# Thermo-Hydro-Mechanical (THM) Perturbations in Bentonite/Argillite Repositories: Heater Tests at Mont Terri and Bure

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# Argillite Coupled THM Modeling Team

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**International Collaboration**

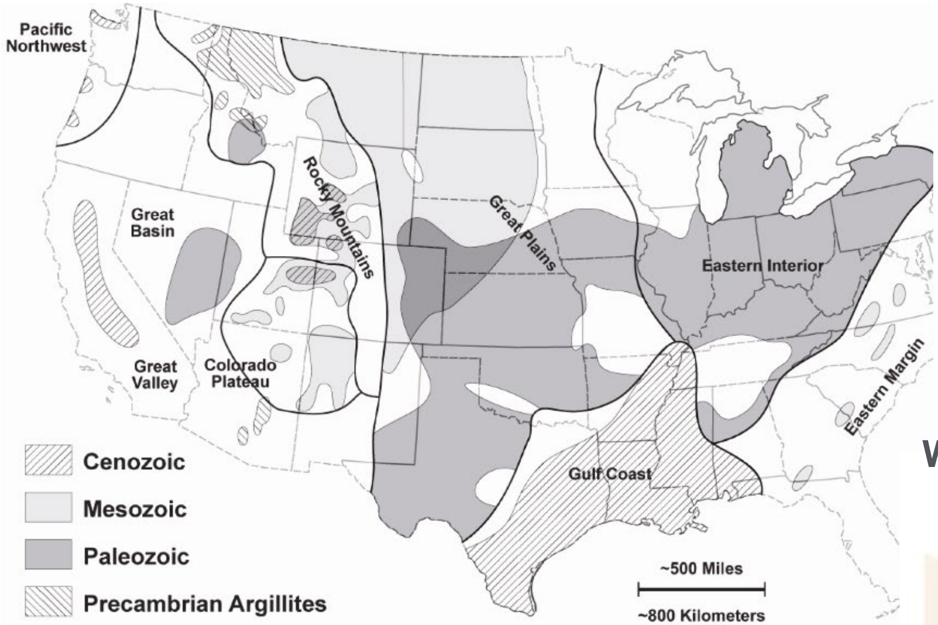
Task Leads from NAGRA and SwissTopo, Switzerland, for Mont Terri heater experiments, in Opalinus Clay.

Task Leads from ANDRA, France, for heater experiments at Bure underground research laboratory in COx Claystone.

DECOVALEX Research Teams (> 10 international teams)

# Argillite Repository Concept

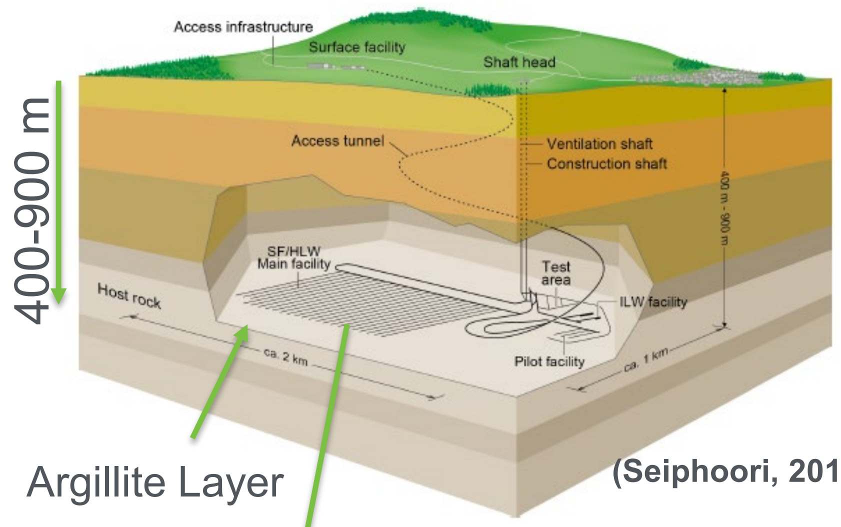
Clay/Shale provinces in the United States (Gonzales and Johnson 1984)

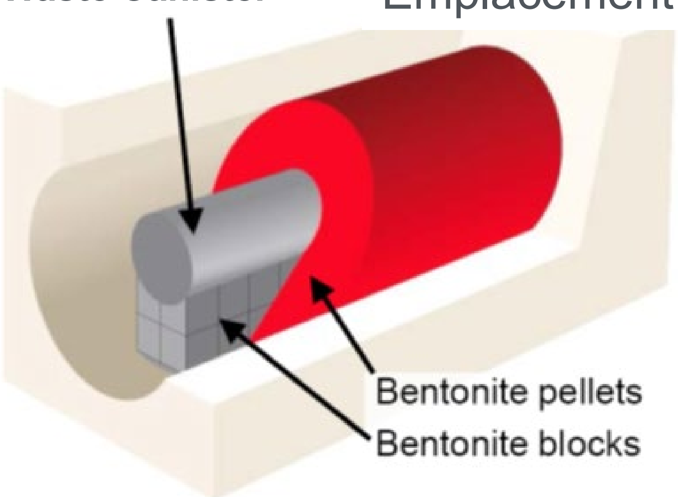



**Barriers:**

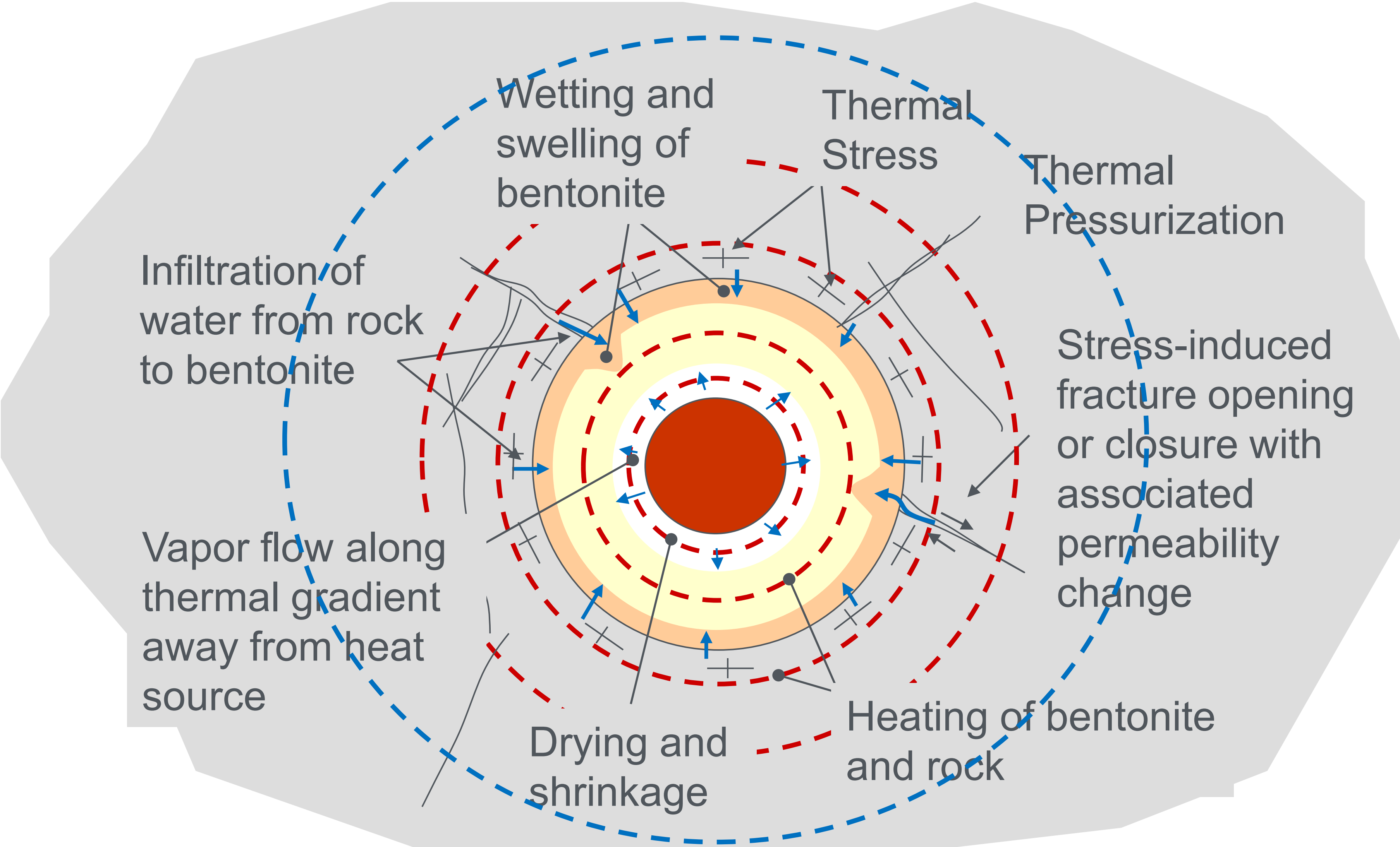
- **Waste canister (containment)**
- **Tight bentonite buffer**
- **"Impermeable" host rock**

The Swiss Design (Multi-Barrier)



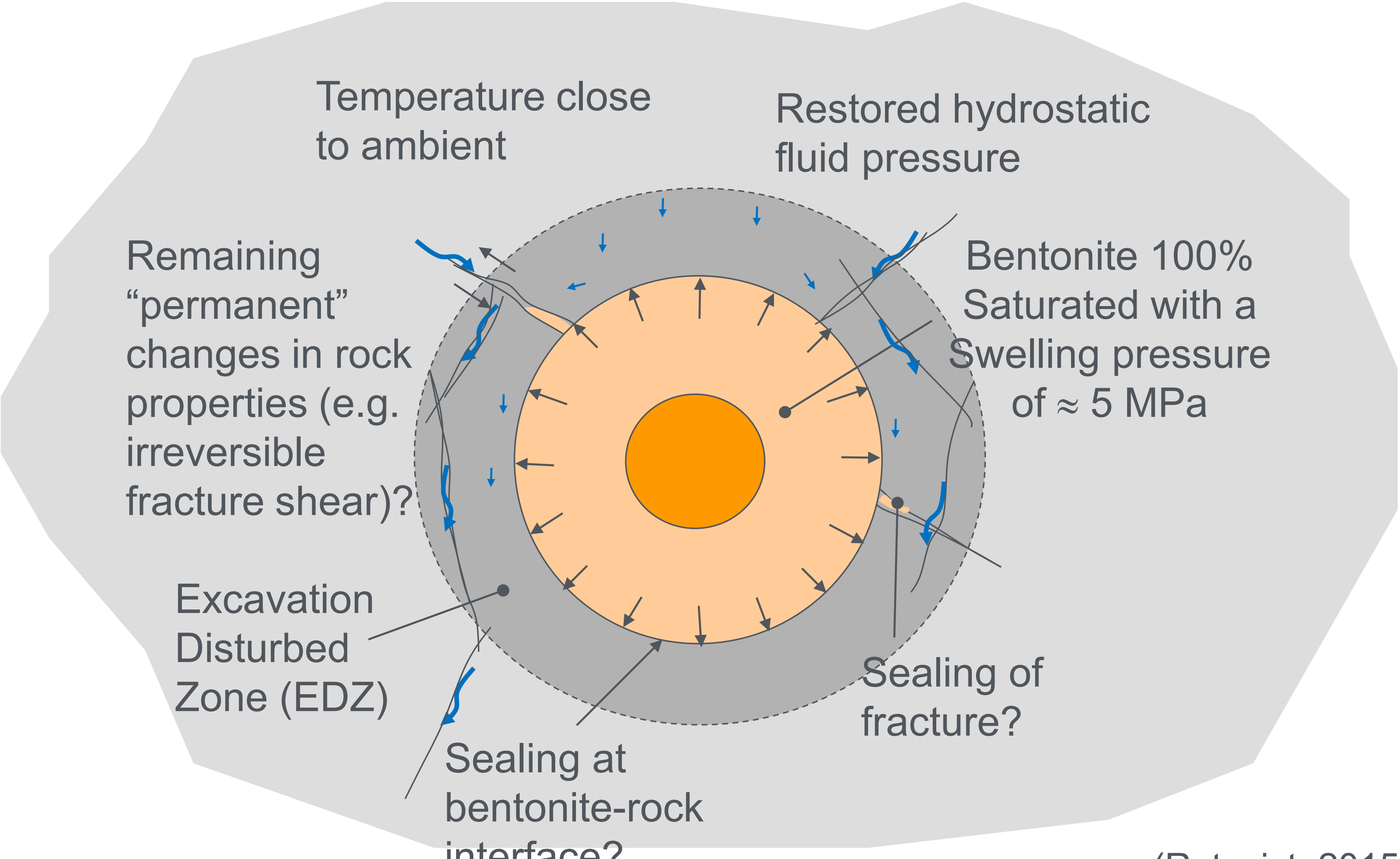



# Short Term (0 to 10,000 years) Thermally Driven Coupled THM Processes




(Rutqvist, 2015)

# Long Term (10,000 to 100,000 years) Impact of Coupled THM Processes

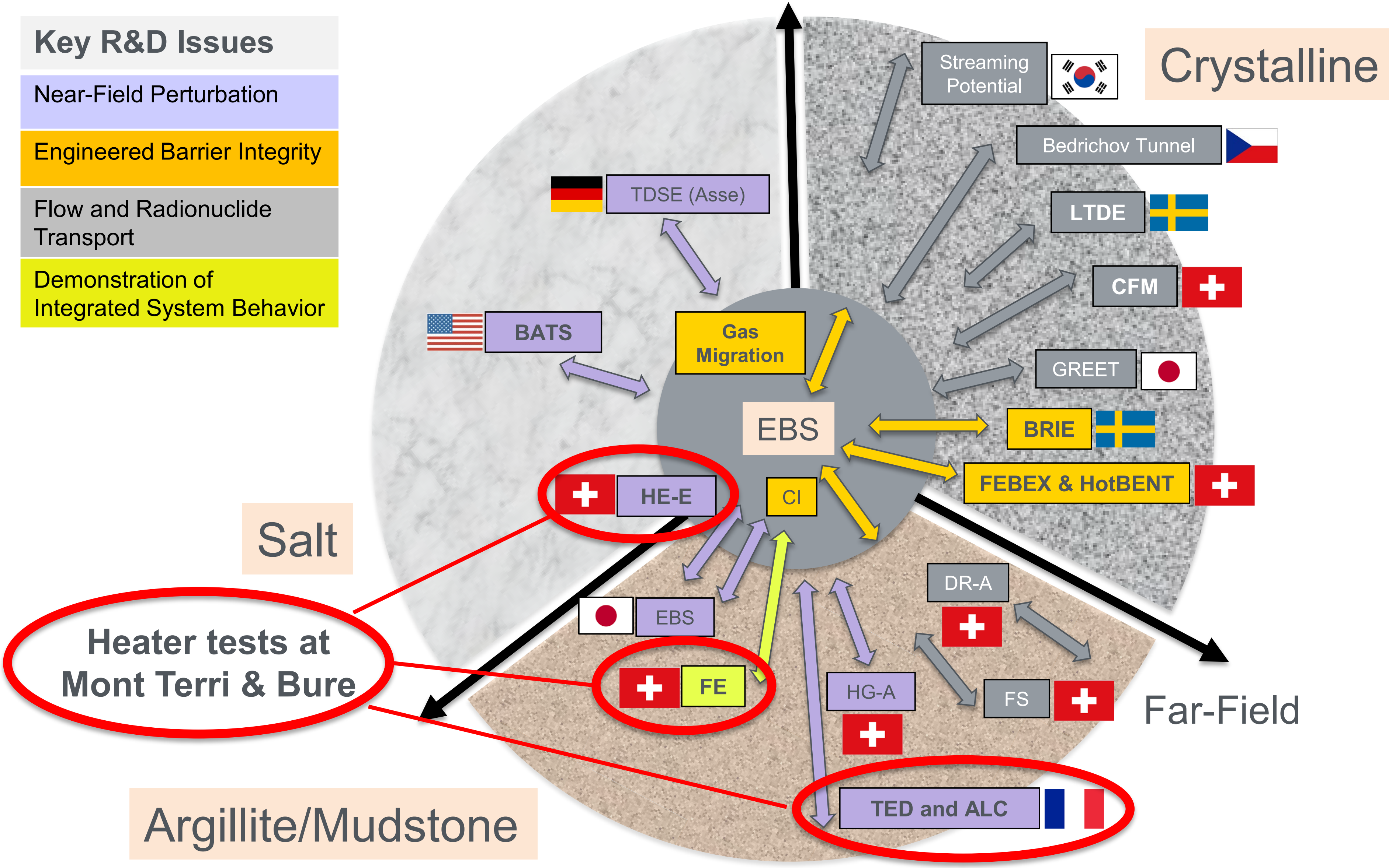



(Rutqvist, 2015)

# International URL Portfolio in a Nutshell

**Key R&D Issues**

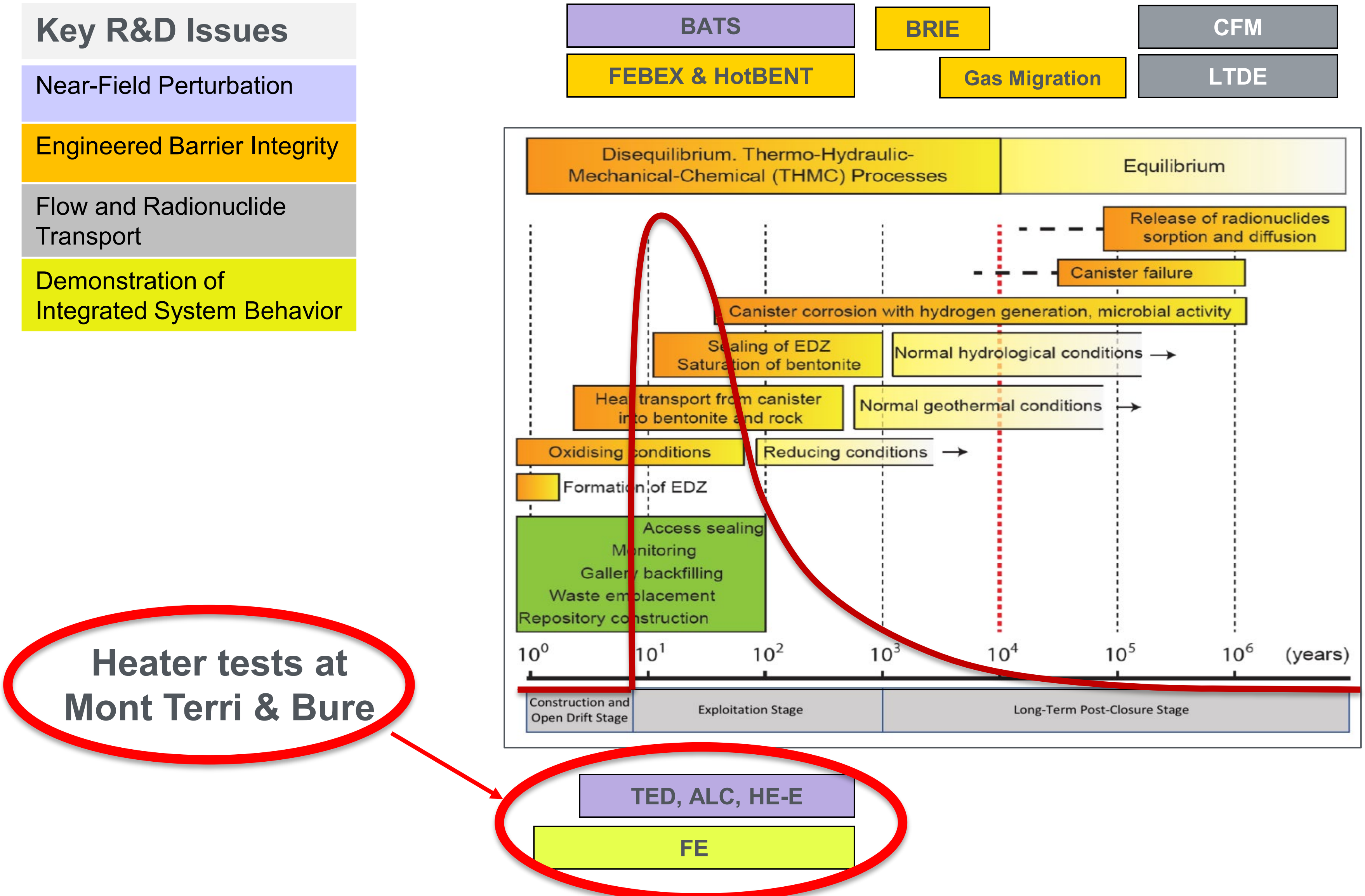
- Near-Field Perturbation
- Engineered Barrier Integrity
- Flow and Radionuclide Transport
- Demonstration of Integrated System Behavior



# Repository Phases and Relevant Processes

**Key R&D Issues**

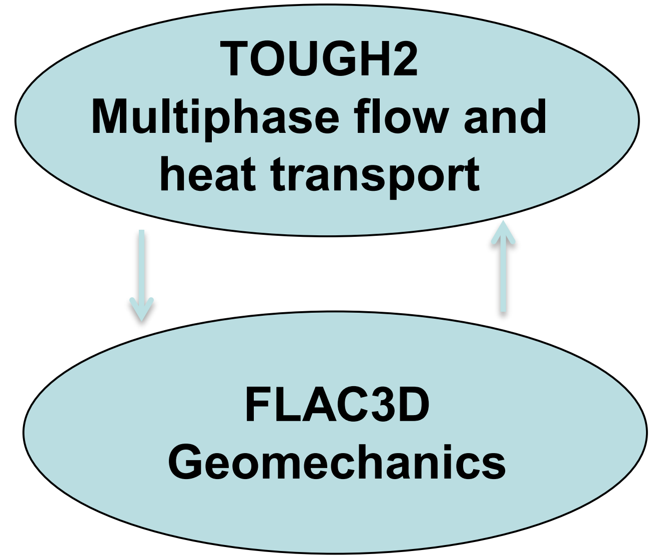
- Near-Field Perturbation
- Engineered Barrier Integrity
- Flow and Radionuclide Transport
- Demonstration of Integrated System Behavior



# A Thermo-Hydro-Mechanical Model Framework

**TOUGH-FLAC Simulator:**

- Linking two established codes (each thousands of users world-wide)
- Both codes continuously developed and applied and in their respective fields
- Large number of fluid and mechanical constitutive material models



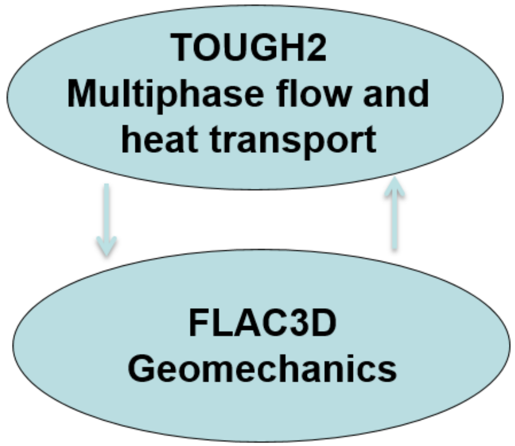

(Rutqvist et al., 2002; Rutqvist 2011; 2017)

- First developed and applied in the Yucca Mountain Project (2000-2008)
- Bentonite and clay rock (from 2011)
- Salt host rock and backfill (from 2013)

**By adding to existing model capability**

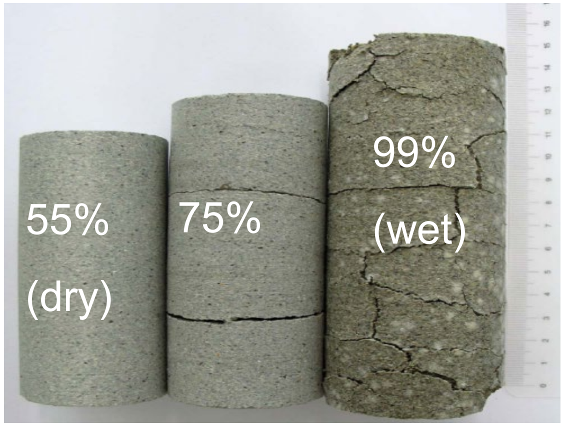
- International TOUGH-FLAC users related to nuclear waste disposal in Germany, United Kingdom, Switzerland, and South Korea

# Added Capability for Bentonite Modeling



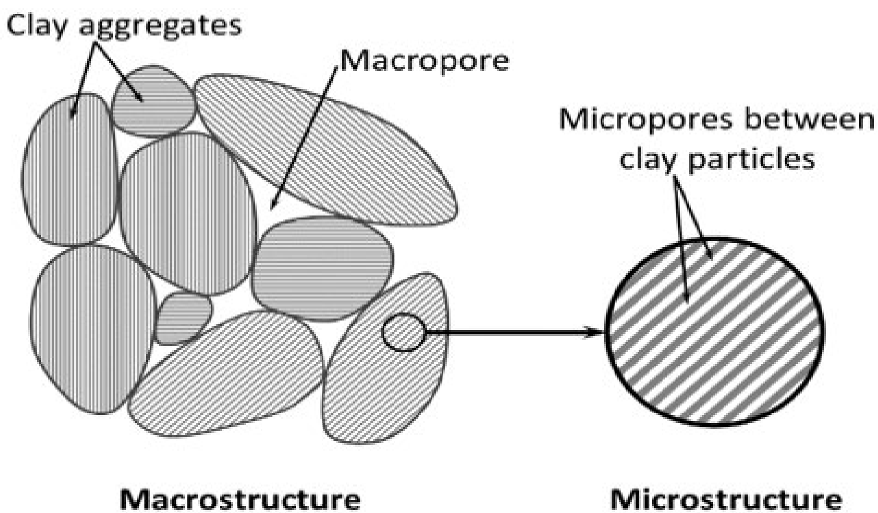

## 1) Barcelona Basic Model (BBM)

- Constitutive model for unsaturated clay
- Dry bentonite is hard and strong (effect of suction)
- Swells with wetting becomes a soft clay




Bentonite blocks stored at different relative humidity (Teodori et al.,2011)

## 2) Barcelona Expansive Model (BExM)




- More advanced constitutive model considering micro- and macro-porosity
- All parameters not readily available for various types of bentonite

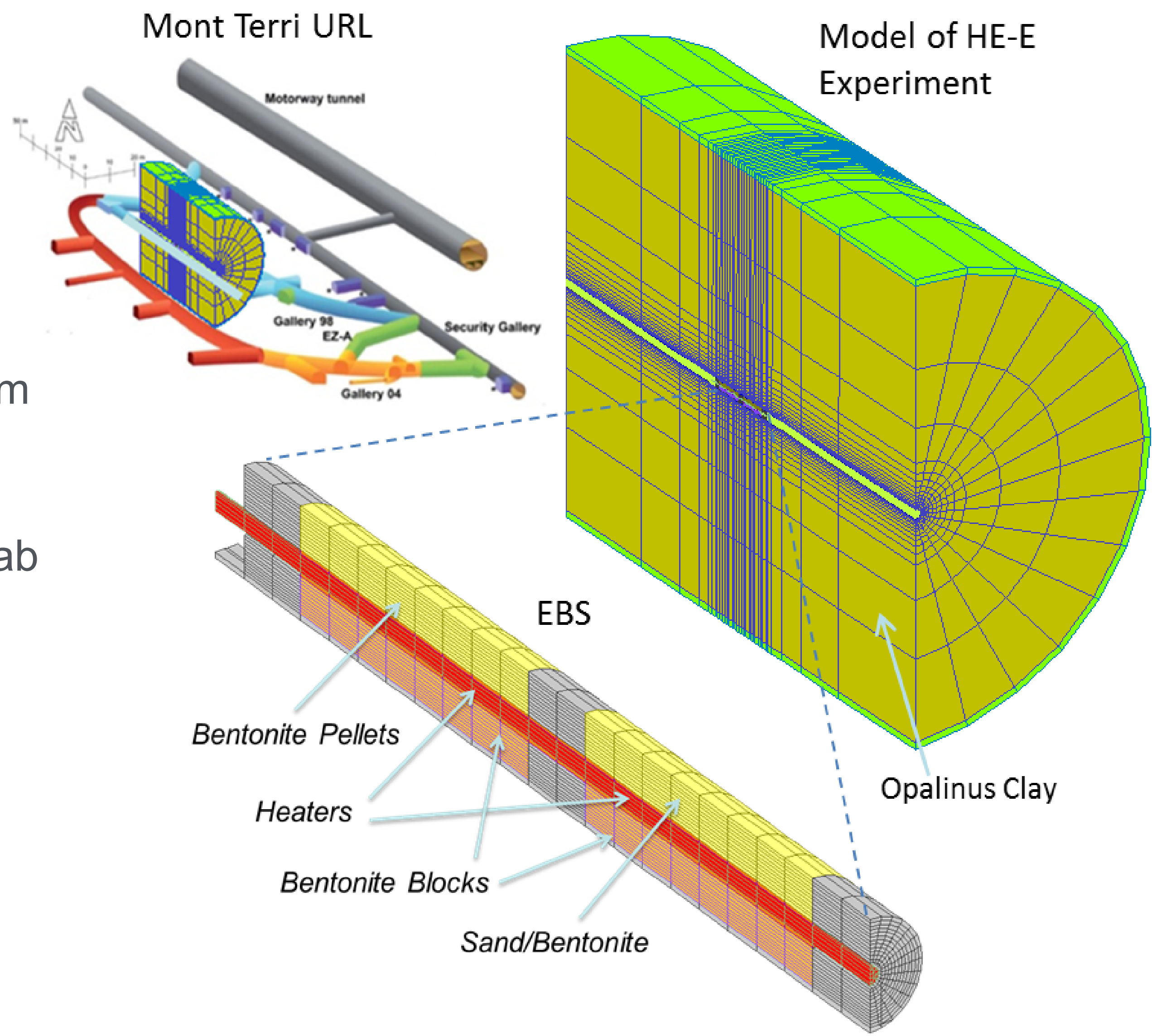
(Rutqvist et al., 2011; 2014; Vilarrasa et al., 2016)

# Model of Mont Terri Half-Scale (HE-E) Experiment in Opalinus Clay (DECOVALEX-2015 Project)

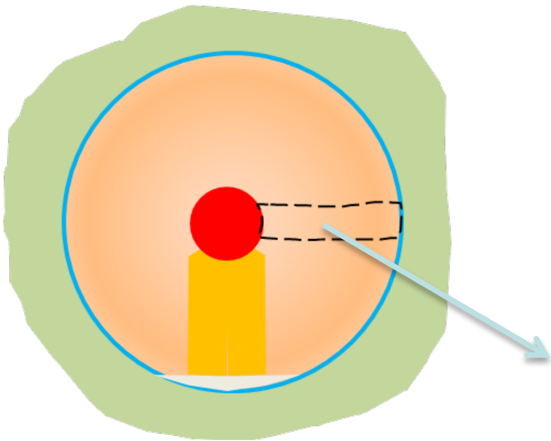
3 years of heating up to 140°C

**Modeling Steps:**

1) Bentonite parameters from lab experiments
2) Opalinus Clay properties from Mont Terri Project (lab and in situ data)
3) Blind prediction of THM response at HE-E experiment
4) Understand field data response and update model



# Coupled Thermo-hydraulic Processes during Resaturation of the Bentonite Buffer



Liquid Darcy Flow:

$$\mathbf{q}_l^w = -\rho_l X_l^w \frac{\mathbf{k}k_{rl}}{\mu_l}\left(\nabla P_l - \rho_l \mathbf{g}\nabla z\right)$$

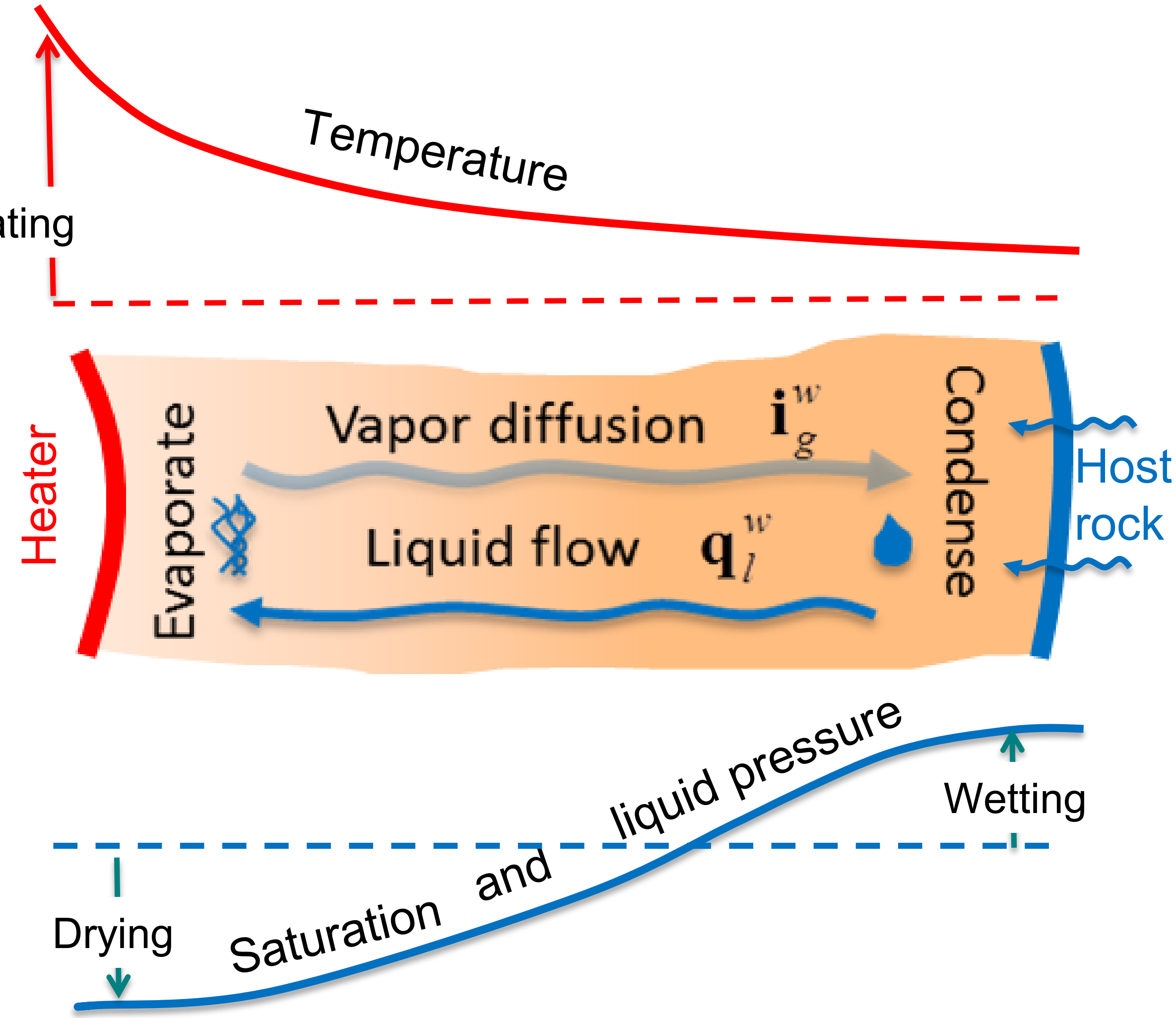
Liquid pressure gradient

Vapor diffusion:

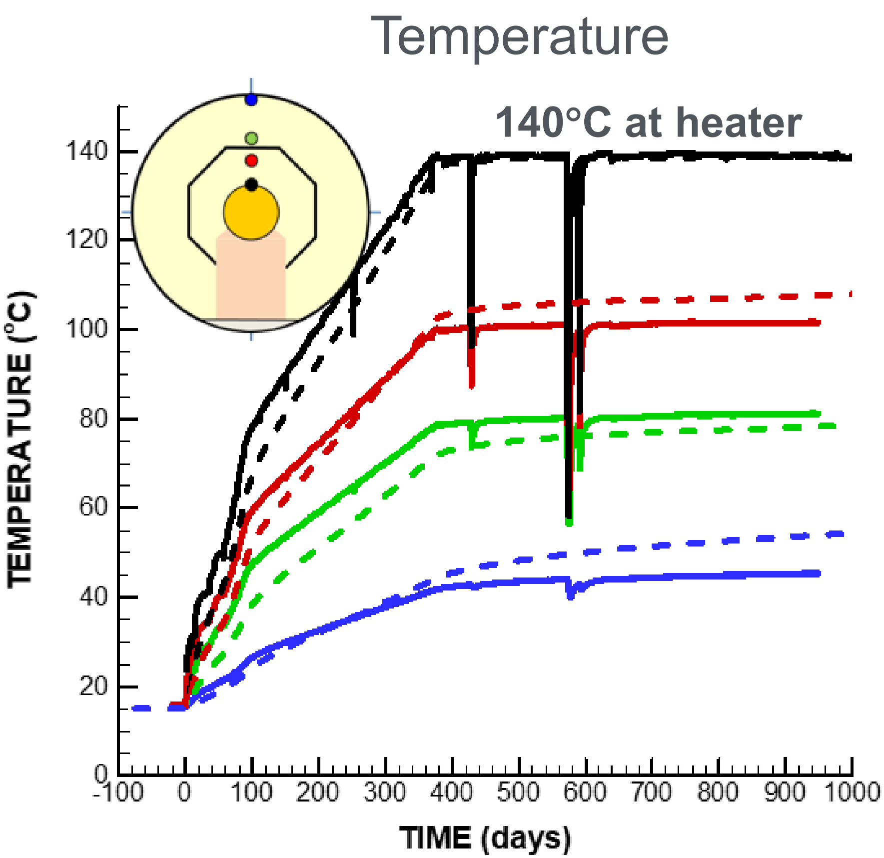
$$\mathbf{i}_g^w = -\rho_g \underbrace{\phi S_g \tau D_g^w}\mathbf{I}\nabla X_g^w$$

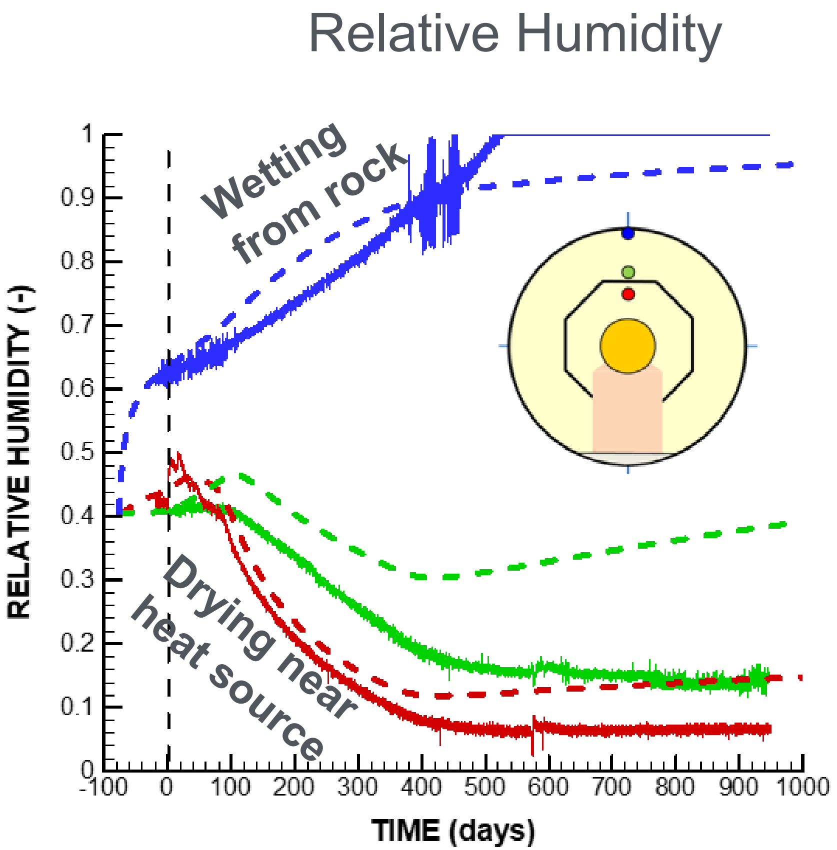
Effective vapor diffusion

Water mass fraction in gas



# Coupled Thermo-hydraulic Processes in the Buffer: Model Prediction versus Measurements



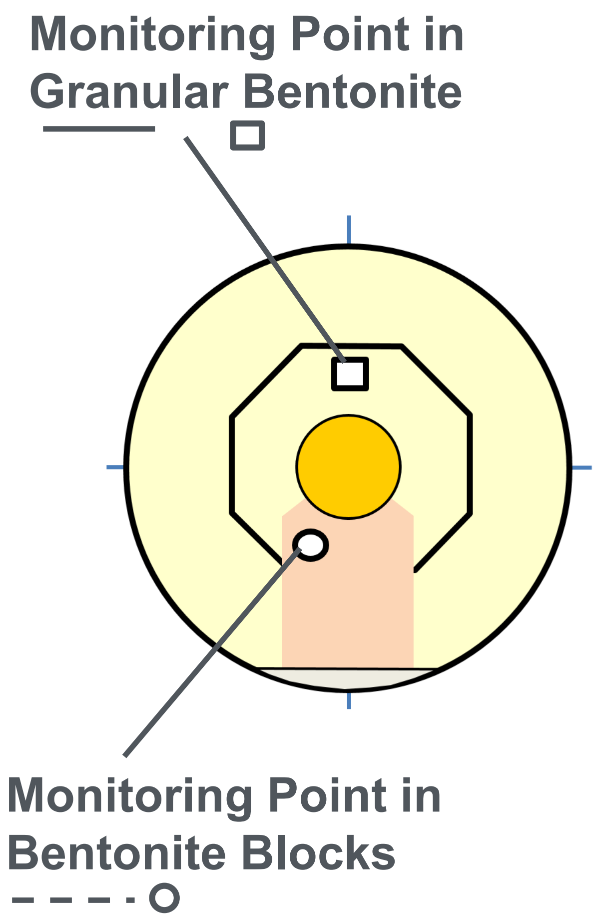



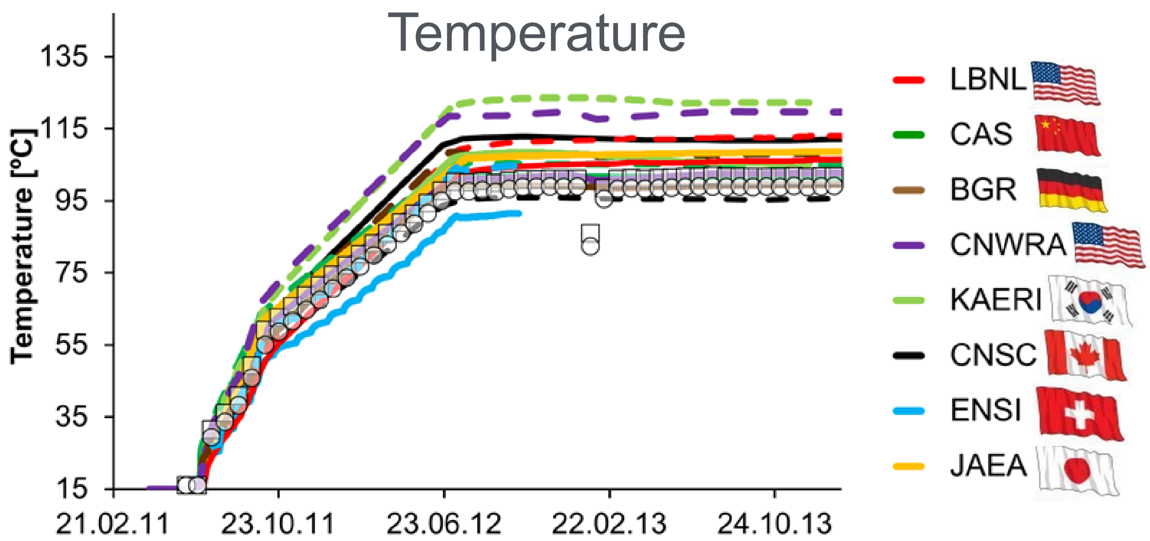

Model Prediction

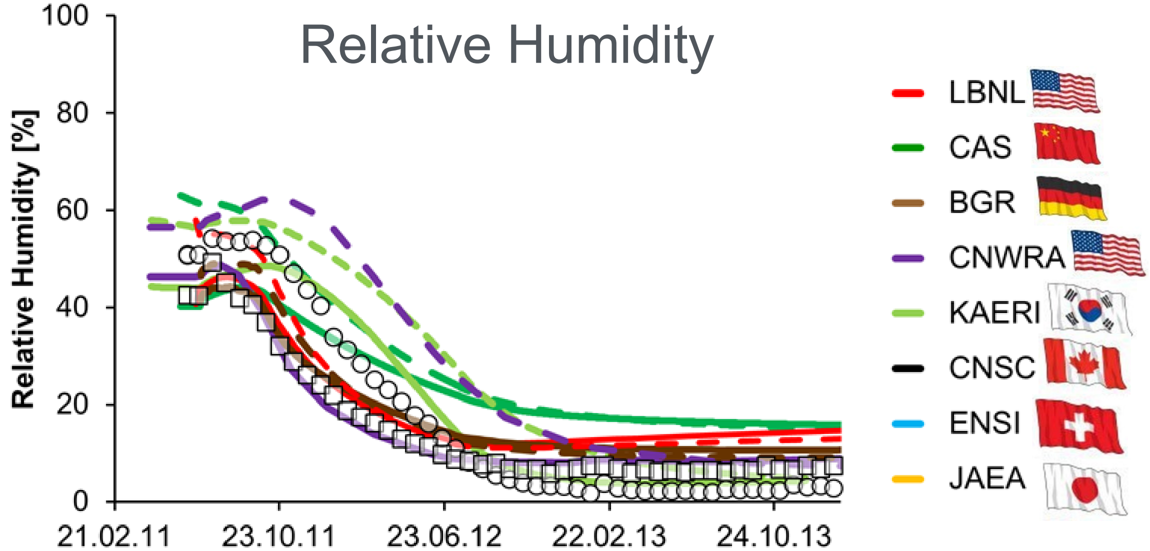
Measurements

- Blind prediction (3 years) reasonably good, although not perfect

# Model Comparison among 8 DECOVALEX Teams

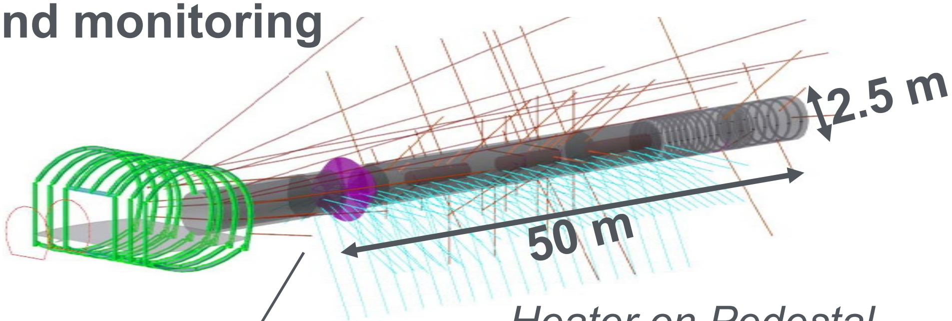


# Mont Terri Full-scale Emplacement (FE) Demonstration Experiment

**Expect 15 to 20 years of heating and monitoring**



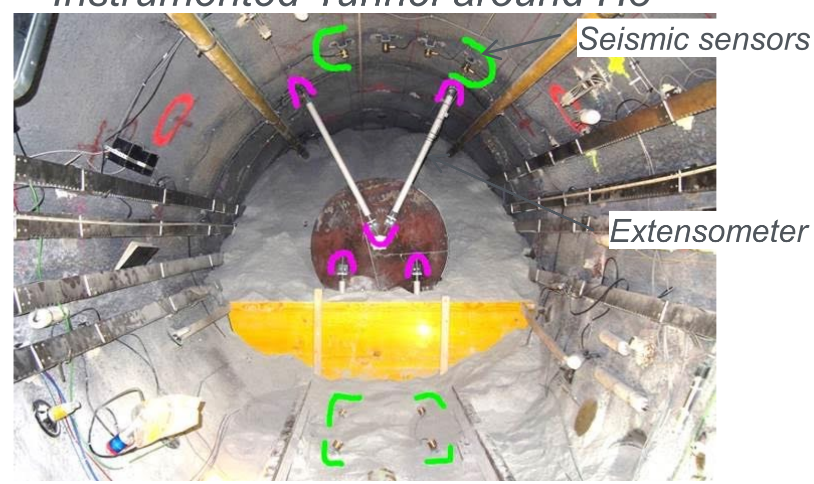

*Bulkhead*

*Heater on Pedestal*

*Bentonite blocks*

*Granular bentonite emplacement*

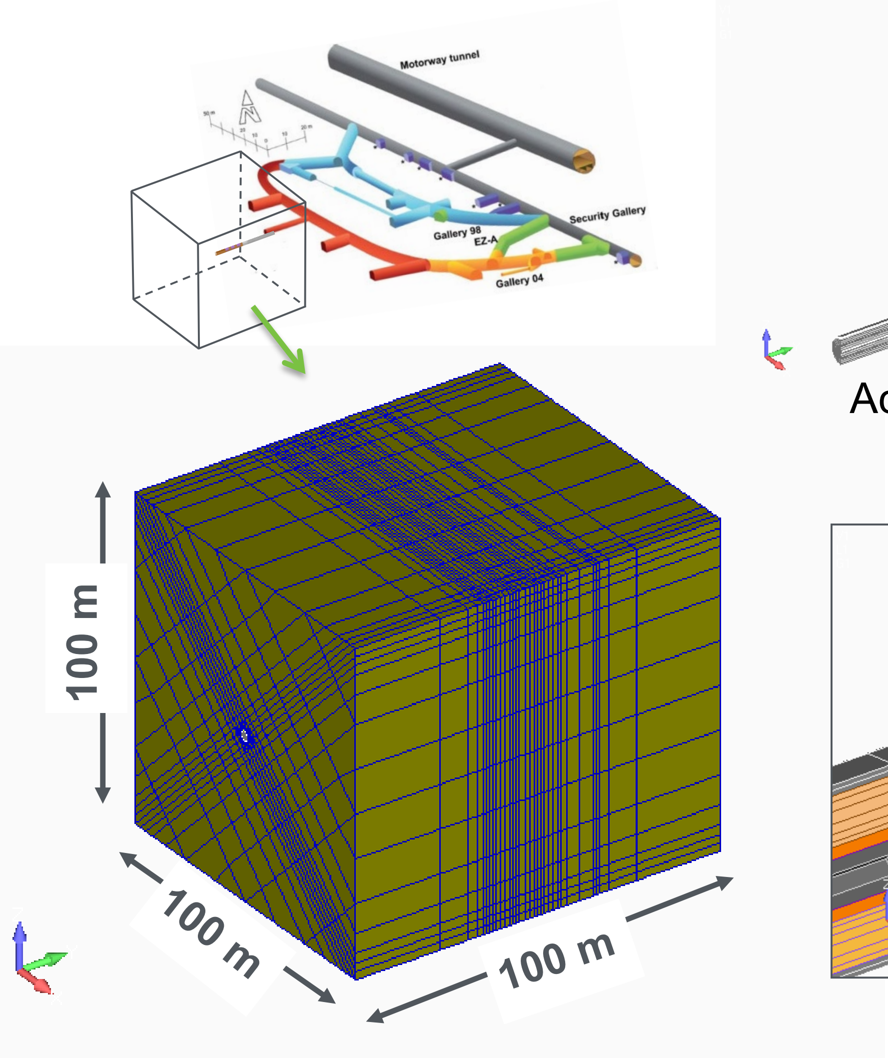
*Instrumented Tunnel around H3*

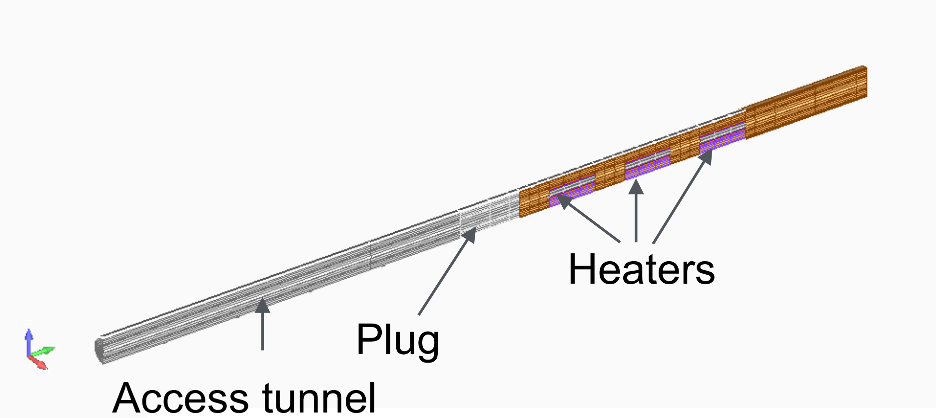


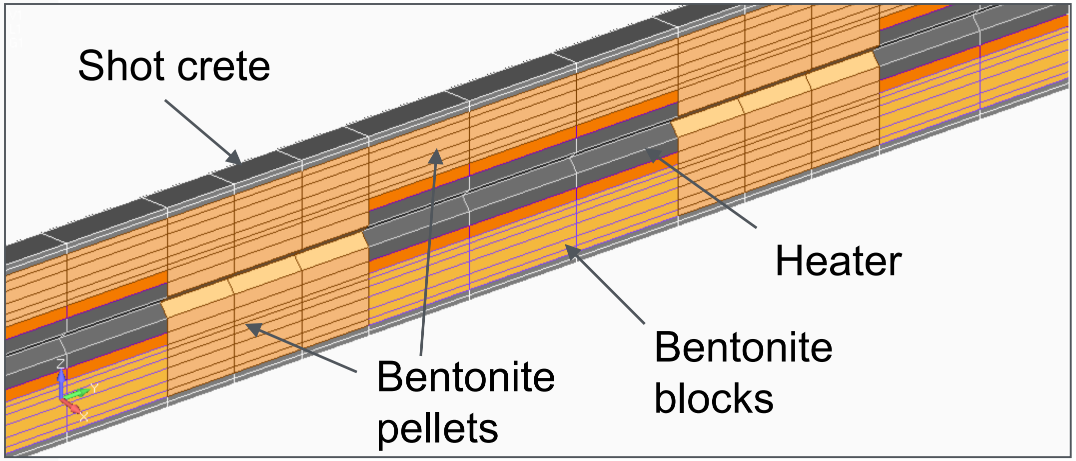

*(All photos by Herwig Muller in NAGRA Daily Reports of Emplacement 9/4/2014-2/15/2015)*

*All heaters turned on from Feb 15, 2015*

# TOUGH-FLAC Model of FE Experiment

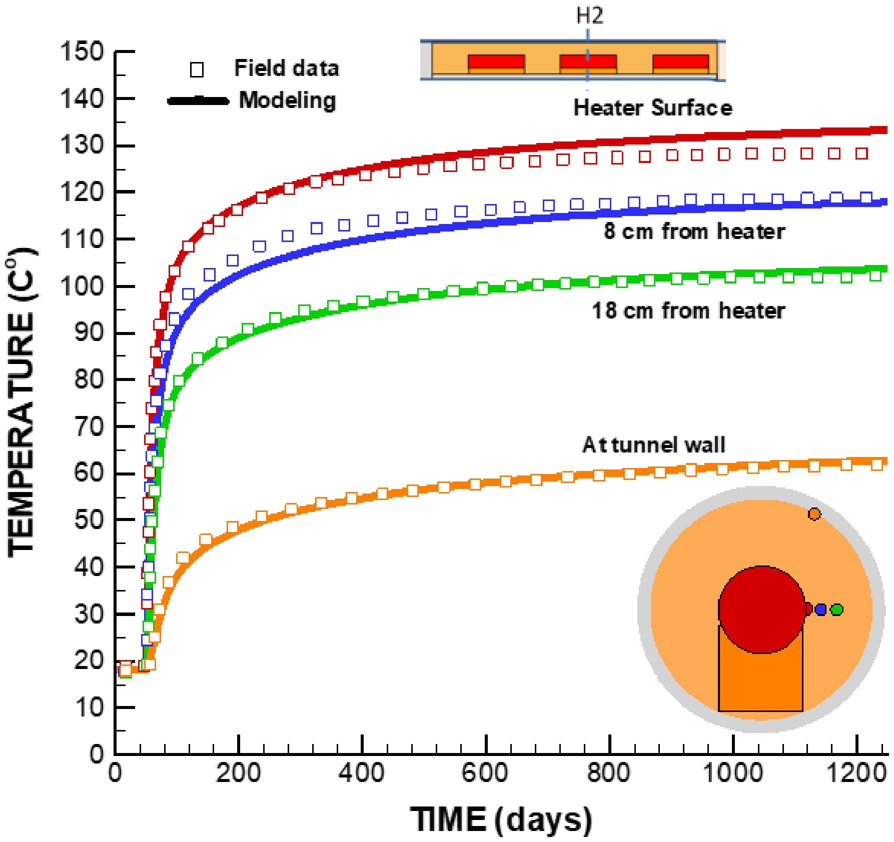


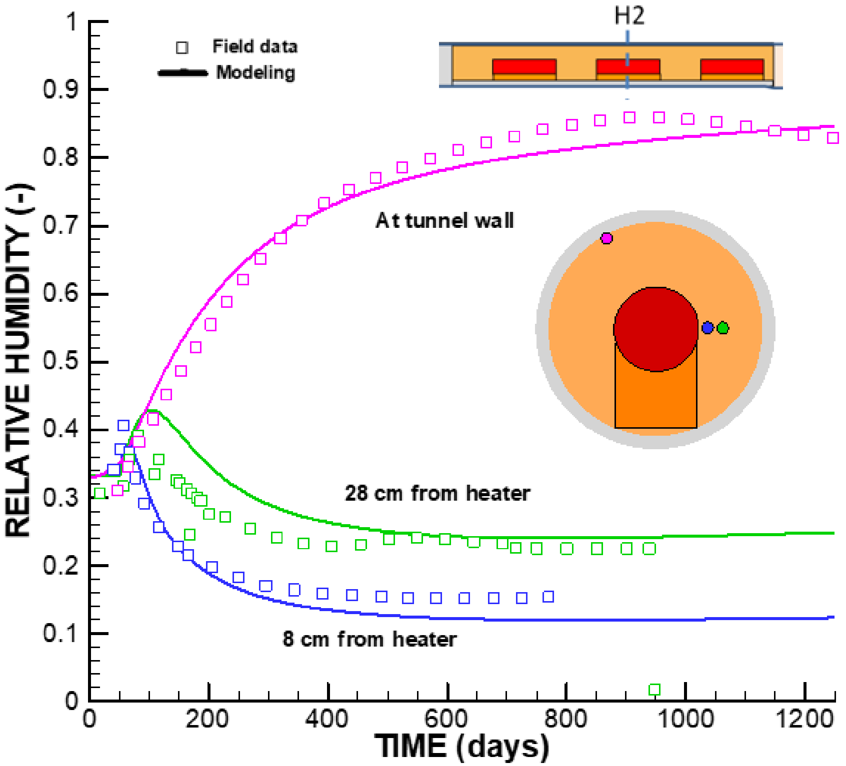




- THM Properties based on previous half-scale (HE-E) model simulations

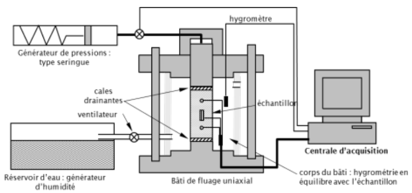
# FE Experiment: Comparison of Modeling and Field Data

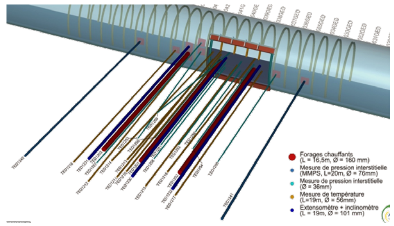


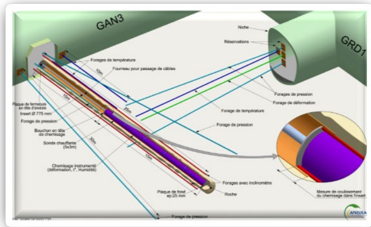



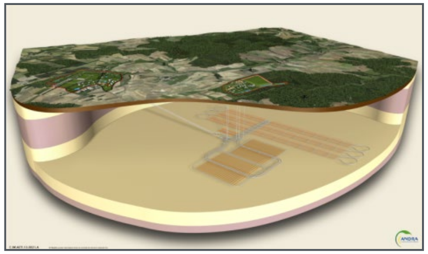

- Good agreement, but for a reduced effective vapor diffusion coefficient compared to that of the half-scale experiment (i.e. not entirely consistent)
- Longer-term field data (e.g. 10 years) will be important to confirm swelling stress evolution in the buffer

# Upscaling of THM Parameters in COx Clay (DECOVALEX Task Led by ANDRA, France)





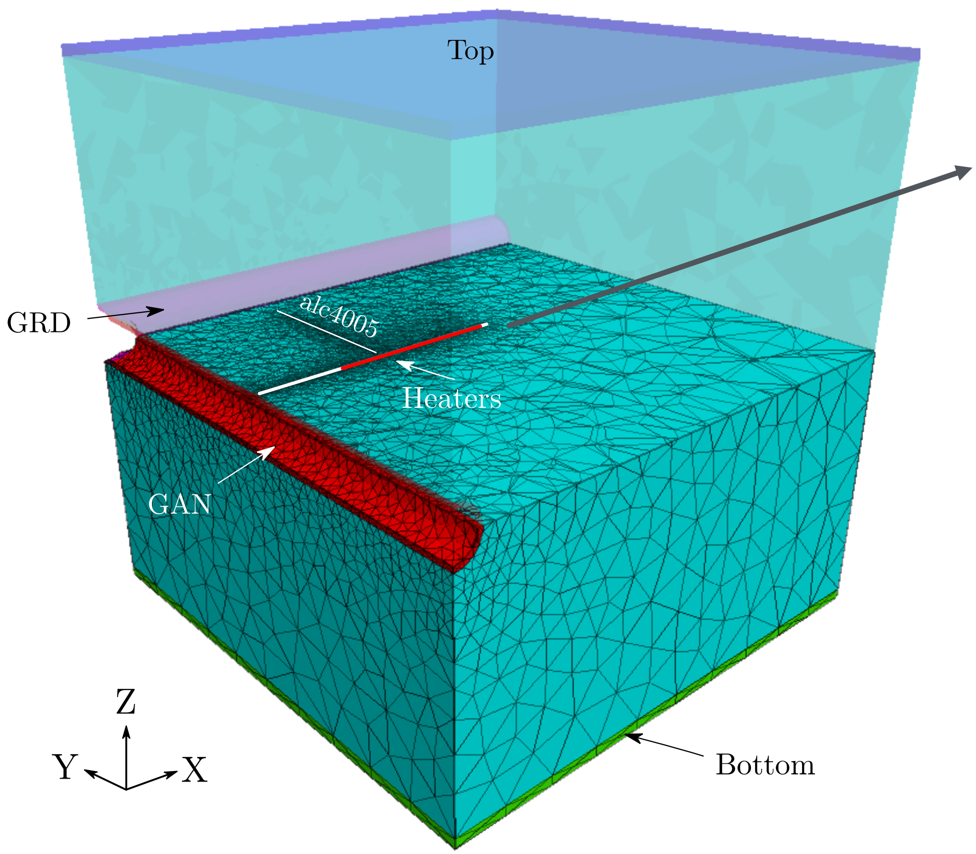



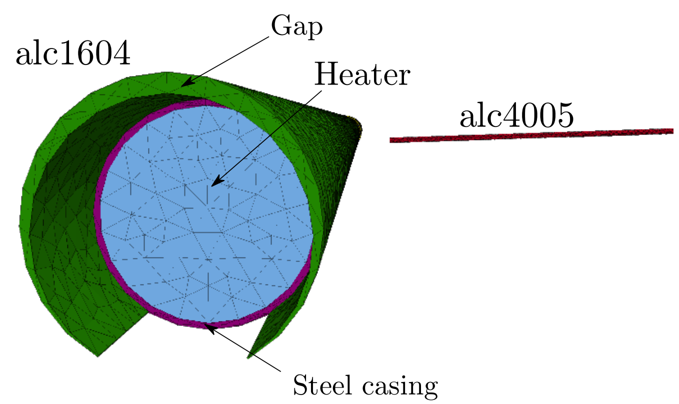
Sample scale — Borehole scale (TED) — Micro-tunnel scale (ALC) — Repository scale

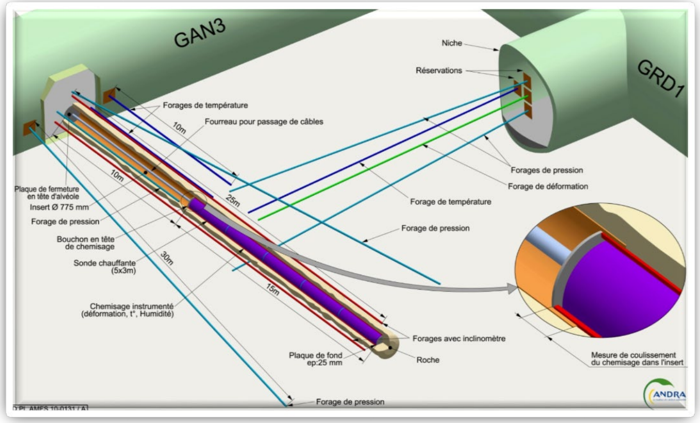
- How to go from sample to a repository scale?
- Heater tests at Bure underground research laboratory (France)
- The host rock consists of Callovo-Oxfordian claystone (COx)
- Main issue studied is thermally induced pore pressure buildup and stress changes around a repository in Argillite

# Modeling of Micro-tunnel Experiment at Bure URL (ALC Experiment)

- Mesh



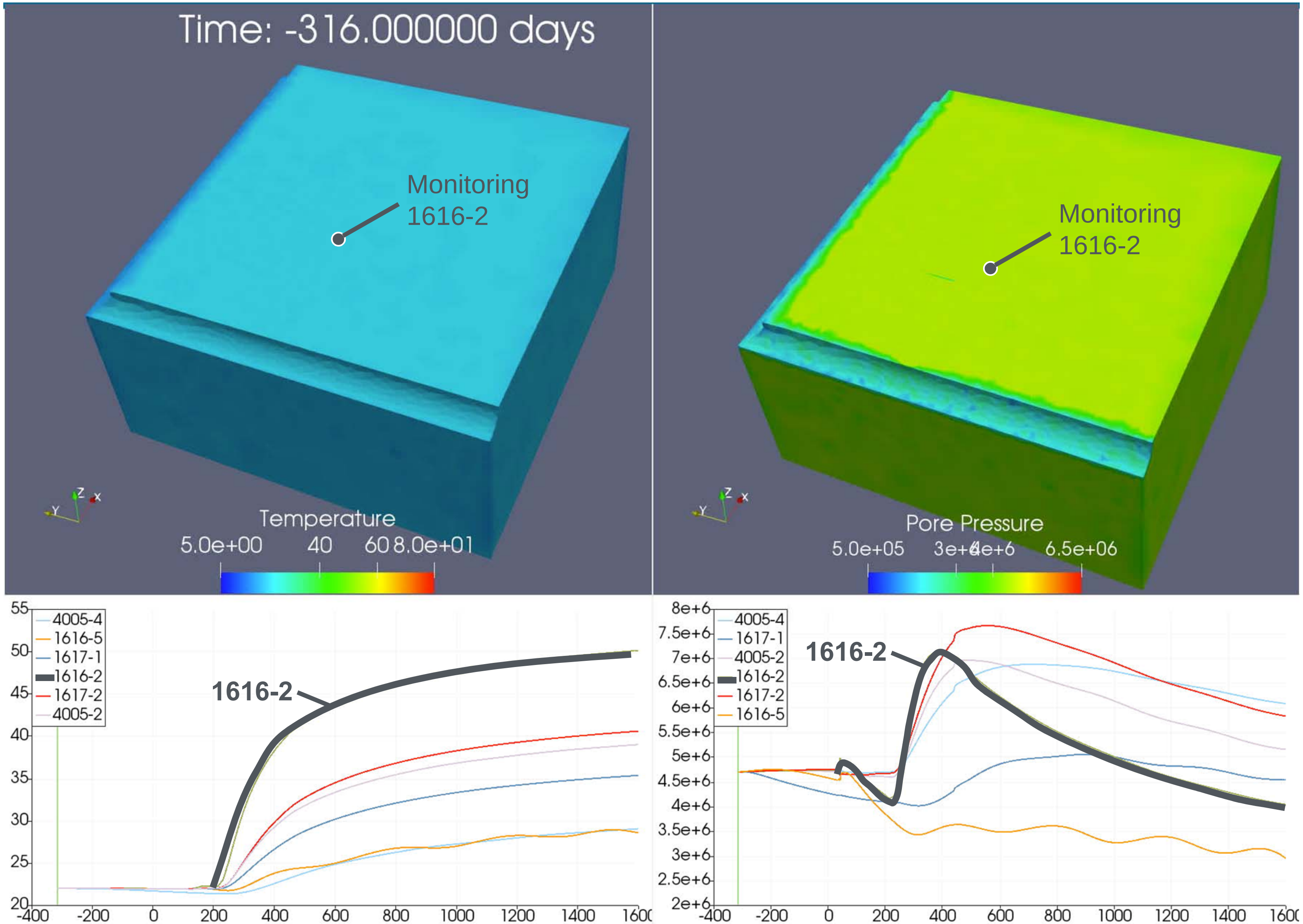



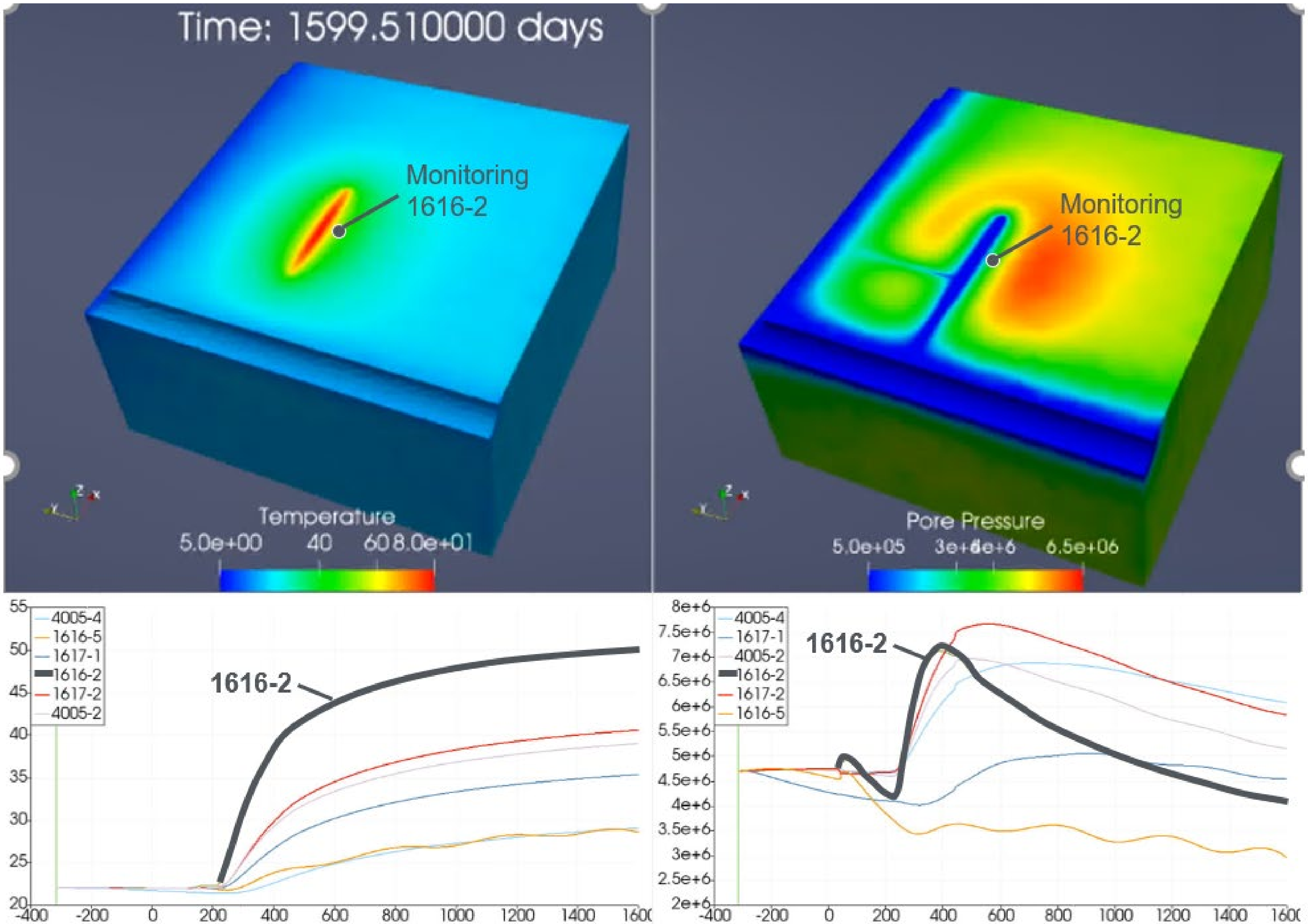

305244 elements in total including boundary elements.

# Modeling of Micro-tunnel Experiment at Bure URL (ALC Experiment)

A movie of thermal pressurization



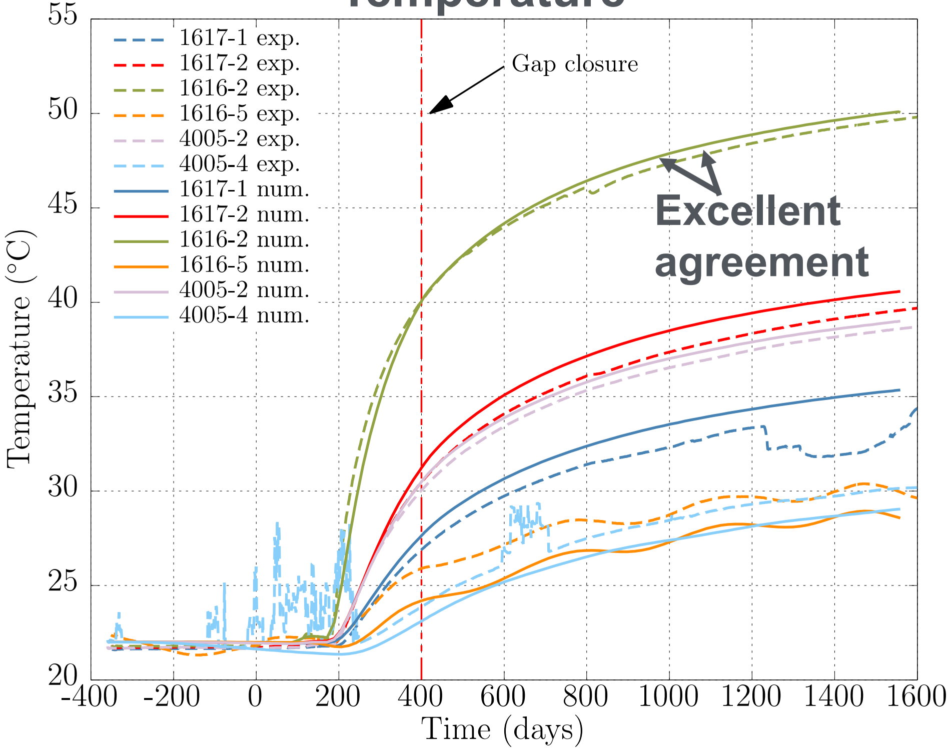
# Modeling of Micro-tunnel Experiment at Bure URL (ALC Experiment)



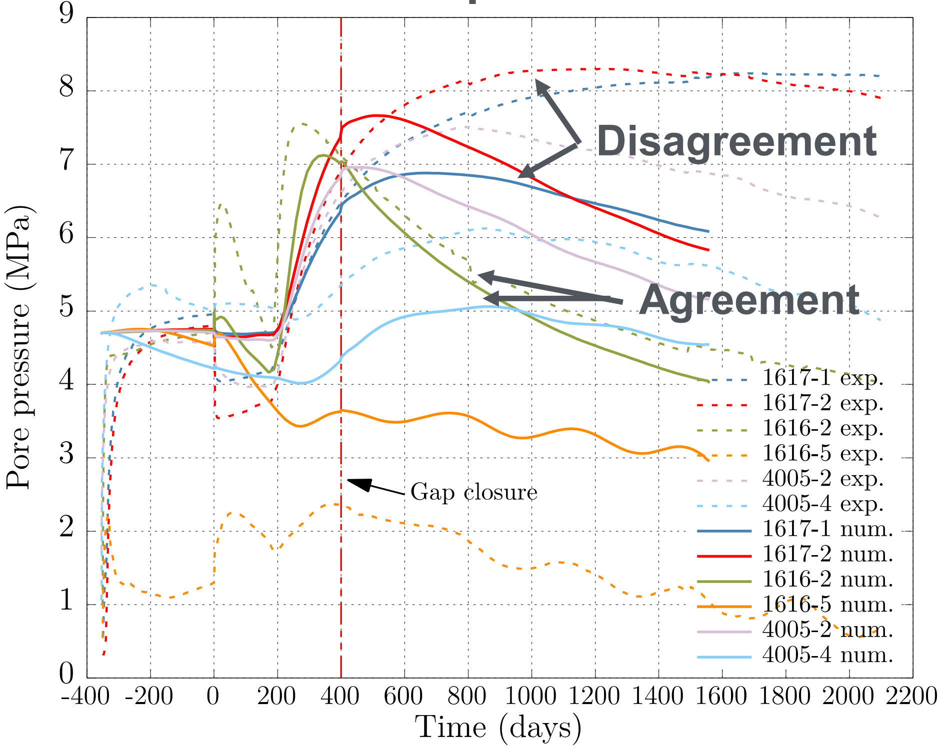
# Modeling of Micro-tunnel Experiment at Bure URL (ALC Experiment)

## Comparison of blind prediction to measurements:

### Temperature

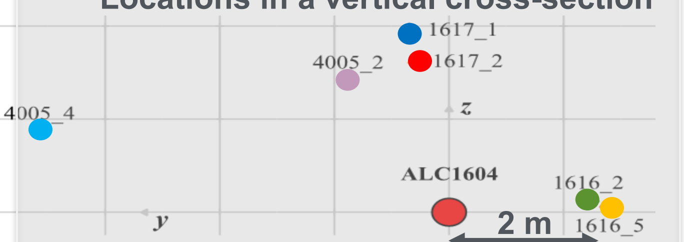



### Pore-pressure




- Temperature in excellent agreement
- Pressure magnitude OK but longer term evolution deviates at some locations

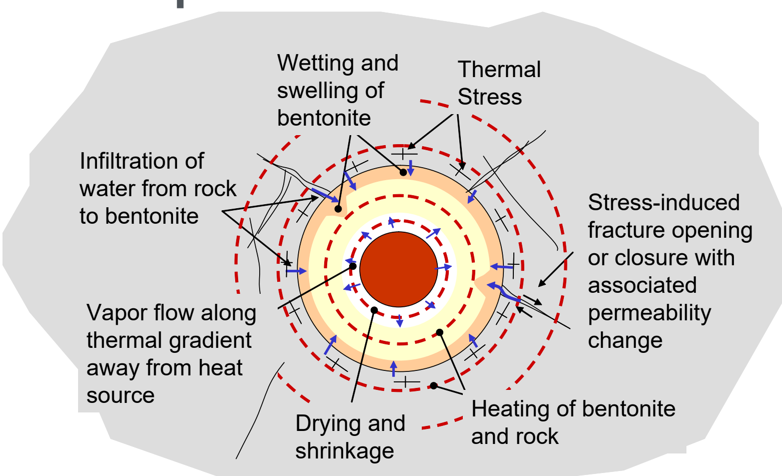
### Locations in a vertical cross-section



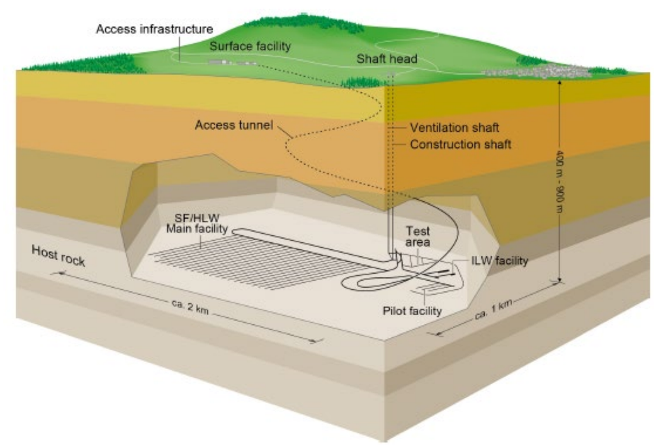
# Output to Geologic Safety Assessment Analysis (GDSA) and Performance Assessment (Pa)

- **Near field of emplacement tunnels in different parts of a repository,** for different FEPs such as nominal case or cases of extensive gas generation.
- **Output** to the PA model: (1) **changes in flow properties** (e.g. permeability and porosity) in the near-field, including the buffer and EDZ, (2) inform PA about local flow created by coupled processes.

**Coupled Processes Model of an Emplacement Tunnel**

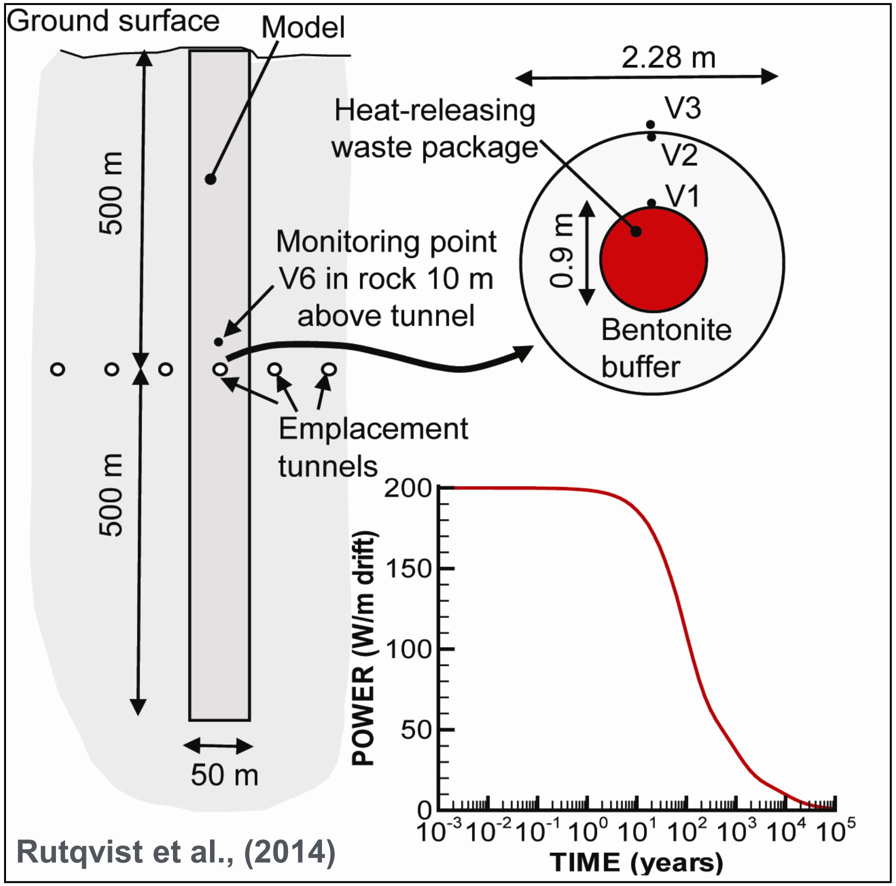


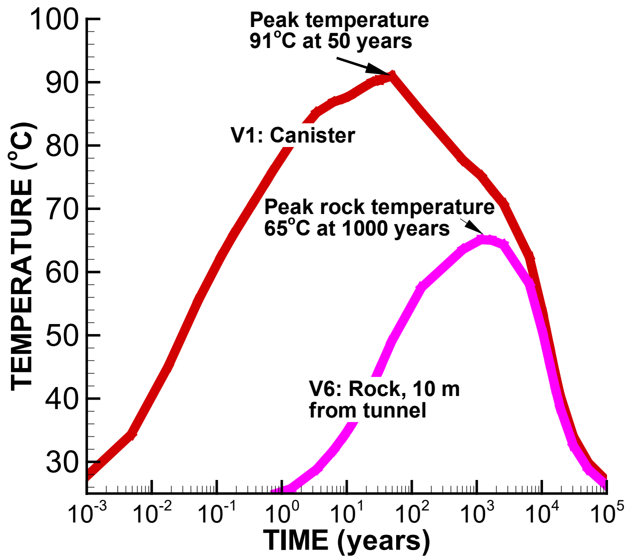

**PA Model of Entire Repository**

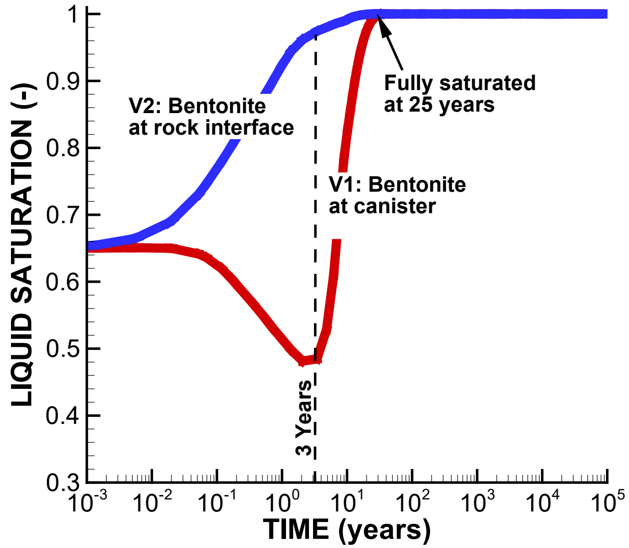



**Example layout from the Swiss Concept (Seiphoori, 2015)**

# Example of Long-term Coupled Processes Simulation of an Emplacement Tunnel

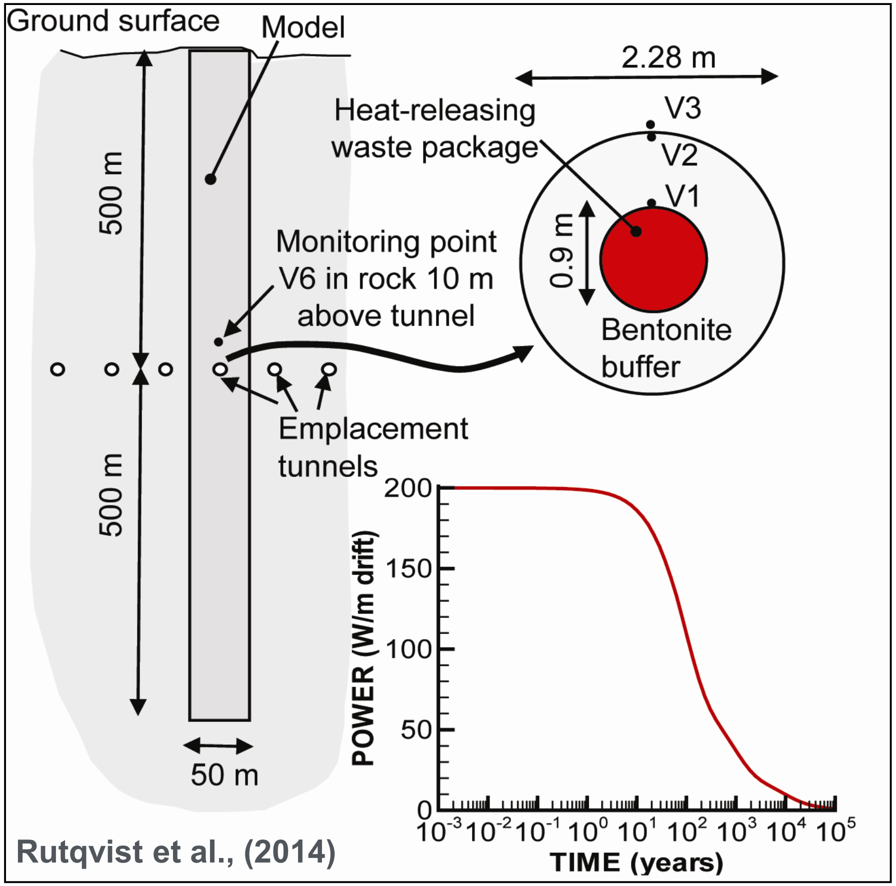


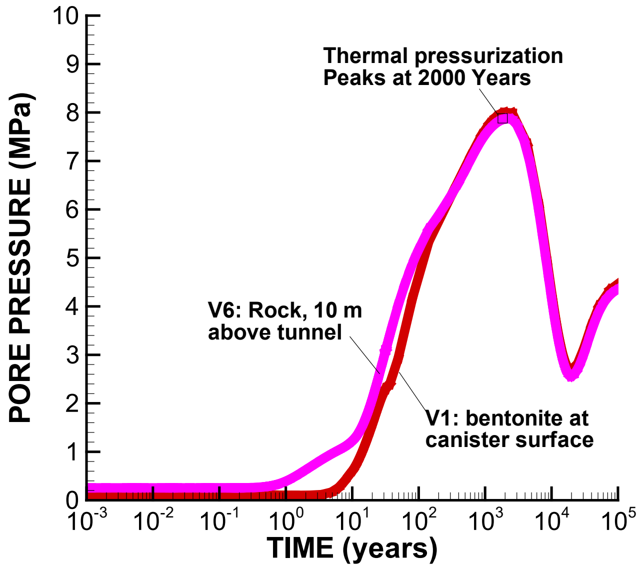



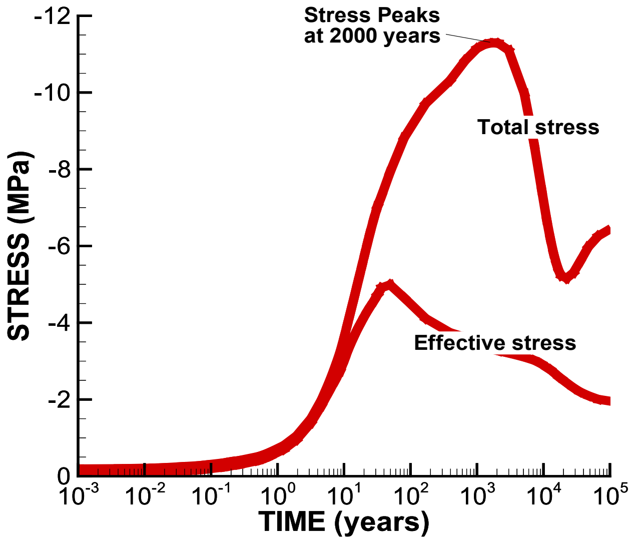




- **Time to peak thermal impact?**
- **Time to full saturation and swelling?**

# Example of Long-term Coupled Processes Simulation of an Emplacement Tunnel



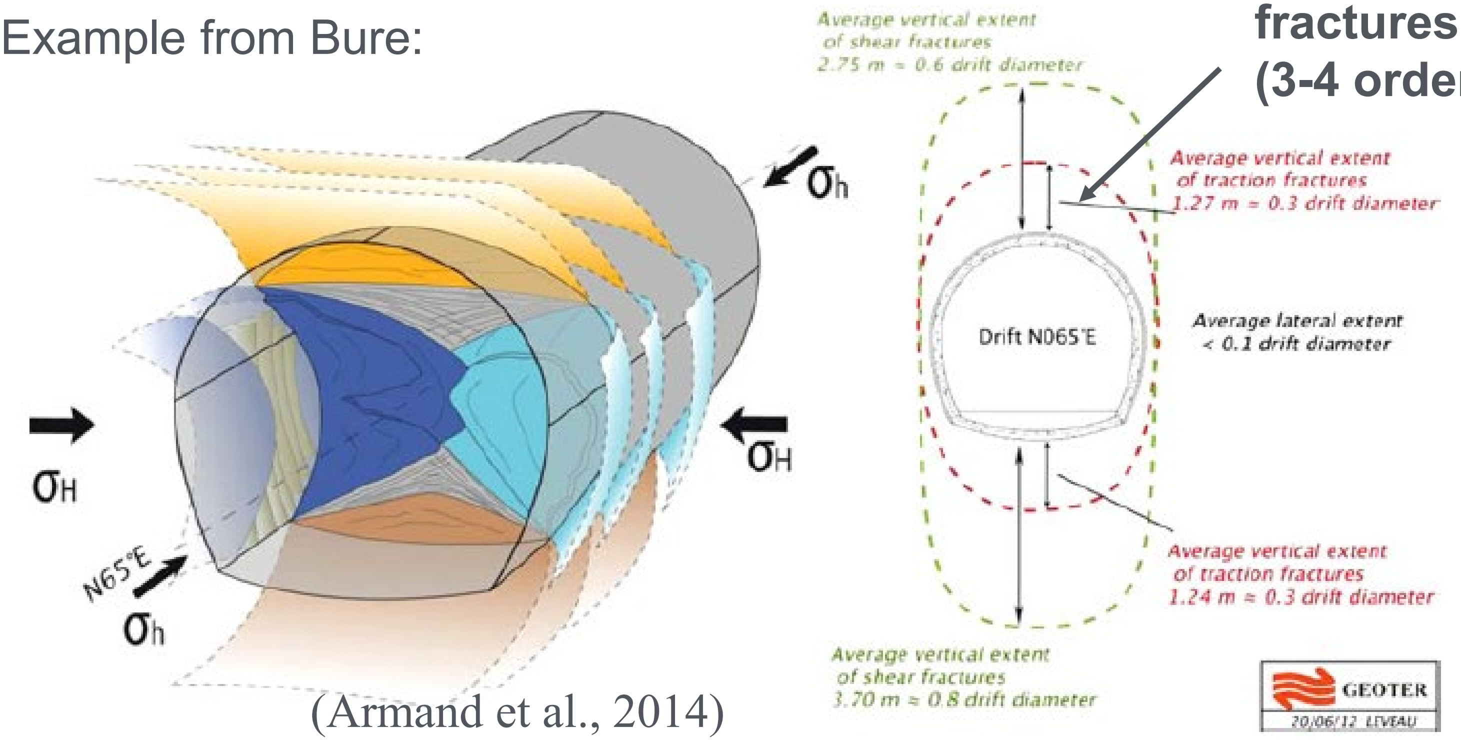

- **Time to peak thermal impact?**
- **Time to full saturation and swelling?**

# Field Observations of Excavation Disturbed Zone (EDZ) in Argillite

- Site specific, i.e. different at Mont Terri and Bure
- Depends on the tunnel direction relative to beddings and stress field

Example from Bure:

**Zone of open fractures k ≈ 1e-17 m$^2$ (3-4 orders increase)**

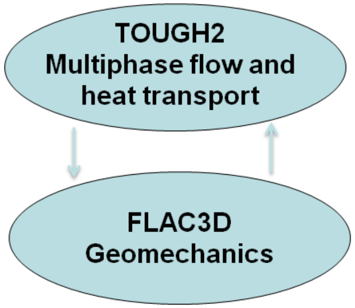



(Armand et al., 2014)

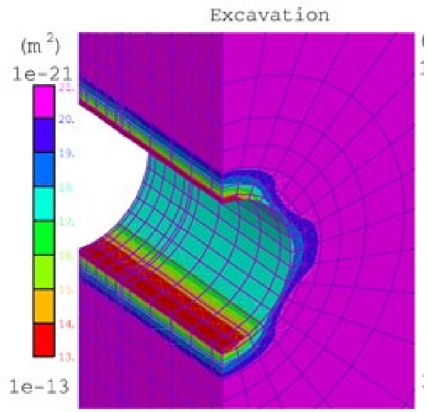
- Sealing and healing observed in laboratory tests and in situ, but underlying mechanisms are not fully understood

# State of the Art and R&D Needs for THM Perturbation in Argillite/Bentonite

- **THM model framework established (TOUGH-FLAC)**
- Constitutive models for bentonite/backfill
  - BBM established, whereas BExM is at the forefront of research for dual-structural behavior
  - Impact of constitutive bentonite behavior on longer-term buffer resaturation processes still not fully understood
- **Constitutive THM models for argillite host rocks**
  - Anisotropic shale THM constitutive model validated
- **Models for EDZ in argillite**
  - Continuum permeability change and damage models, as well as discrete fracture models have been applied
  - No established model for damage, sealing and healing
  - Site specific studies at Mont Terri and Bure URLs
- **Very active research in European Programs**
  - Switzerland, France, Belgium, Germany, UK.,…..

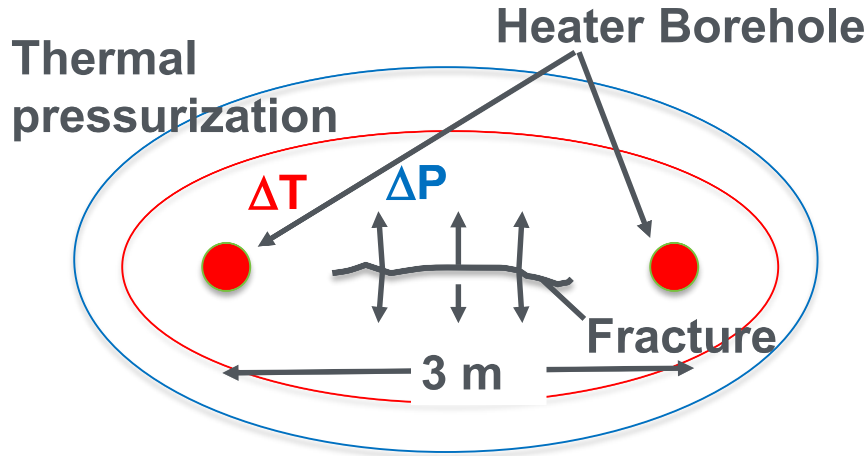




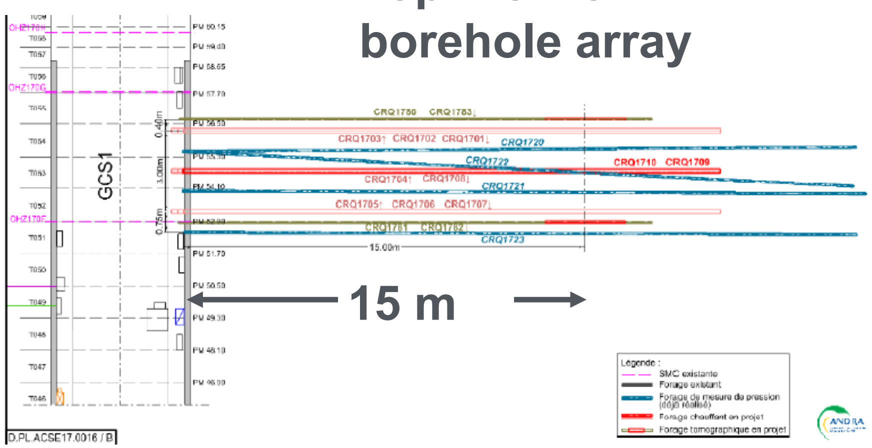


# Potential Future DECOVALEX-2023 Task (Thermal-pressurization Fracturing)

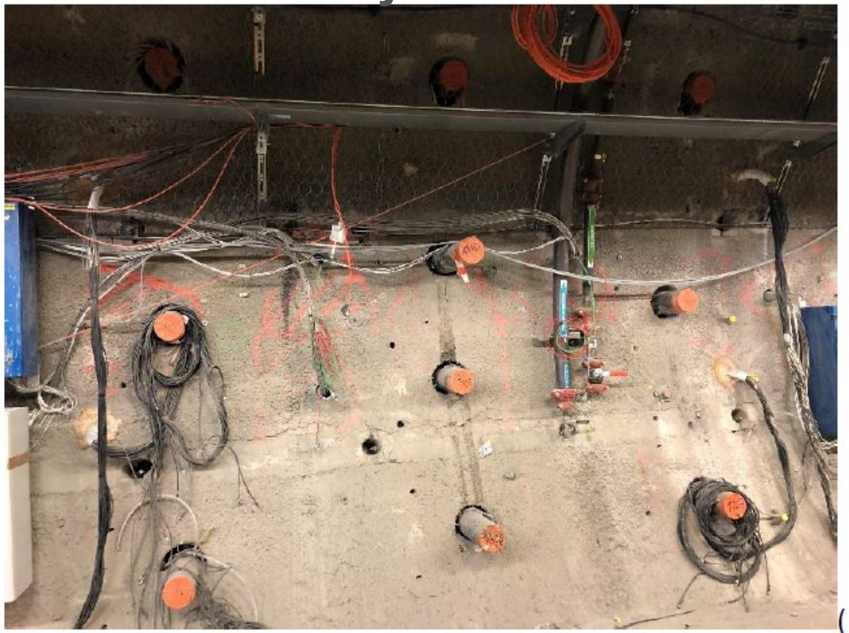
**Task proposed by ANDRA for DECOVALEX-2023 with field data from Bure URL**




**Top View of borehole array**




**Borehole array on tunnel wall**



# Summary

- Much progress has been accomplished in understanding thermo-hydro-mechanical (THM) perturbation in bentonite/argillite, through international research collaborations
- Advanced numerical modeling tools have been developed and underground experiments provide data for model testing and validation at a relevant scale
- Modeling of such experiments has shown that thermal processes can be predicted with confidence, whereas hydraulics and mechanics are more uncertain
- Model input parameters for bentonite and Argillite can be up-scaled from laboratory data, but certain parameters, such as those for the excavation disturbed zone are best characterized in situ

# References

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# Acronyms and Abbreviations

| | |
|---|---|
| ALC | Micro-tunnel experiment at Bure |
| ANDRA | National Radioactive Waste Management Agency, France |
| BExM | Barcelona Expansive Model |
| BBM | Barcelona Basic Model |
| BGR | Federal Institute for Geosciences & Natural Resources, Germany |
| CAS | Chinese Academy of Sciences, China |
| CNSC | Canadian Nuclear Safety Commission, Canada |
| COx | Callovo-Oxfordian claystone |
| DECOVALEX | DEvelopment of COupled Models and their VALidation Against EXperiments |
| EBS | Engineered Barrier System |
| EDZ | Excavation Damage Zone (or Excavation Disturbed Zone) |
| ENSI | Swiss Federal Nuclear Safety Inspectorate, Switzerland |
| FE | Full-scale Emplacement Experiment at Mont Terri |
| FEPs | Features, Events, and Processes |
| FLAC | Fast Lagrangian Analysis of Continua |
| GDSA | Geological Disposal Safety Assessment |
| HE-E | Half-scale heater experiment at Mont Terri |
| KAERI | Korea Atomic Energy Research Institute, Republic of Korea |
| LBNL | Lawrence Berkeley National Laboratory |
| NAGRA | Swiss waste management organization |
| PA | Performance Assessment |
| Swisstopo | Federal Office of Topography, Switzerland |
| TED | Thermal Experiment |
| THM | Thermo-hydro-mechanical |
| THMC | Thermo-hydro-mechanical-chemical |
| TOUGH | Transport Of Unsaturated Groundwater and Heat |

# Questions?

Clean. **Reliable. Nuclear.**