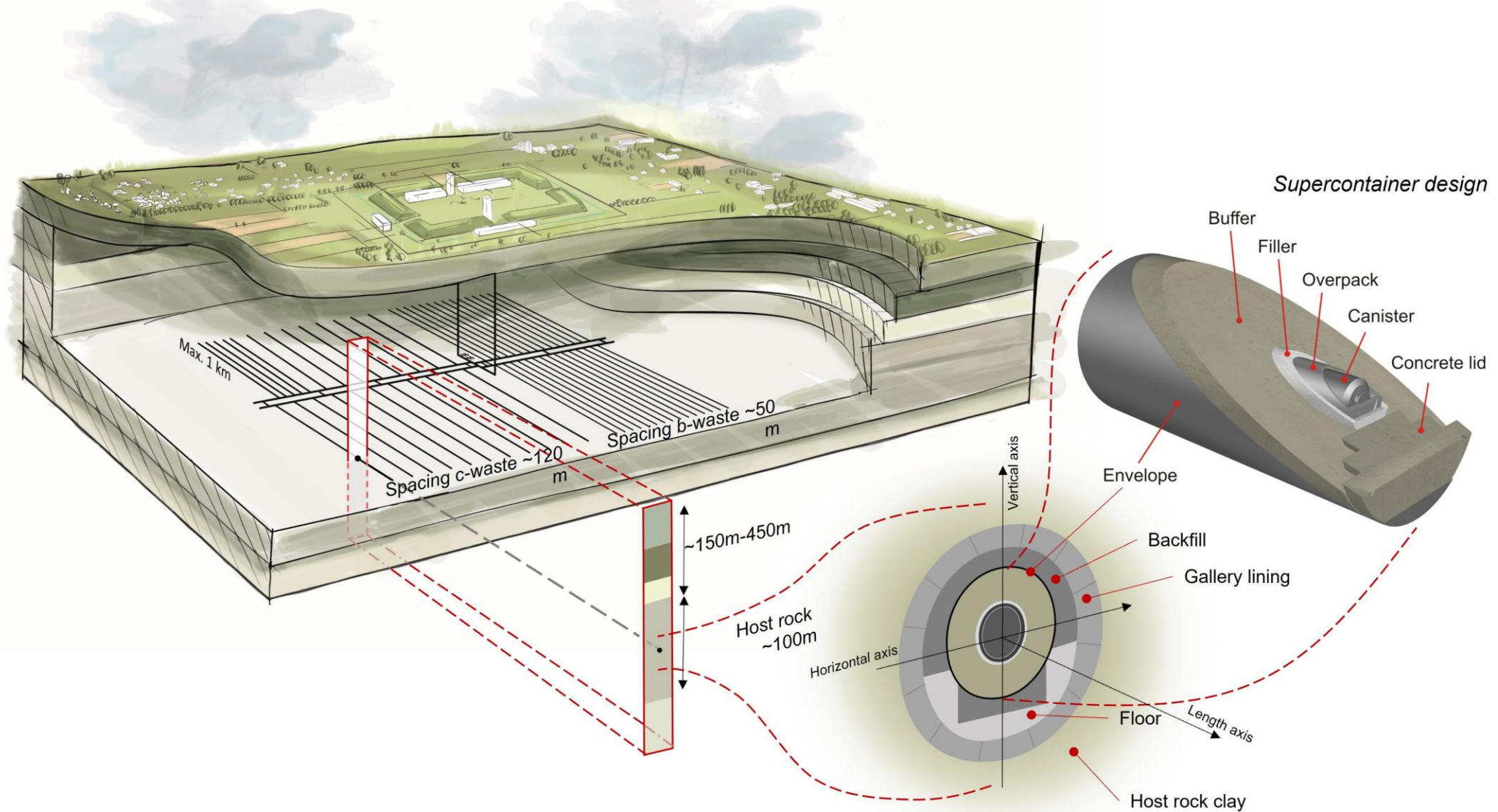
Repository concept development

Illustration: former EBS concept for the disposal of spent fuel assemblies
ONDRAF/NIRAS report SAFIR 2 (1991)

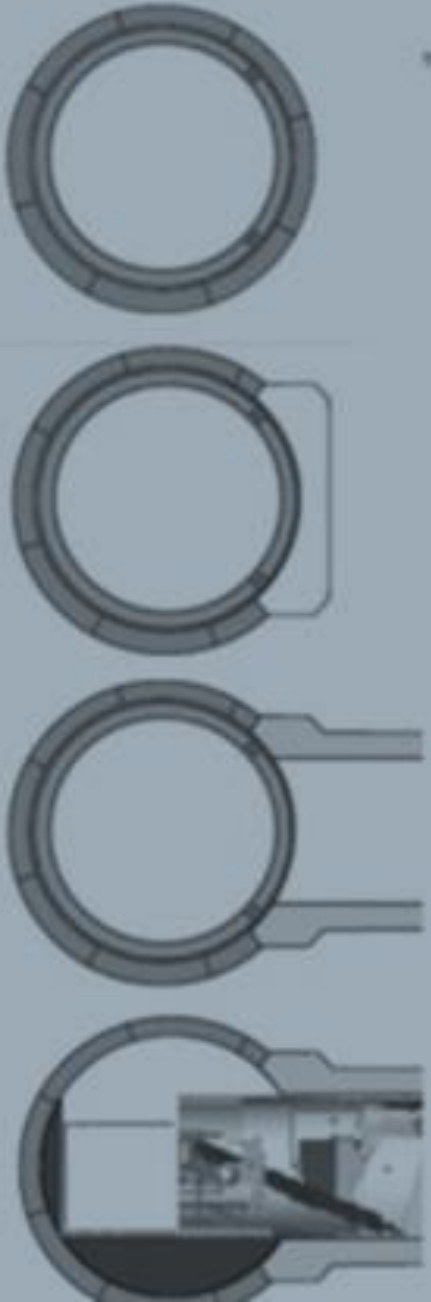
Drivers for concept development

- Industrial excavation and construction techniques
 - ◆ Current shafts, crossings, lining designs strongly inspired by HADES
- Consistent EBS & repository layout development
 - ◆ Multiple engineered components that work together in addition to the host rock to provide multiple levels of protection
 - ◆ Practicality & safety of operational phase
- Shift towards a more generic concept
 - ◆ Boom Clay at Mol → Boom Clay or Ypresian clays at sufficient depth: currently considering reference concepts in clay at 200, 400 and 600 m depth

Current repository concept



Crossing



Shaft



Summary

Illustration: current design for repository crossings and shafts
ONDRAF/NIRAS "Techno" reports (2019)

Summary

- HADES and repository concept were born as twins
- Today's Belgian repository concept is more generic but HADES has continued to support its development through a dual role:
 - ◆ Test bed for repository building technologies & components (this presentation)
 - ◆ In situ characterisation of a potential (type of) host rock as a barrier and for the study of repository-induced effects (next presentations)

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40 years of investigation into the thermo-hydromechanical (THM) behaviour of Boom Clay in the HADES URL

Exchange meeting HADES40

Tabloo, 9 December 2022

Xiangling Li, A. Dizier, G. Chen, J. Verstricht, S. Levasseur

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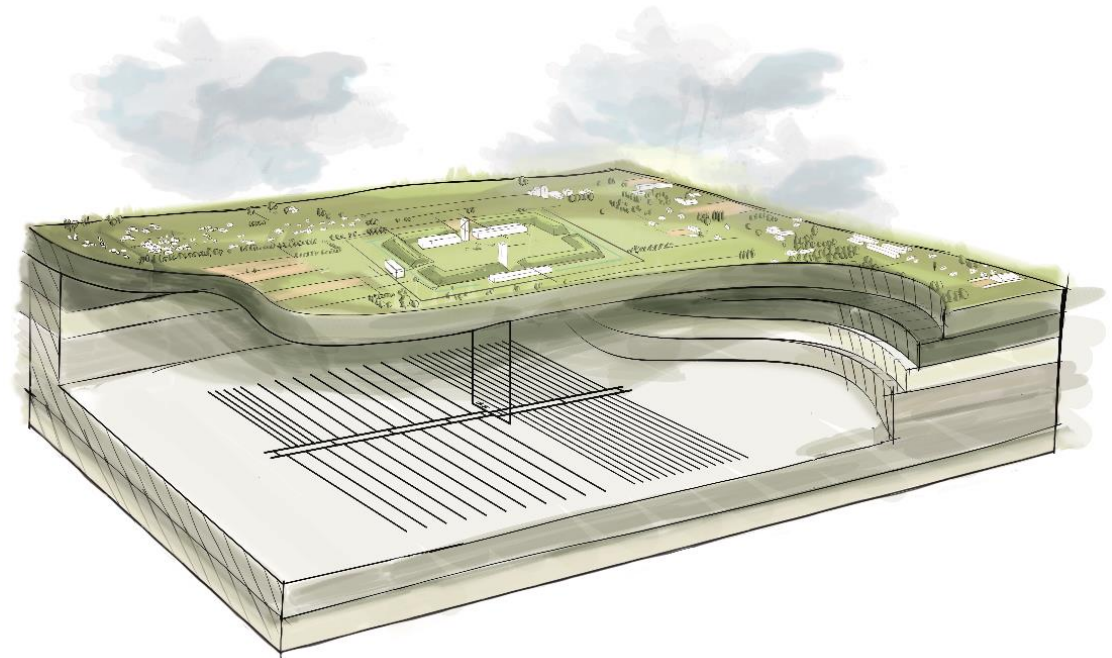
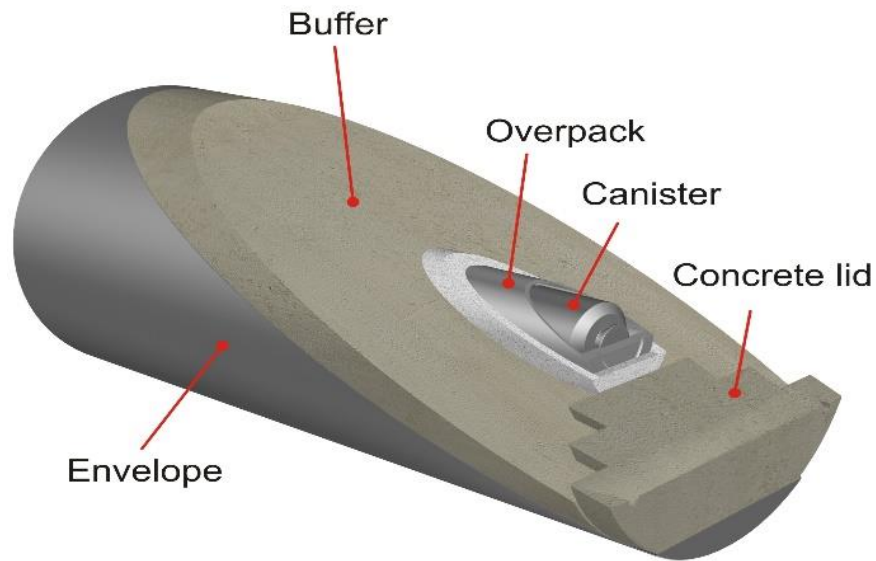


sck cen

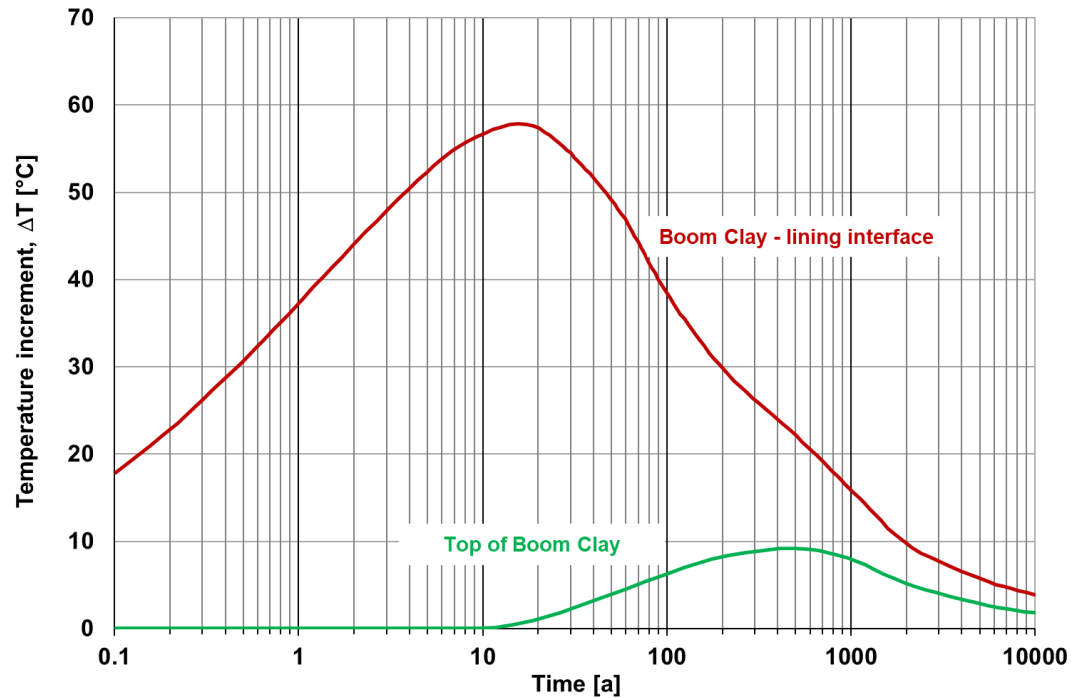
ESV EURIDICE GIE

Context

- High Level and/or Long-Lived radioactive wastes, what are the long term solutions ?
- Deep Geological Disposal in galleries located in low permeable geological host formations (poorly indurated clays)
- Engineering Barrier System (EBS) (Belgian concept)



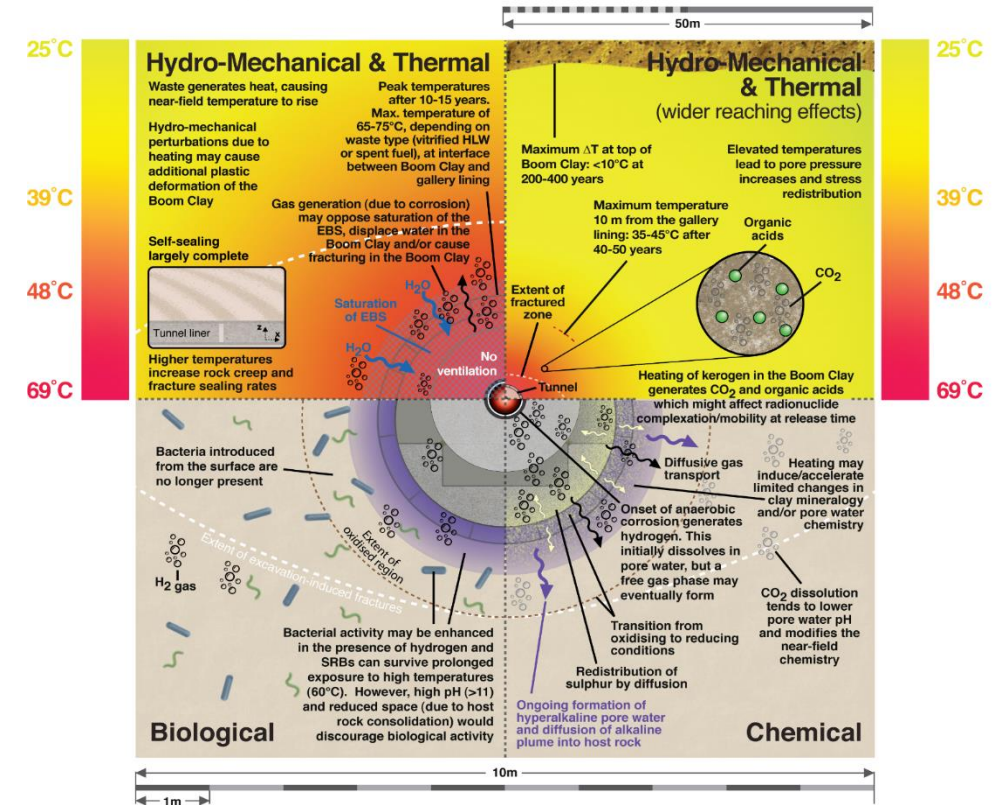
Thermal perturbations induced by Disposal of HLW and/or SF



Modelled Temperature evolution around a disposal gallery

(Example of spent fuel for a disposal at HADES URL depth where initial temperature is about 16°C)

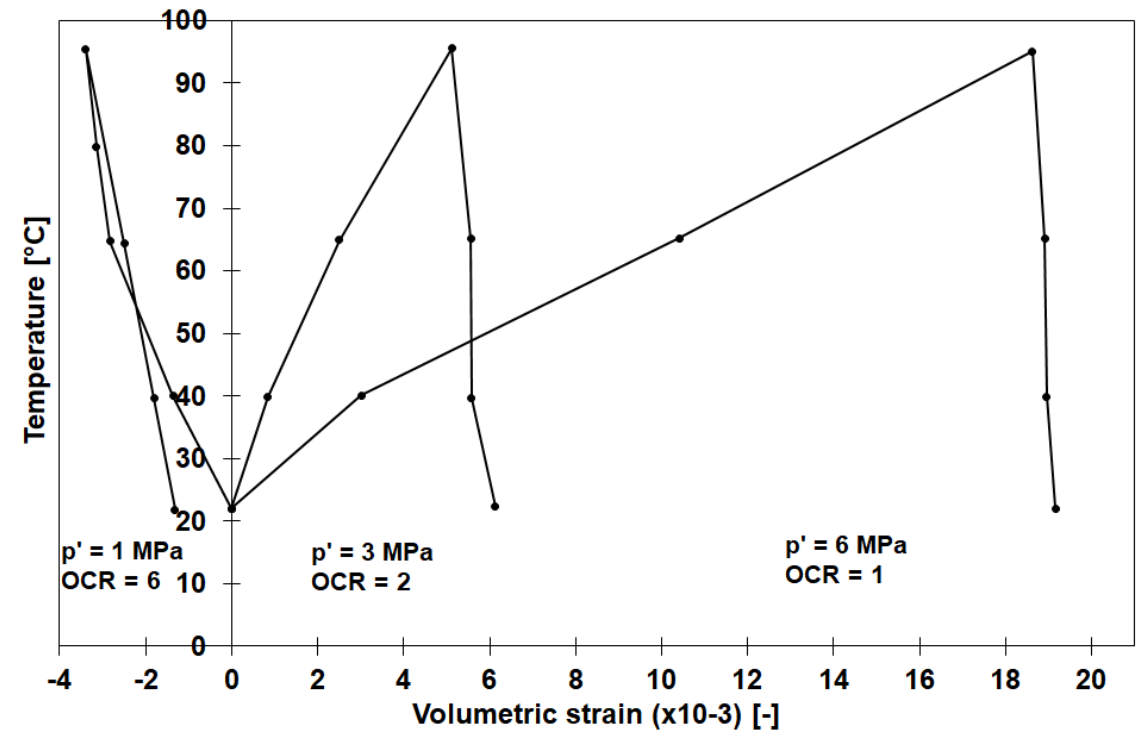
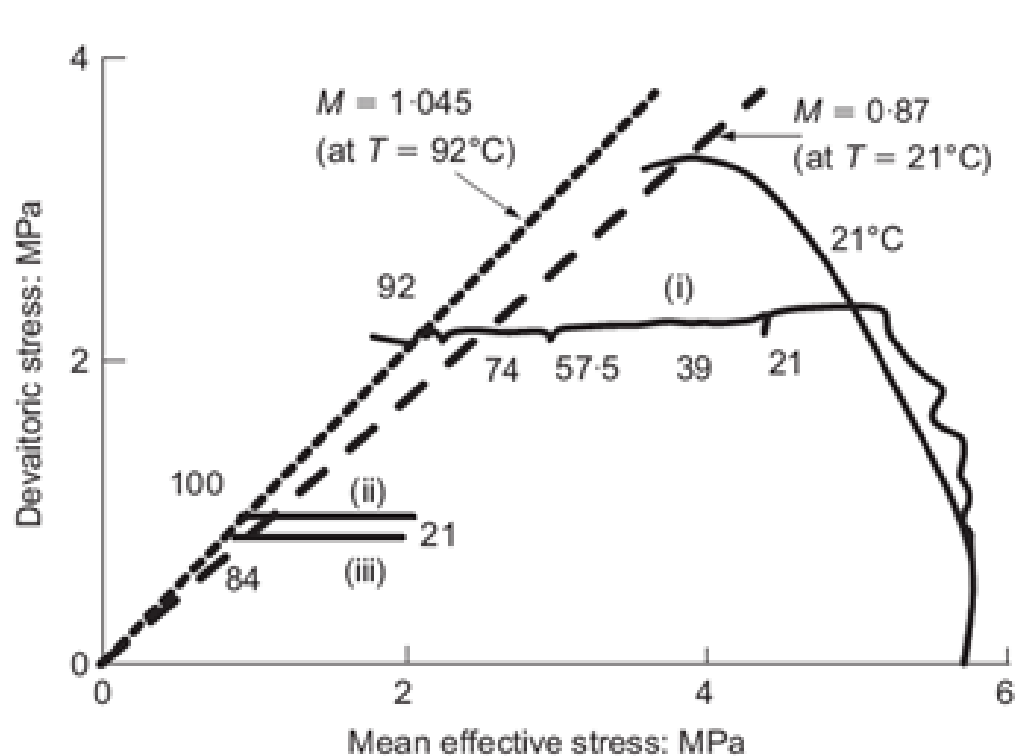
Thermal phase (showing peak temperatures)



Thermal – Hydro - Mechanical disturbances

How to study the Thermo-Hydro-Mechanical behaviour ?

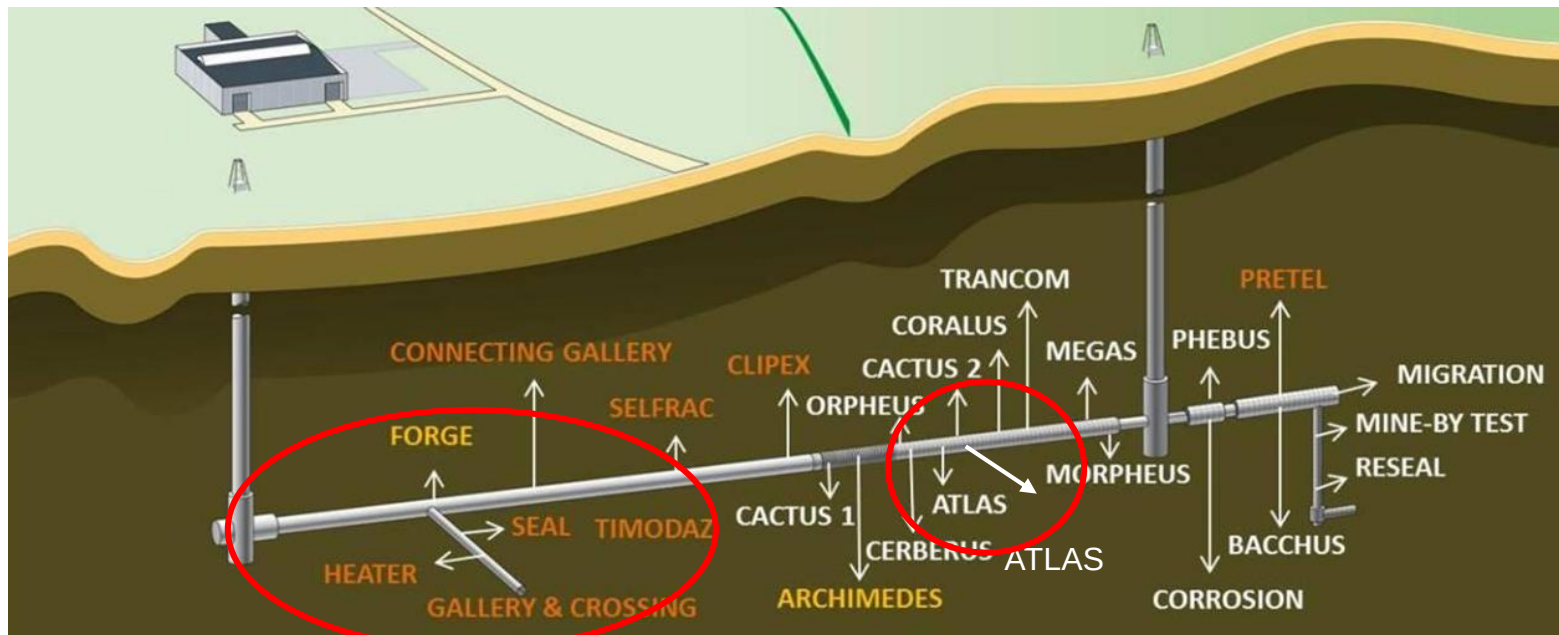
1. Surface Laboratory tests : oedometer tests, triaxial tests under different THM conditions



Dependence of the OCR

How to study the Thermo-Hydro-Mechanical behaviour ?

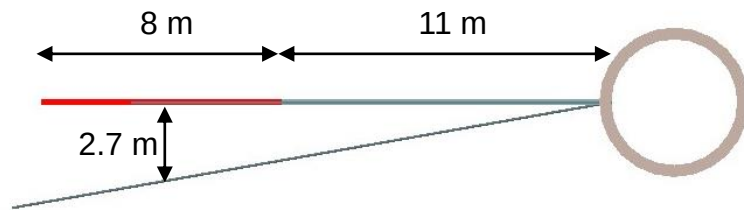
2. *In situ* tests and monitoring in the HADES Underground Research Laboratory (URL) in Mol



- BACCHUS I, II (1988 - 1995)
- CERBERUS (1985 - 1999)
- CACTUS I, II (1990 - 1994)
- ATLAS I, II, III, IV (1992 -...)
- PRACLAY (2014-...)

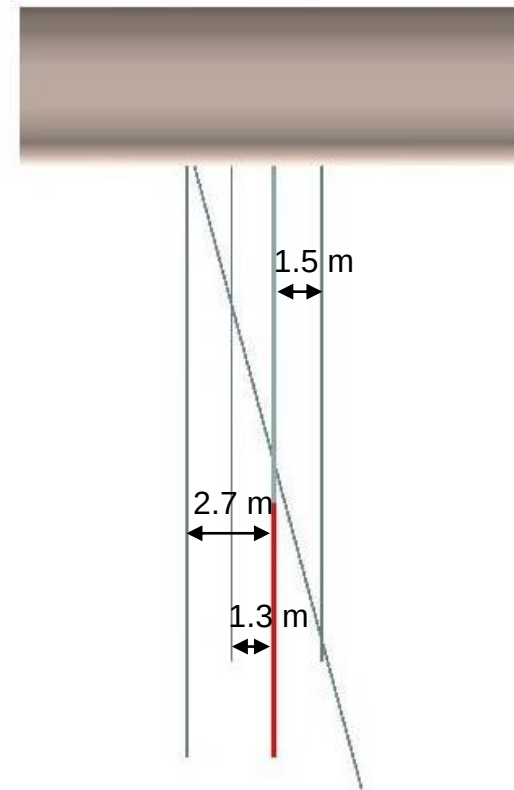
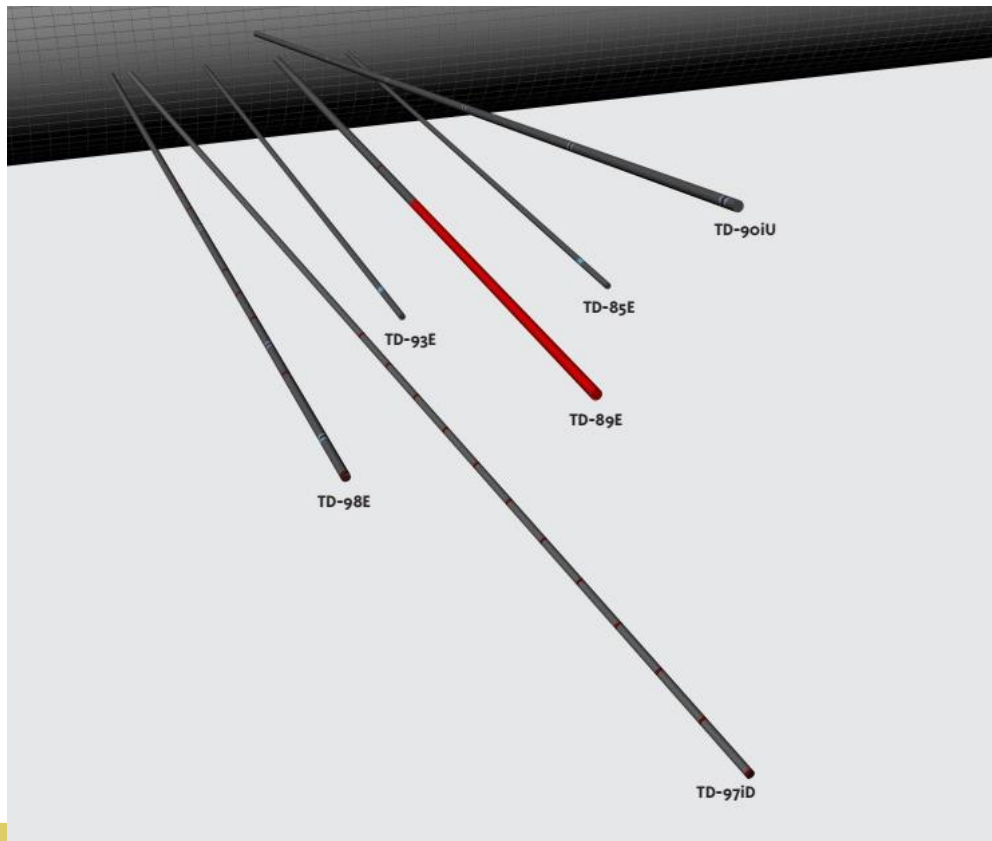
- +
 - Permeability testings
 - LT monitoring
 - Etc.

Small scale ATLAS heater test: test set-up



Test drift
Heater
Observation boreholes

*Illustration ATLAS III
experiment*



Small scale ATLAS heater test: test set-up

ATLAS instrumentation :

- Kulite pressure sensors on the heating probe
- Piezometer filter
- Flat-jacks and biaxial stressmeter
- TC

Central borehole with the heating probe

Illustration of a piezometer filter with twin tube connection

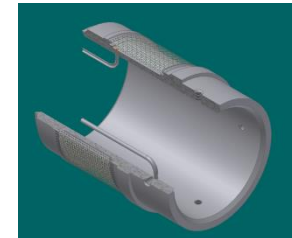
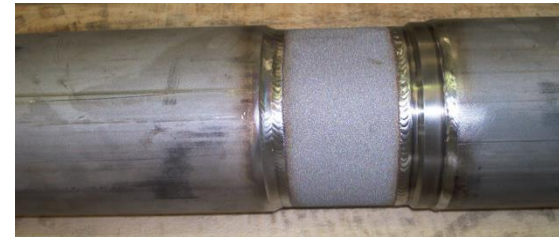


Illustration of an instrumented casing



Flat-jacks

Biaxial Stressmeter

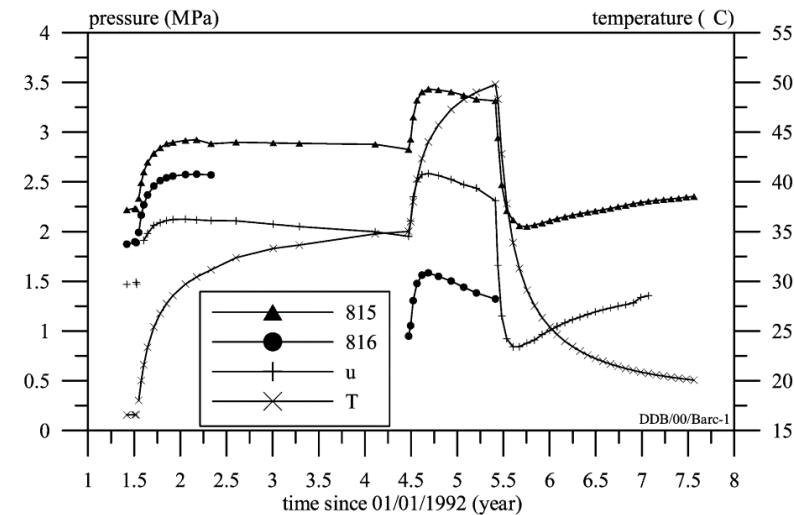
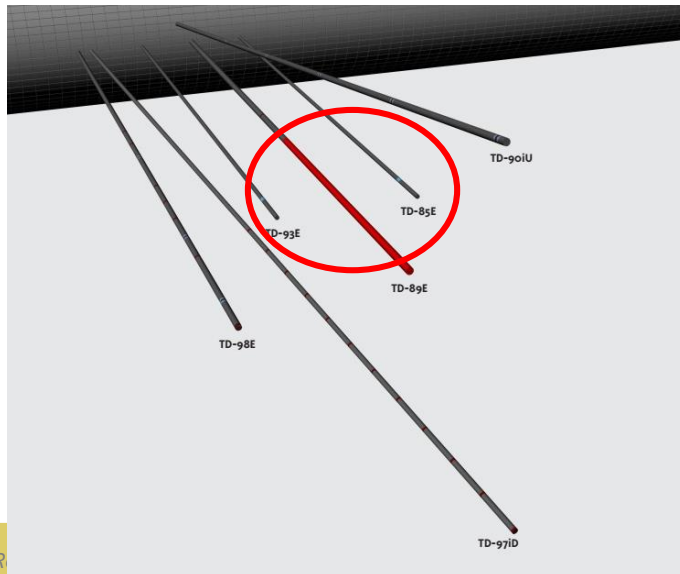


Small scale ATLAS heater test: ATLAS I-II

ATLAS heater tests: 4 tests in 2 stages

- **ATLAS I-II**

- 2 observation boreholes drilled in the same horizontal plane than the heater
- 3 years of heating at 112 W/m (ATLAS I) + 1 year of heating at 225 W/m (ATLAS II) (1993 – 1997). Cooling in one step.
- Limitations:
 - Relatively little instrumentation and low data acquisition rate (manual)
 - Sharp heating transients



Small scale ATLAS heater test: ATLAS III&IV

ATLAS heater tests: 4 tests in 2 stages

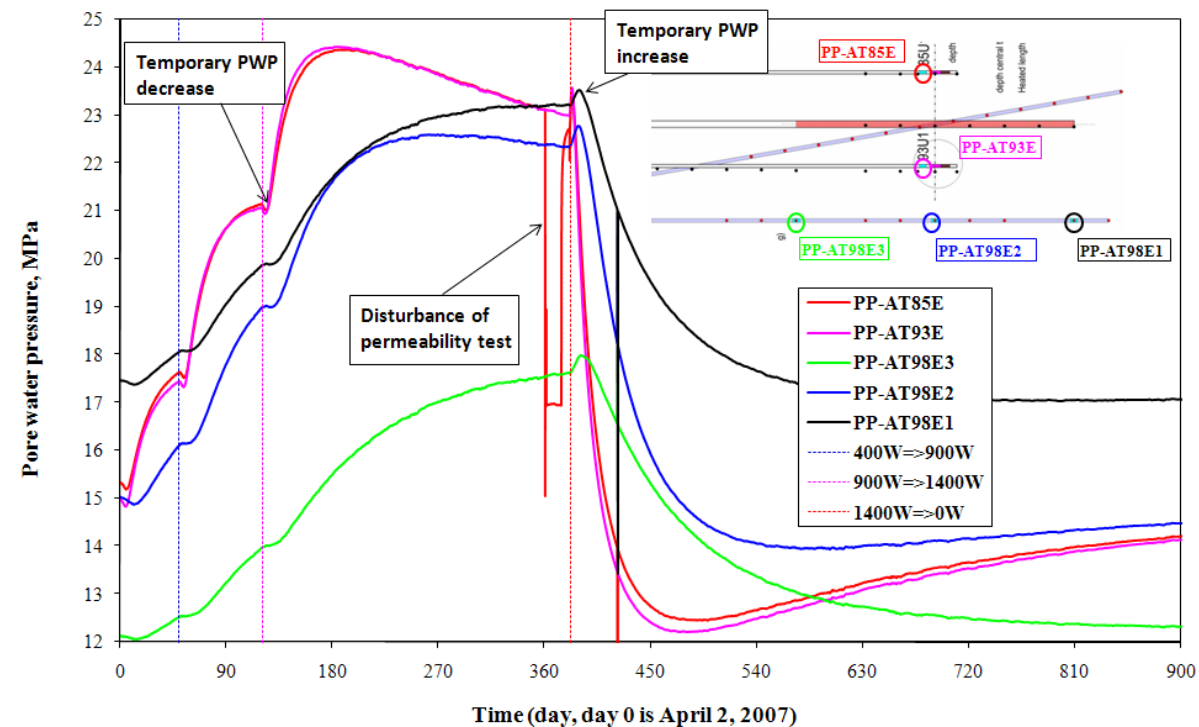
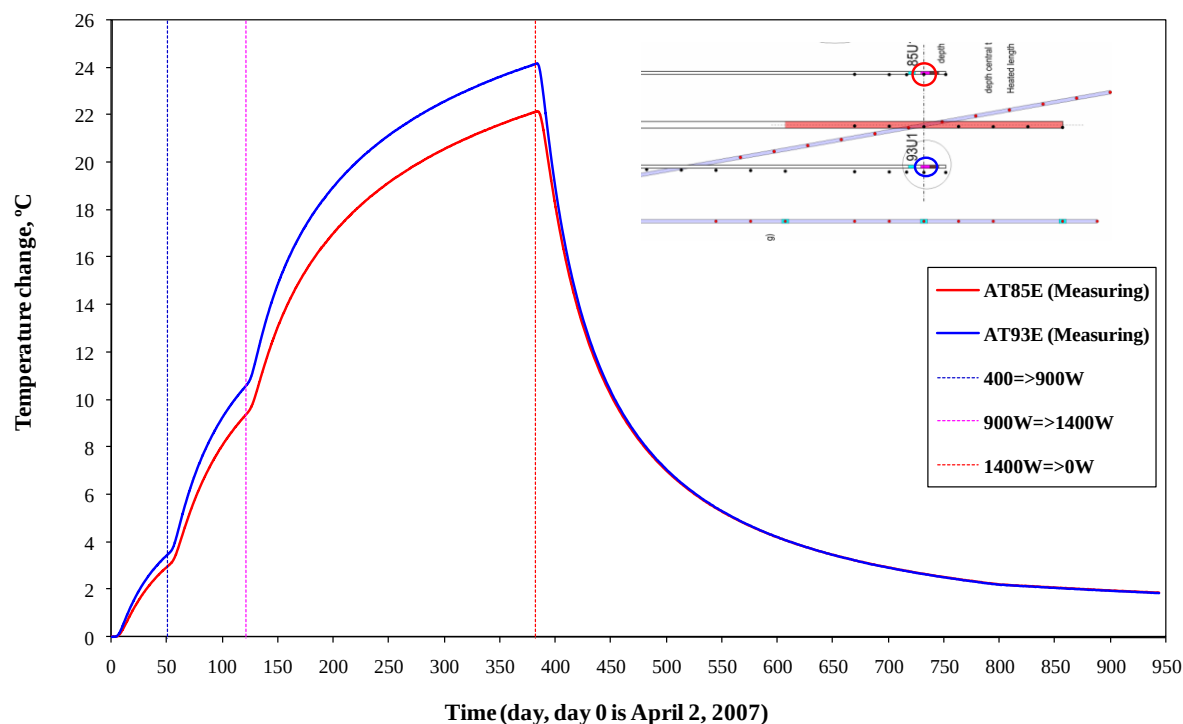
- **ATLAS III & IV**

- Additional boreholes (horizontal and inclined) + Additional T & p_w sensors
- Stepwise heating in 1 year: $0 \rightarrow 50 \rightarrow 112 \rightarrow 175$ W/m. Cooling in one step.
- Same heating strategy for ATLAS III (2007 – 2008) and ATLAS IV (2011 – 2012)
- Improvements:
 - High data acquisition rate
 - Investigation of thermal anisotropy

➔ representative of far field

Small scale ATLAS heater test : observations

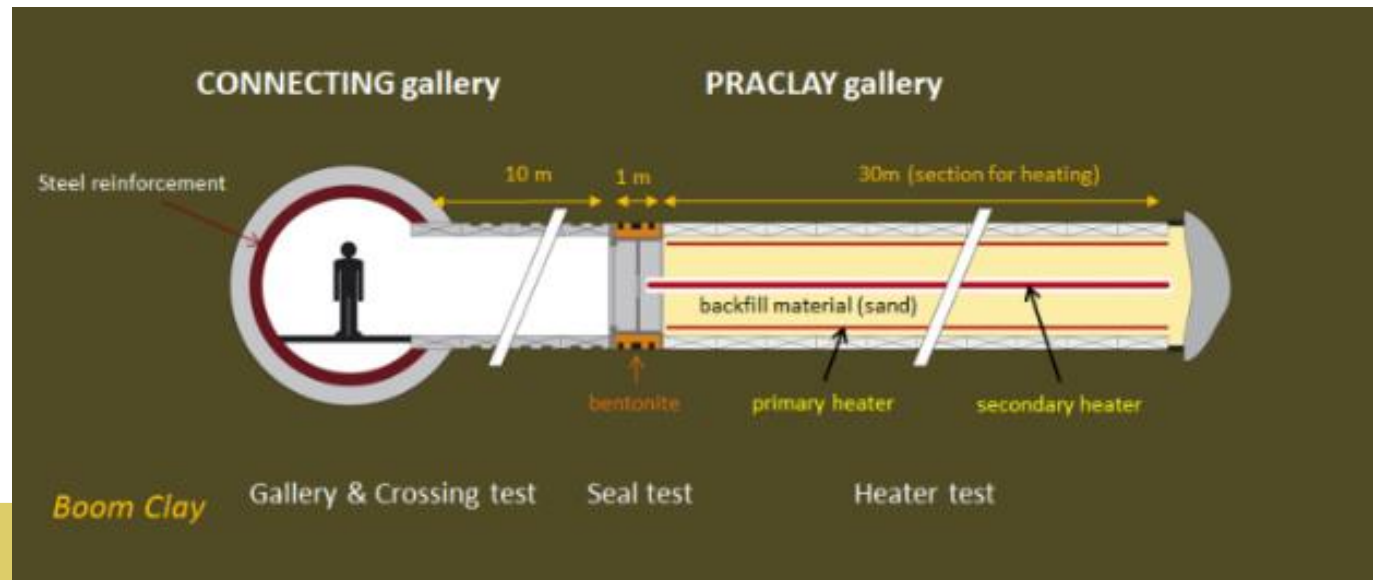
ATLAS III: Temperature and pore water pressure evolution



The large scale PRACLAY Heater test

The PRACLAY in – situ Experiment in URL HADES

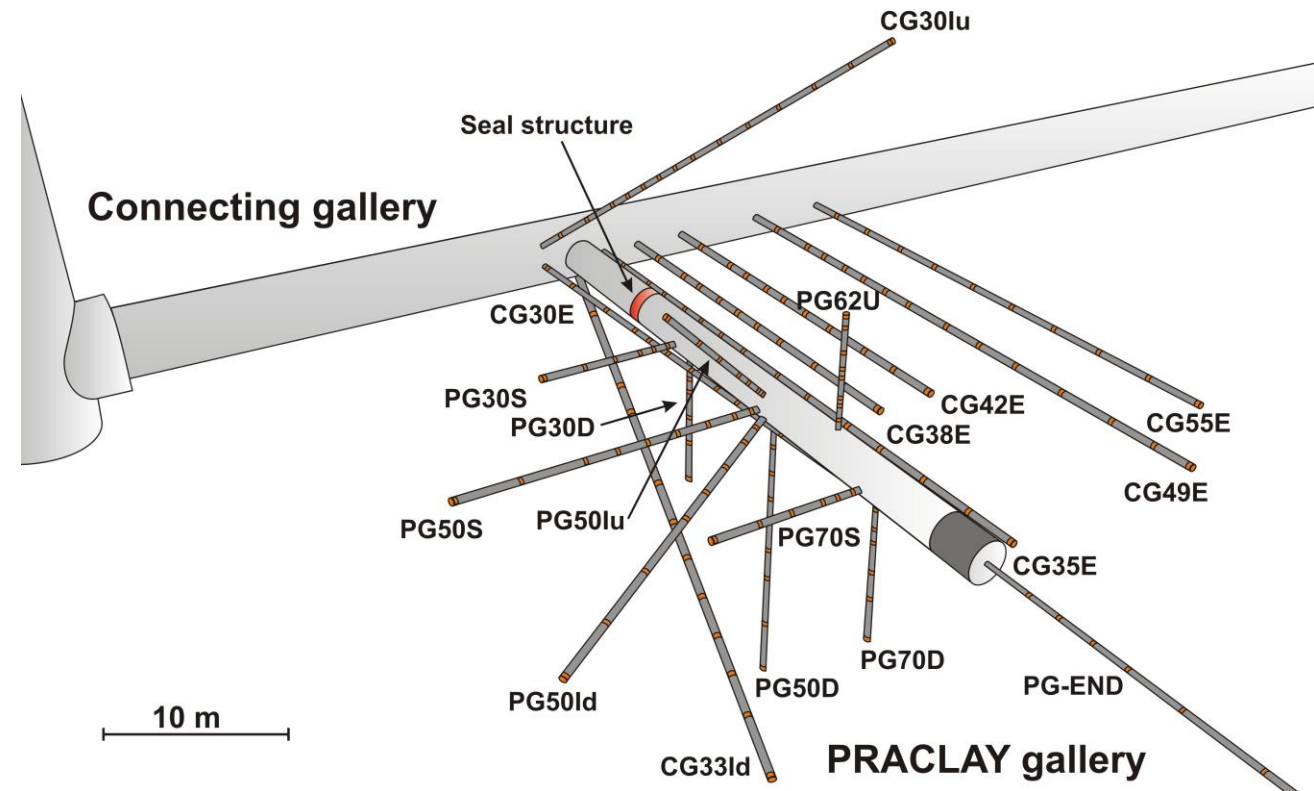
- Gallery and Crossing test
 - Feasibility of constructing a gallery with industrial techniques
 - Feasibility of constructing a crossing between two galleries
- Large scale-heater test ➔ Simulate the heat-emitting high-level radioactive waste
(Under a conservative THM conditions)
- Seal test ➔ Design and installation of the hydraulic seal



The large scale PRACLAY Heater test

Monitoring network: temperature, pore water pressure, stresses...

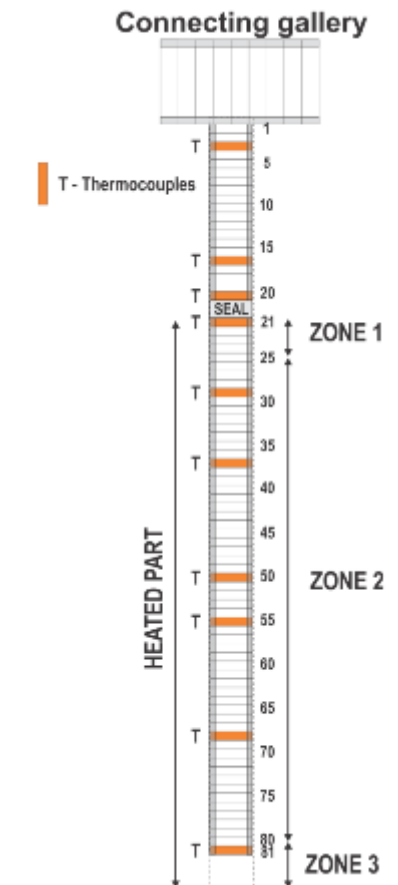
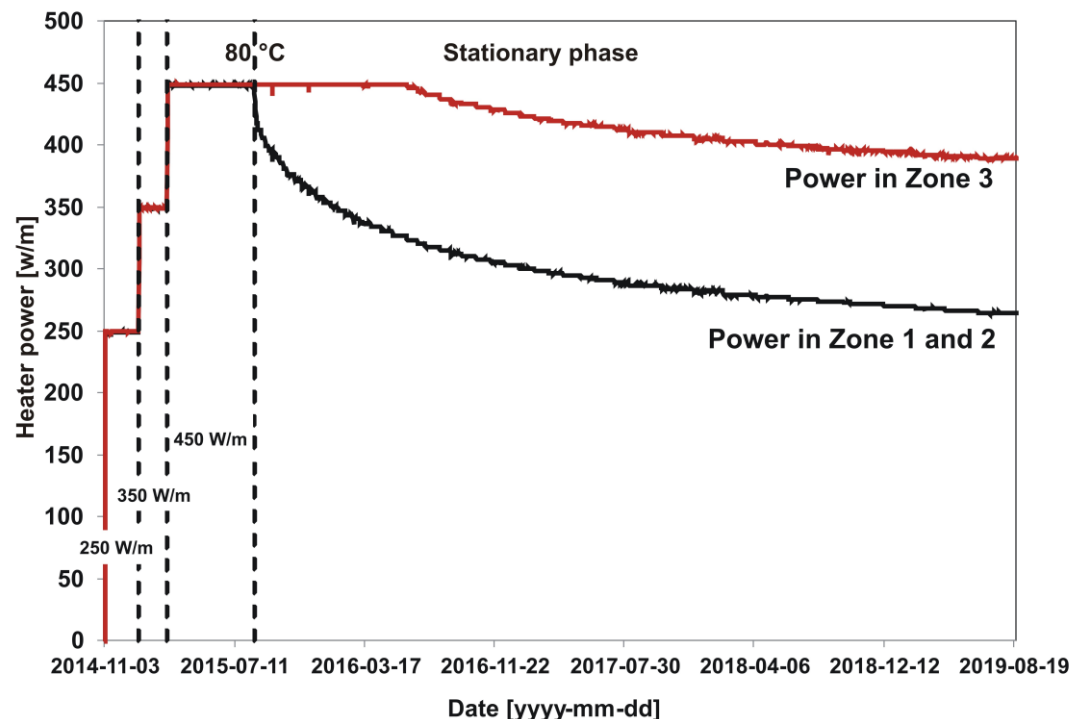
- Number of sensors: about 1100



The large scale PRACLAY Heater test

PRACLAY thermal loading plan:

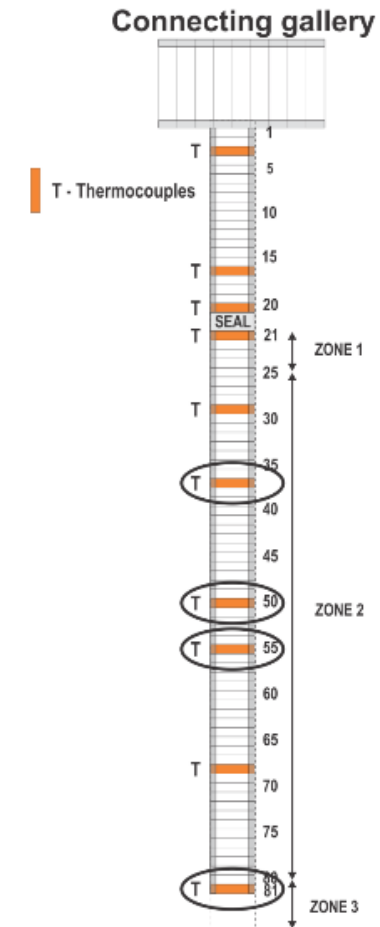
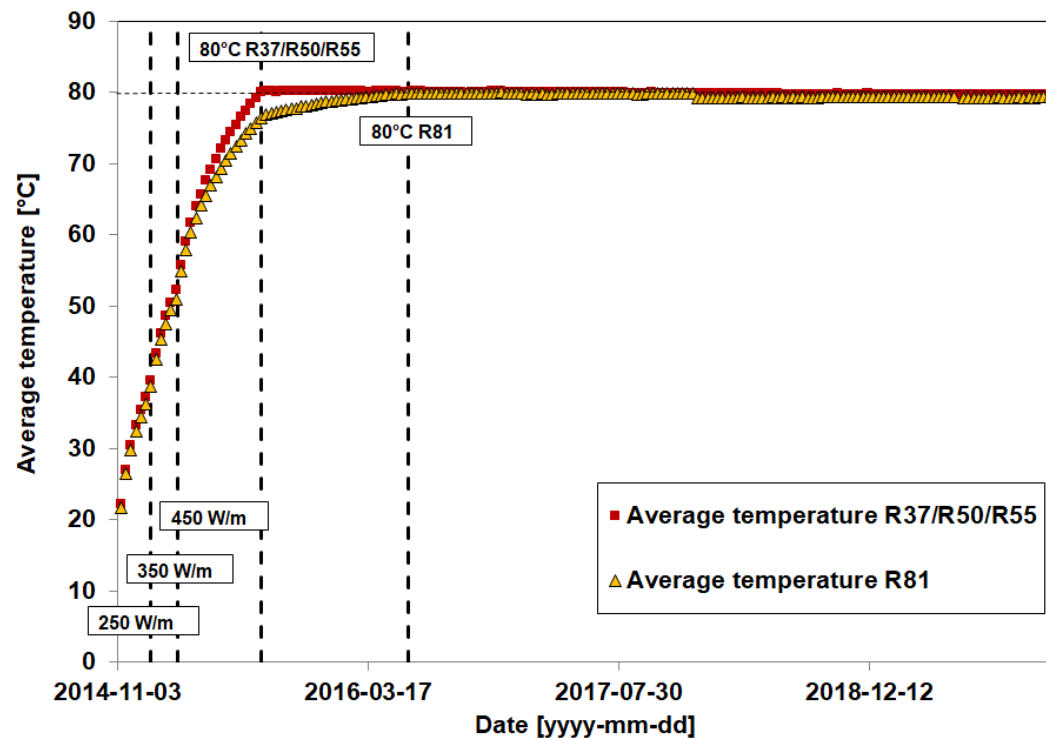
- 3 heating steps to reach 80°C at Boom Clay/ concrete lining interface , Maintain for 10 years
- About 72 °C at Boom Clay/ concrete lining interface is reached after ca. 15-20 years for SF



The large scale PRACLAY Heater test

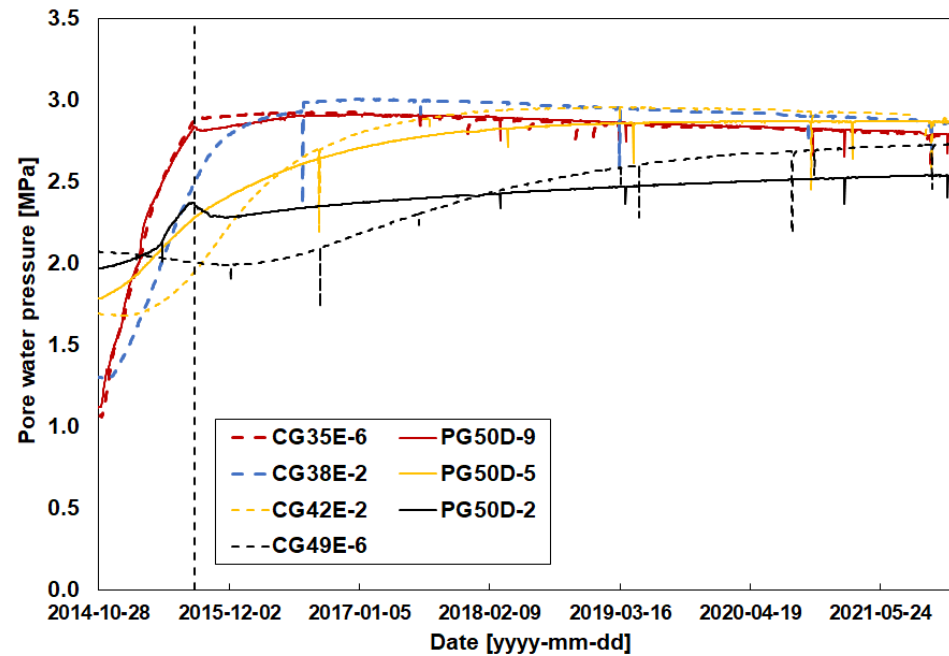
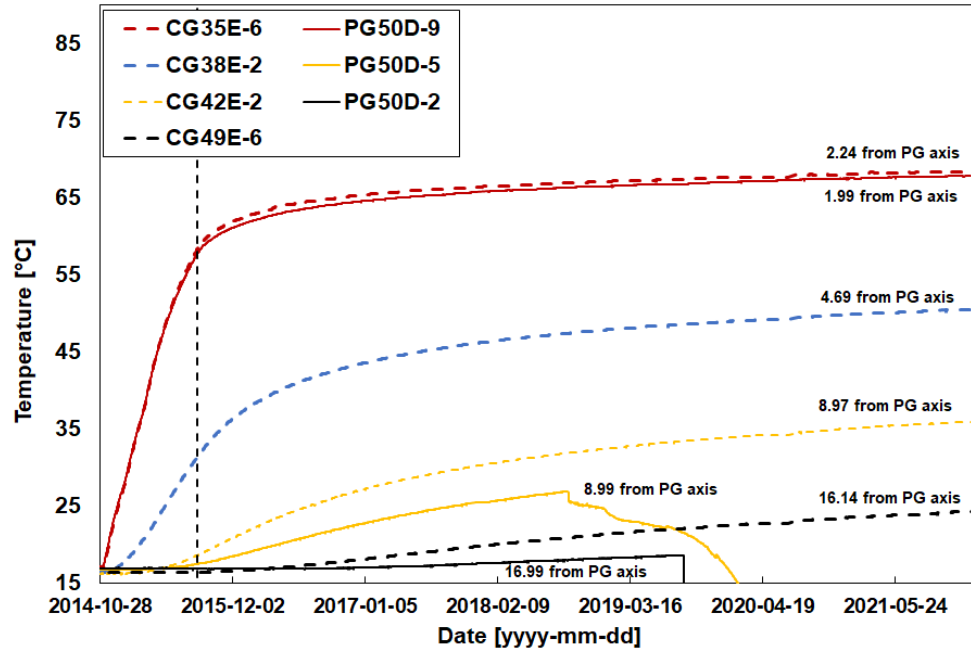
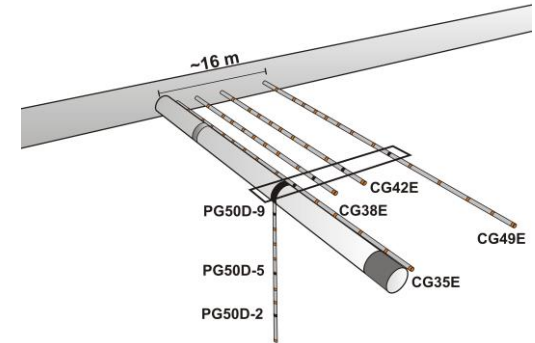
PRACLAY thermal loading plan:

- Increase of the temperature in the concrete lining
- Current situation: 80°C at Boom Clay/ lining interface



The large scale PRACLAY Heater test

Temperature and pore water pressure evolution in Boom Clay



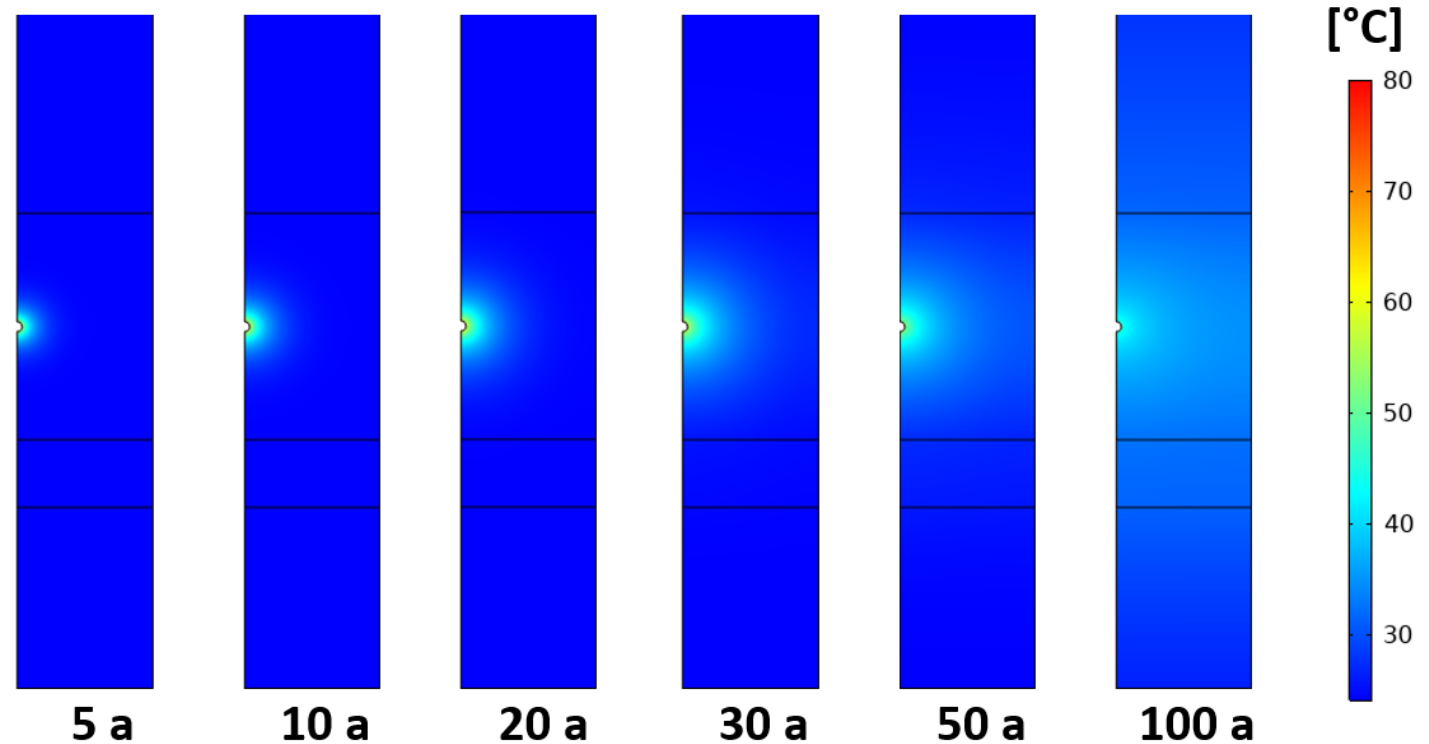
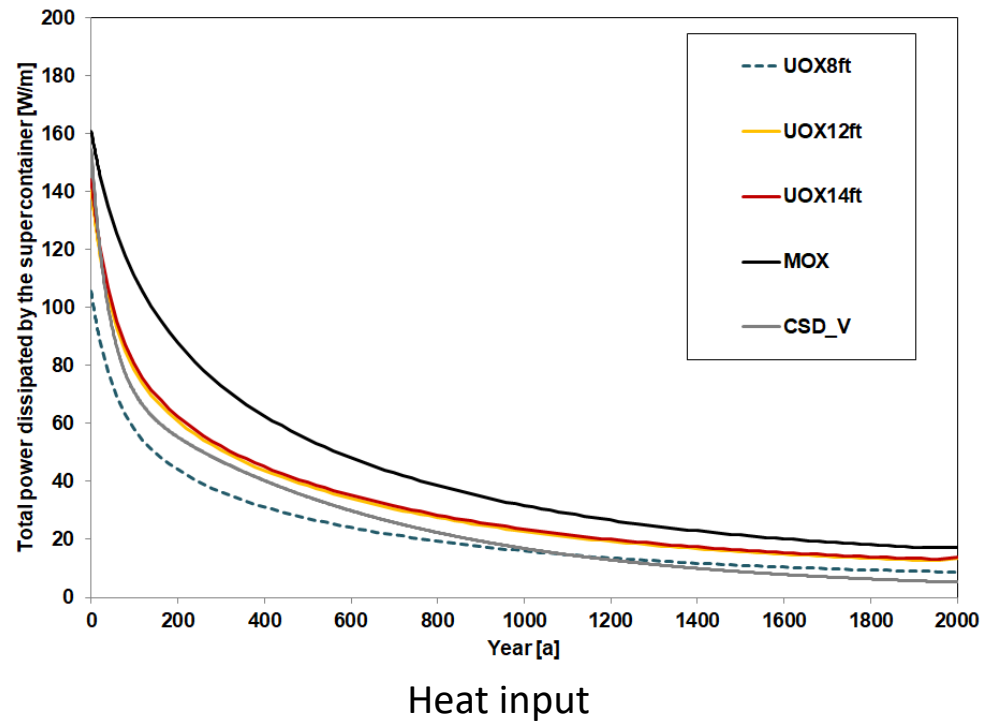
Conclusions from in situ tests

In-situ THM experiments in poorly indurated clay (Boom Clay)

- Complementary work between the ATLAS and the large scale PRACLAY heater tests
- Large scale heater test:
 - No interruption of the heater system (good performance of the test set-up)
 - Boom Clay
 - ✓ Anisotropic responses, as expected (vertical vs horizontal profiles)
 - ✓ No indication of abrupt changes in pore water pressure nor large displacement
 - ✓ Up to now, the clay is able to sustain the thermal load
 - Seal fulfils its role as a hydraulic cut-off
- Interpretation of both tests gives a set of parameters/ properties (next presentation with Chen G.)
 - ➔ Important information for simulating a geological disposal facility

Finite element analysis of a DGR

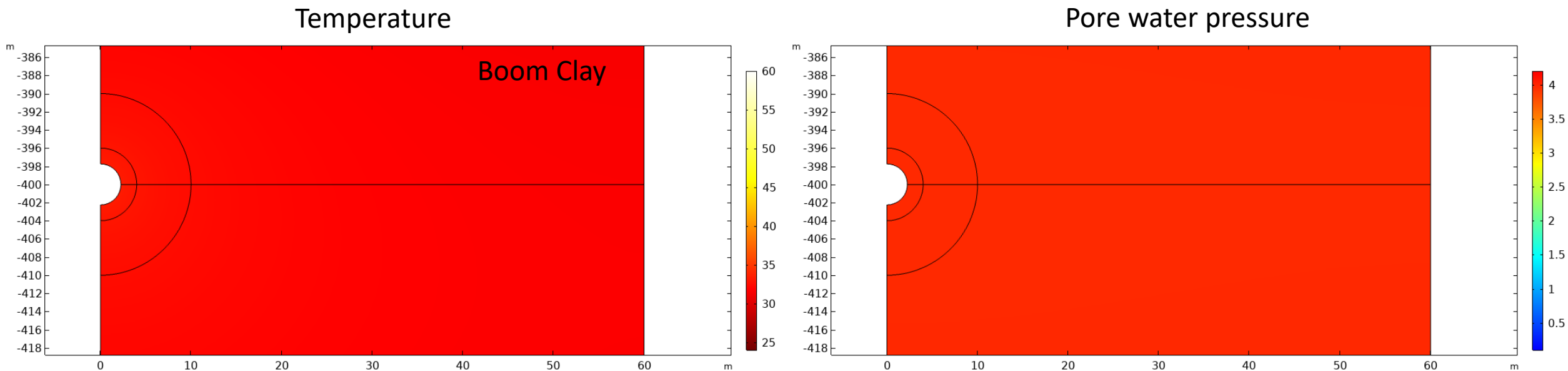
Fully coupled THM finite element modelling with COMSOL® for a geological disposal facility at 400 m deep in a poorly indurated clay formation



Temperature distribution

Finite element analysis of a DGR

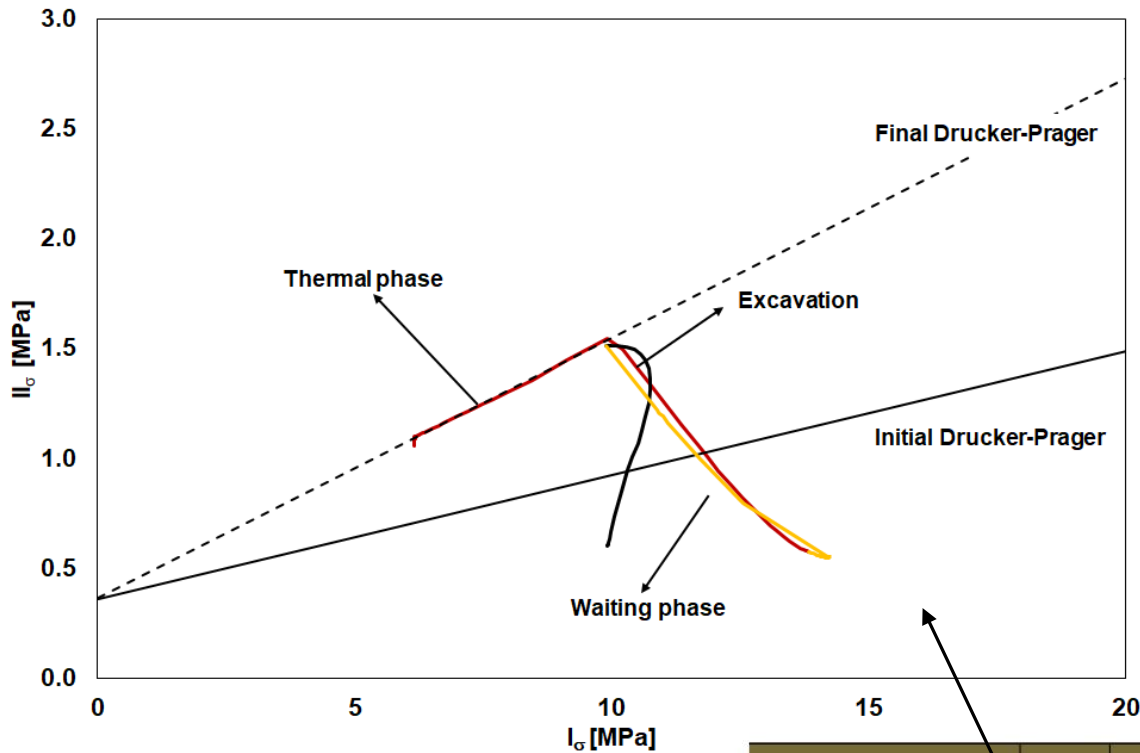
Fully coupled THM finite element modelling with COMSOL® for a geological disposal facility at 400 m deep in a poorly indurated clay formation



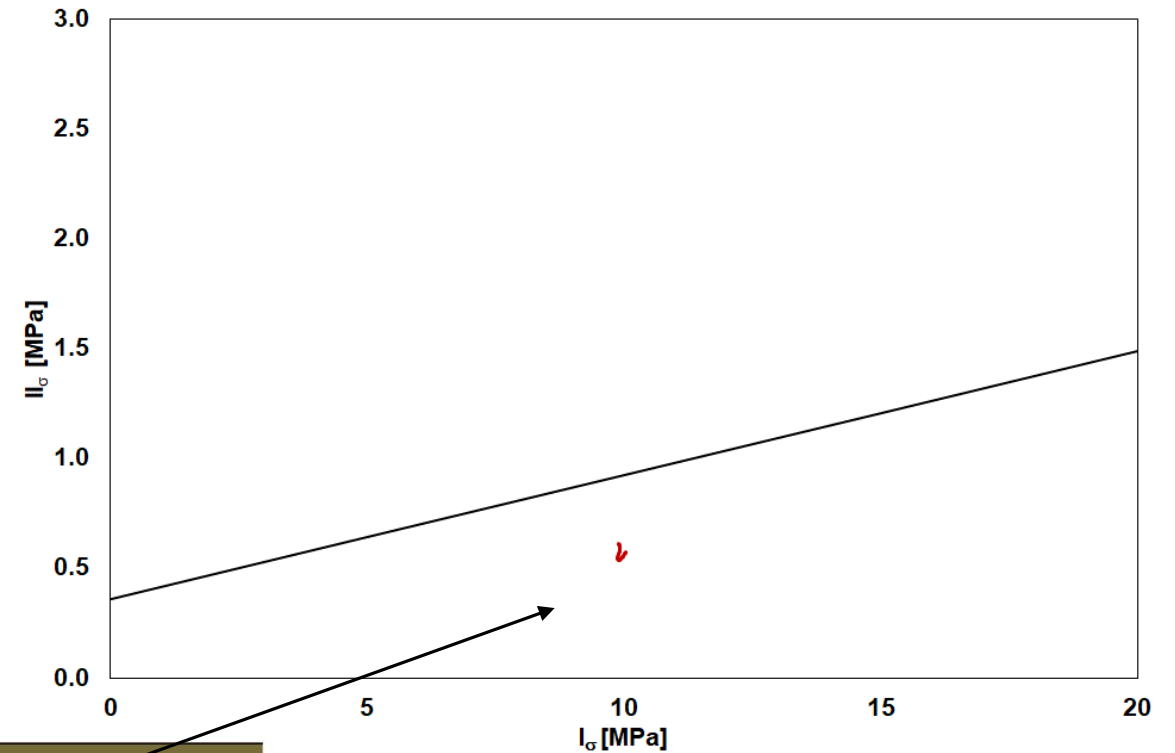
After 2000 years of heating

Finite element analysis of a DGR

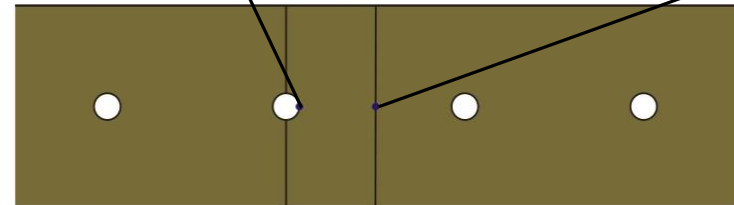
Mechanical analysis in the Boom Clay – analysis of the potentially damaging process



Stress path at the wall



Stress path at mid distance between two DG



Conclusions

Long term investigation in THM coupled processes in poorly indurated clay

- Laboratory tests: THM properties/ parameters under well controlled boundary conditions but with relatively small volume of soil
- In situ tests: larger volume of soil and interpretation by back-analysing the measurements
 - ➔ both kind of tests are complementary
 - ➔ determination of a set of THM properties/ parameters to model a GDF
 - ➔ important input for the design/ optimization of a GDF

Future focus of the THM behaviour:

- Mechanical plastic anisotropy
- Long term behaviour

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Characterisation of Boom Clay anisotropic THM behaviour from two in-situ heating tests

Exchange meeting HADES40

Tabloo, 9 December 2022

G.J. Chen, X.L. Li, A. Dizier, J. Verstricht, X. Sillen, S. Levasseur

guangjing.chen@euridice.be



sck cen

ESV EURIDICE GIE

Outline

- ☐ **THM processes and characterisation**
- ☐ **From small scale to large scale heater test**
- ☐ **Combined numerical interpretation and characterisation**
- ☐ **Summary**

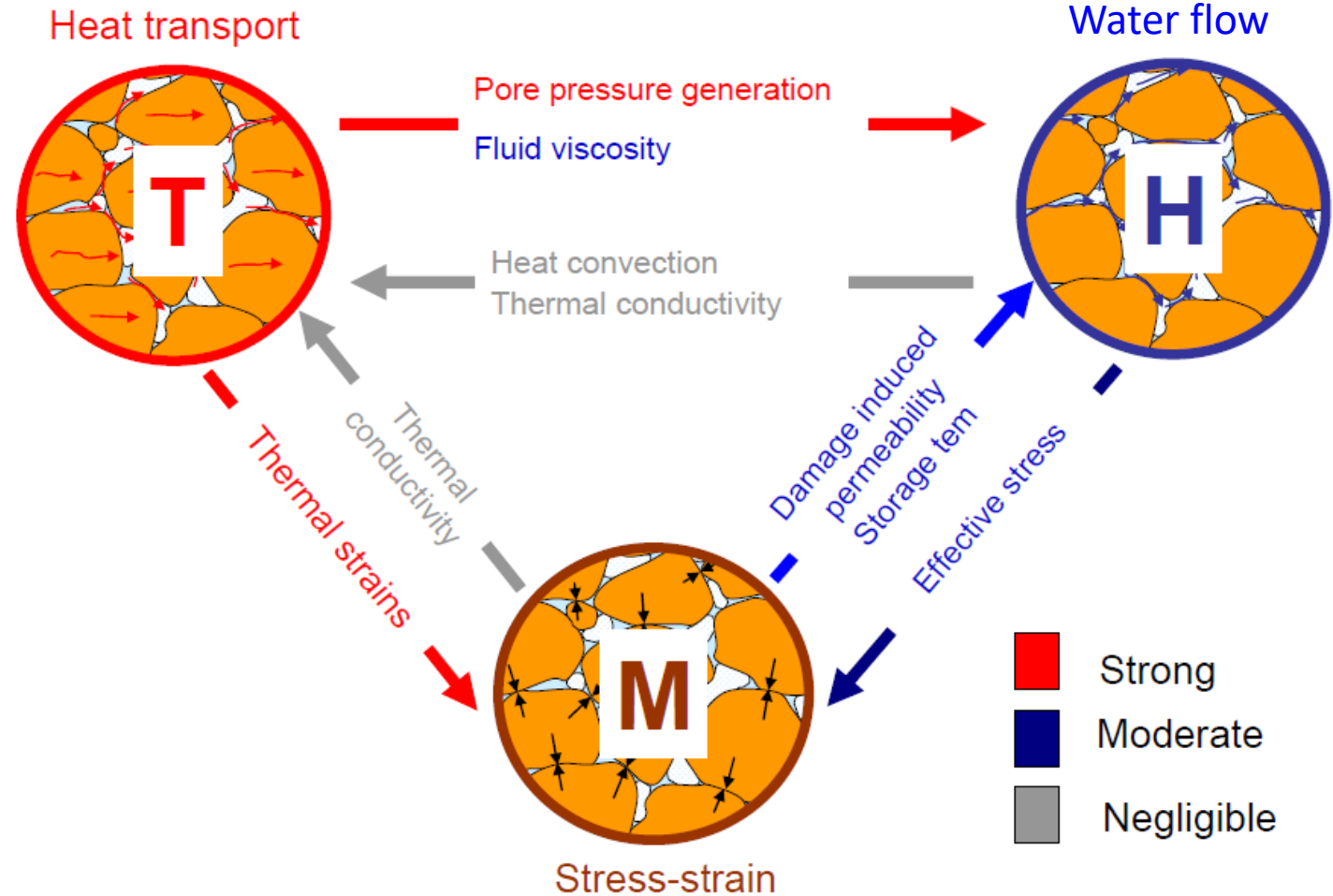
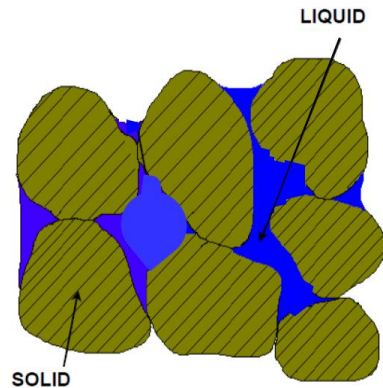
THM processes and characterisation

❑ Boom Clay is saturated with low permeability

❑ Major THM processes and coupling

❑ Major THM parameters

- Thermal parameters: λ , C
- Hydraulic conductivity: $K(T)$, $v(T)$
- Thermal expansion coefficient: $\alpha_w(T) \gg \alpha_s$
- Elastoplasticity parameters: E , ν , c , ϕ ,



THM processes and characterisation

- ❑ Existing Boom Clay THM knowledge
 - From laboratory characterisation programs and in situ tests in HADES
- ❑ This study focuses on refining THM knowledge from ATLAS IV and PRACLAY
 - Combined interpretation
 - THM Anisotropy

THM processes and characterisation

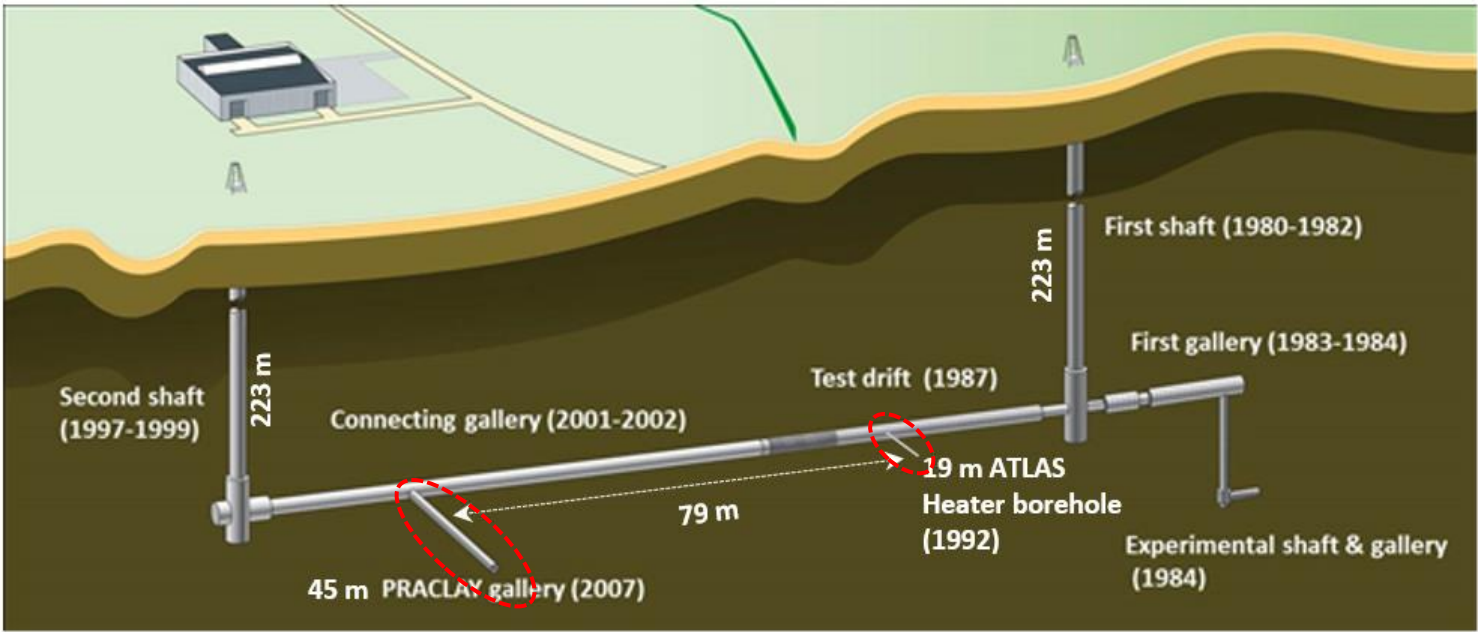
- ❑ Consequence of deposition process and subsequent burial history
- ❑ Anisotropy is an additional layer of complexity
- ❑ Anisotropy of Boom Clay at the site of HADES URL:
 - In situ stresses: σ_h , σ_v
 - THM properties: λ_h , λ_v , K_h , K_v , E_h , E_v , ...
- ❑ Anisotropy explains DZ shape, far field HM perturbations



Clay pit (surface)

From small-scale ATLAS IV to large-scale PRACLAY Heater test

- ❑ Two in situ heater tests for Boom Clay THM characterisation
 - Small-scale ATLAS IV: 2011-2012
 - Large-scale PRACLAY: 2014-



Heater test		ATLAS IV	PRACLAY
Duration		408 days	> 10 years
Heater	Diameter	0.19 m	2.5 m
	Length	8 m	33 m
	Power	≤ 175 W/m	≤ 450 W/m
Monitoring	Extent	1.3 < R < 4.5 m	Up to 29 m (in EDZ and zone beyond)
	T _{max} in clay	41 °C	80 °C
	P _{max} /ΔP _{max}	3.3/1.0 MPa	3.0/1.9 MPa
	THM	Yes	Yes

Combined numerical interpretation and characterisation

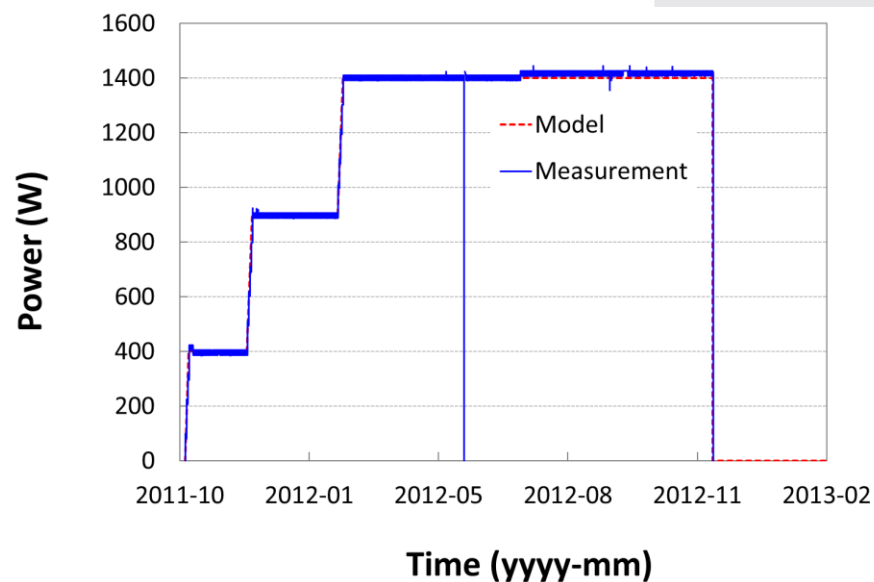
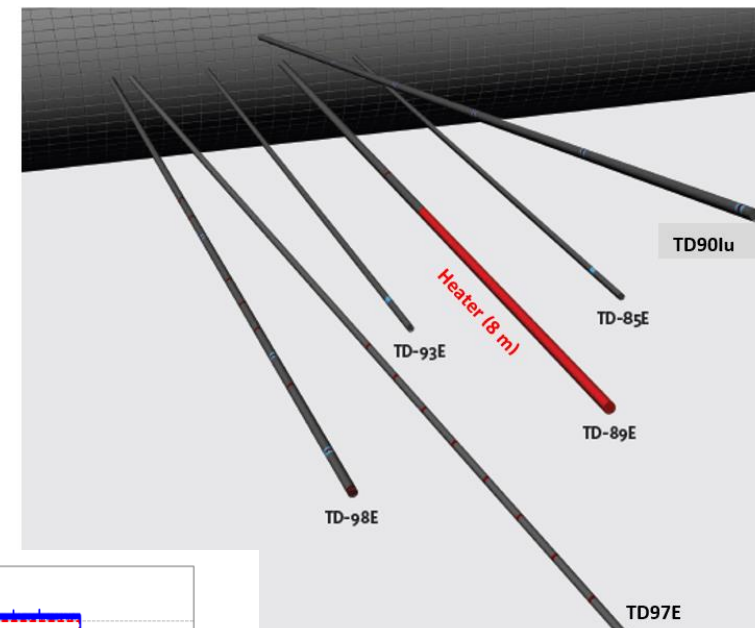
ATLAS IV Heater test

Main Objective

- ❑ Simple geometry and boundary conditions, essentially only Boom Clay (Modeller's dream!)
- ❑ Validate and/or improve knowledge on THM behaviour in far field
 - Moderate line heat source
 - Limited mechanical disturbance

Modelling

- ❑ Full 3D THM model
 - Anisotropic THM model
 - Heater power boundary condition



Combined numerical interpretation and characterisation

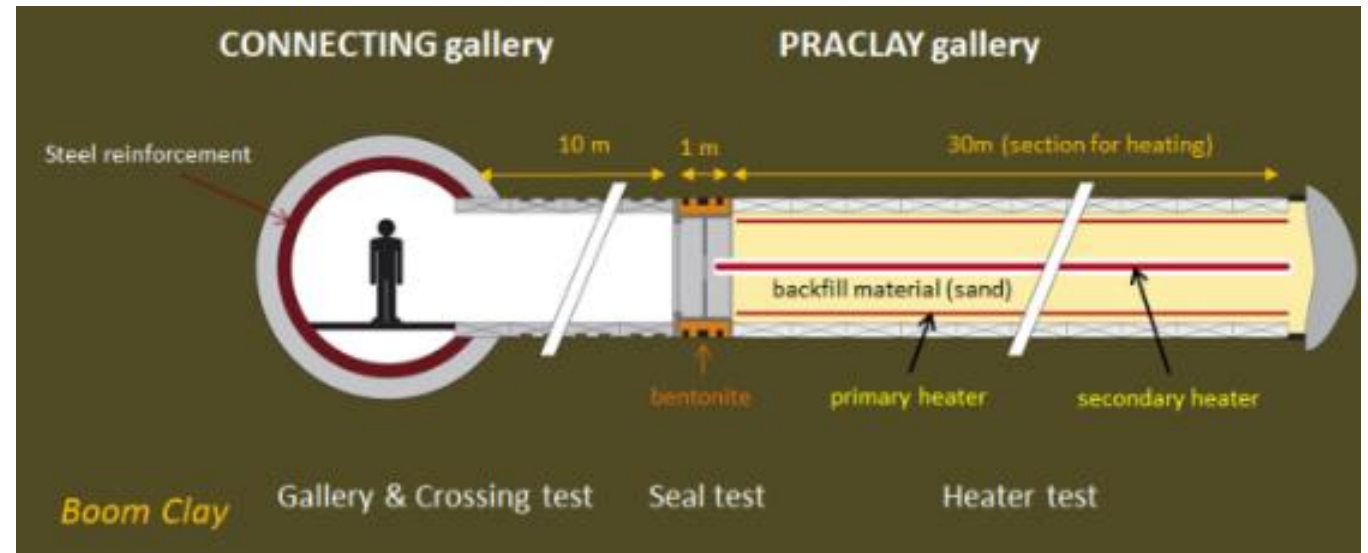
PRACLAY Heater test

Main Objective

- ❑ At a scale more representative of a disposal gallery
 - More materials
 - Combined impacts of excavation and heating
- ❑ Validate and/or improve THM knowledge on both near-field and far-field Boom Clay

Modelling

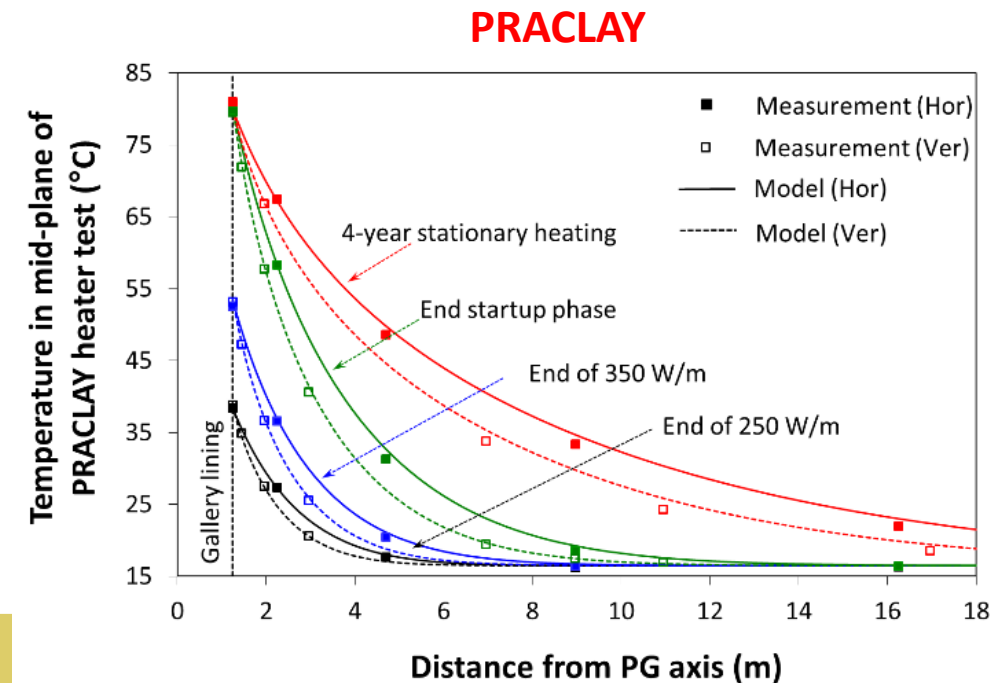
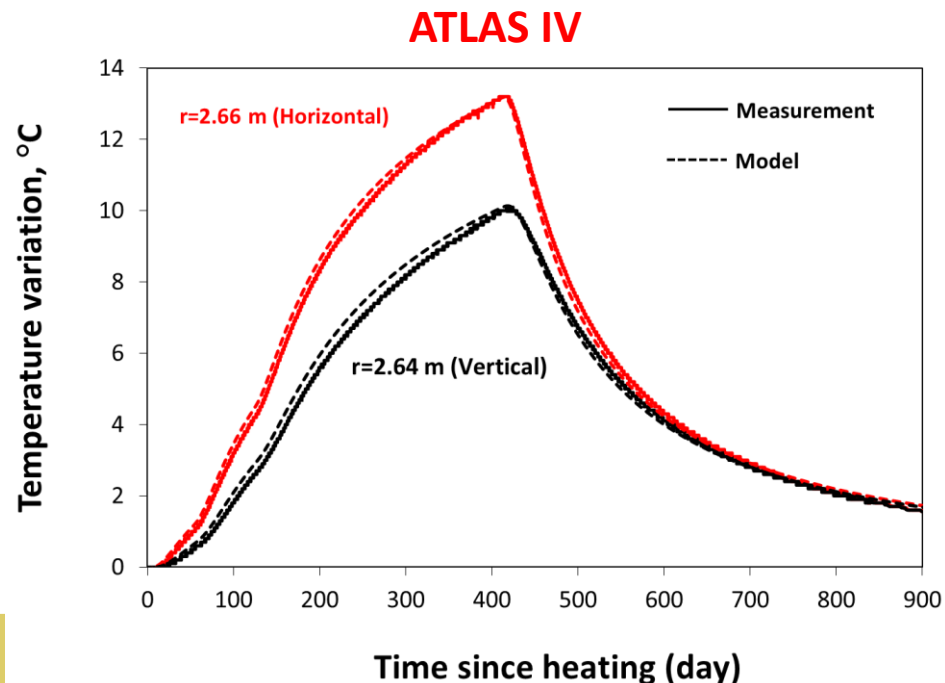
- ❑ 2D-Axis THM, 3D T, 2D-PS THM models
 - Isotropic/Anisotropic THM model
 - Heater power/Temperature boundary condition



Combined numerical interpretation and characterisation

□ Temperature

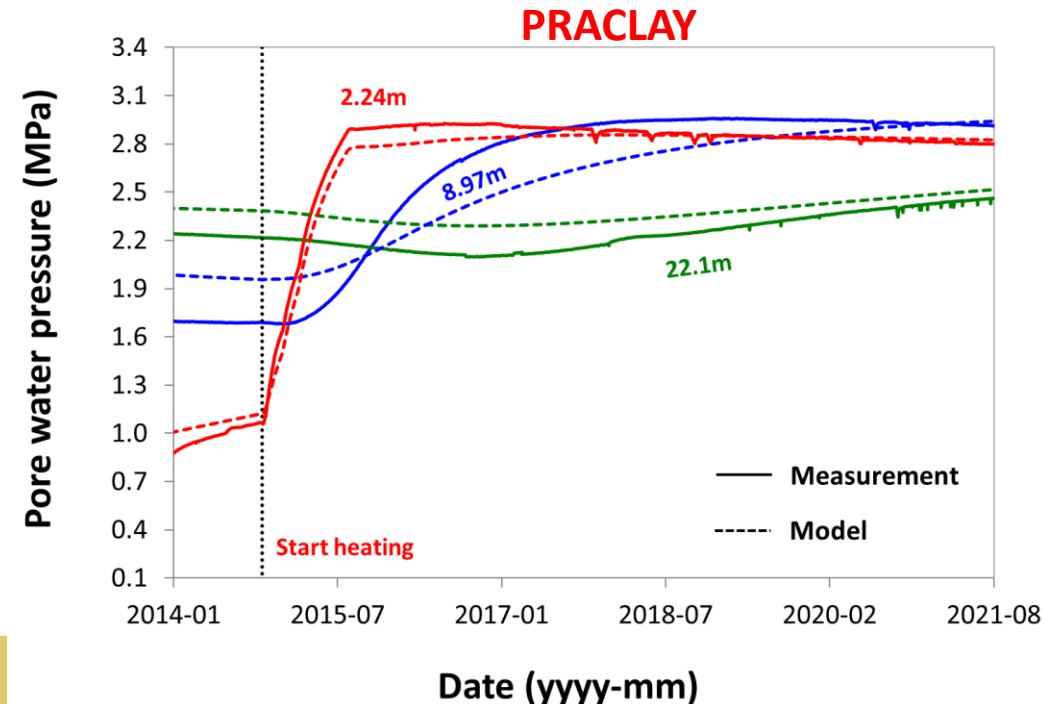
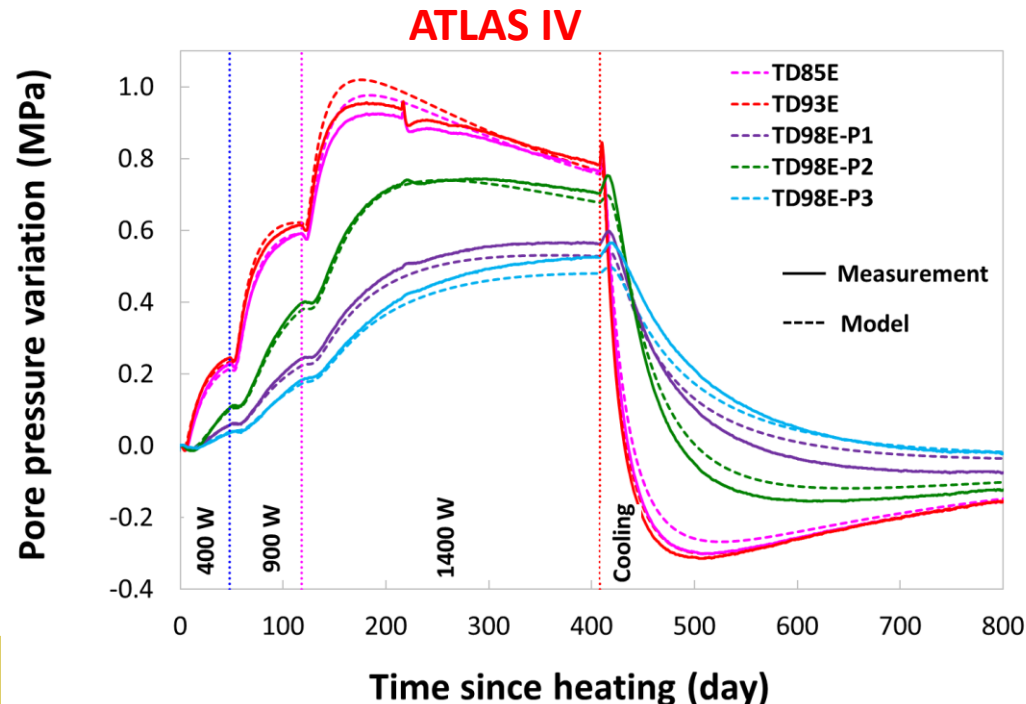
- $\{\lambda_h, \lambda_v\} = \{1.90, 1.20\}$ W/(mK) for both tests
- Good agreement at almost all sensors (Chen et al, 2022, Acta Geotechnica)
- Not significant impact of the excavation and heating on Boom Clay thermal conductivity



Combined numerical interpretation and characterisation

□ Pore water pressure in **horizontal** plane

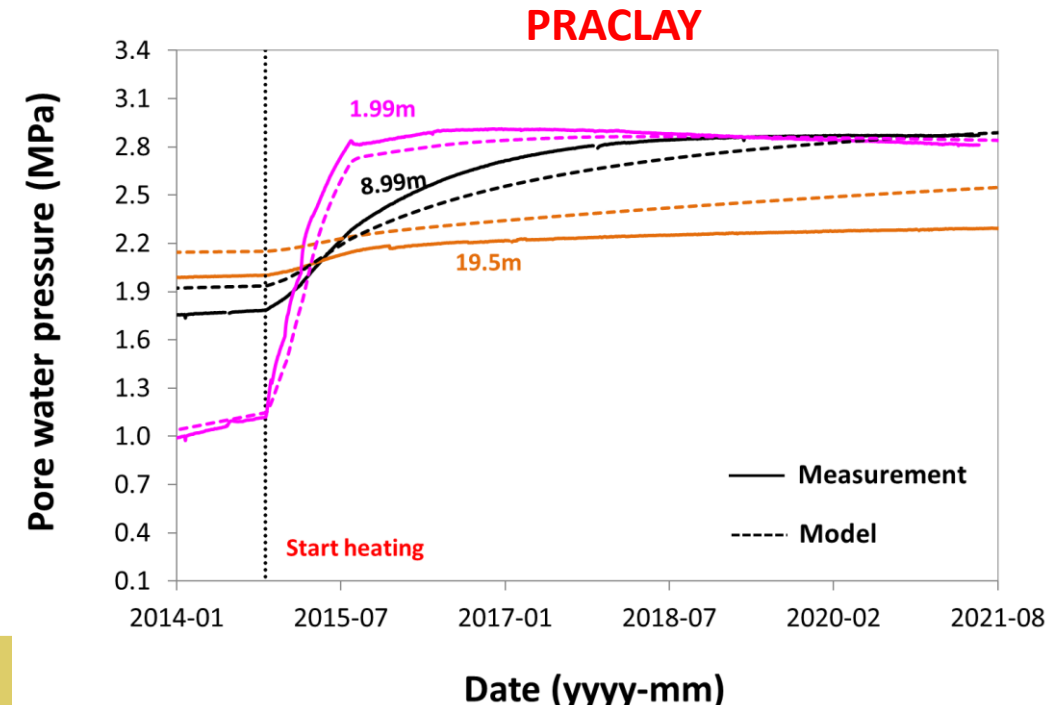
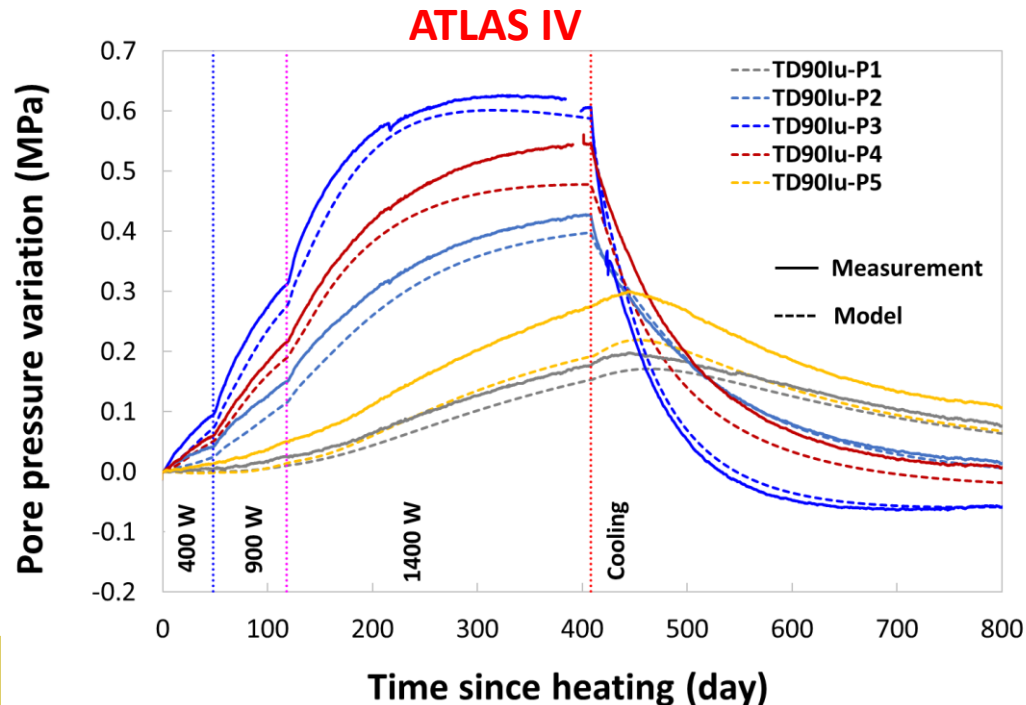
- Temporary pore pressure decrease/increase after power increase/decrease
- The same set of anisotropic THM model parameter values
- Reasonably well capture the trend and magnitude for both tests



Combined numerical interpretation and characterisation

□ Pore water pressure in **vertical** plane

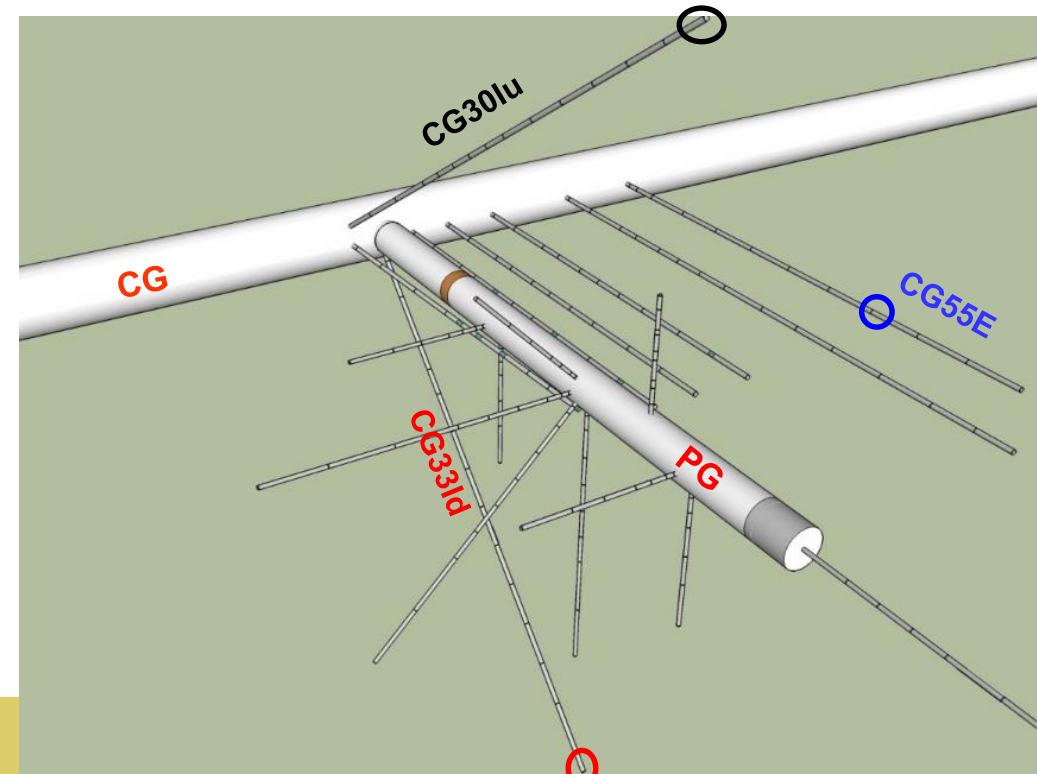
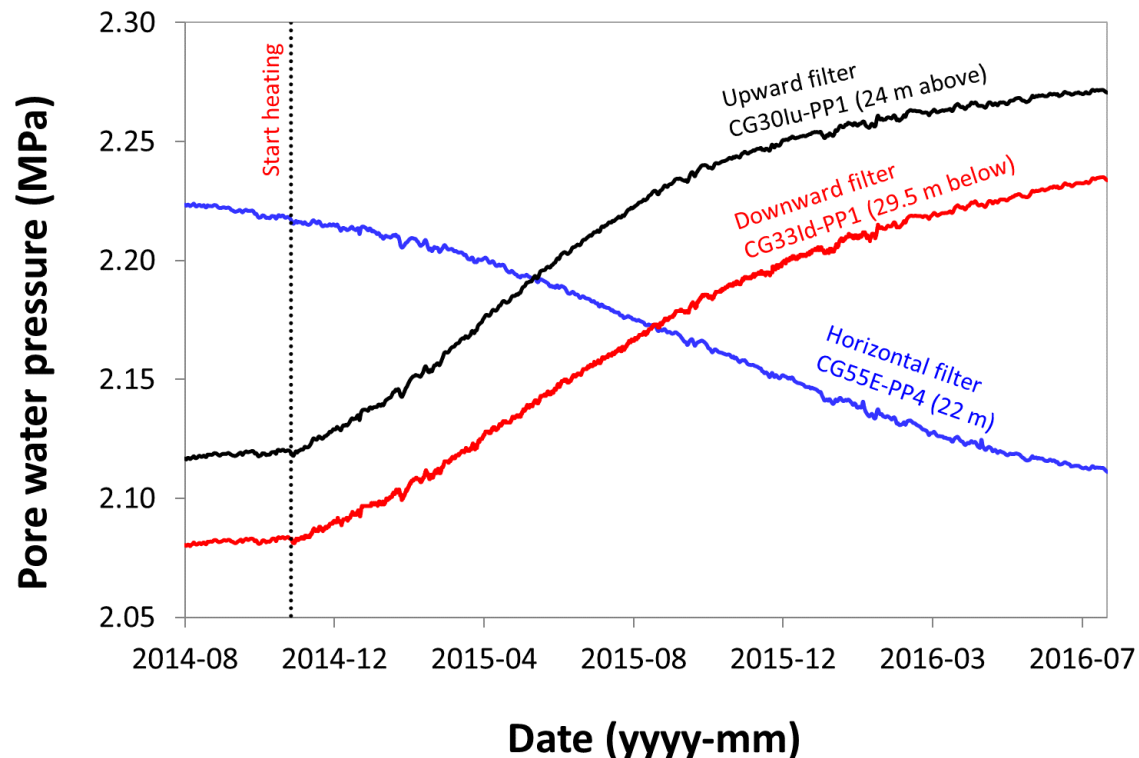
- Pore pressure increase/decrease after power increase/decrease
- The same set of anisotropic THM model parameter values
- Reasonably well capture the trend and magnitude for both tests



Combined numerical interpretation and characterisation

□ Far-field HM perturbation

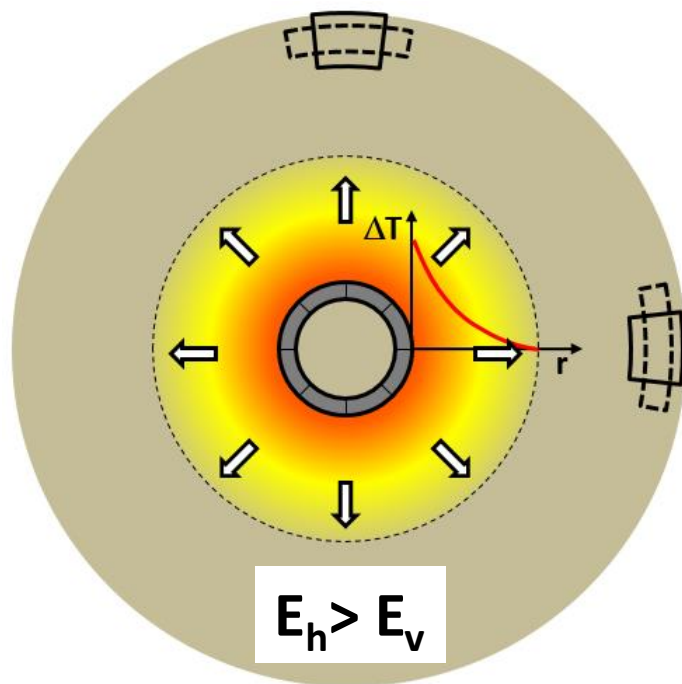
- Different variation trend after heating
- Effect of anisotropy



Combined numerical interpretation and characterisation

□ Mechanical anisotropy and HM coupling

Extension < compression $\Rightarrow$ contraction $\Rightarrow P_w \uparrow$



Extension > compression $\Rightarrow$ dilation $\Rightarrow P_w \downarrow$

Summary

- ❑ Boom Clay THM behaviour has been characterized from
 - A large number of laboratory characterisation program
 - In-situ tests in HADES URL
- ❑ The present combined numerical interpretation of ATLAS IV and PRACLAY
 - The same set of anisotropic THM parameter values well reproduce the anisotropic THM responses

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Stability analysis and long term behaviour of deep tunnels in clay formation

Exchange meeting HADES40

Tabloo, 9 December 2022

A. Dizier, M. Scibetta, G. Armand, J. Zghondi, T. Georgieva, G. Chen, J. Verstricht, X.L. Li, D. Léonard, S. Levasseur

Arnaud.dizier@euridice.be



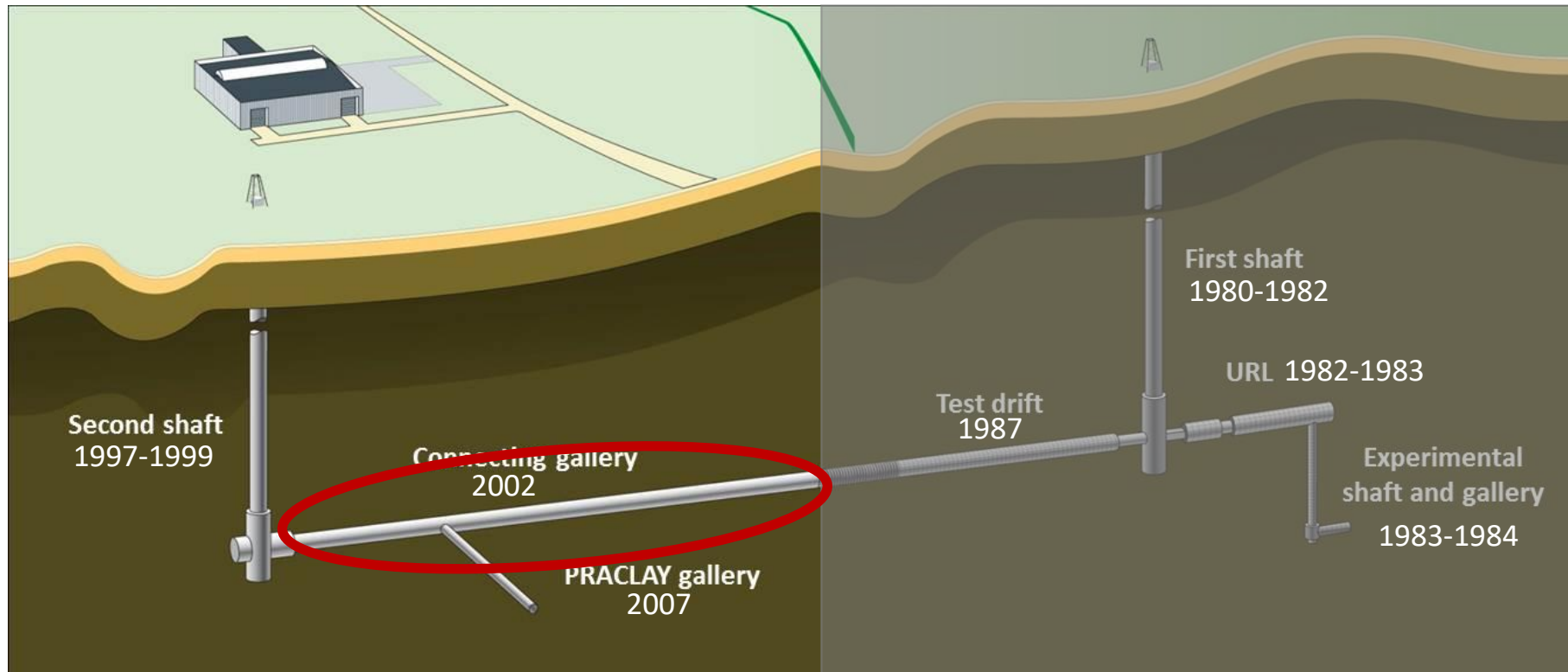
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Introduction

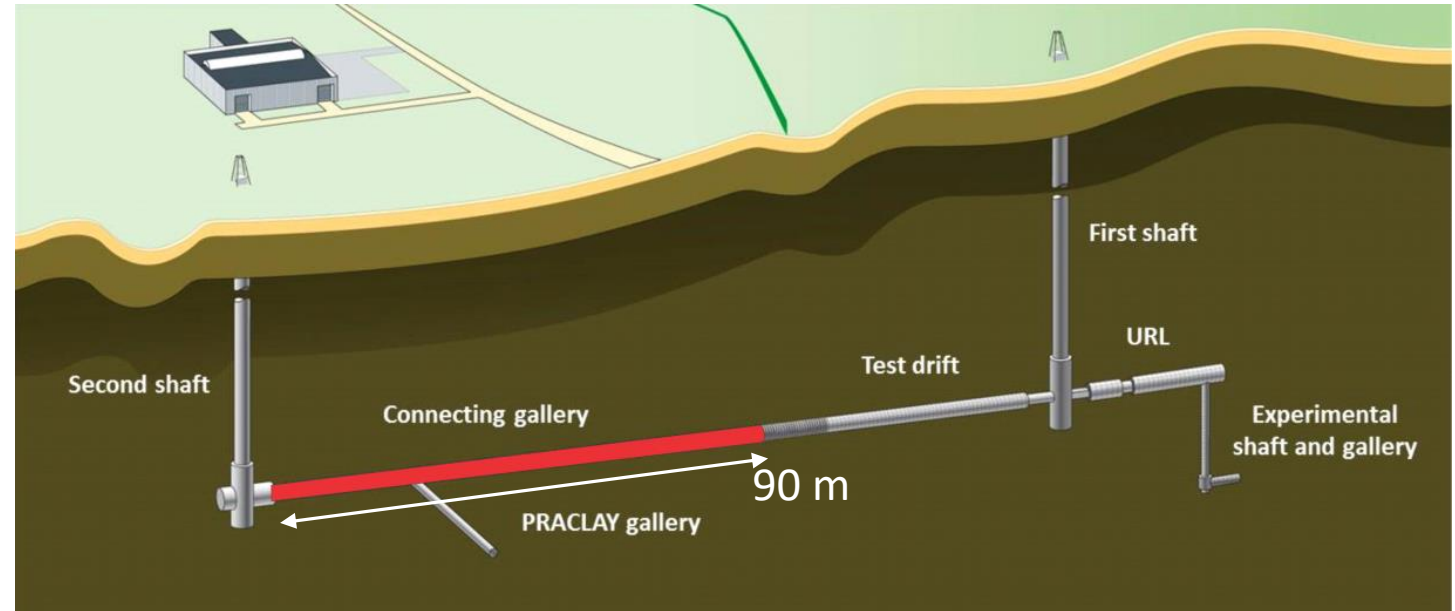
HADES Underground Research Laboratory (URL) in Mol

Construction in 2 phases (pioneering phase, industrial phase)



Connecting Gallery construction

- External diameter: 4.8m
- Internal diameter: 4.0m
- Unreinforced concrete
- Concrete C75/90



Connecting Gallery construction

- Average rate of 3m/day (Excavation in 2 months from Jan 02 – Mar 02)
- Wedge block system

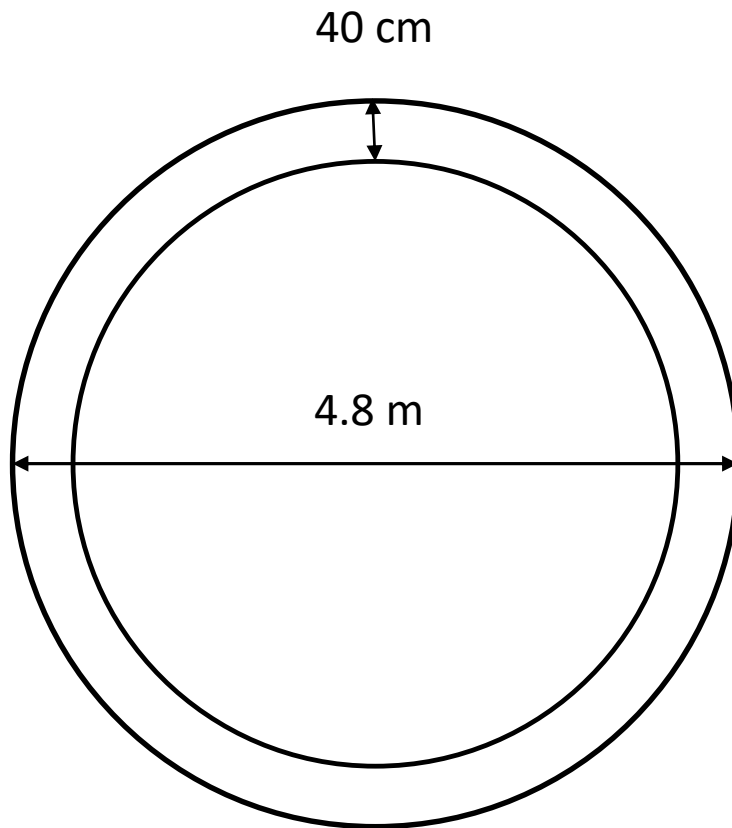


Is it still safe to enter in the gallery?

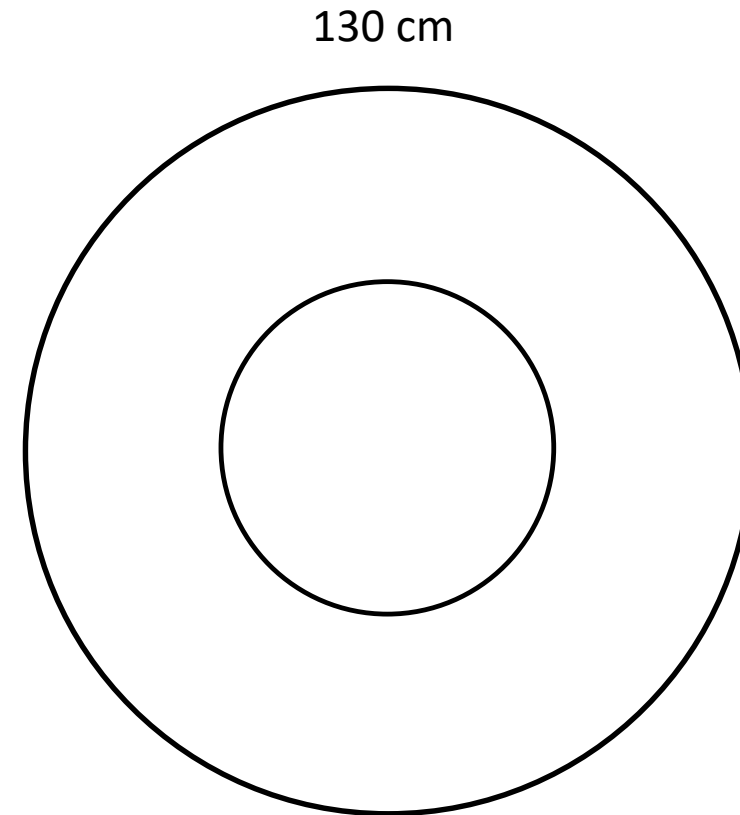


Input for the optimisation of the design

→ How to limit the over-design



Connecting gallery in the URL



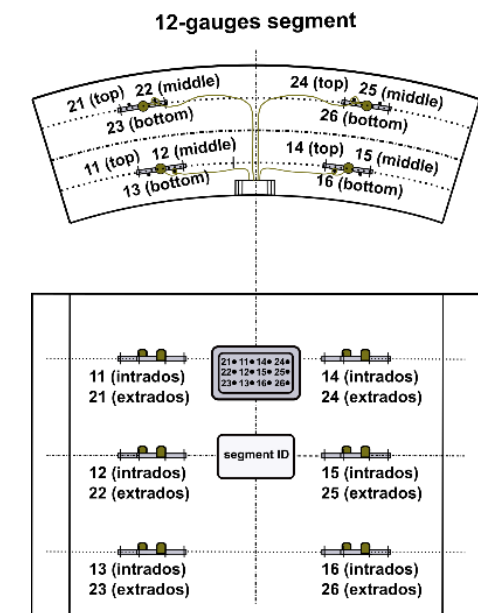
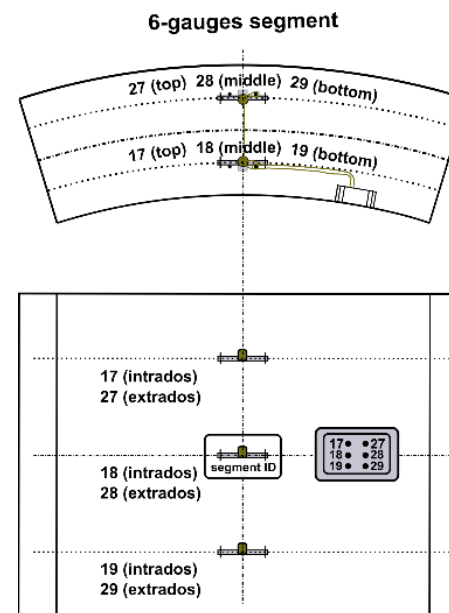
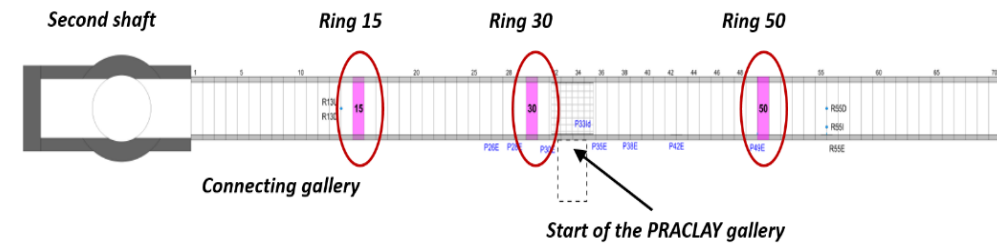
Connecting gallery at 600 m with current knowledge

Stability analysis of the Connecting gallery

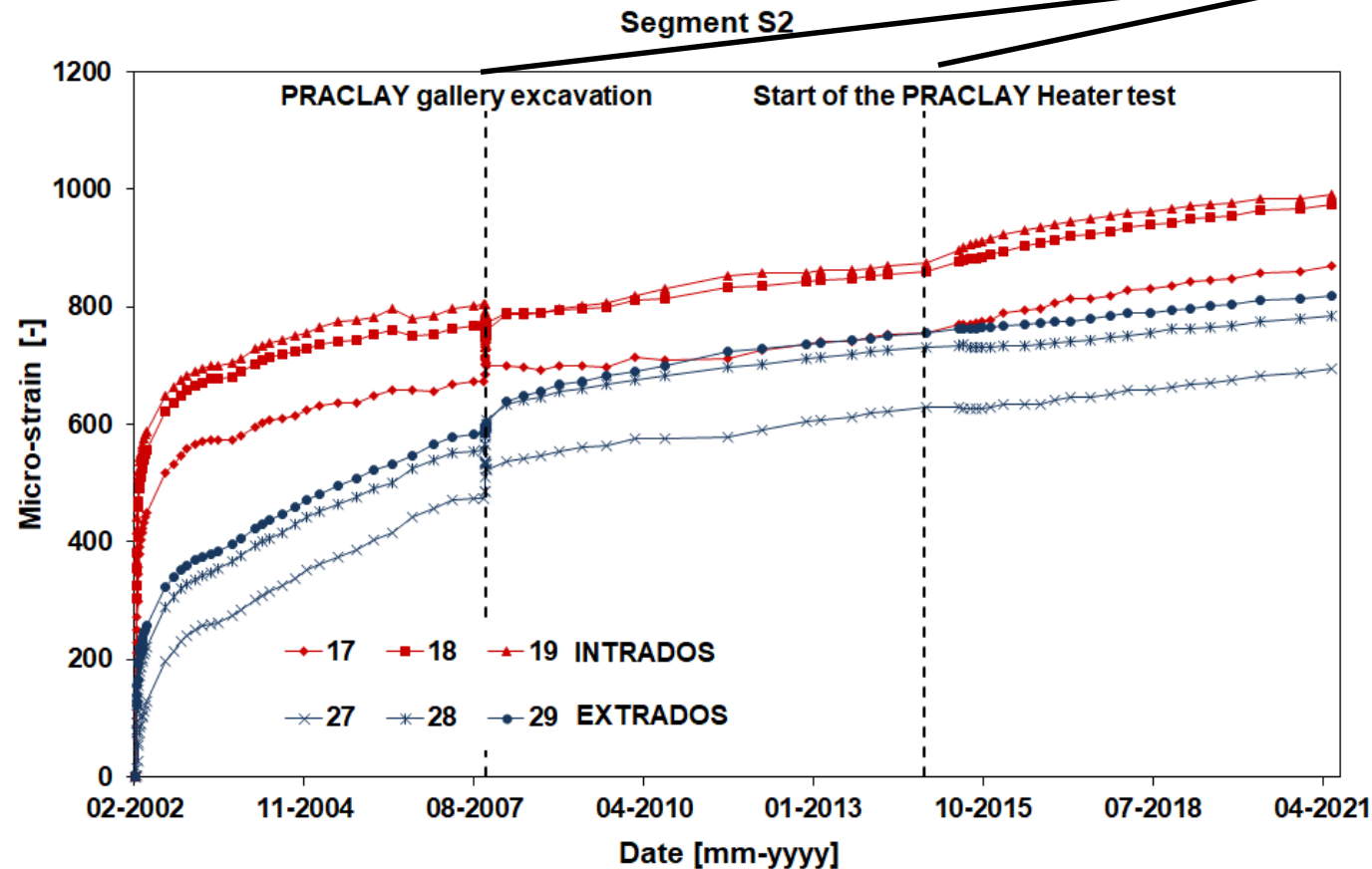


Embedded vibrating wire strain gauges

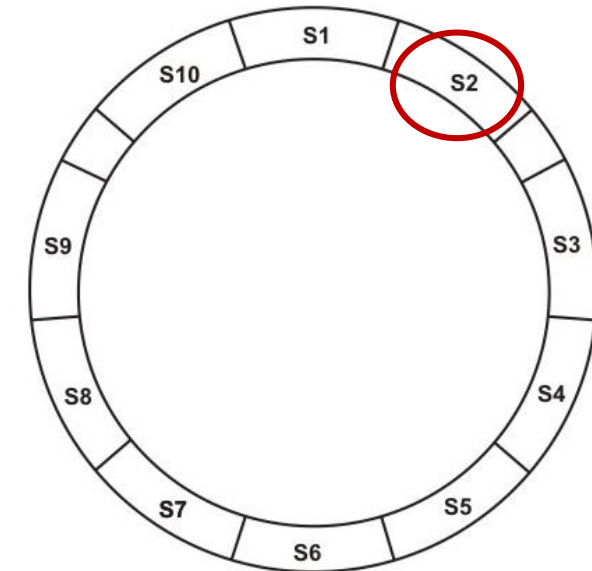
- Total of 270 gauges



Strain evolution ring 30 (S2)

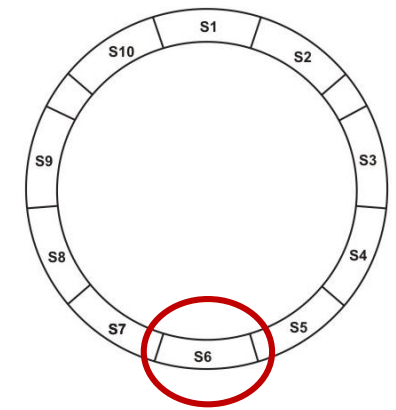


PRACLAY Gallery excavation : 2007
PRACLAY Heater test : 80°C at Boom Clay lining-interface

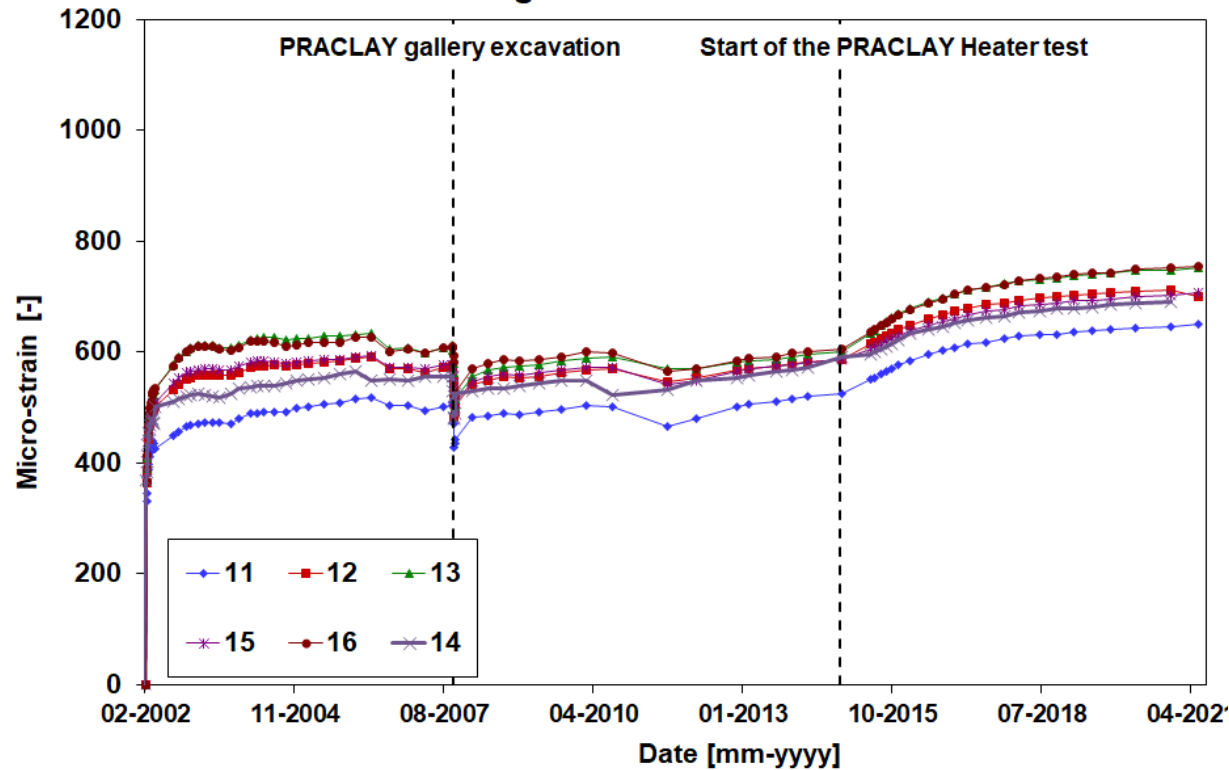


Strains positive in compression

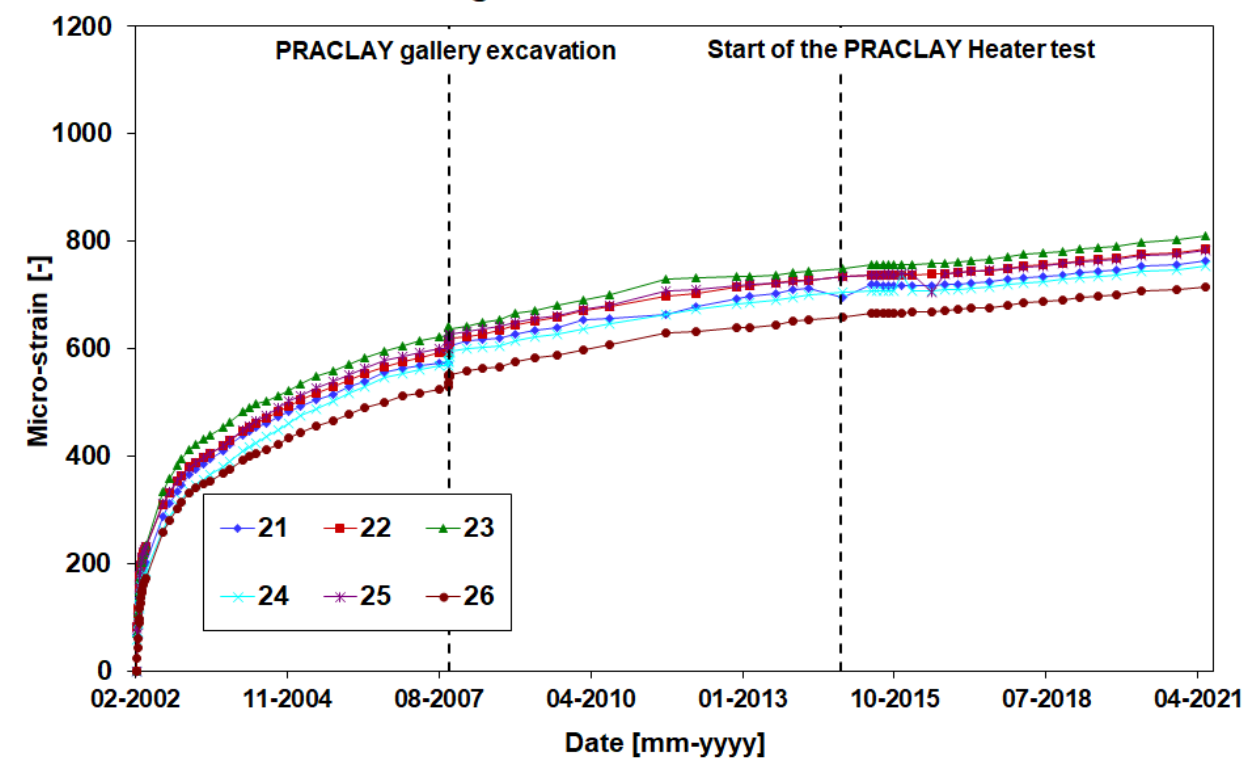
Strain evolution ring 30 (S6)



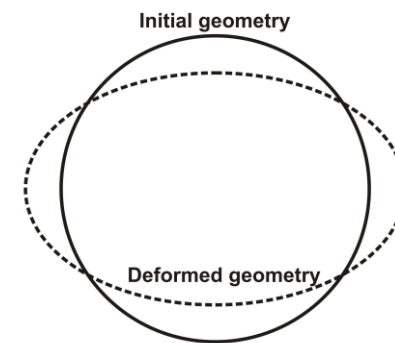
Segment S6 - intrados



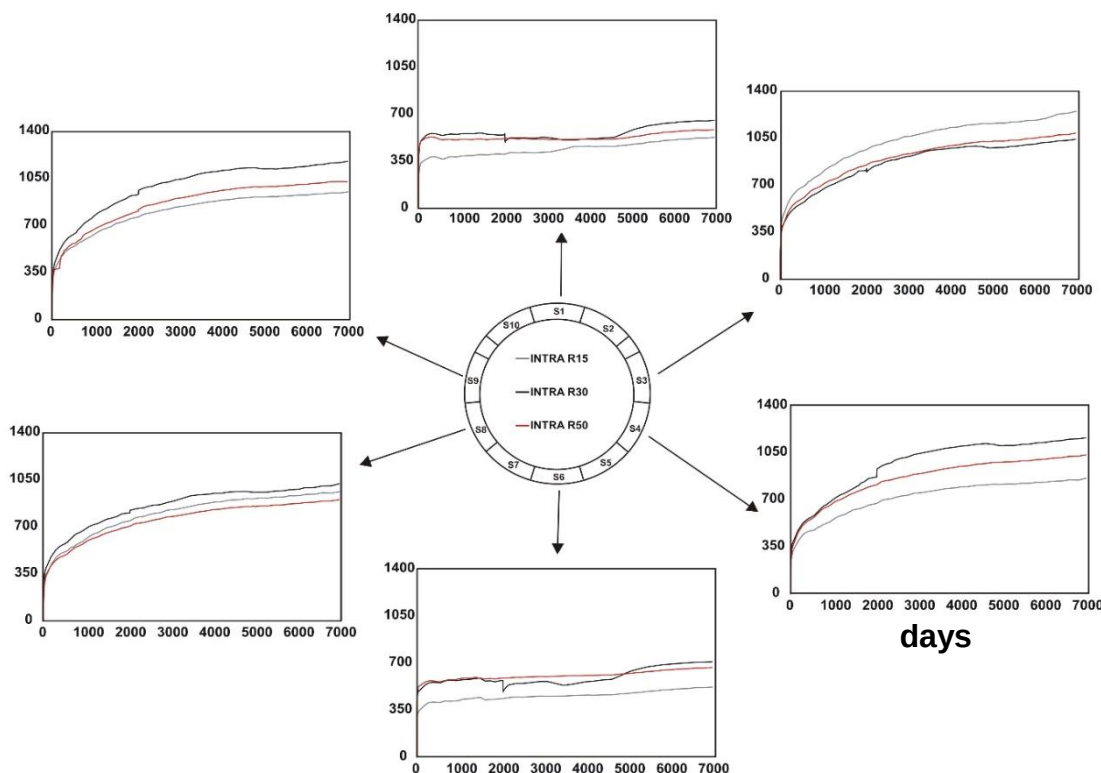
Segment S6 - extrados



Strain evolution of the 3 rings



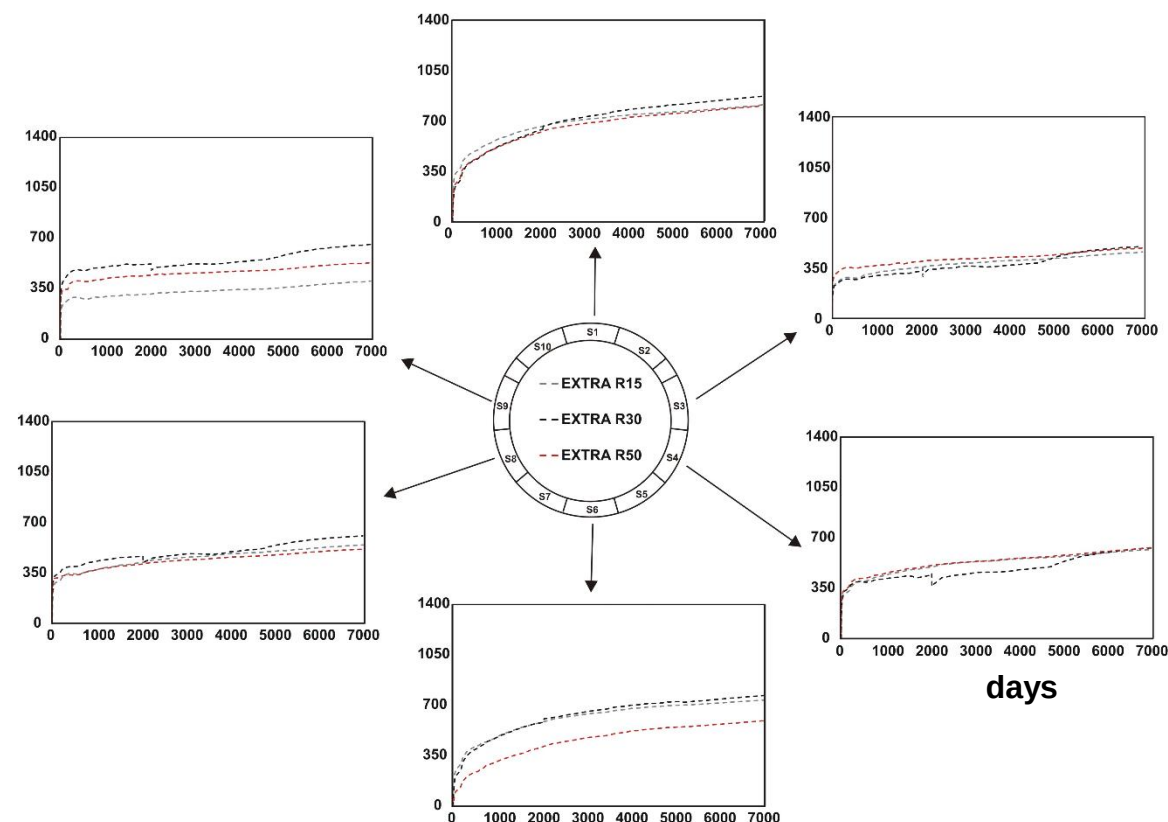
micro-strain



Intrados

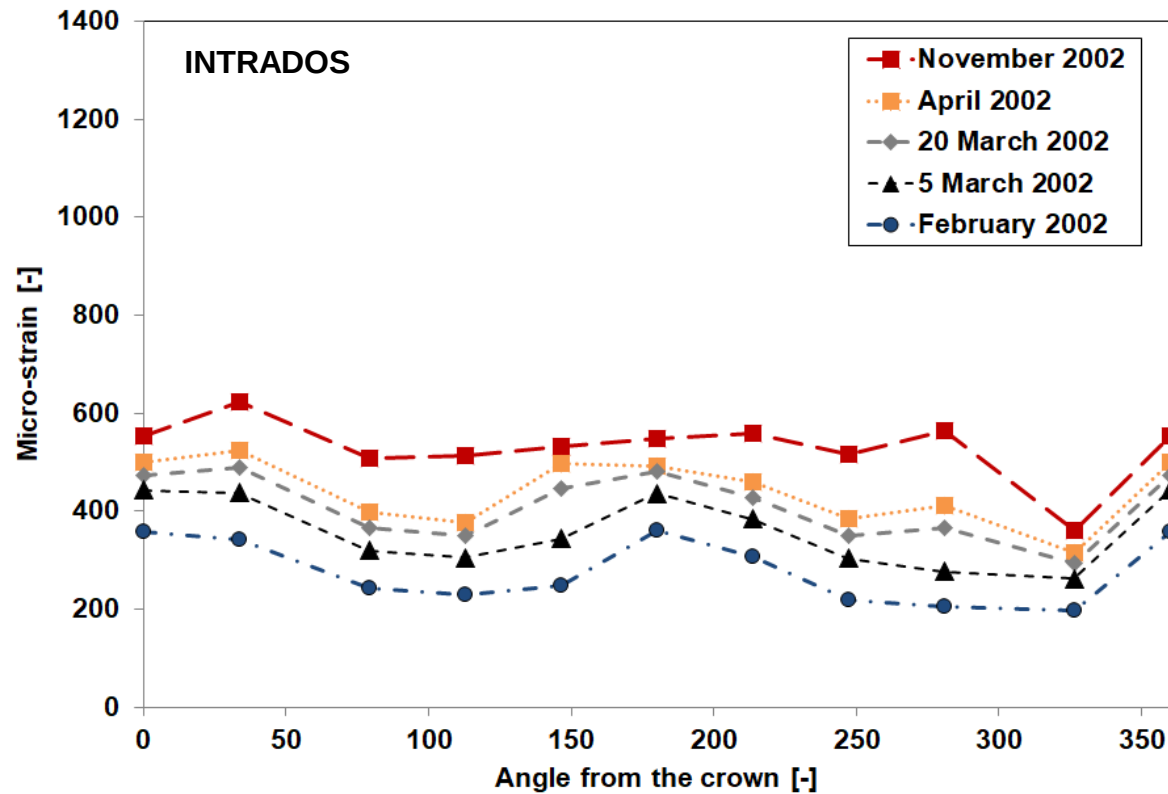
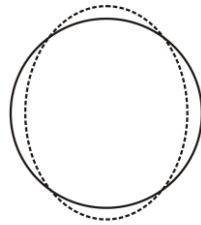
Vertical pressure > Horizontal pressure

micro-strain

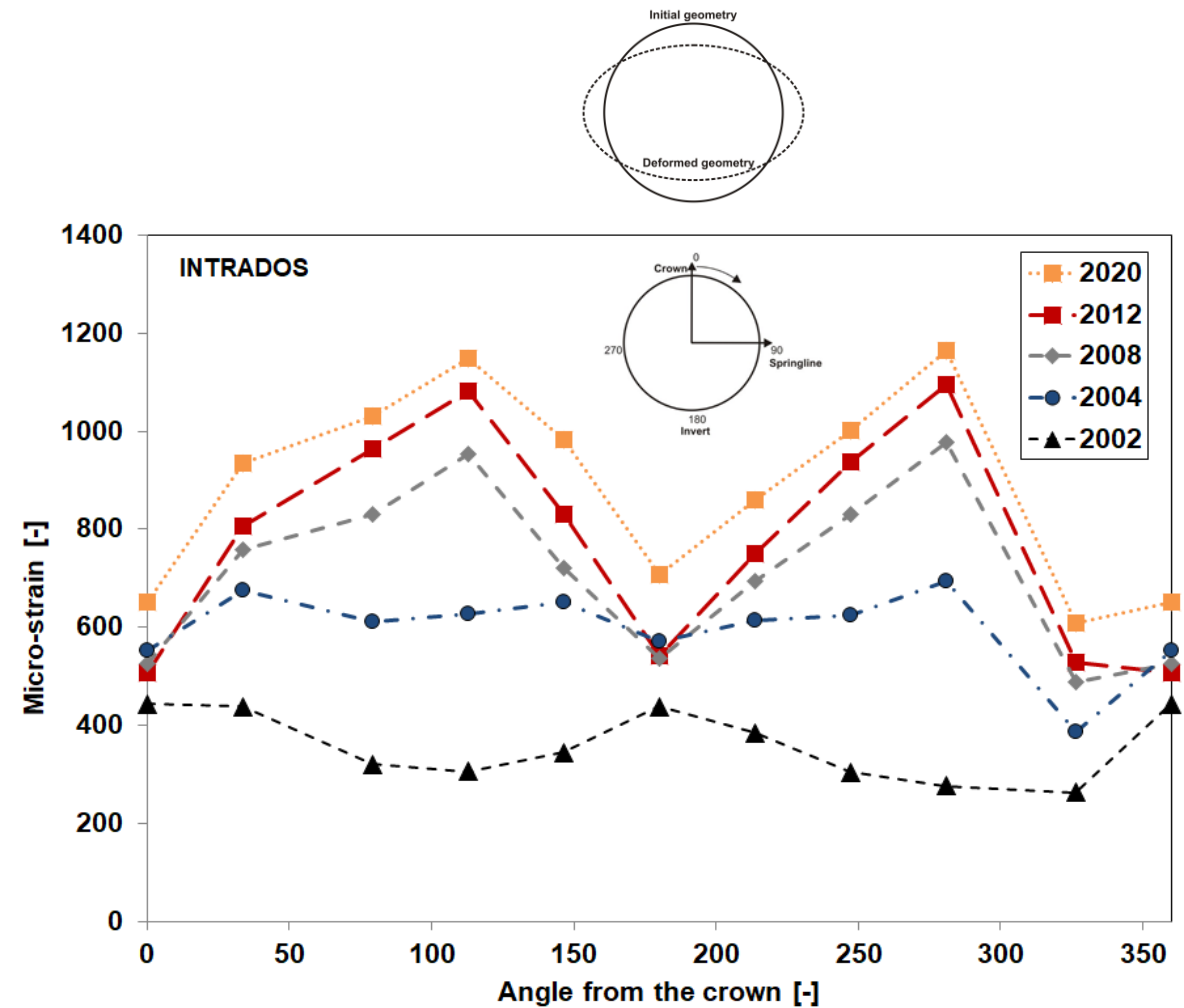


Extrados

Distinction short-term / long-term at intrados



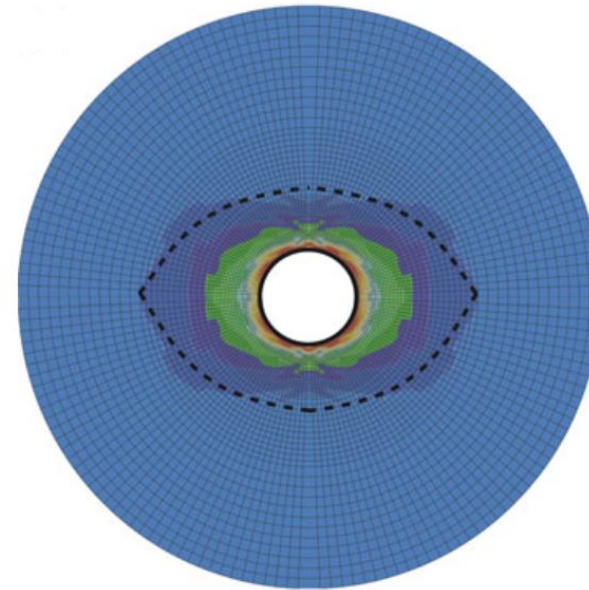
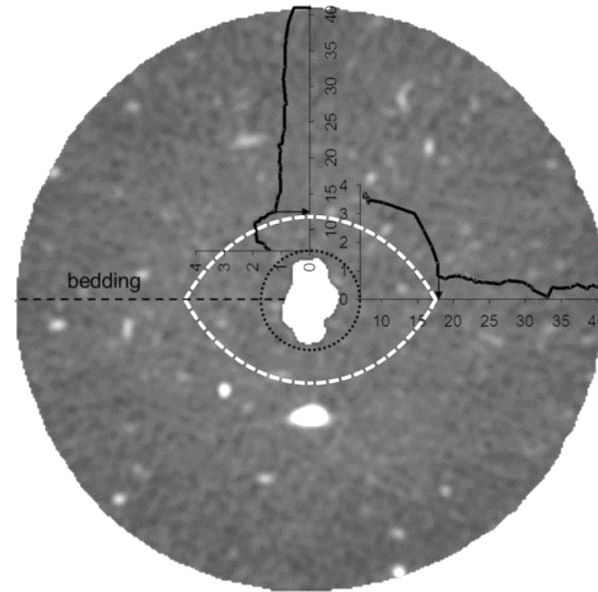
short term over 1 year



Long term over 20 years

Interpretation short-term / long-term

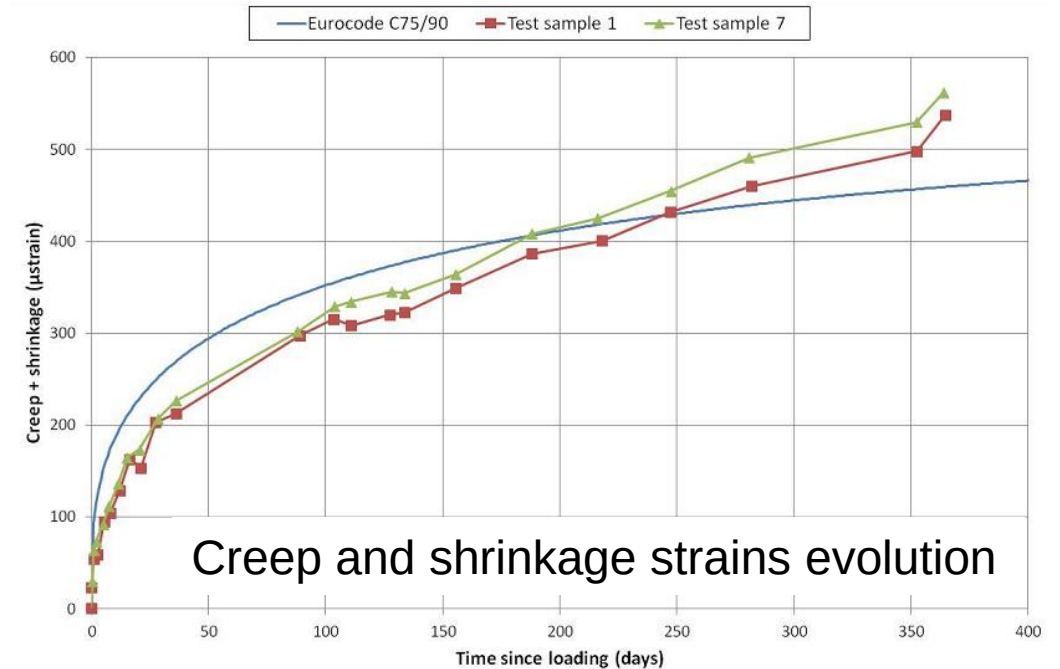
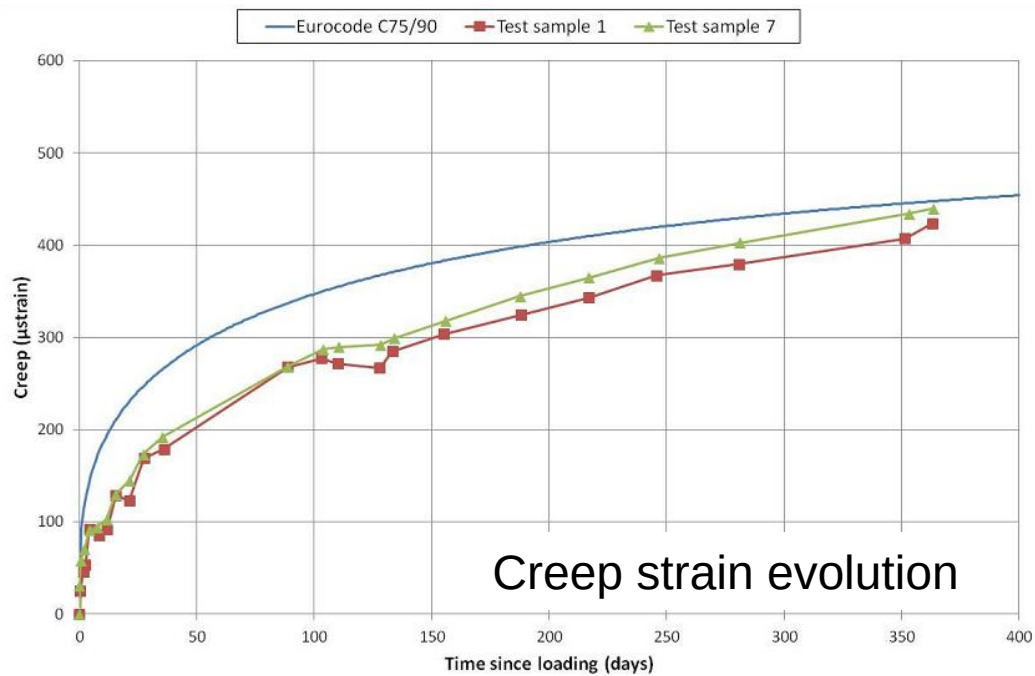
- Short term: anisotropic properties of the clay formation
 - Confirm at laboratory scale (Hollow cylinder test)
 - Larger horizontal displacement (similar to the Connecting Gallery excavation)



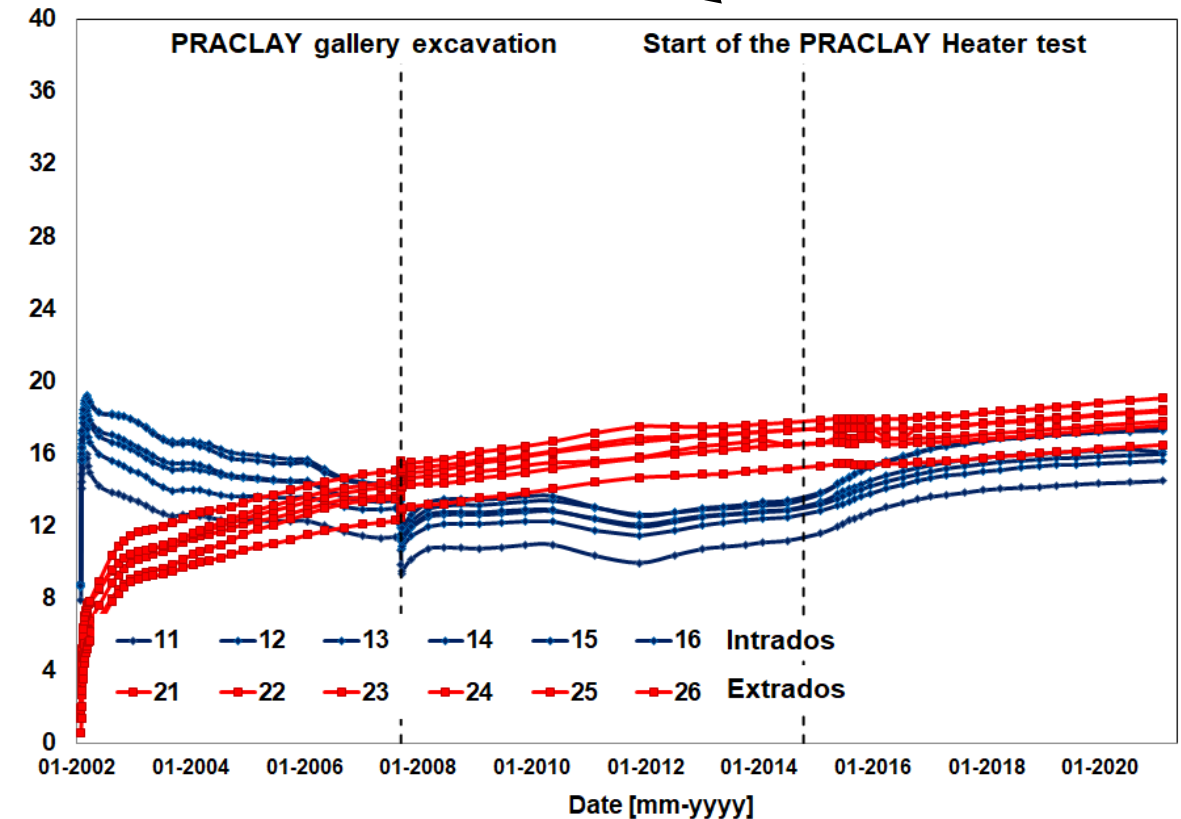
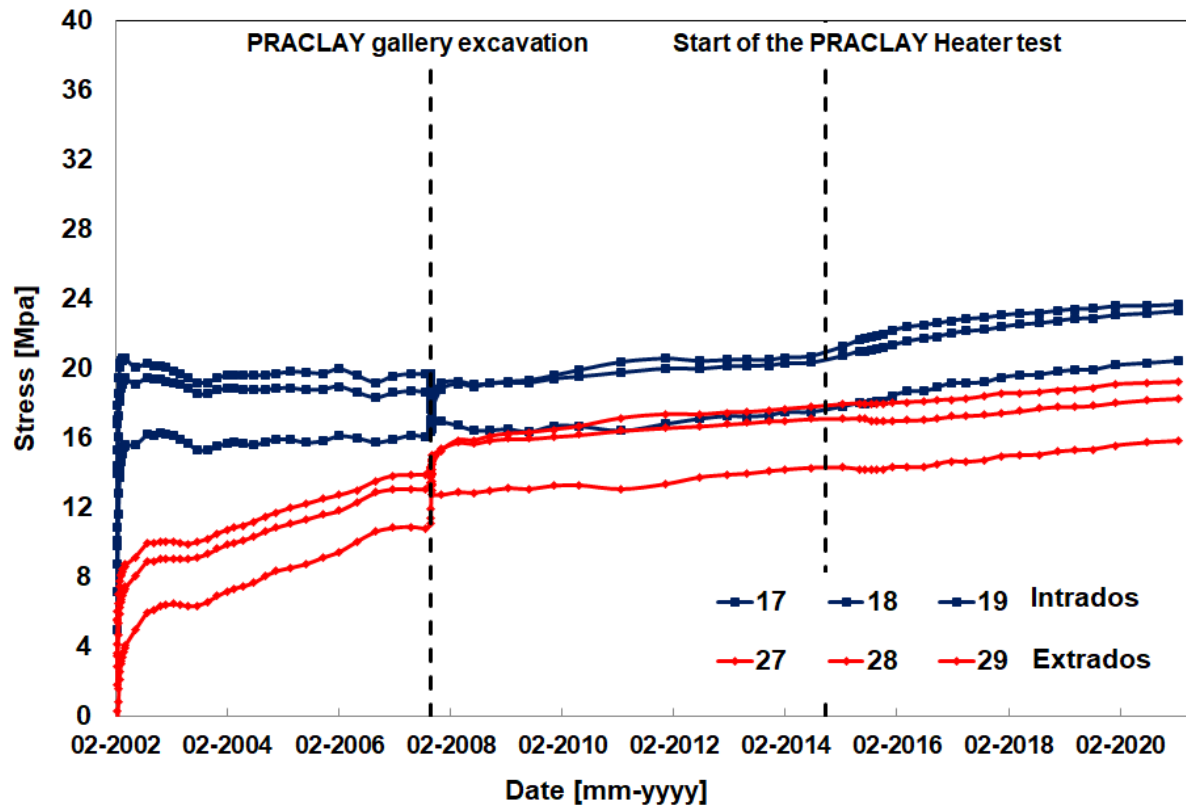
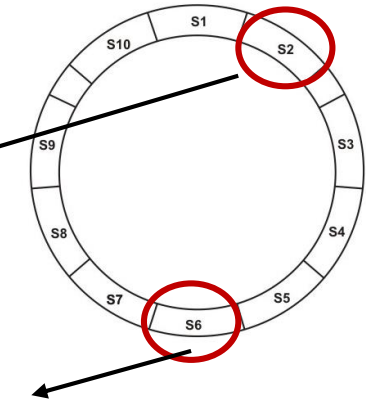
- Long term: anisotropy of the loading conditions (K_0) François et al. 2014

Analysis of the stresses based on the measured strains

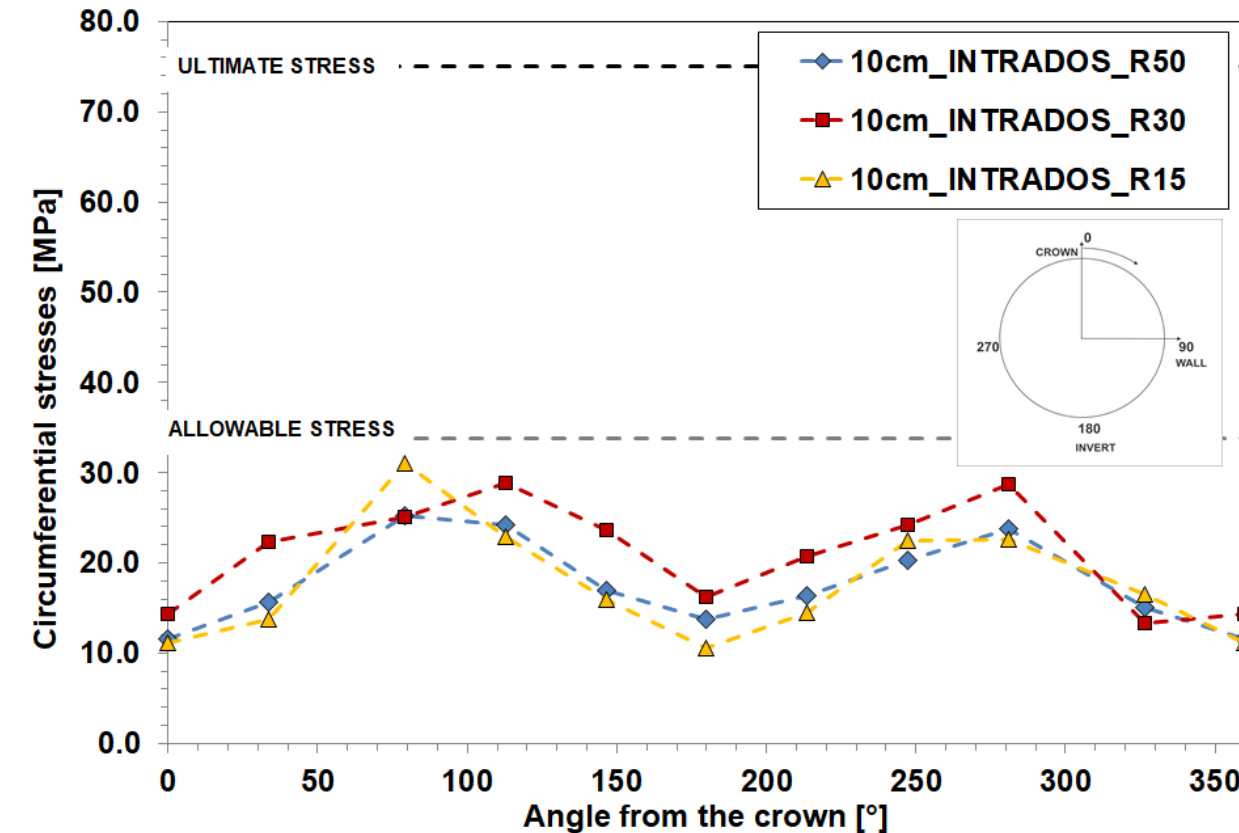
- EUROCODE 2 creep and shrinkage law for the concrete calibrated with experimental results (UGent)
- Study started ENGIE TRACTEBEL (2012-2016)



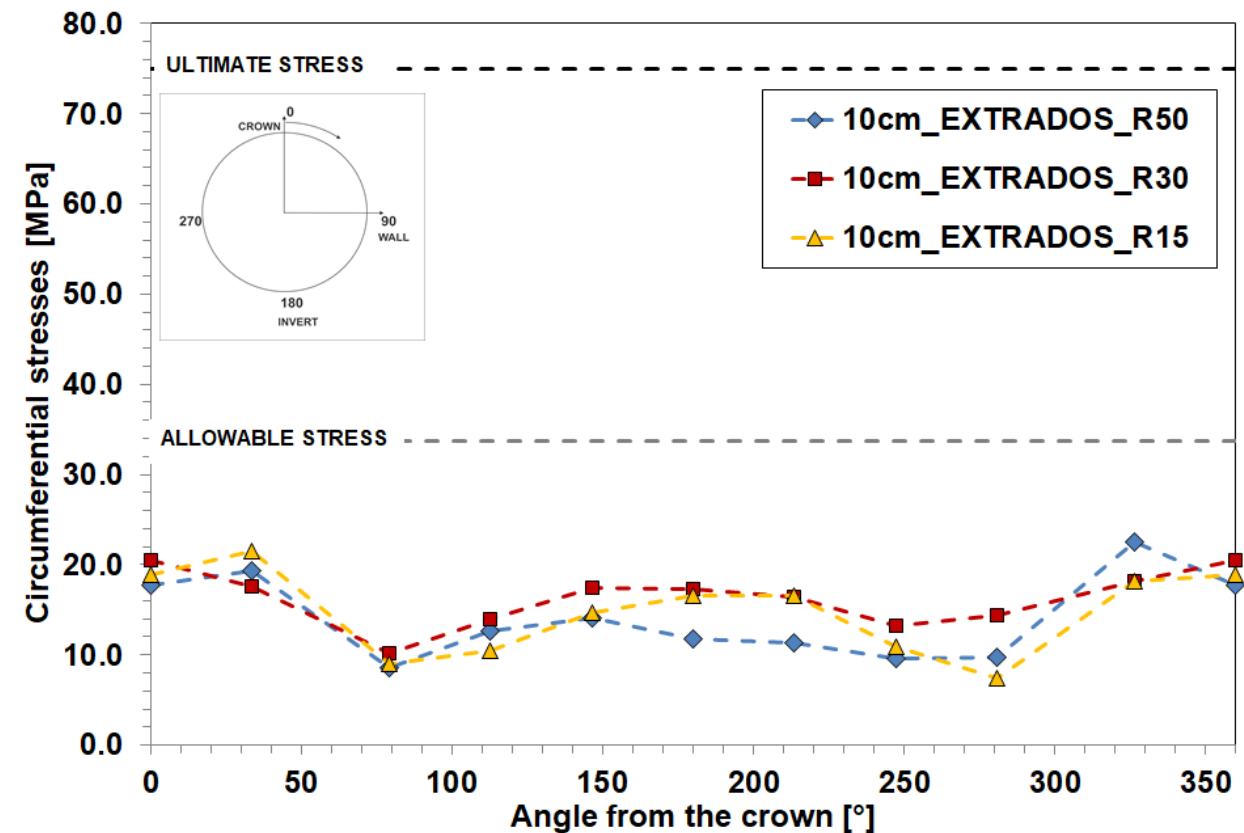
Stresses evolution in Ring 30 (S2 and S6)



Average stress distribution for the three rings



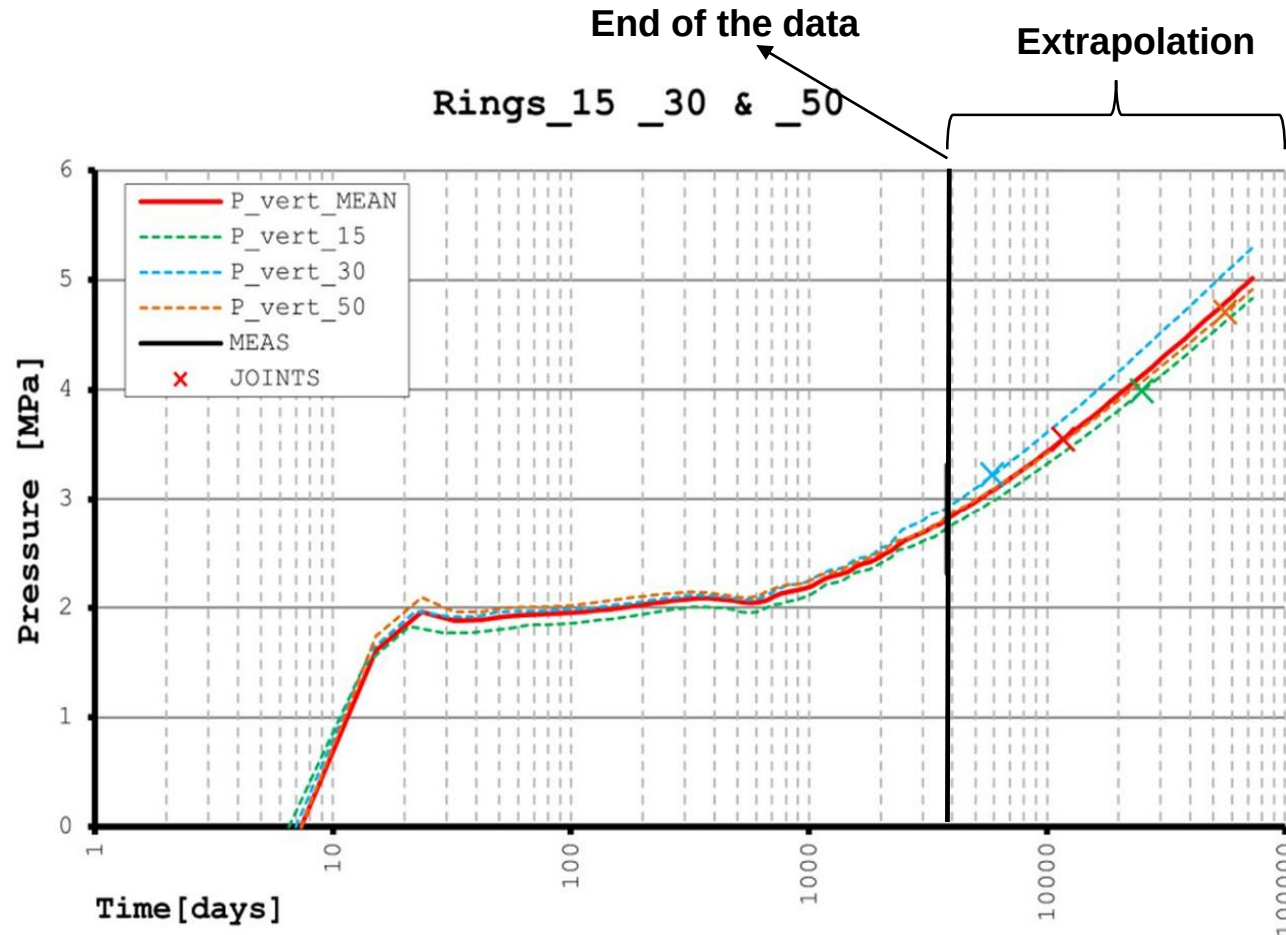
Intrados



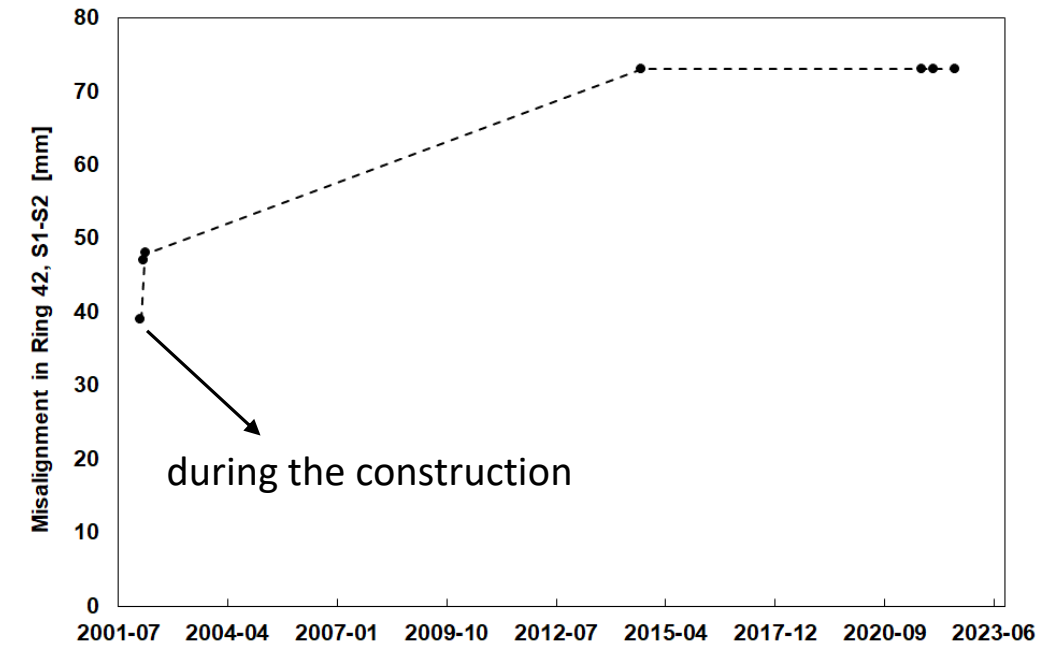
Extrados

Long term pressure acting on the lining

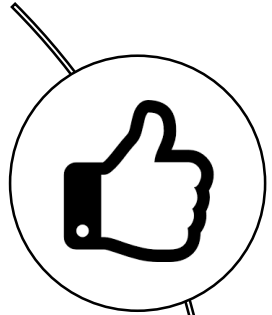
Collaboration with ENGIE TRACTEBEL



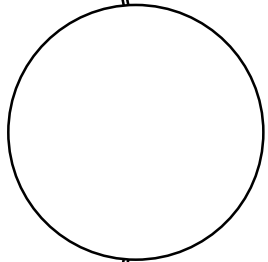
Visual inspection - misalignments



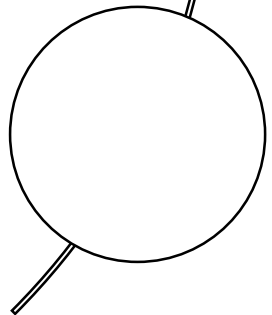
Yes it is safe!



No imminent gallery stability concern



Monitoring data embedded into a comprehensive framework



Input for a geological disposal facility

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ONDRAF / NIRAS



Large-scale *in-situ* migration experiment with ^{14}C -labelled natural organic matter colloids in Boom Clay.

What does 25 years of experience teach us?

Norbert Maes, Joan Govaerts, Delphine Durce,
Marc Aertsens, Dorien Verhaegen (SCK CEN)

Stéphane Brassinnes (ONDRAF/NIRAS)



Context

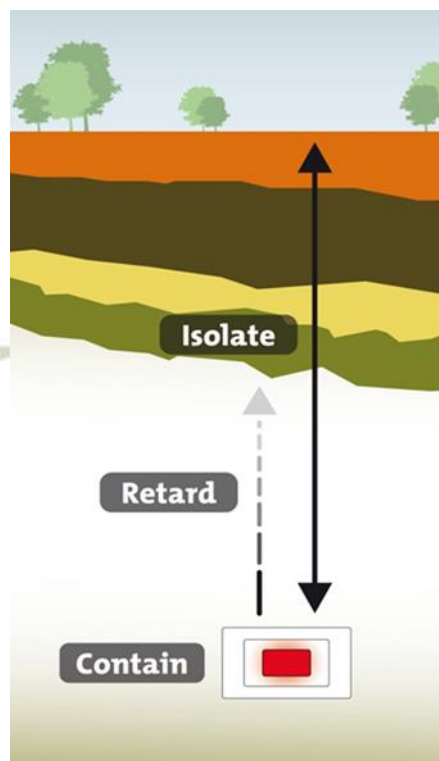
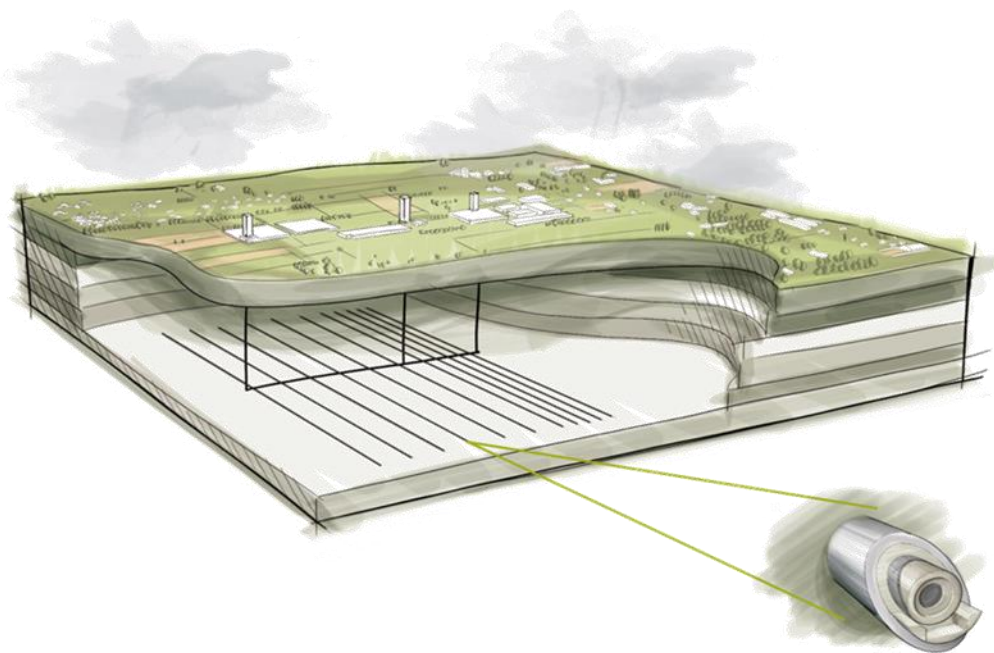
Studying transport of OM (lab + in-situ)

Modelling in-situ experiment 2010 & 2022

Conclusions

Context – Geological Disposal research in Belgium

Focus on clays as host formations → Boom Clay



- Boom Clay has been intensively studied since the 50's
- Boom Clay is taken as a reference host formation to study feasibility of Geological Disposal in poorly indurated clays and to develop a generic SFC approach
- 22/11/2022 Royal Decree: Decision in principle for Deep Disposal as solution for long-lived L/I/HLW (B&C)

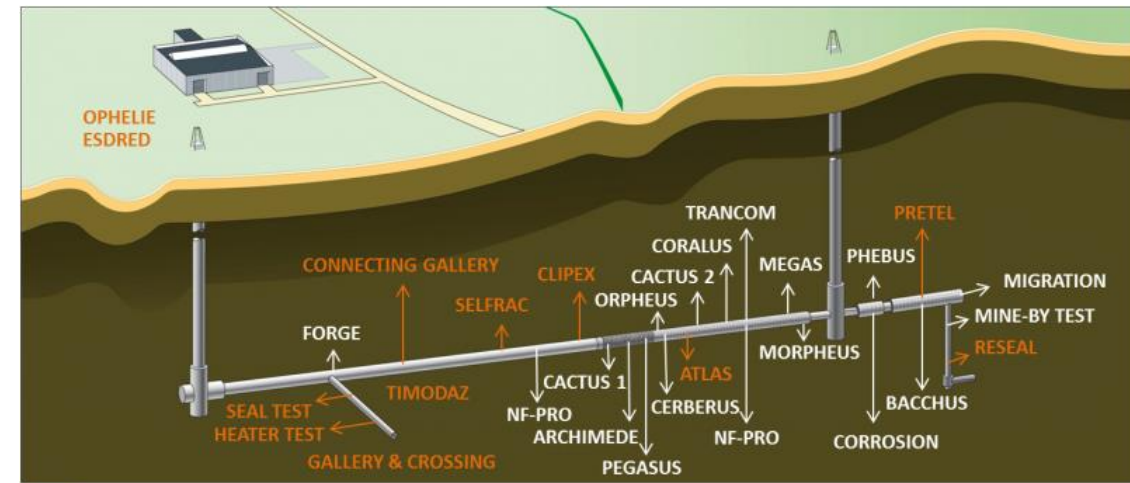
Context – Boom Clay

- Boom Clay (BC) - Compositions

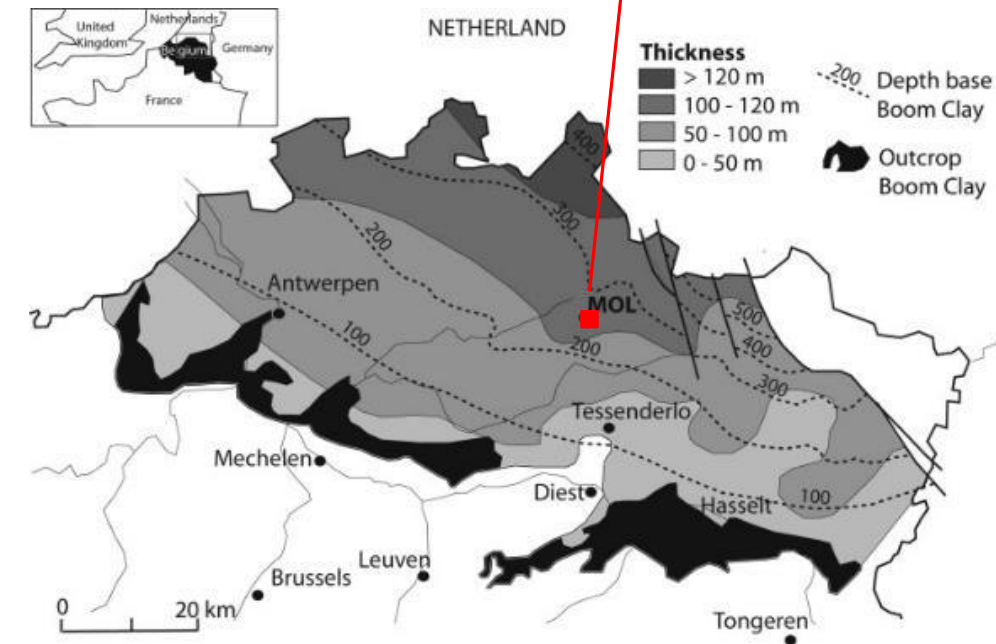
Clay minerals	30-60 wt%
Quartz	15-60 wt%
Feldspars	1-10 wt%
Carbonates	1-5 wt%
Pyrite	1-5 wt%
Organic carbon	1-5 wt%

- Pore water composition @ Mol
 - 0,014 mol/l NaHCO_3 -type water
 - on average 115 mgC/L Dissolved Organic Matter (DOM)**
 - Increasing salinity towards NE
- HADES URL since 1980 (-225 m)

(De Craen et al., 2004; Durce et al., 2015)

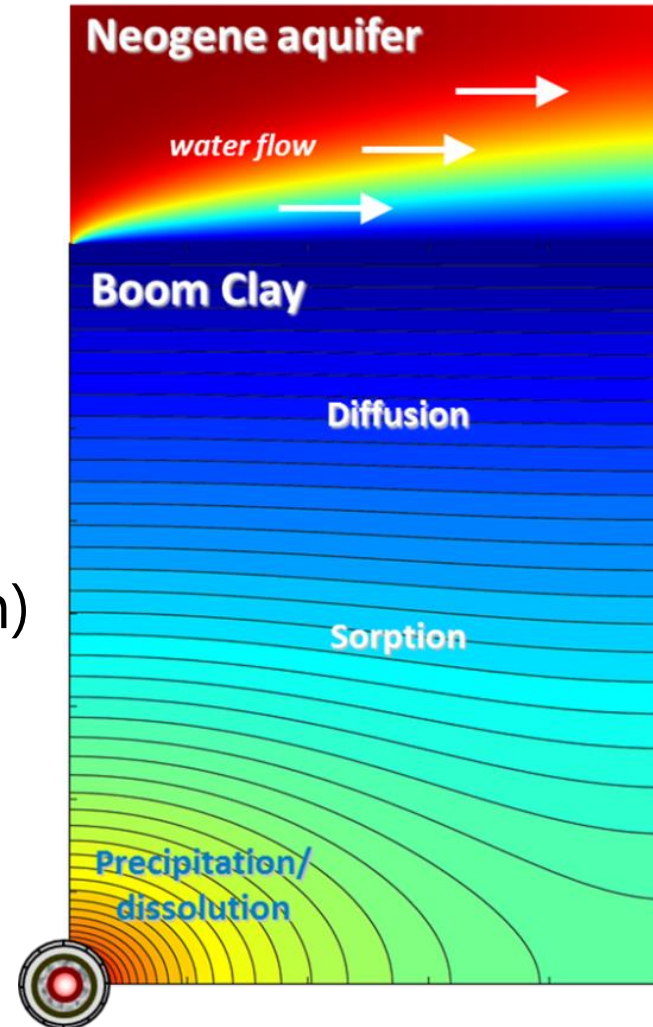


gecoördineerd door ESV EURIDICE



Context - Building a knowledge basis for the processes related to radionuclide transport

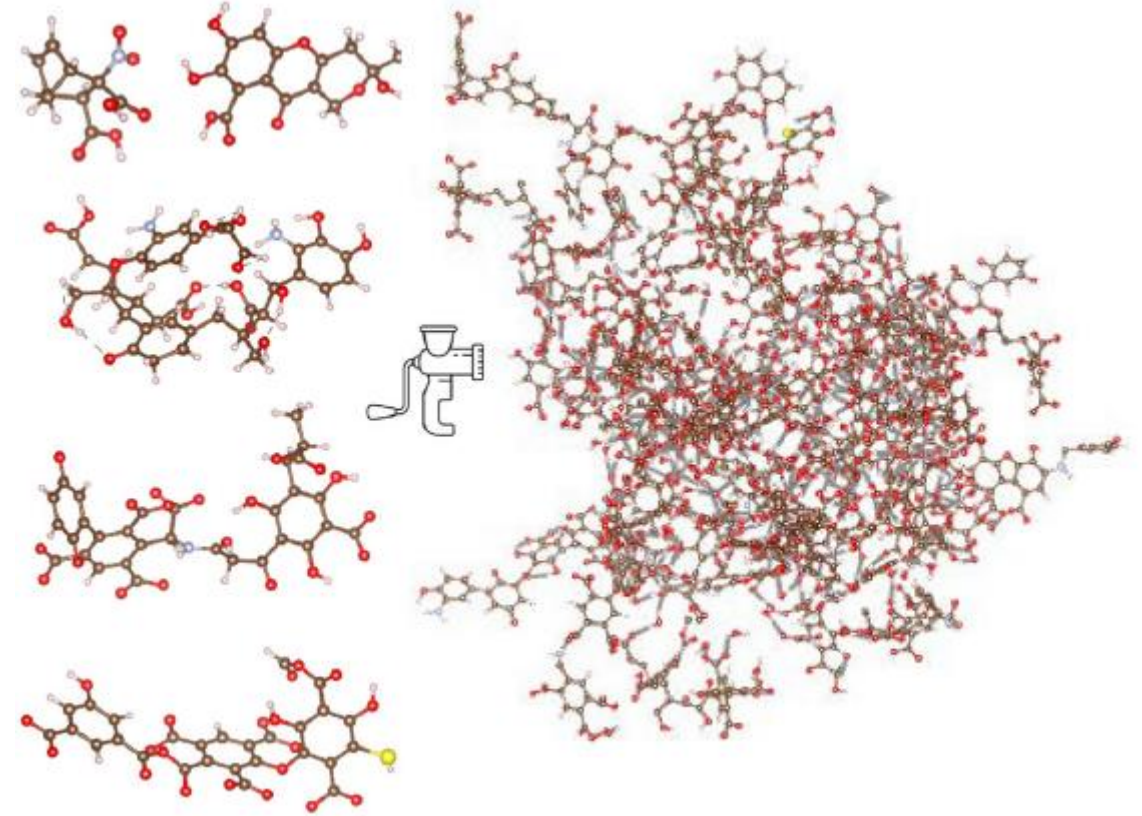
- Geochemistry
 - “Chemical environment”
 - Radionuclide (RN) speciation
- Transport related processes
 - RN sorption processes
 - RN transport by diffusion (and advection)
- Perturbations impacting RN migration
 - Physical
 - Chemical



Why do we emphasise on dissolved organic matter?

DOM in Boom Clay are mainly “humic substances” (plant degradation products)

- *Macromolecules* (and aggregates of macromolecules)
- *Polyfunctional* (different types of surface functional groups)
- *Heterogeneous* in terms of mass/size distribution, elemental composition, functionality,...
- *Can not be described in a thermodynamic way* like another type of complexing ligand (CO_3^{2-} ,...)



(Gerzabek et al. 2021, DOI: 10.1002/jpln.202100360)

Impact of Dissolved Organic Matter (DOM) on Radionuclide (RN) transport

- The majority of safety relevant RN (TM, FP, La, Ac) interact with DOM

→ *Tends to mobilise the radionuclides through:*

- Increase in solubility by complex/colloid formation
- Decrease in sorption on clay surfaces compared to "free RN"

But

- these RN-DOM complexes/colloids tend to dissociate
- these large molecules are limited in their movement through small pores ("filtration"-effect)

→ *Need to understand the processes*

→ Experiments are designed (lab & In-situ) to study the transport behaviour of OM and RN-OM which enables us to describe (to certain extent) the processes



Context

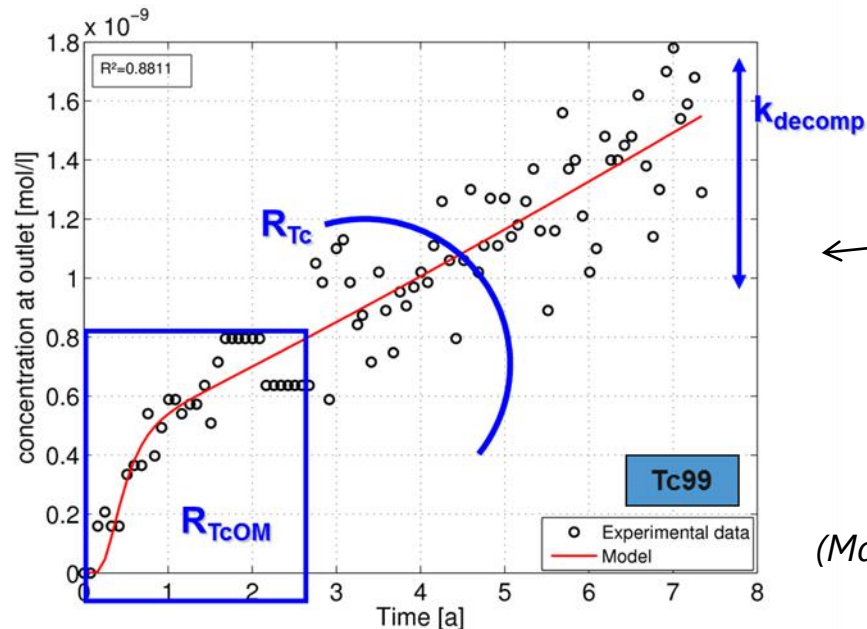
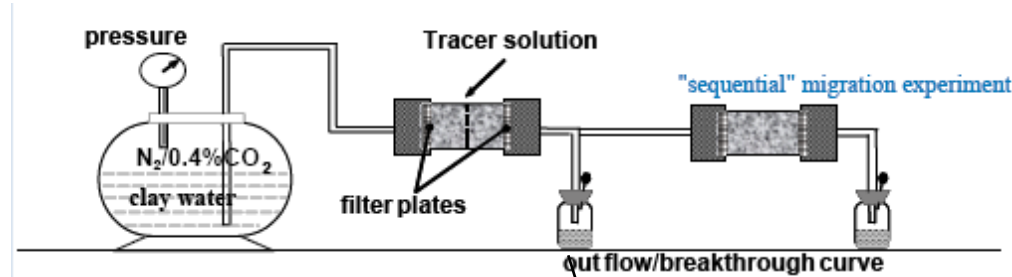
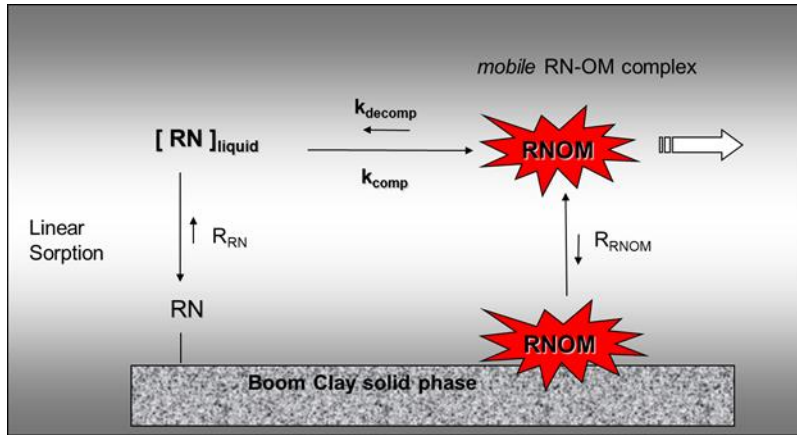
Studying transport of OM (lab + in-situ)

Modelling in-situ experiment 2010 & 2022

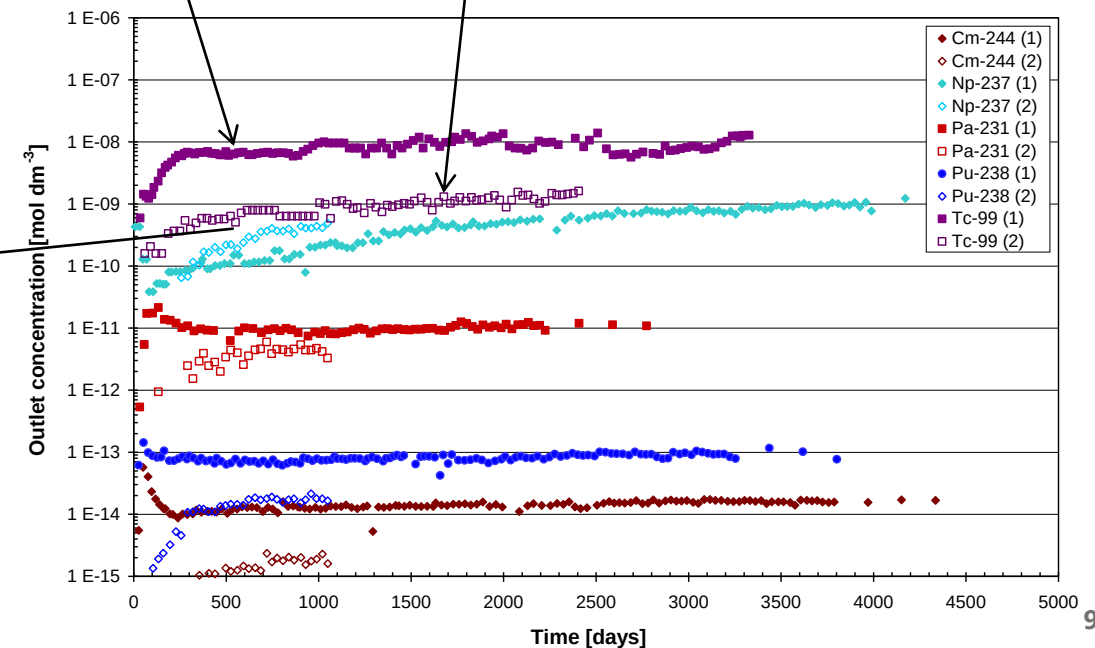
Conclusions

Studying NOM linked RN transport @ lab scale – retention and Long Term stability of the RN-OM complex

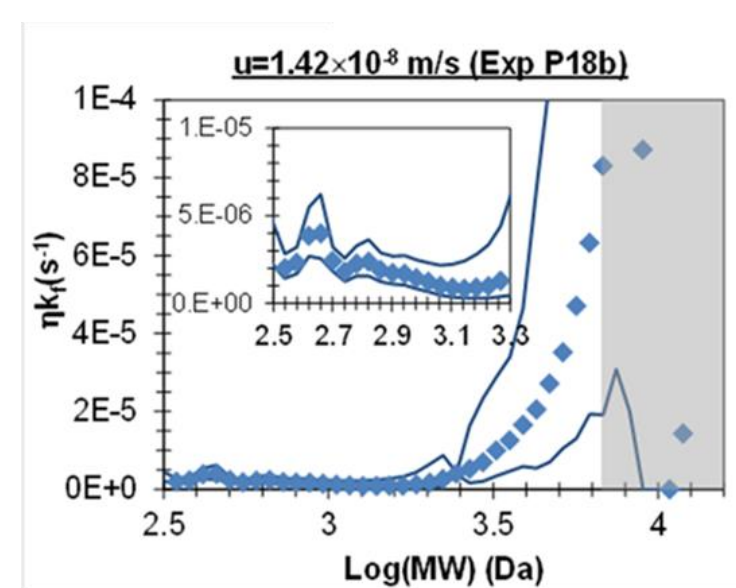
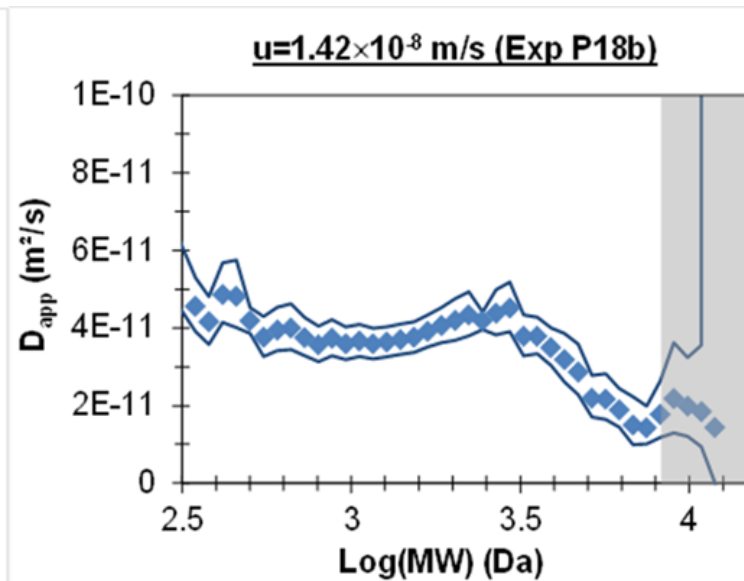
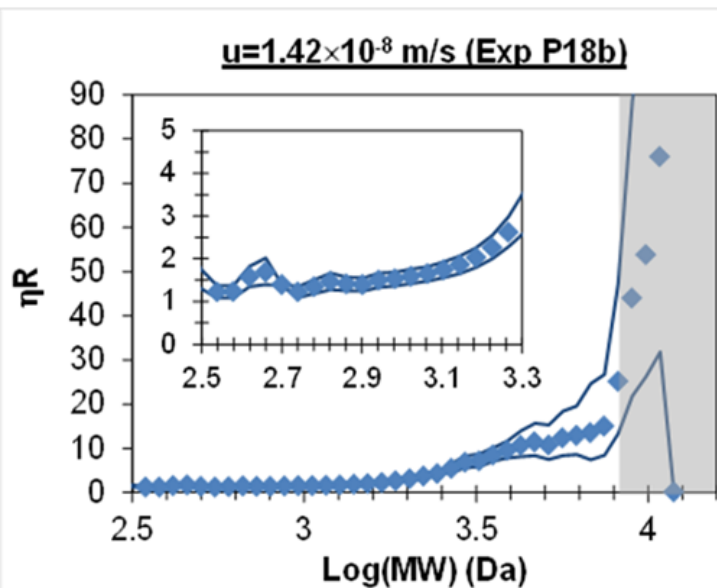
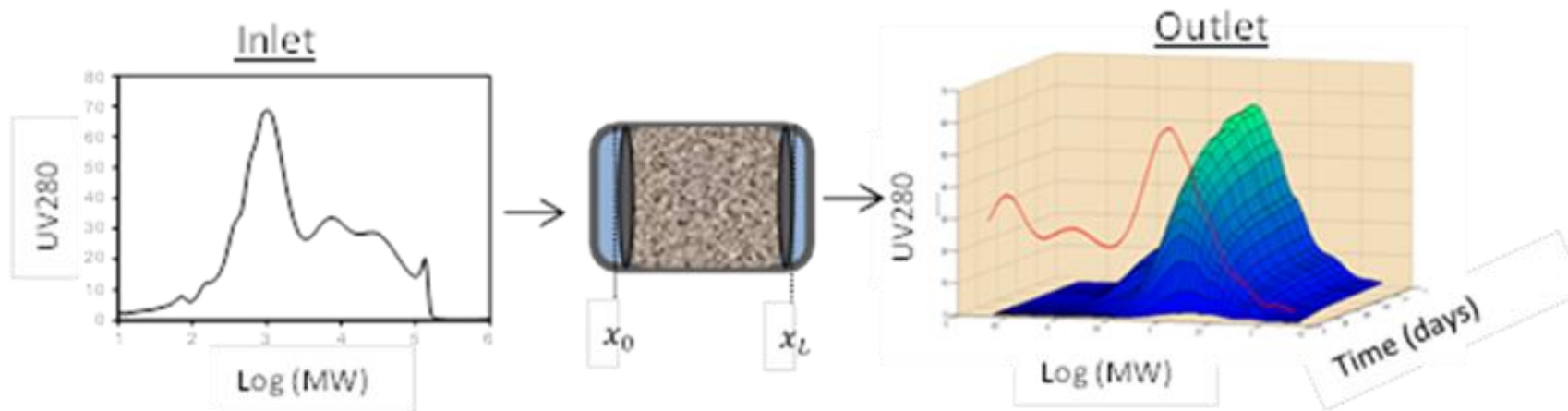
- conceptual model and parametrisation (D_{RN-OM} , D_{RN} , R_{RN-OM} , R_{RN} , $LOGK$, K_{DECOMP})



(Maes et al., 2011)

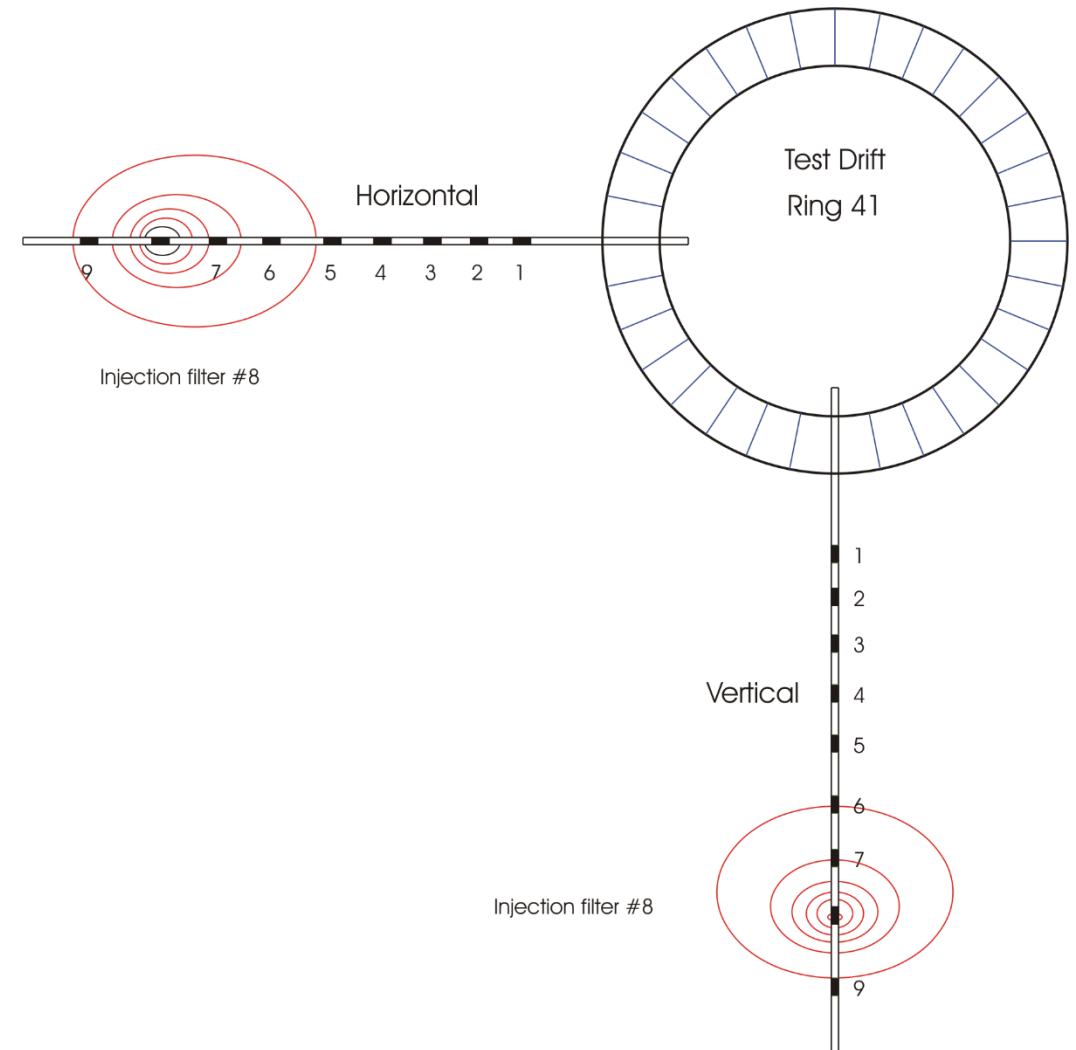


Studying NOM diffusion @ lab scale – effect of size



NOM migration @ large scale – enlarge confidence by “validation” of models at large spatio-temporal scale

- The TRANCOM TDR41H/V piezometer tests in HADES
 - 2 piezometers: vertical / horizontal
- Initiated in 1997 as part of the N/O co-funded EC TRANCOM-CLAY project (Dierckx et al., 2000)
- Circulation of ^{14}C -labelled Boom Clay Dissolved Organic Matter in filter 8
- Sampling at neighbouring filters
 - 7 (at 0,35m)
 - 6 (at 0,85 m)





Context

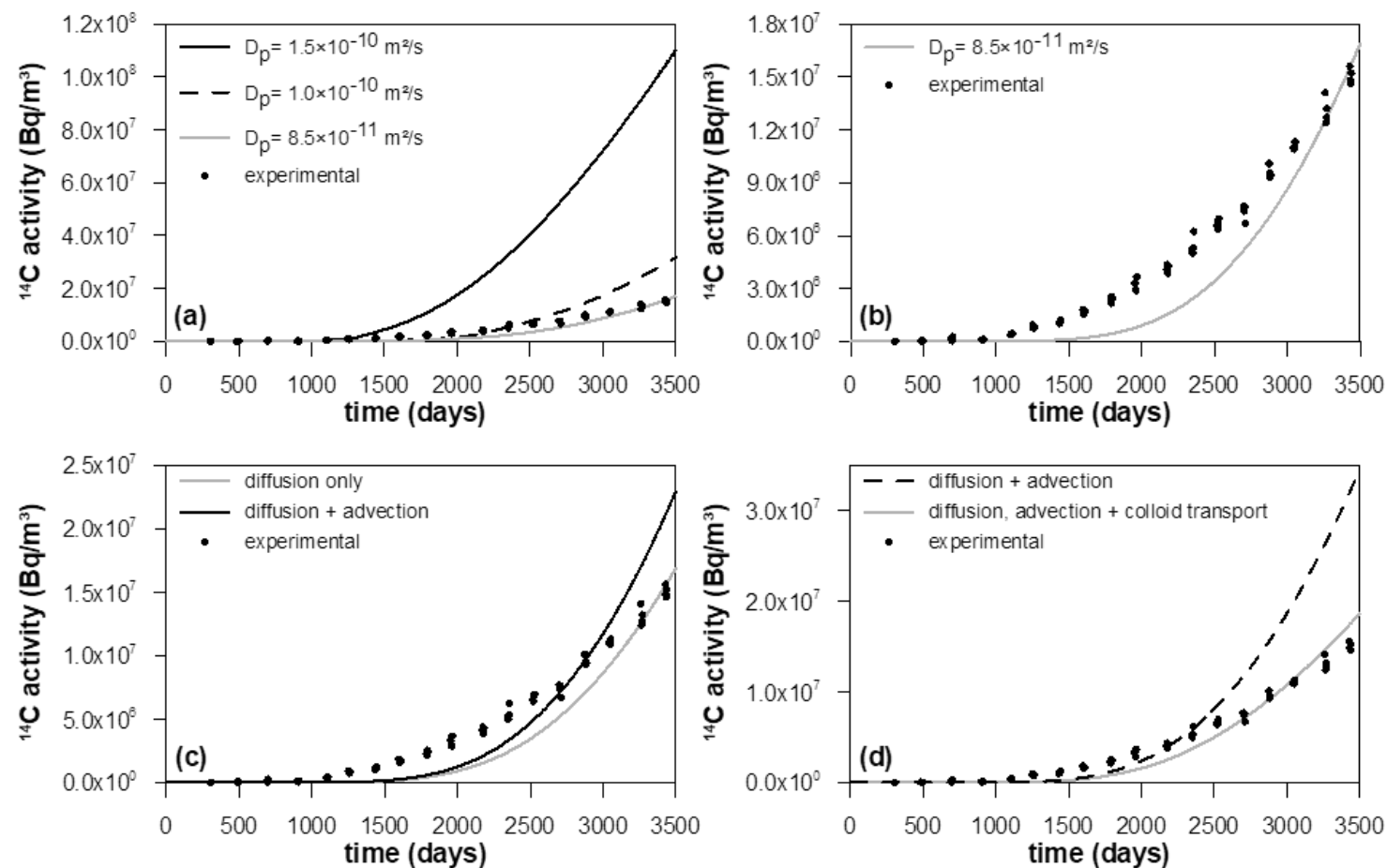
Studying transport of OM (lab + in-situ)

Modelling in-situ experiment 2010 & 2022

Conclusions

First modelling in 2010 – 13 years of migration

- Modelling with HYDRUS-2D of BT at closest filters (F7 - 35 cm)
- Diffusion-advection model
 - One species, single value for D_p and nR
 - Hydraulic gradient measured between filter 7&8
 - Filtration term added - attachment/detachment kinetics
- Model optimised for Vertical piezometer, then tested for Horizontal piezometer (anisotropy for K_h and D_p)



. (Martens et al., 2010)

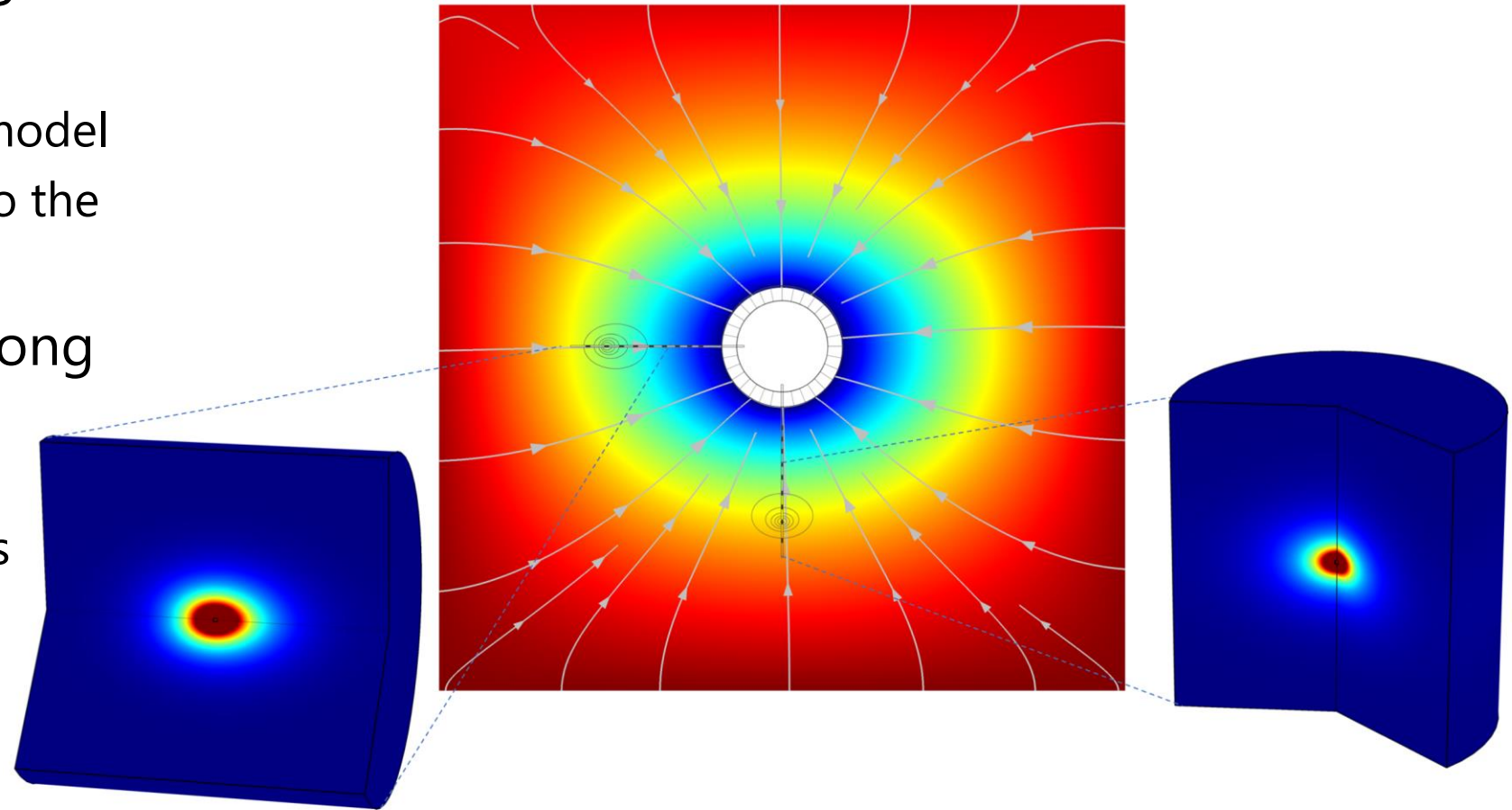
Update 2022 (25 years): 12 more years of data

(Govaerts et al., 2022)

- Objective: to keep the model as simple as possible by stepwise building the transport model and adding complexity (parameters and processes) at each step.
- Each step adds a process which is well supported in the field of (colloid) transport modelling, building on basic and well known mathematical and physical concepts.
- Improvements wrt 2010 modelling
 - Upgrade hydraulic model
 - Include measurements at 2 filters located at 85 cm (F6V/F6H) which were still below DL in 2010
 - Simultaneously fit 4 sampling filters (two of each piezometer) using an automated procedure

Model setup (2022)

- Drainage towards HADES
URL gallery
 - 2D cartesian hydraulic model
 - Velocities are mapped to the transport models
- Transport of ^{14}C -NOM along piezometers
 - two separate 2D axisymmetric models

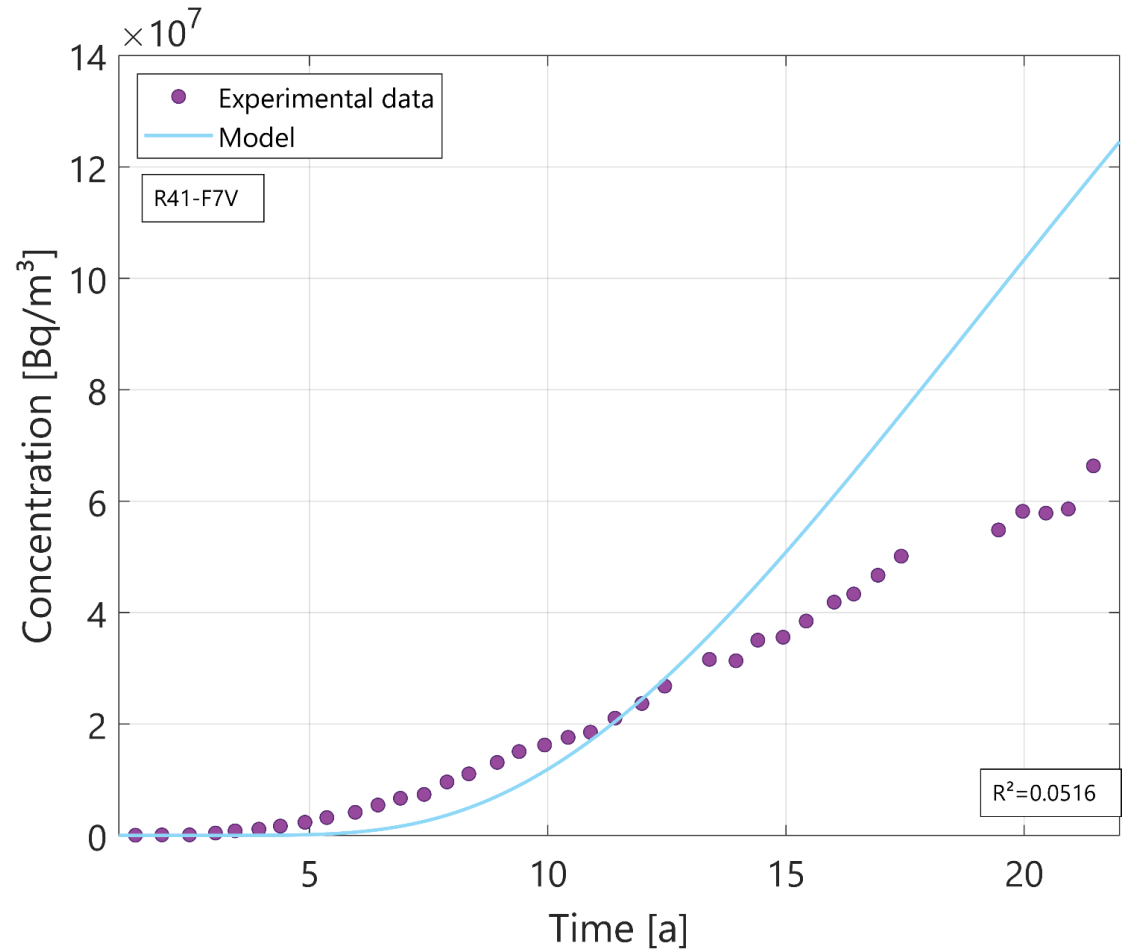
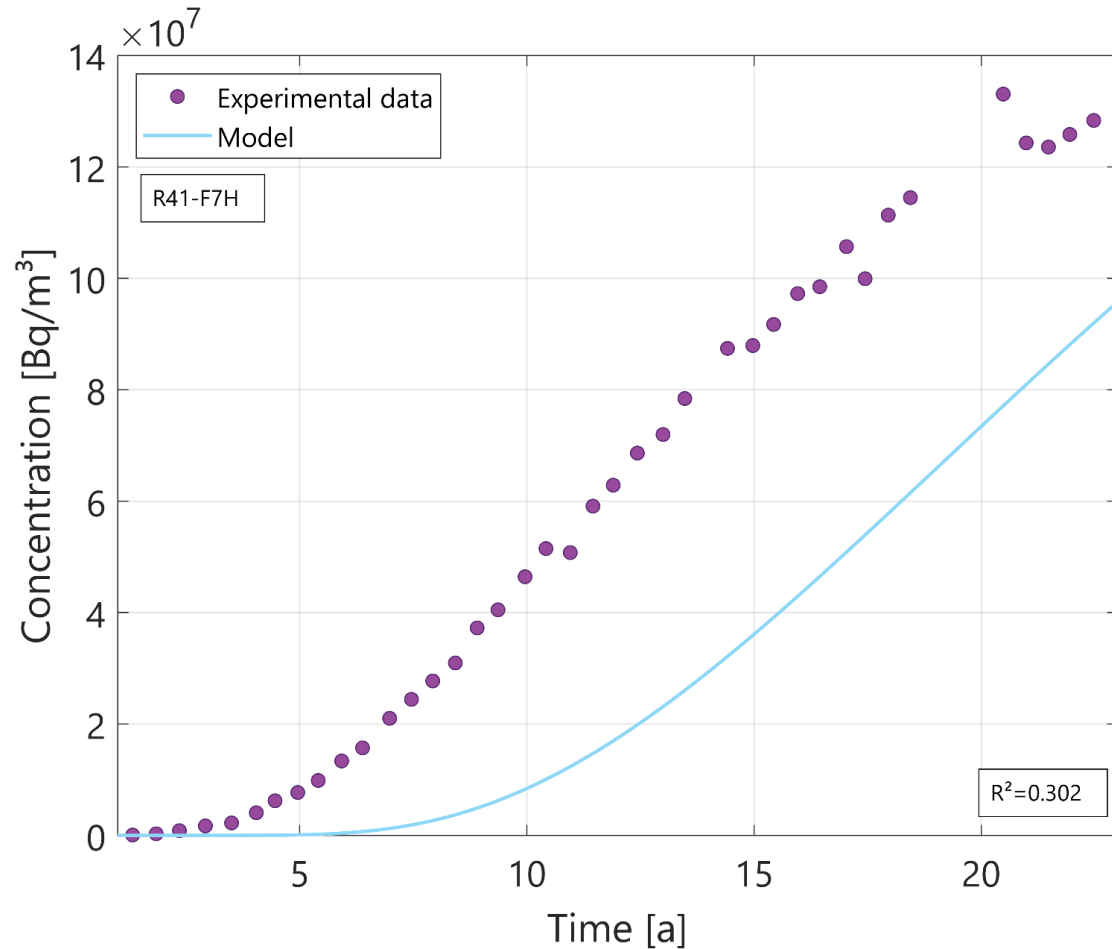


Stepwise model building

Step	Model Name	Description	#fit parameters	Improvement Fit Quality (relative to previous step)
0	Model_Di	Isotropic diffusion using one species, no advection	1	-
1	Model_D1	Anisotropic diffusion using one species, no advection	2	16.5%
2	Model_D2	Anisotropic diffusion using two species, no advection	6	85.2%
3	Model_AD2	+ advection	8	0.4%
4	Model_AD2_cap 2	+ different capacity factors used in the vertical and horizontal piezometer setup	8	3.7%
5	Model_AD2_cap 2_imm	+ immobilization of the slow species (kinetics)	9	34.5%
6	Model_AD2_cap 2_imm2	+ different immobilization kinetics for the vertical and horizontal piezometer	10	8.7%

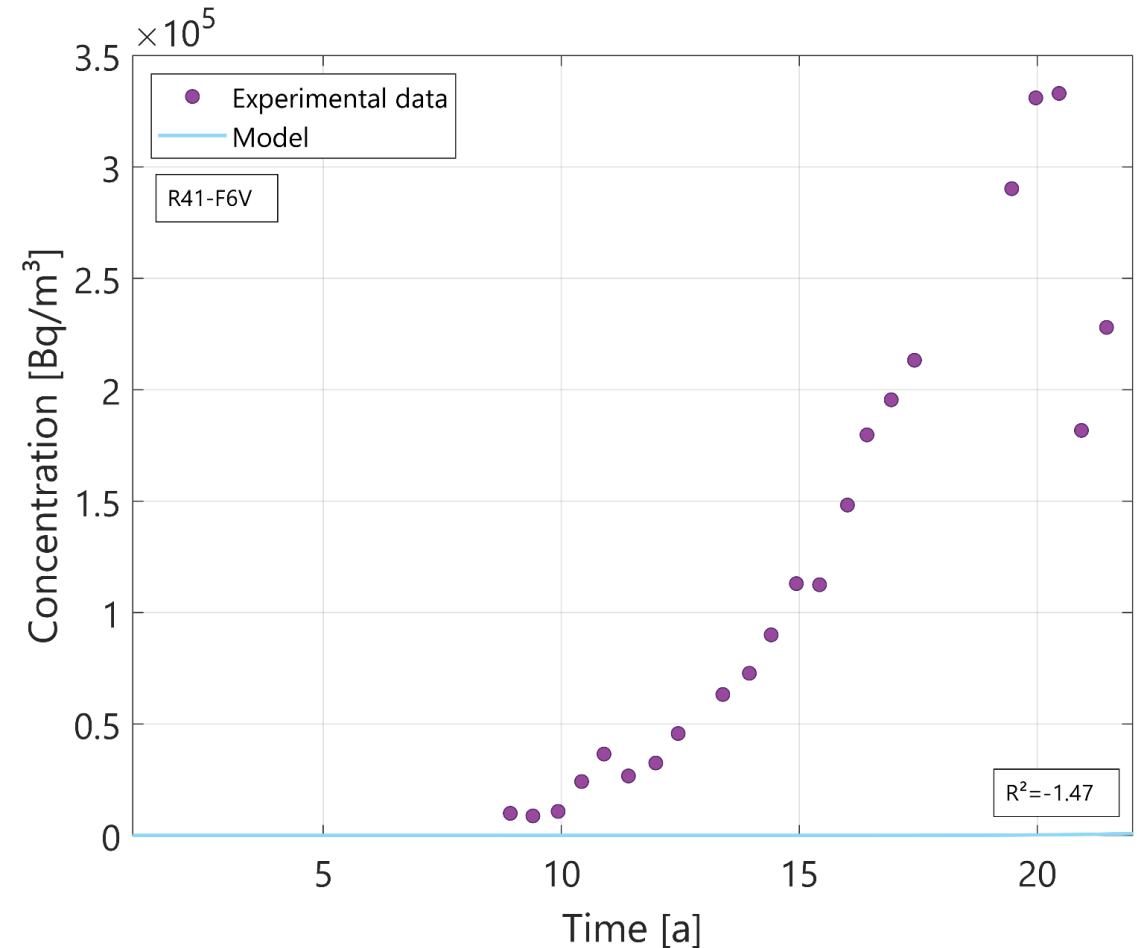
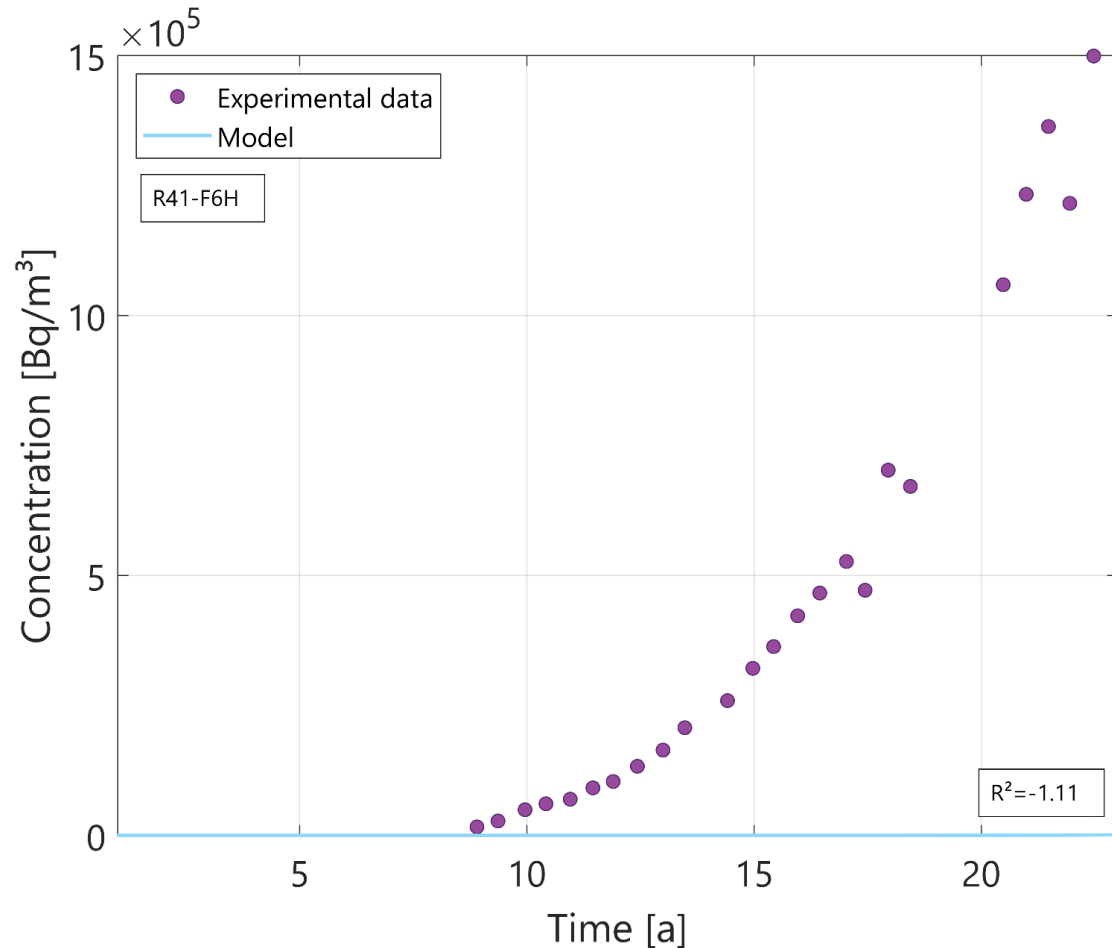
Step 0: Model_Di – Filters at 35 cm (F7)

- Isotropic diffusion using one species, no advection



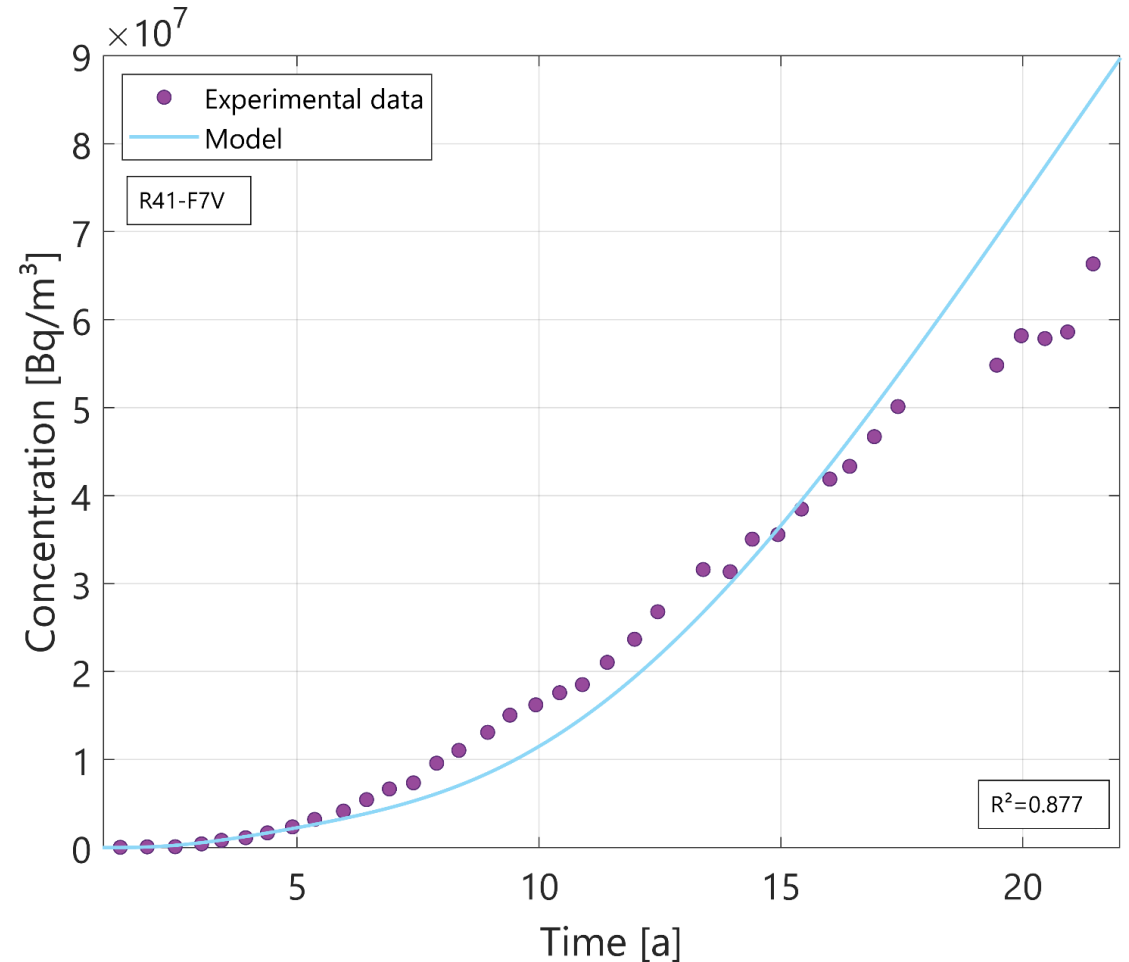
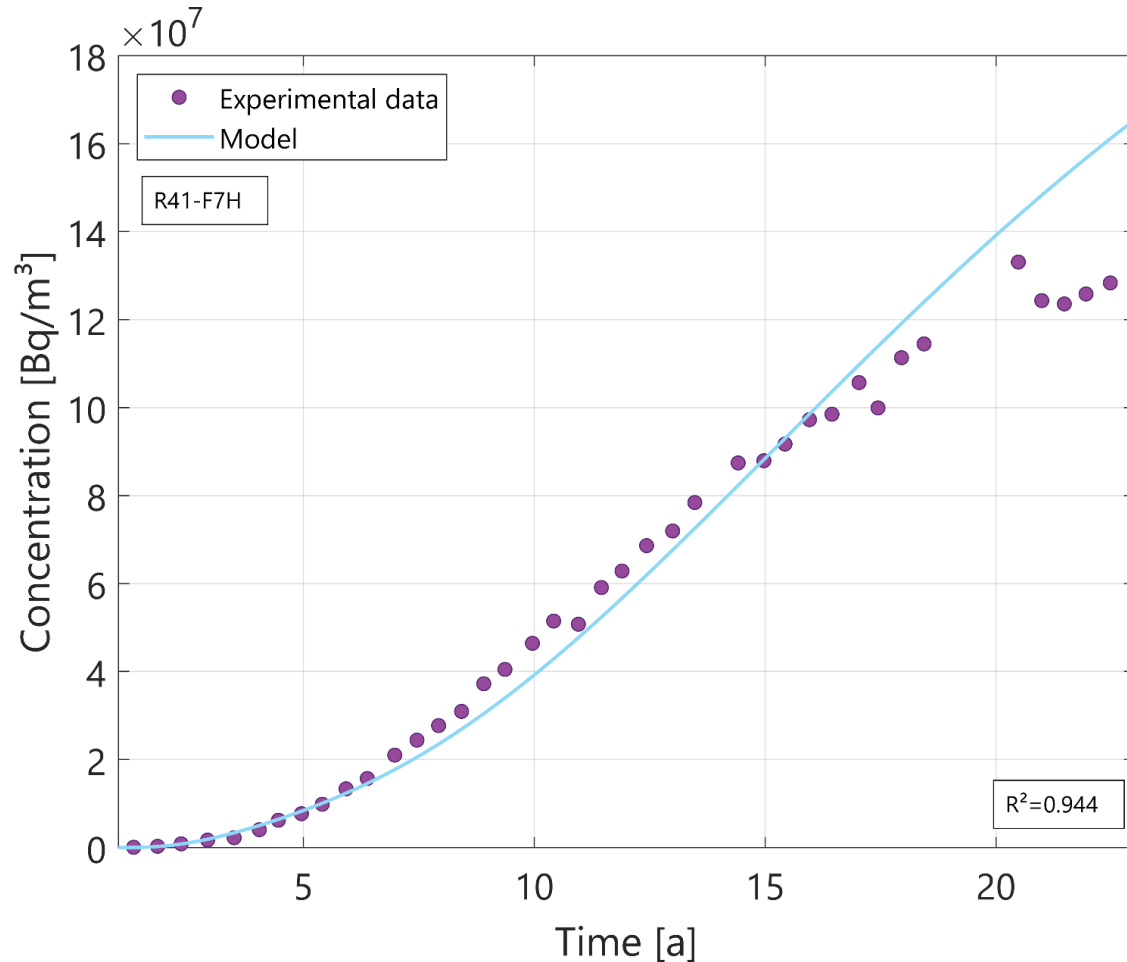
Step 0: Model_Di – Filters at 85 cm (F6)

- Isotropic diffusion using one species, no advection



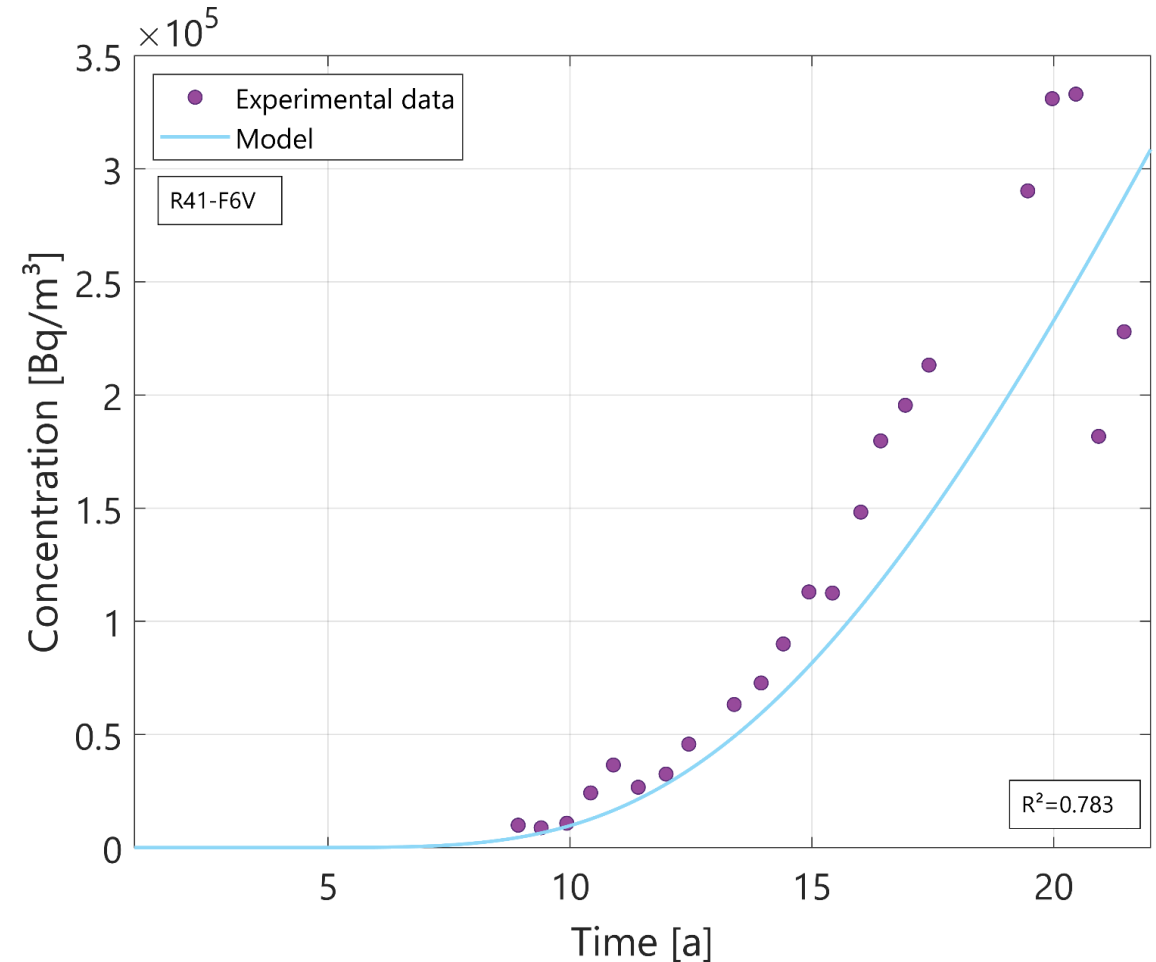
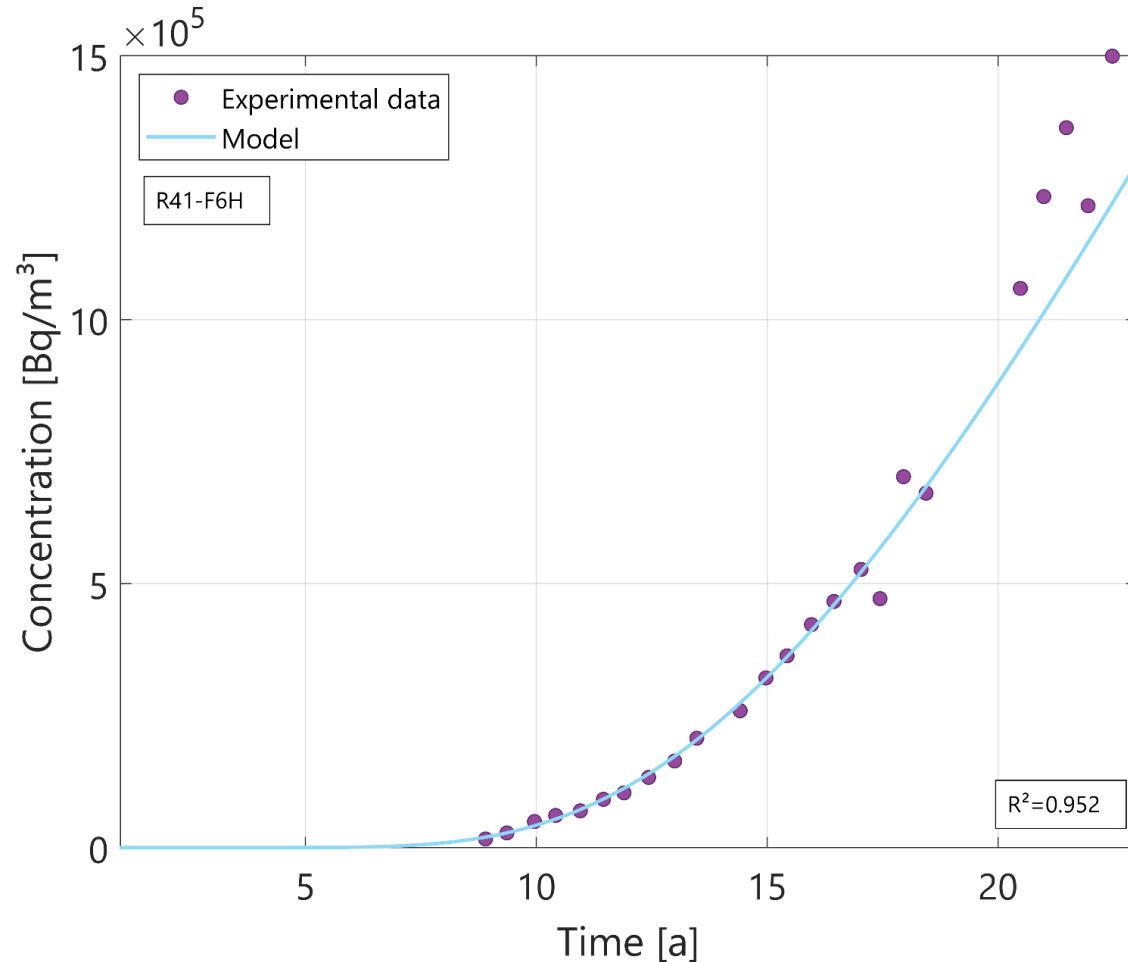
Step 2: Model_D2 – Filters at 35 cm (F7)

- Anisotropic diffusion using two OM species (one 'fast' & one 'slow')
- 85% improvement in fit quality (wrt. previous step Model_D1)



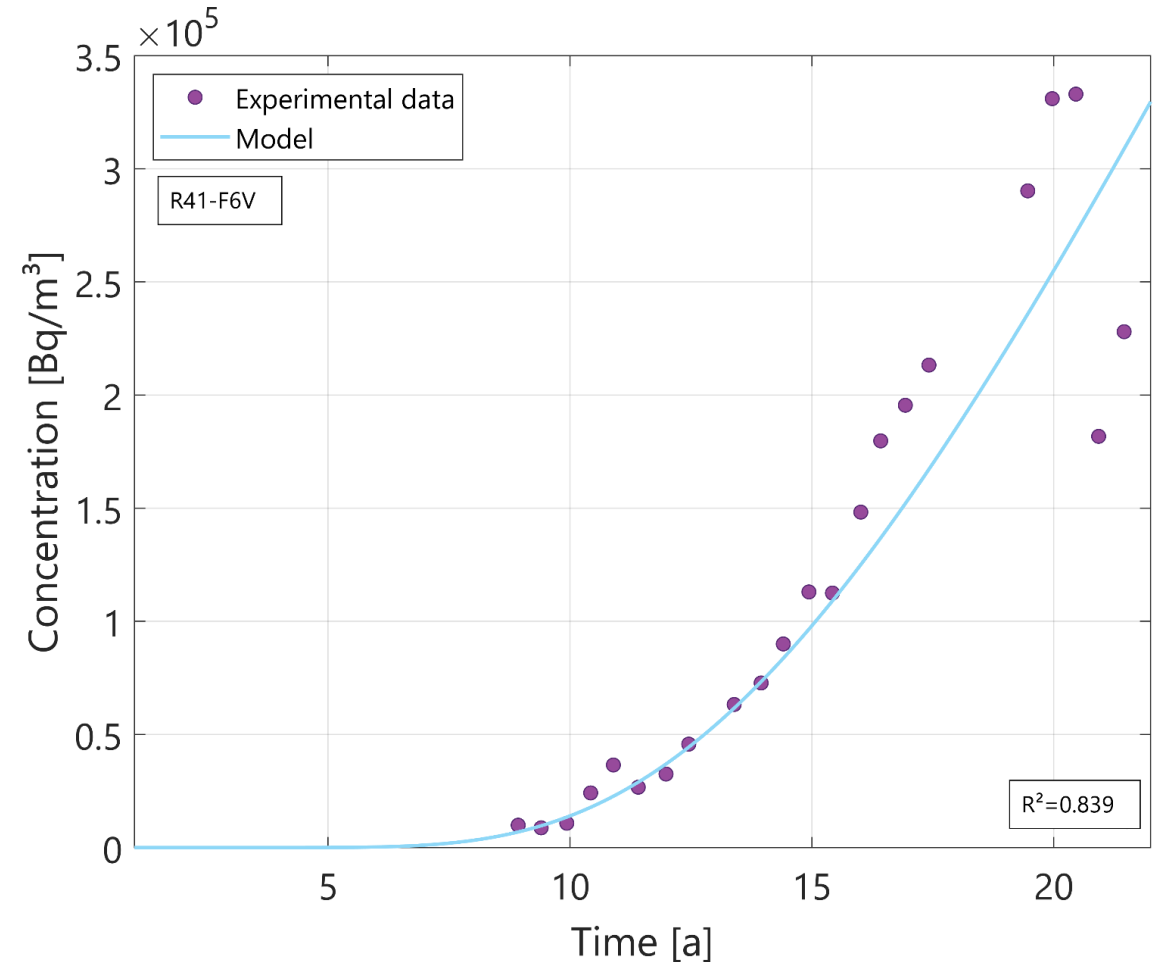
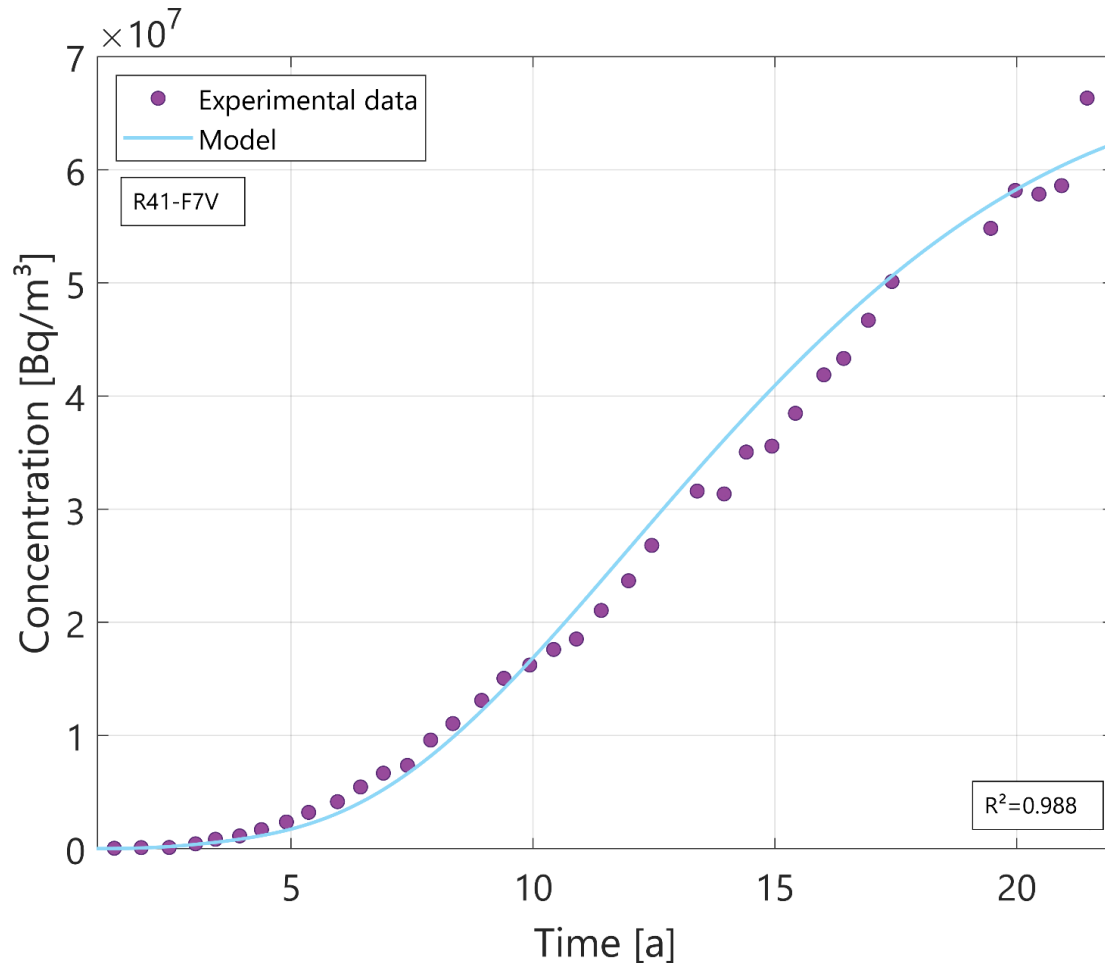
Step 2: Model_D2 – Filters at 85 cm (F6)

- Anisotropic diffusion using two species (one 'fast' & one 'slow')
- 85% improvement in fit quality (wrt. previous step model_D1)



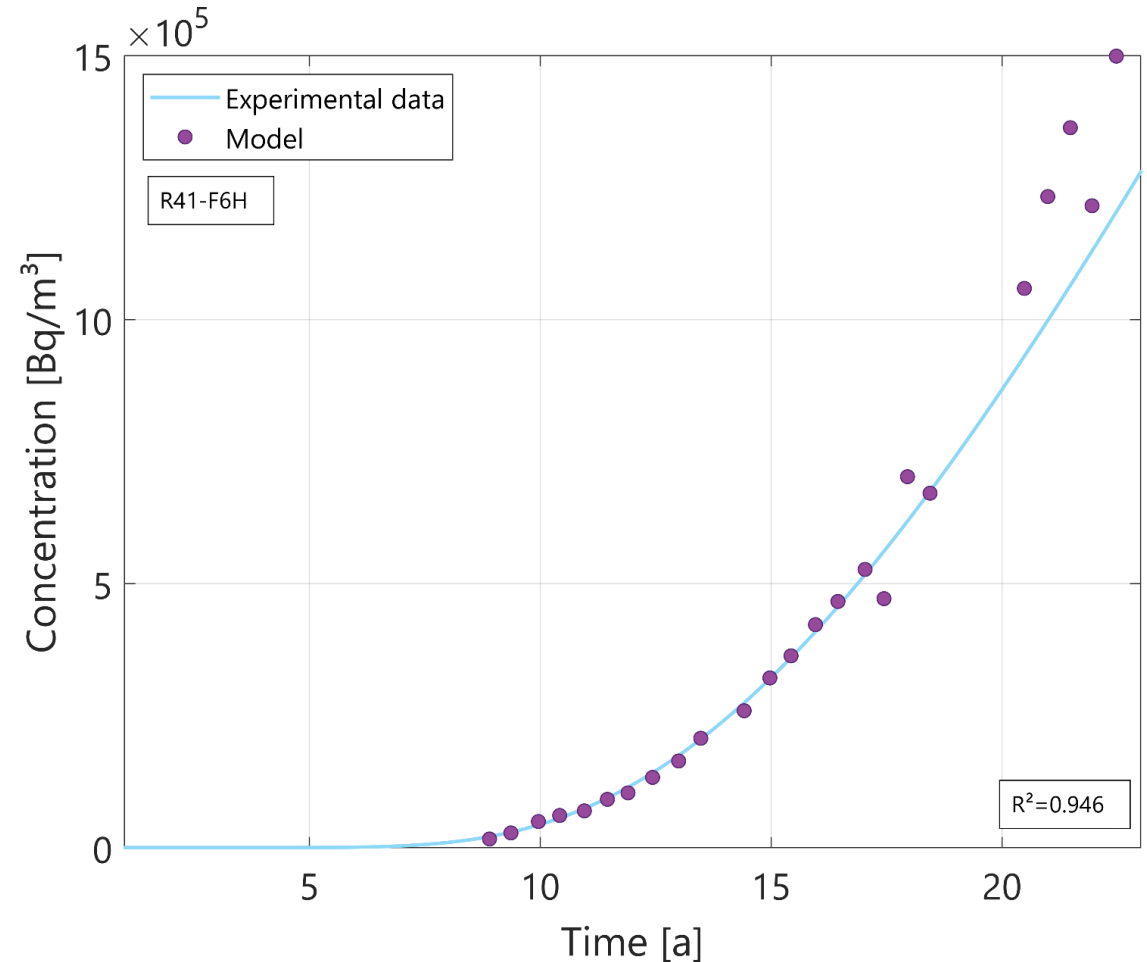
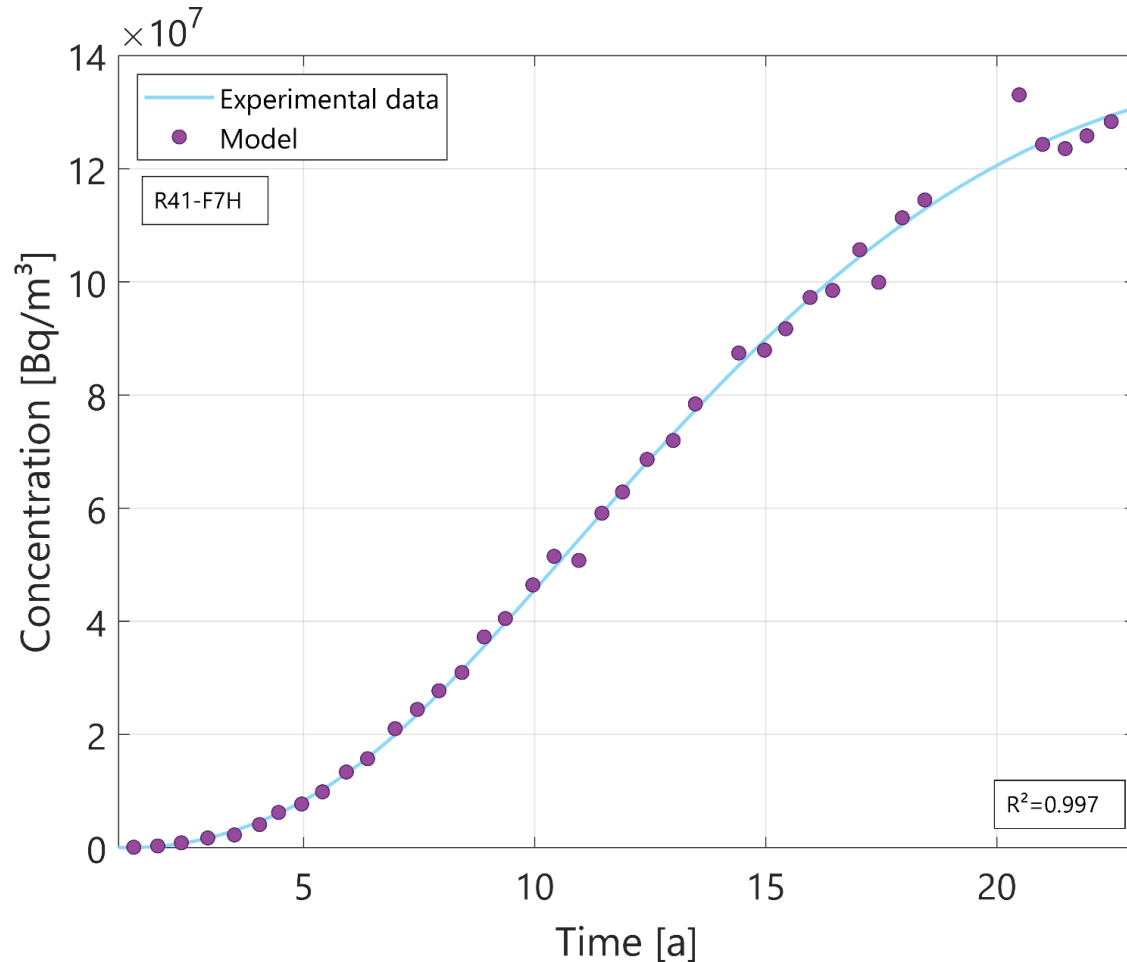
Last steps: Model_AD2_cap2_imm (vertical piezo)

- Immobilisation (irreversible kinetics) of slow compound – one kinetic constant
- ~40% improvement



Last steps: Model_AD2_cap2_imm2 (horizontal piezo)

- Immobilisation (irreversible kinetics) of slow compound – 2 kinetic constants
- ~40% improvement



Key findings - update modelling 2022

- Unique set of long term and meter-scale data of NOM transport
- Accurately reproducible by moderately complex model without overfitting
 - Two species (2 size fractions)
 - Diffusion(/advection)
 - Anisotropy Boom Clay
 - Reversible retardation (physical and/or chemical)
 - Irreversible attenuation of slower/larger species
- Diffusion is the dominant process
 - Best fit values are well within the range obtained with lab scale experiments
- Upscaling for PA:
 - vertical diffusion coefficient
 - Irreversibility on experimental time scale vs. PA-timescale → caution !



Context

Studying transport of OM (lab + in-situ)

Modelling in-situ experiment 2010 & 2022

Conclusions

Conclusions

- Understanding the impact of DOM on RN transport is needed as part of the knowledge base in support of a safety case
- Requires extensive studies at different scales (both x and t)
- In-situ large scale (& Long term) diffusion tests are an important part in the upscaling process
 - Unique test cases for validation of models and parameters
 - Demonstration of our understanding of underlying processes

This study was carried out in the framework of a public-public cooperation between SCK CEN and ONDRAF/NIRAS.

This cooperation concerns scientific research and technical-scientific support for the safe management of radioactive waste on short-, middle- and long-term, including training and education on this subject.

With this partnership, ONDRAF/NIRAS and SCK CEN want to strengthen and consolidate their collaboration within strategic research domains of the Belgian national programme for radioactive waste management. In this way, a robust framework is created with a view on increased efficiency and long-term continuity of knowledge and expertise within the Belgian programme.



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Belgian Nuclear Research Centre
Studiecentrum voor Kernenergie
Centre d'Etude de l'Energie Nucléaire

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Stichting van Openbaar Nut
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Gas transport in Boom Clay: the role of the HADES URL in process understanding

E. Jacobs & L. Yu (SCK CEN), G.J. Chen (ESV EURIDICE),
S. Levasseur (ONDRAF/NIRAS)

Geological disposal of radioactive waste

→ **Multi-barrier system =**

Natural geological barrier

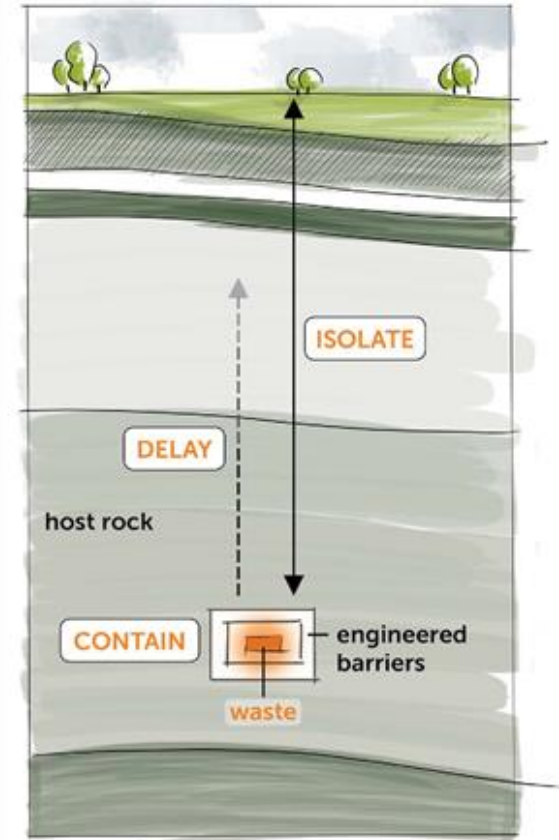
+ Engineered Barrier System (EBS)

Role: **contain and isolate the waste from the biosphere** by

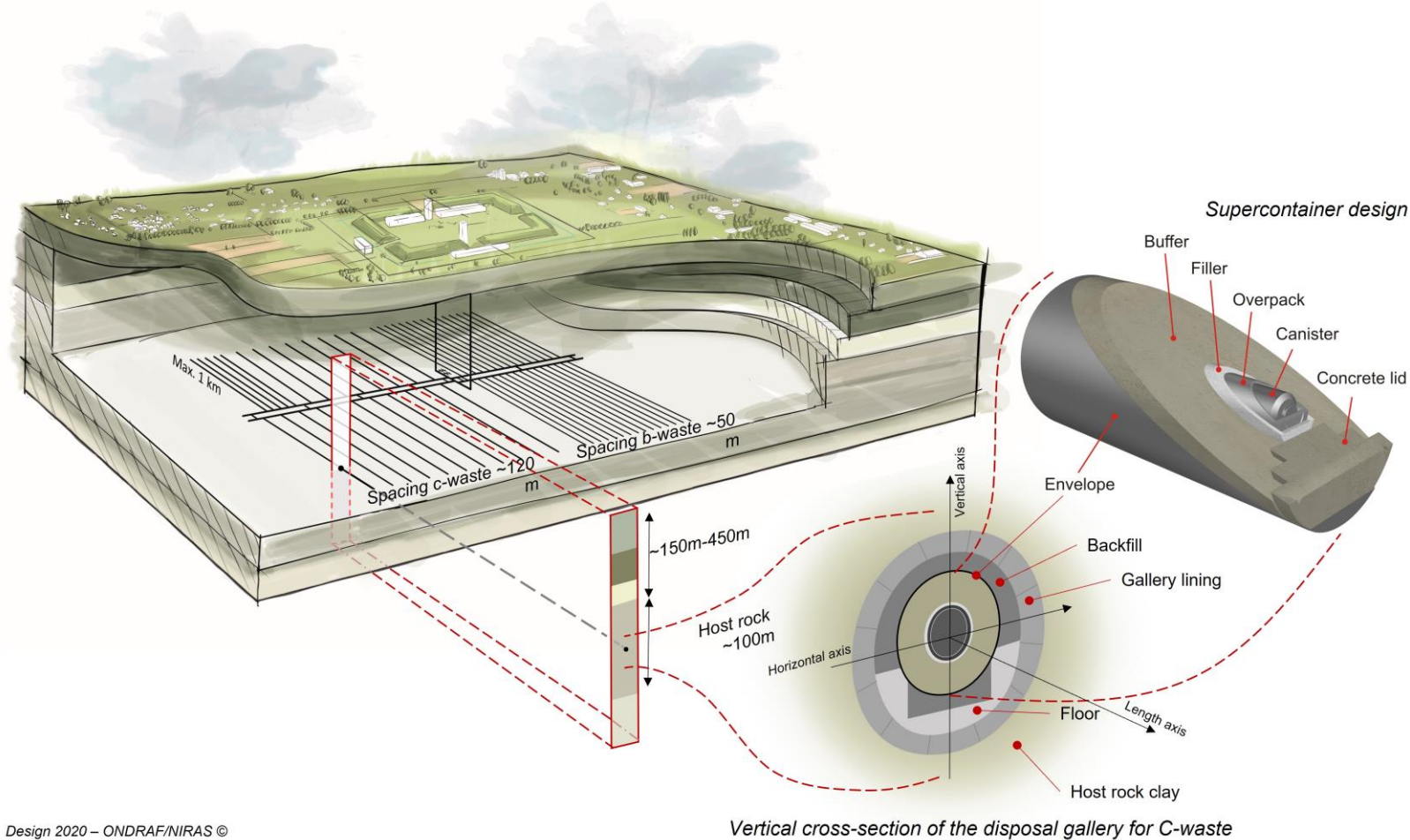
- ♦ providing stable environment to the EBS
- ♦ confining radionuclides

→ **Clays exhibit excellent properties for the containment and confinement of radionuclides** (low permeability, sorption capacity, swelling/self-sealing capacity ...)

→ Boom Clay one of the potential geological layer in Belgium



Gas in geological disposal: significant volume



Design 2020 – ONDRAF/NIRAS ©

- several times the excavated volume
- generated over a long time period
- can be pressurized
- can be evacuated in different ways

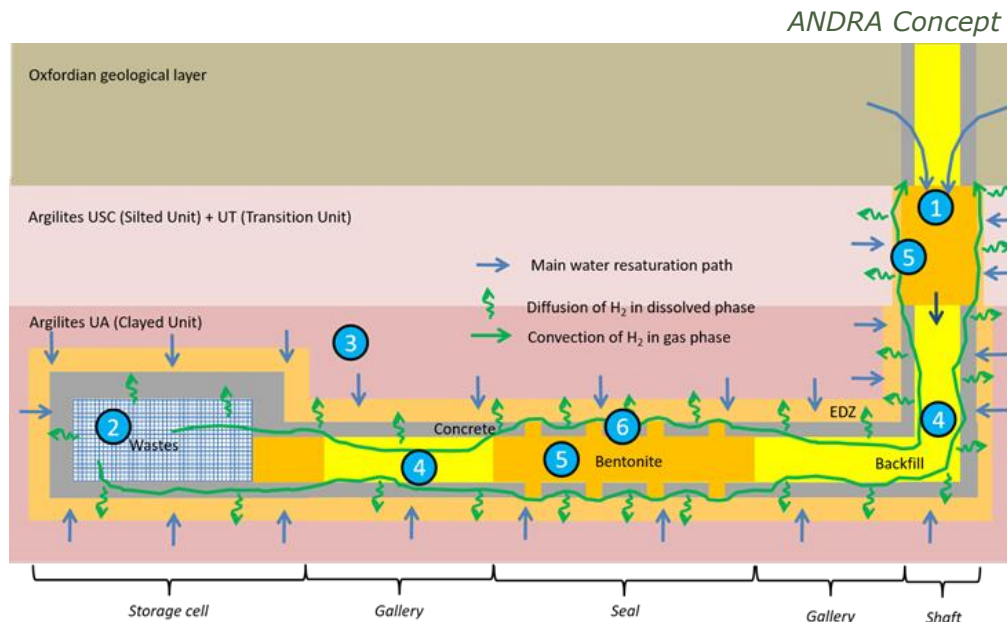
GAS = Mostly hydrogen, produced by anaerobic corrosion of steel and reactive metals present in the waste, in their packaging and in the EBS + Degradation of organic waste & radiolysis

Gas issue

How to ensure that perturbations induced by gas production and evacuation will not alter the clay properties for the containment and confinement of contaminants and not affect the functioning of the multi-barrier system?

→ Most concepts around the world adapt the **general architecture of the repository** to have

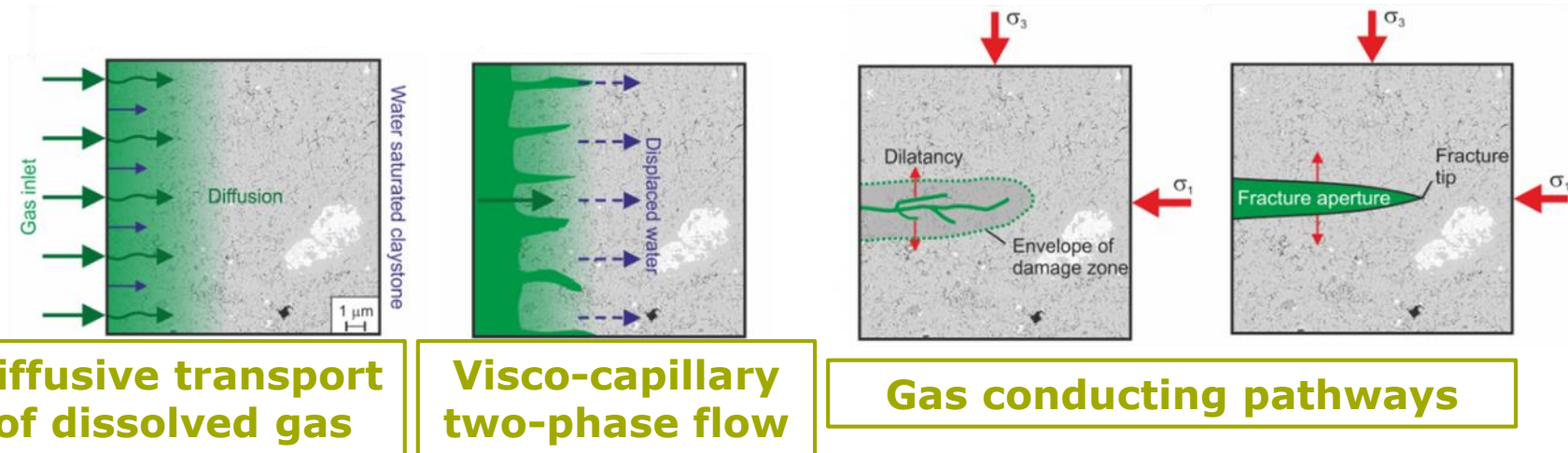
- Sufficient expansion volume available
- Continuous release and evacuation



Need to determine the capacity for gas evacuation out of the disposal system

- Research conducted by ONDRAF/NIRAS and SCK CEN (and partners), with the support of HADES URL, on the characterization of gas transport modes in Boom Clay

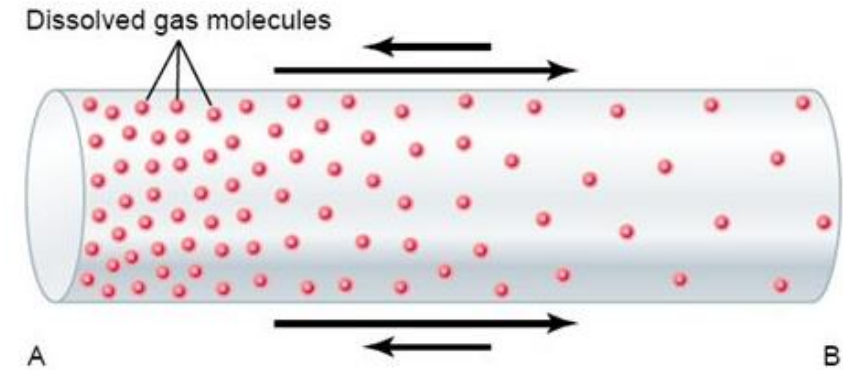
Gas transport modes in clays



(adapted from Marshall et al. 2005 and Cuss et al. 2014)

Diffusive transport of dissolved gas

- **Dissolved gas transported by molecular diffusion in pore water**
 - ♦ Gradient of concentration as driving force
 - ♦ Advection of dissolved gas is negligible
- **Limited capacity of diffusive transport**
 - Limited solubility of gas in pore water
 - Molecular diffusion slow process



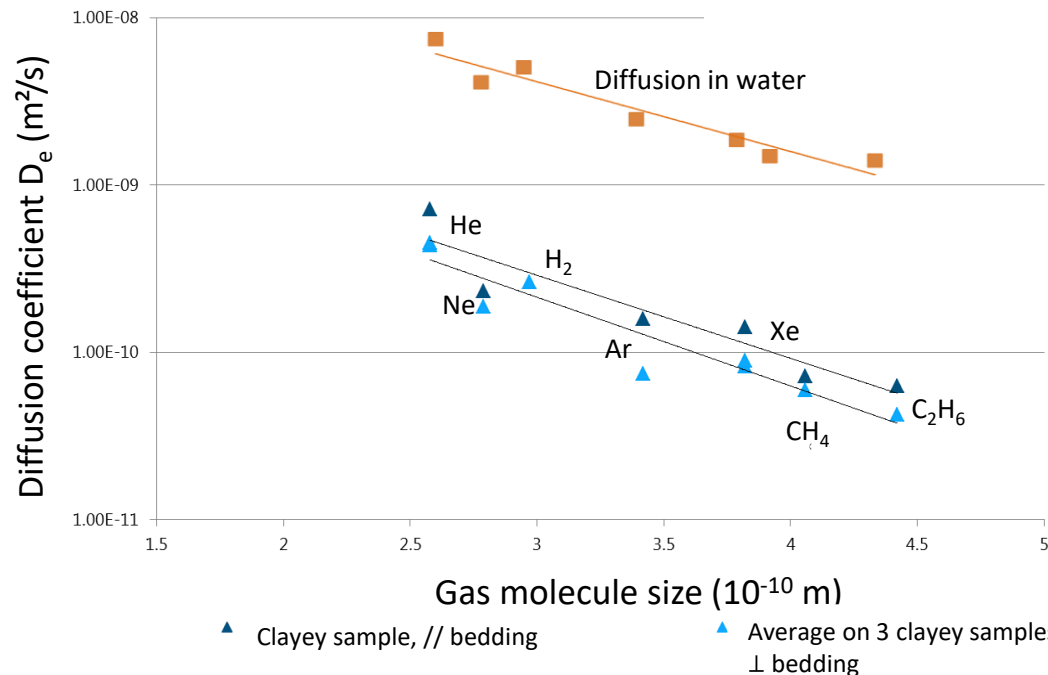
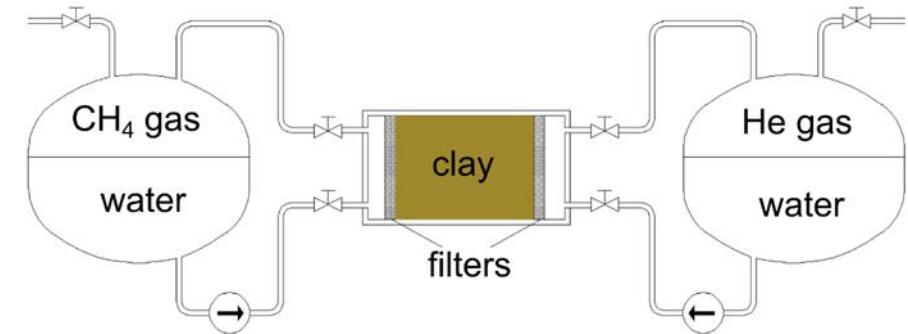
→ What is the capacity of gas evacuation by diffusion?

→ Need to estimate the diffusion coefficient of dissolved gas in saturated Boom Clay

Estimation of diffusion coefficients of dissolved gases in clays through 'double-through-diffusion' tests (SCK CEN)

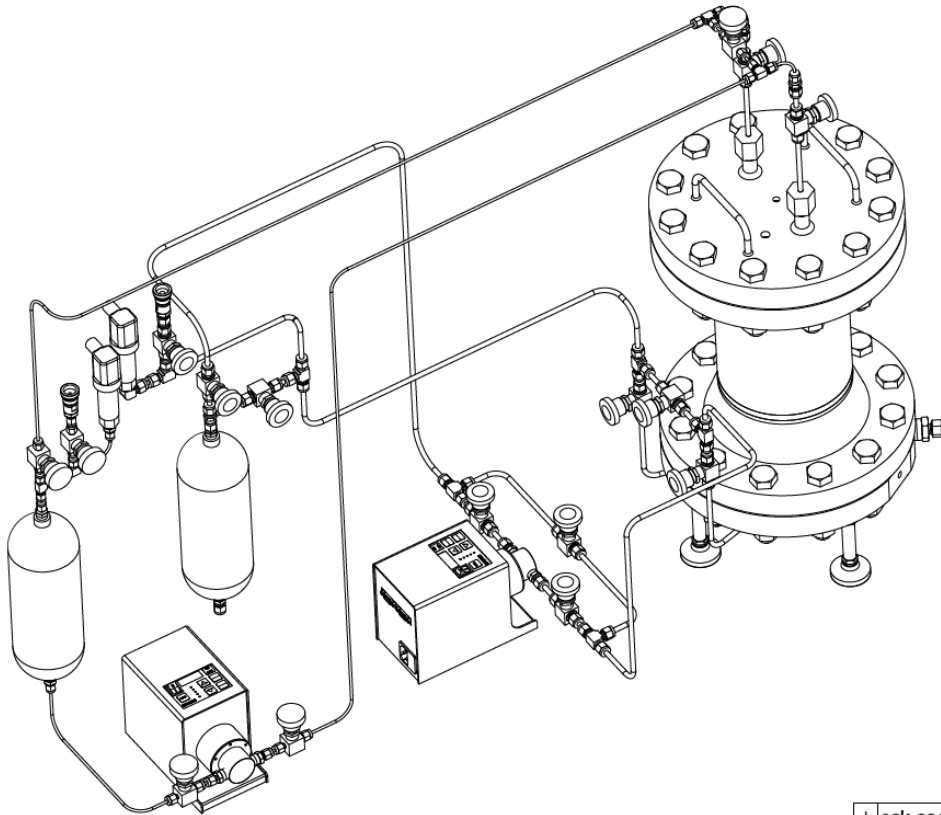
Monitoring of evolving concentrations of dissolved gases within each vessel

→ **Accurate estimates of apparent diffusion coefficients for various dissolved gases**
(Jacops et al. 2013, 2015, 2016)

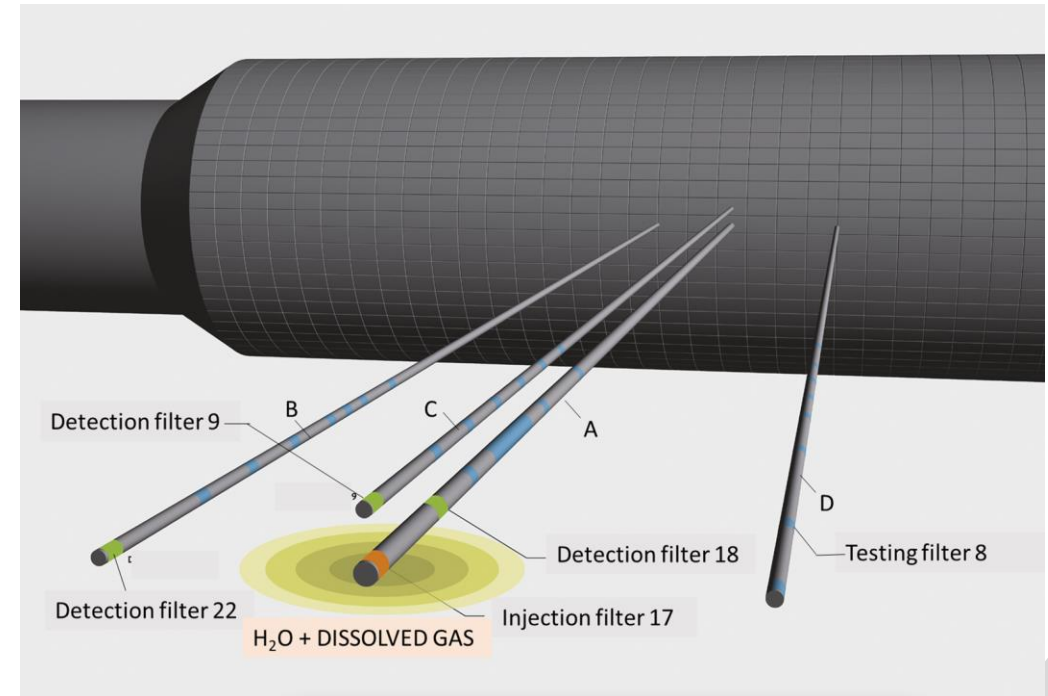


What are the effects of mechanical conditions and of scale?

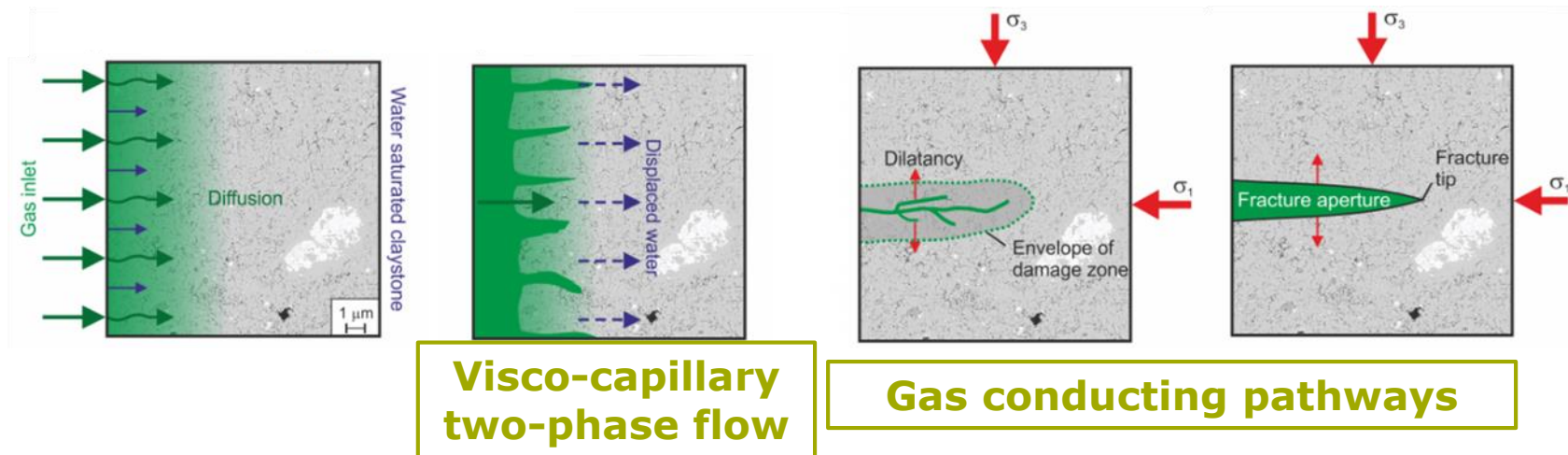
Lab diffusion test under confining pressure – *on-going*



In situ diffusion test in HADES URL (NEMESIS experiment) – *on-going*



What if gas evacuation by diffusion is not sufficient?



(adapted from Marschall et al. 2005 and Cuss et al. 2014)

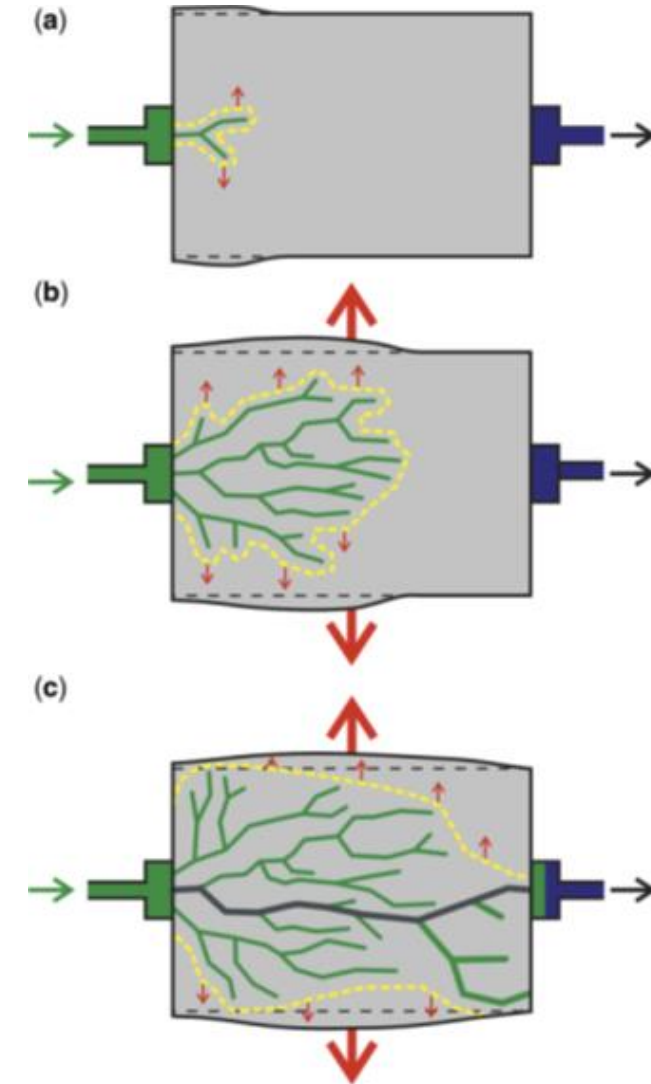
Visco-capillary two-phase flow vs Gas conducting pathways

- When gas production rate exceeds the capacity of evacuation by diffusion of dissolved gas, **formation of free gas phase in the porous media**
 - ♦ enter the porous media when capillary effects are overcome
 - ♦ flow controlled by gas permeability and water retention curve

→ **Two-phase flow model**
= generalized form of Darcy's law with relative permeabilities and capillary pressures between phases

- If the gas pressure keeps increasing, deformation of the pore space and **formation of discrete pathways controlled by the mechanical behaviour of the porous media**

→ **Gas conducting pathways**
= gas transport properties function of deformation

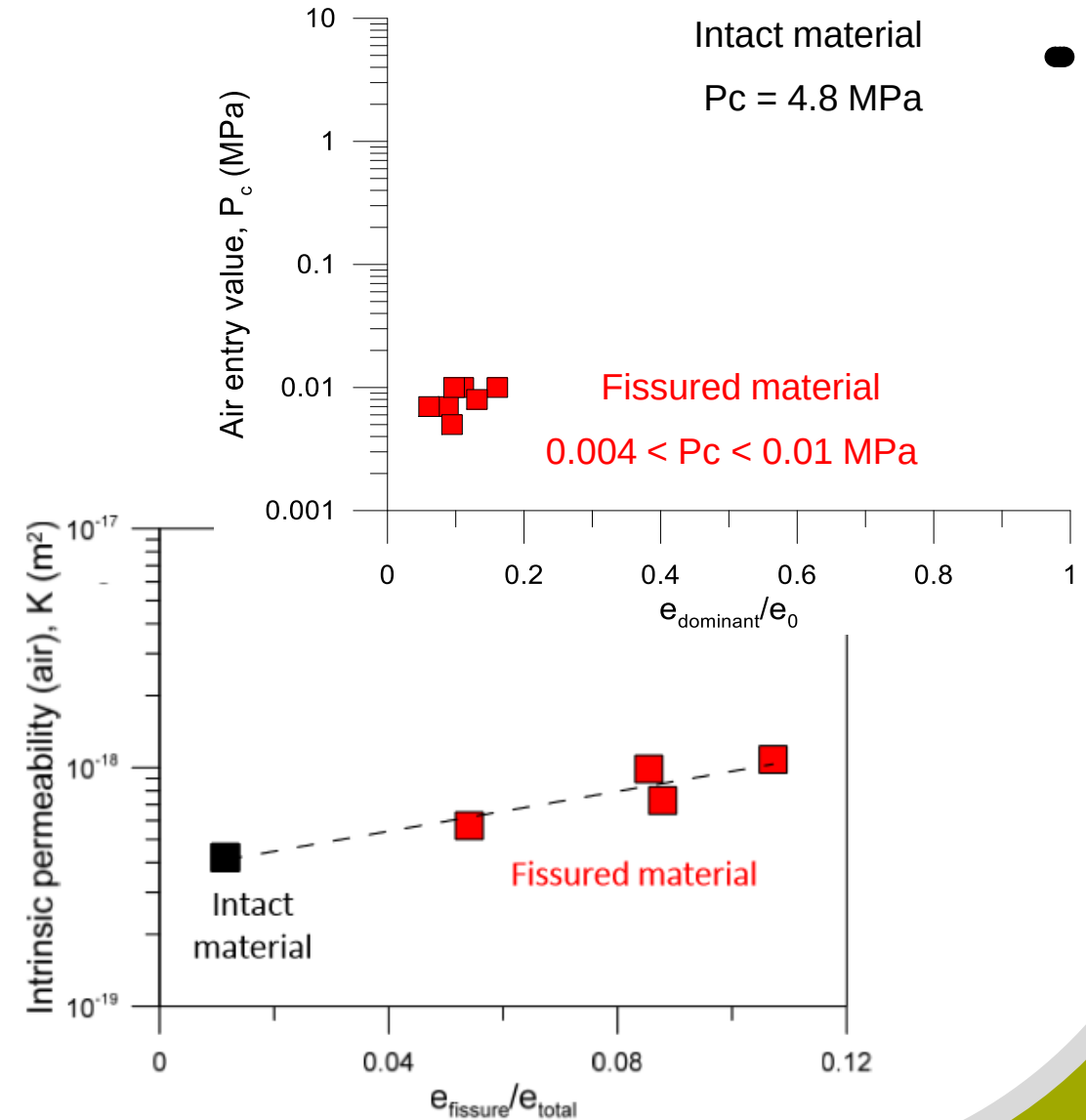
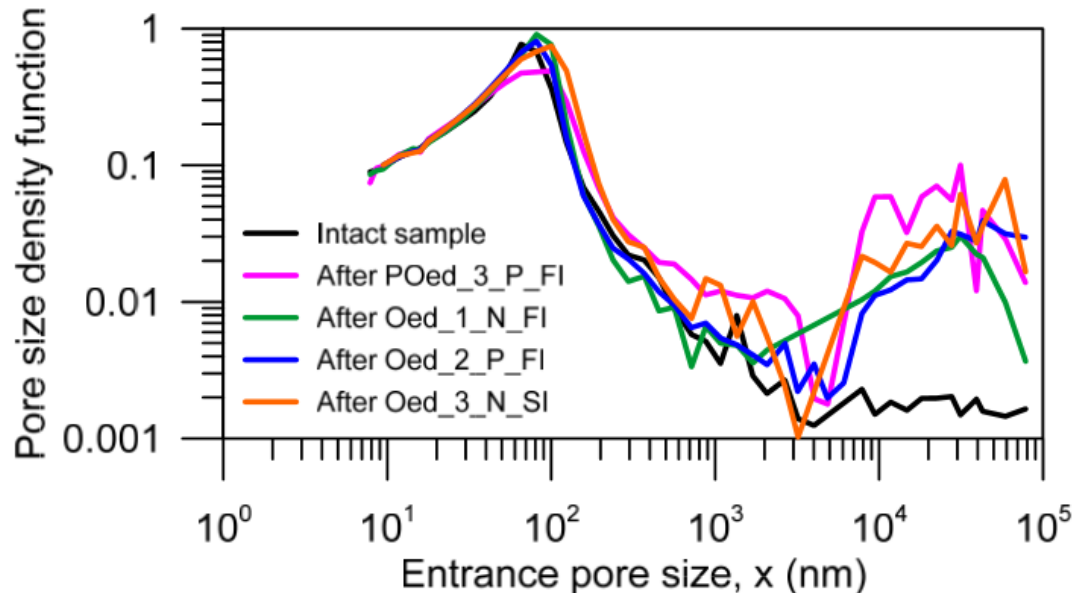


Example of air injection tests in water saturated Boom Clay in oedometric conditions

(CIMNE; Gonzalez-Blanco, 2017)

Microstructural changes

- formation of new pores with no modification of matrix porosity
- clay matrix remains saturated
- minor effects on gas permeability
- major effects on gas entry pressure

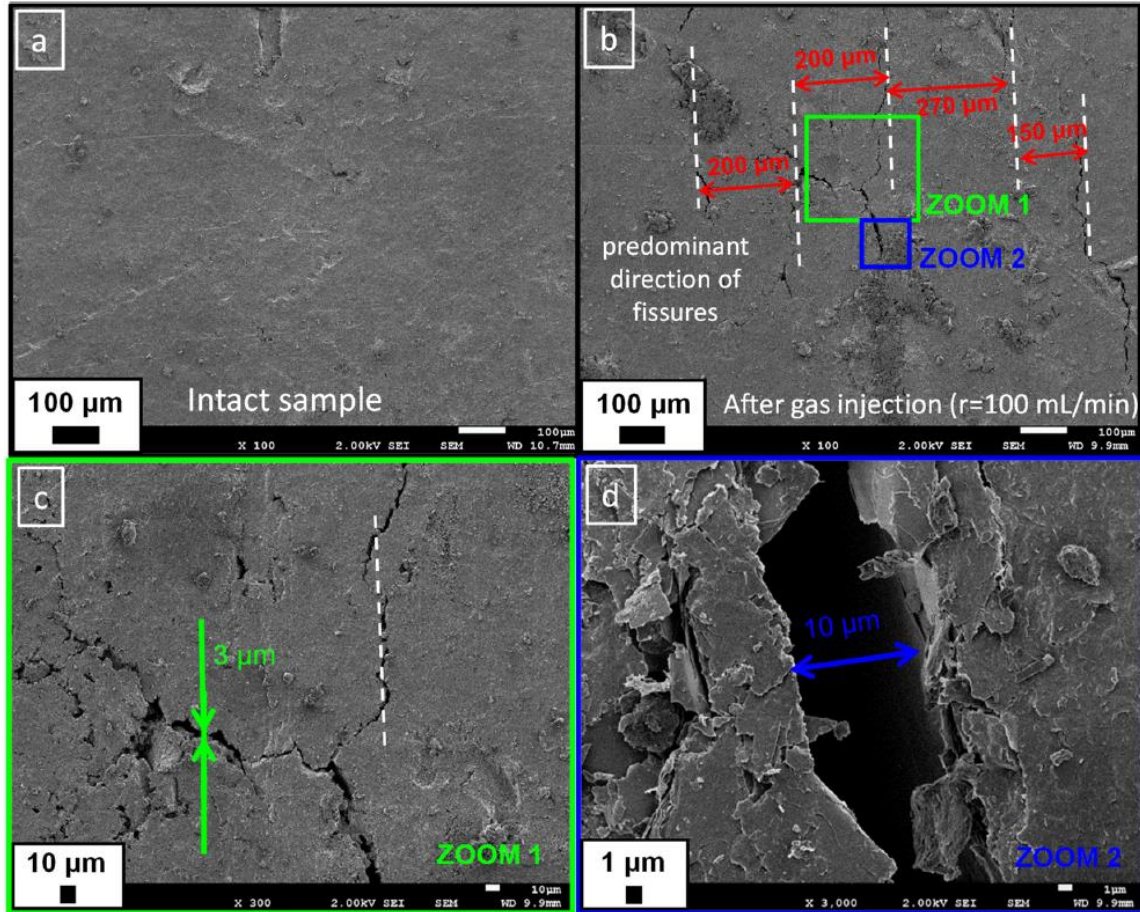


Example of air injection tests in water saturated Boom Clay in oedometric conditions

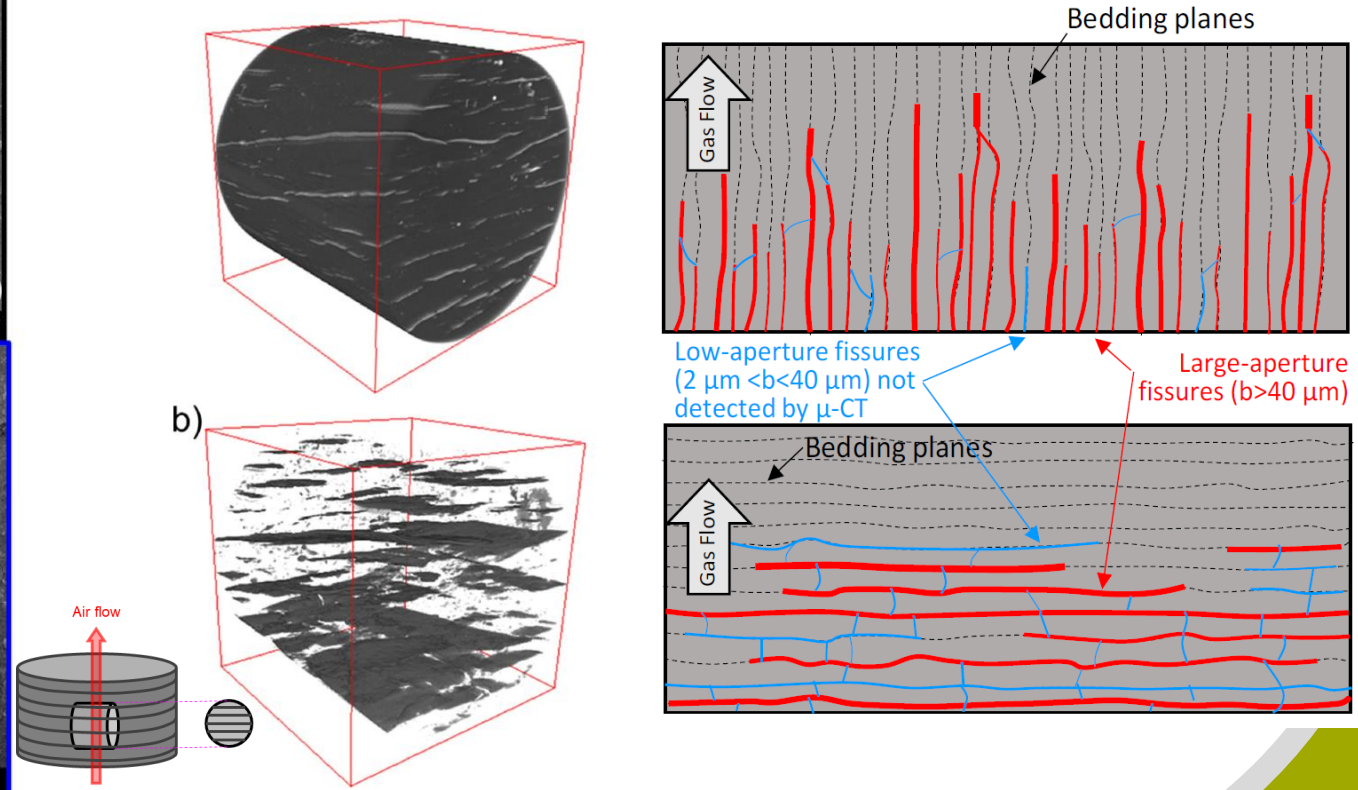
(CIMNE; Gonzalez-Blanco, 2017)

- **Role of imaging**

Internal microstructure using filled-emission scanning electron microscopy (FESEM)



Bedding planes and pre-existing fissures open to govern gas flows



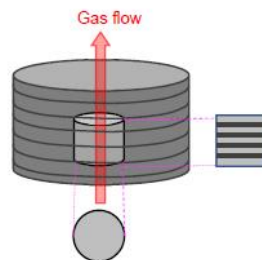
*μCT imaging after filtering process, 3D reconstruction of the fissure pattern
Sample with bedding planes orthogonal to flow*

Example of successive gas injection dissipation tests in water saturated Boom Clay in oedometric conditions (CIMNE; EURAD-GAS)

The response during the second injection is rather similar to the first injection

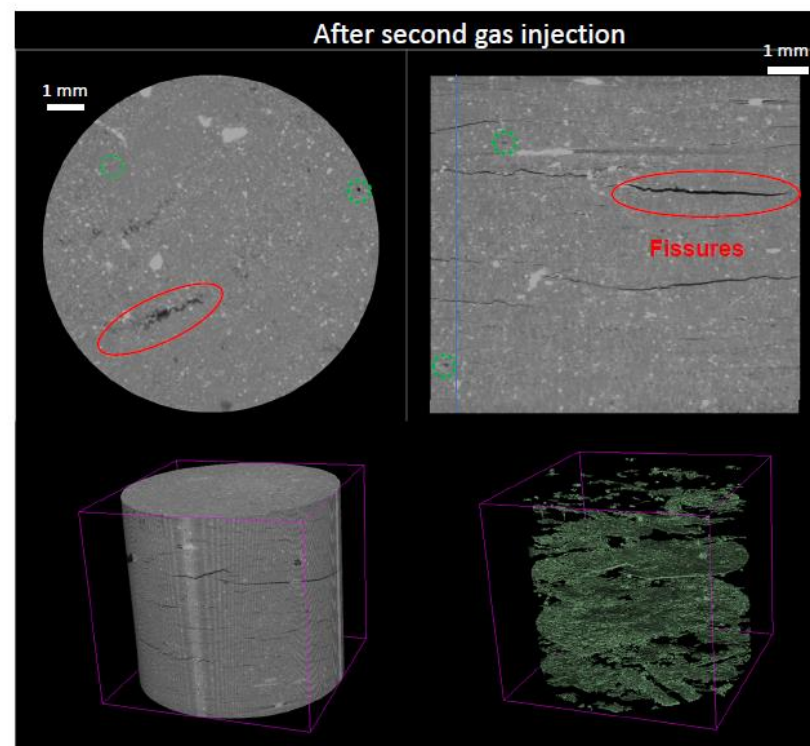
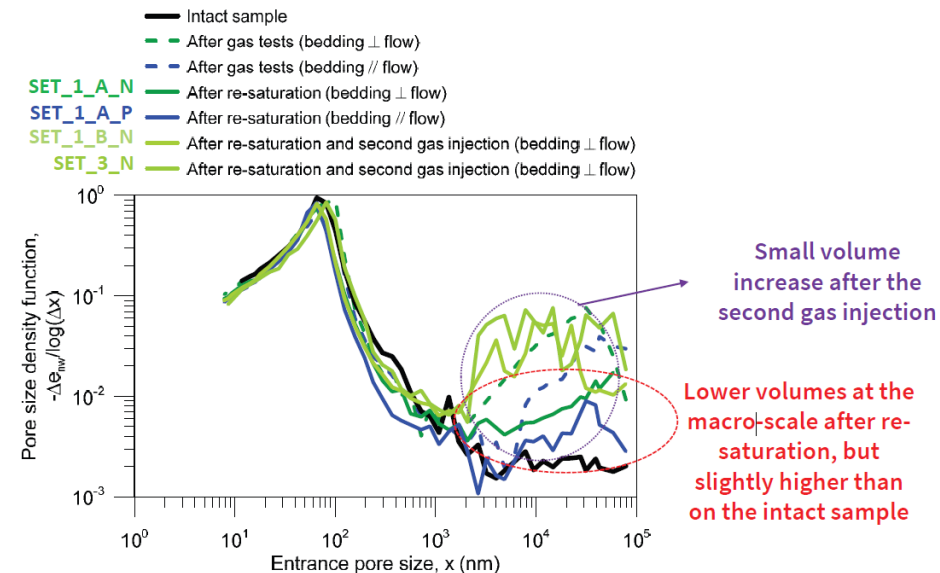
→ good self-sealing of gas-induced fissures

→ but memory of the previous gas pathways



Pixel size 10 μm

22/11/21



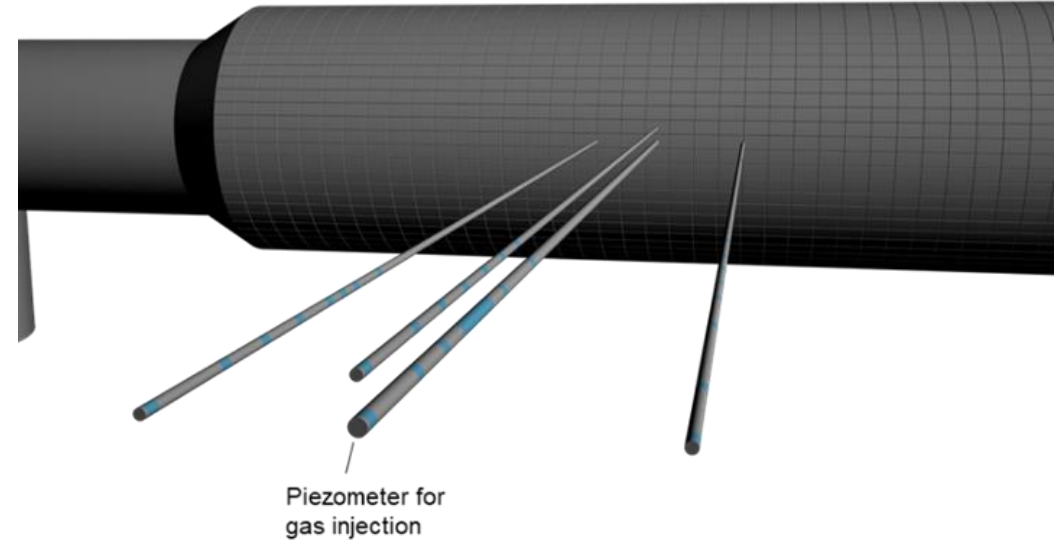
Large-aperture fissures and large pores are detected after the second gas injection. Low-aperture fissures bridging bedding planes can be discern, despite still unconnected (not continuous) ($< 20 \mu\text{m}$)

In situ gas injection test in HADES URL

*Example of E5 MEGAS Experiment
(SCK CEN; Volckaert et al. 1995)*

Progressive injection of Helium until breakthrough

- a preferential pathway formed along injection borehole: **significant role of interfaces**
- **self-sealing capacity of clay remains**



Conclusions of lab test programme and pioneering in situ experiments are in line

→ **Formation of gas induced pathways depends on**

→ **Hydromechanical boundary conditions**

→ **Boom Clay behaviour**

without altering the self-sealing capacity of clay

Key role of HADES URL: mimic repository conditions

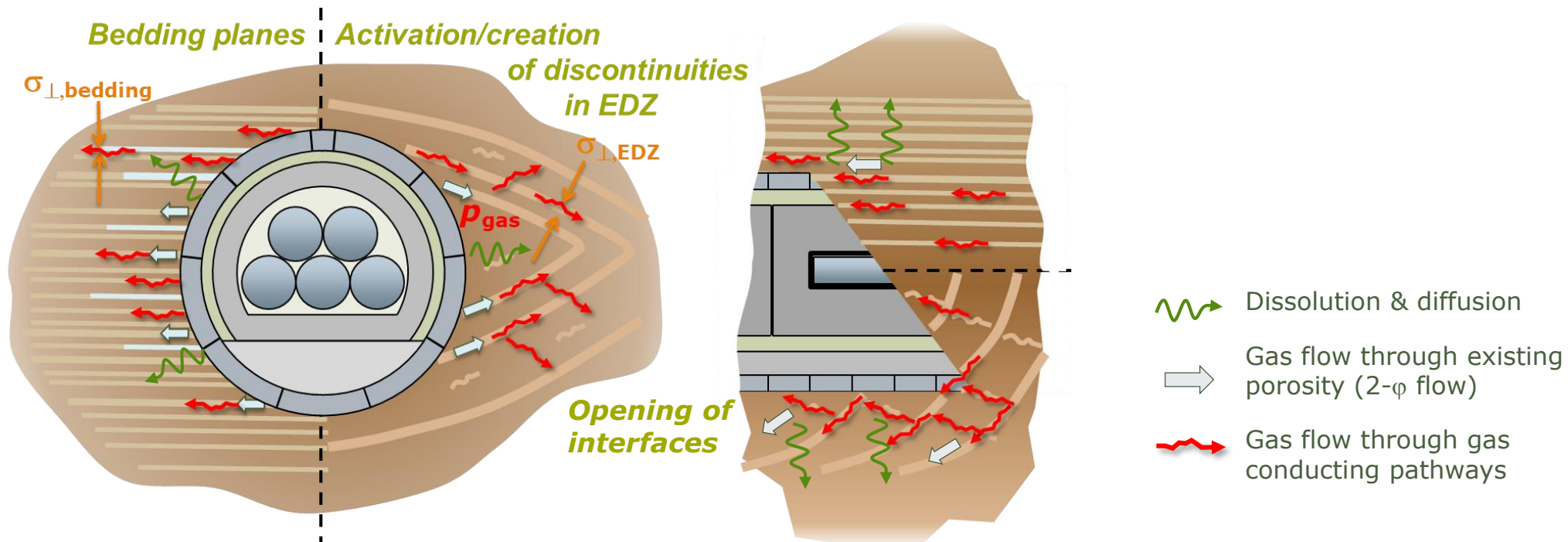
- Over the last 30 years, several experiments have been conducted to study gas transport in Boom Clay at lab-scale and in the HADES URL

- Various processes and phenomena
- Strongly linked to hydromechanical coupling



What are the gas transport regimes active at the scale of a geological disposal system?

What are their potential impact on repository integrity and performance?



Thank you for your attention

***Thanks to all partners who are working with
ONDRAF/NIRAS on the characterization of gas transport
modes in the Boom Clay***



sck cen

CIMNE^R

