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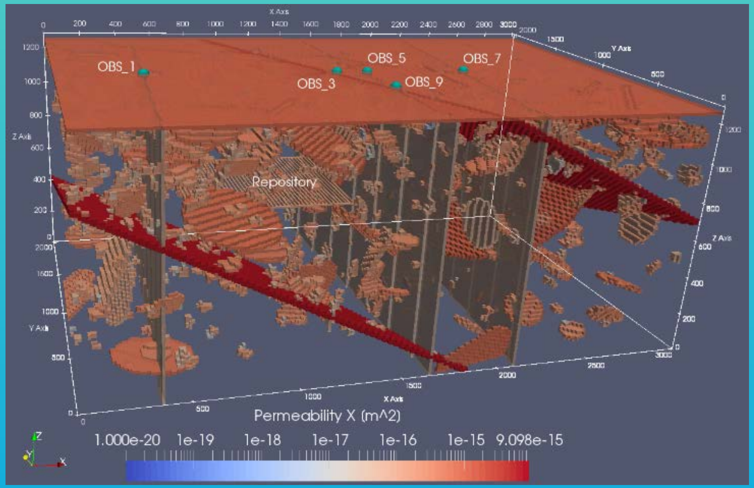

Modeling of the Long-Term Integrity of the Argillite Host Rock Barrier

U.S. Nuclear Waste Technical Review Board
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U.S. DEPARTMENT OF ENERGY
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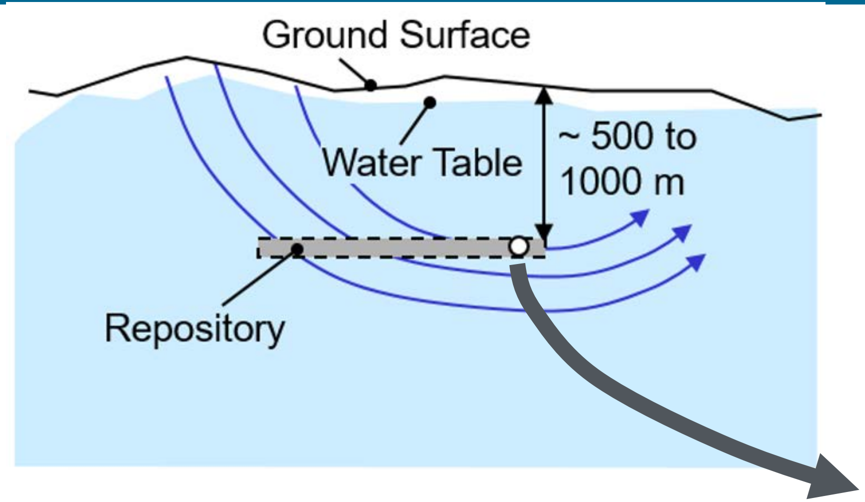
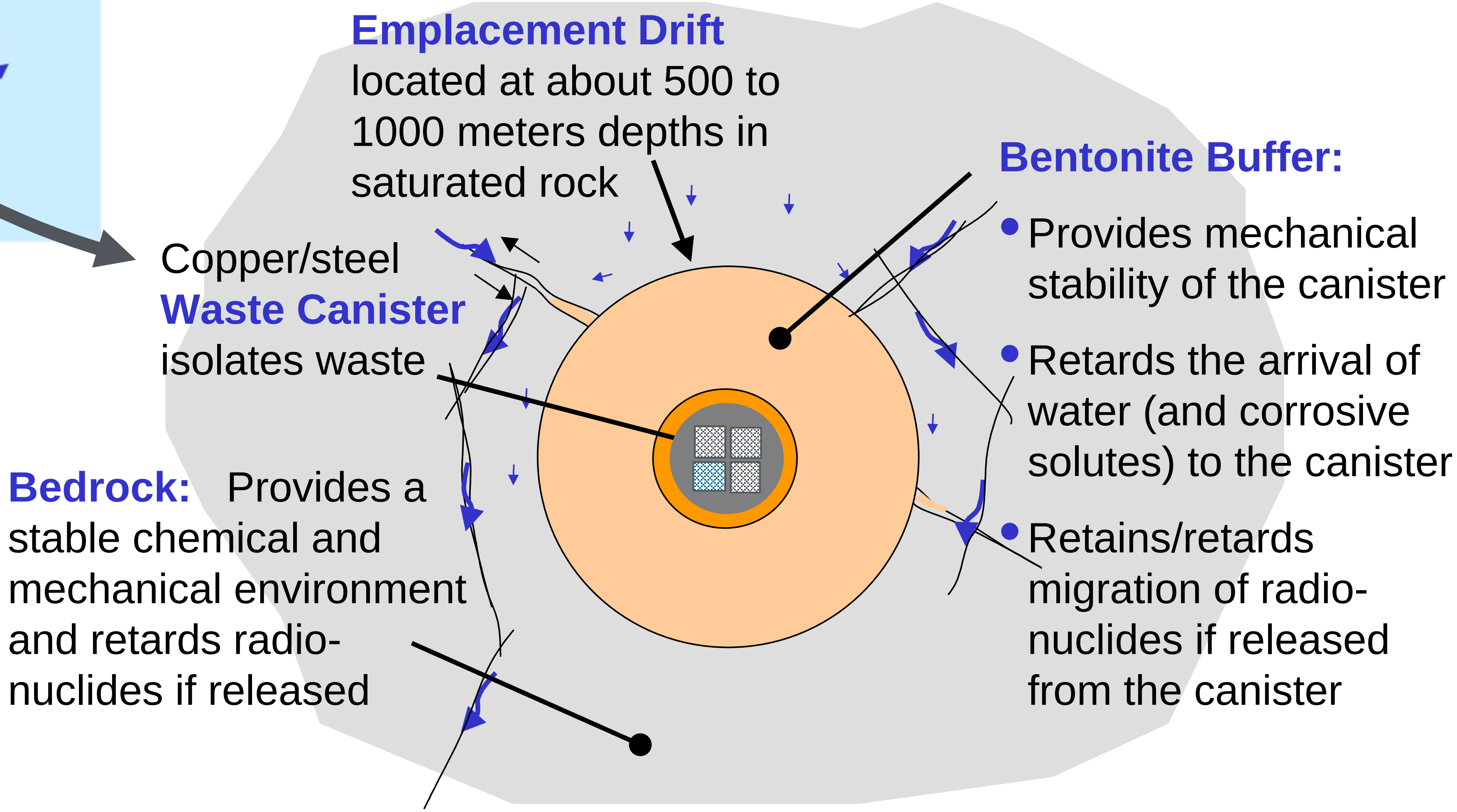
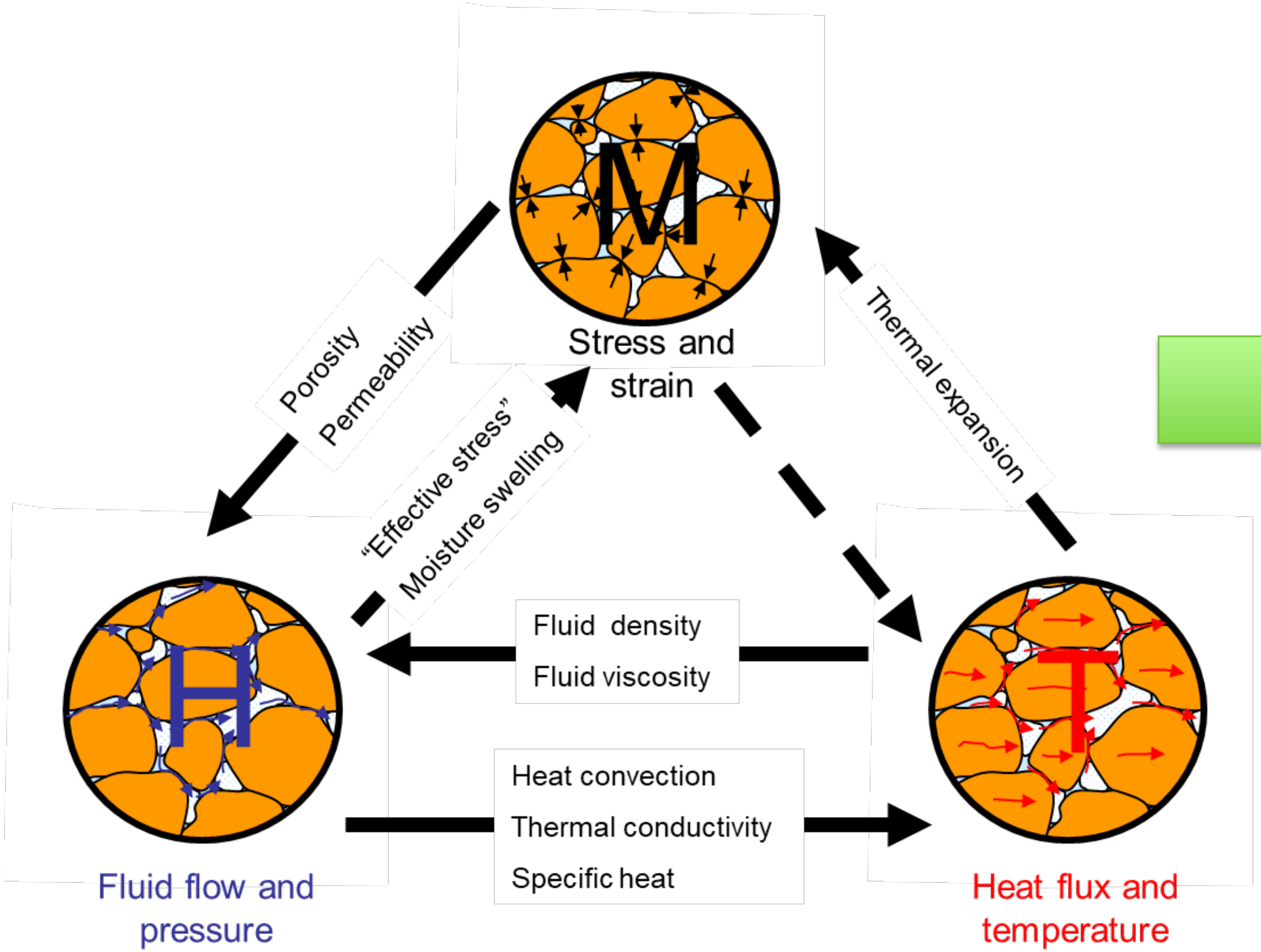
Barriers and Functions



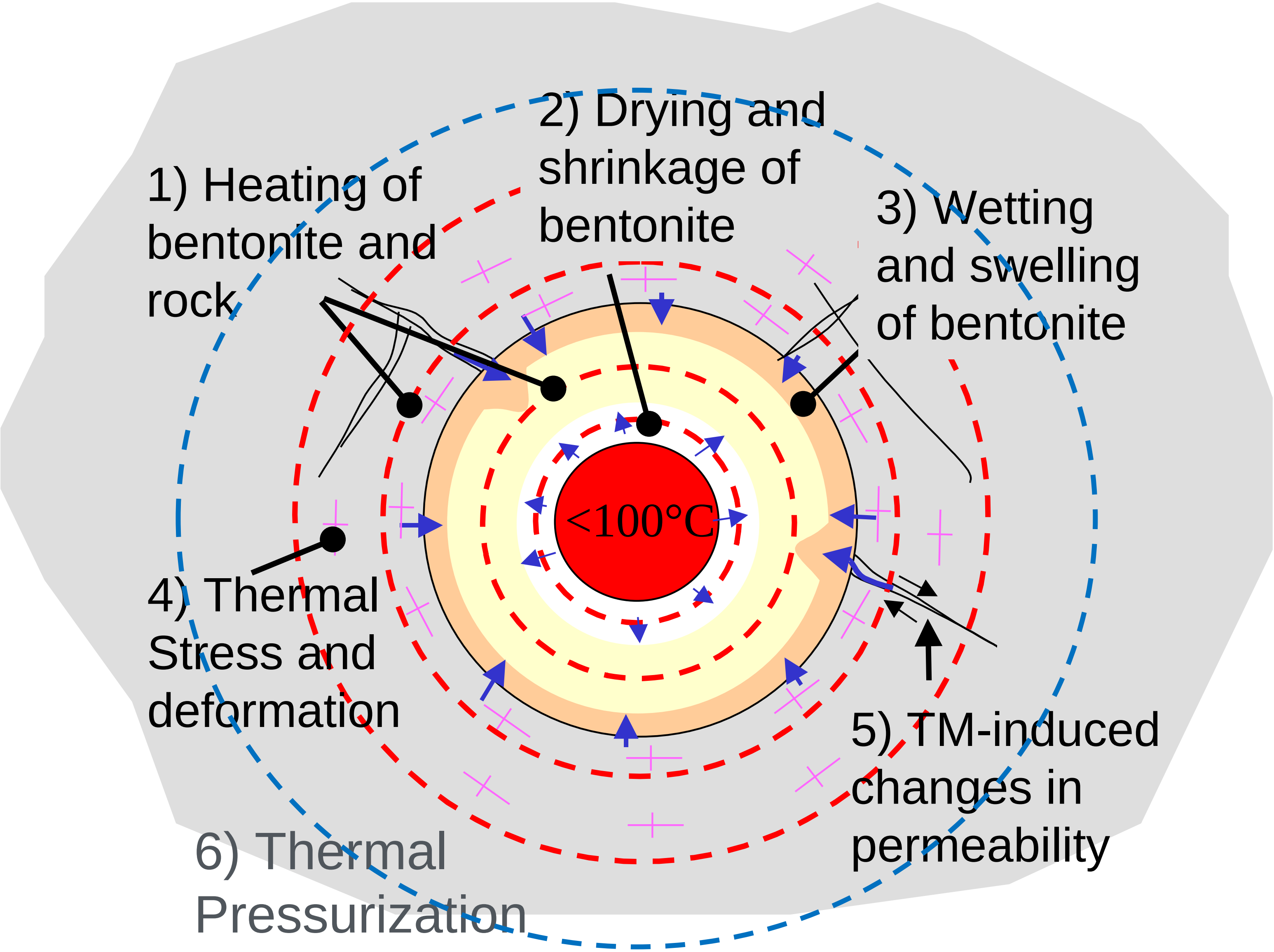


Thermal-Hydraulic-Mechanical (THM) Couplings



Impact on barrier integrity and contaminant transport?

Short Term (0 to 1000 years) Thermally Driven Coupled THM Processes



(Rutqvist, 2015)

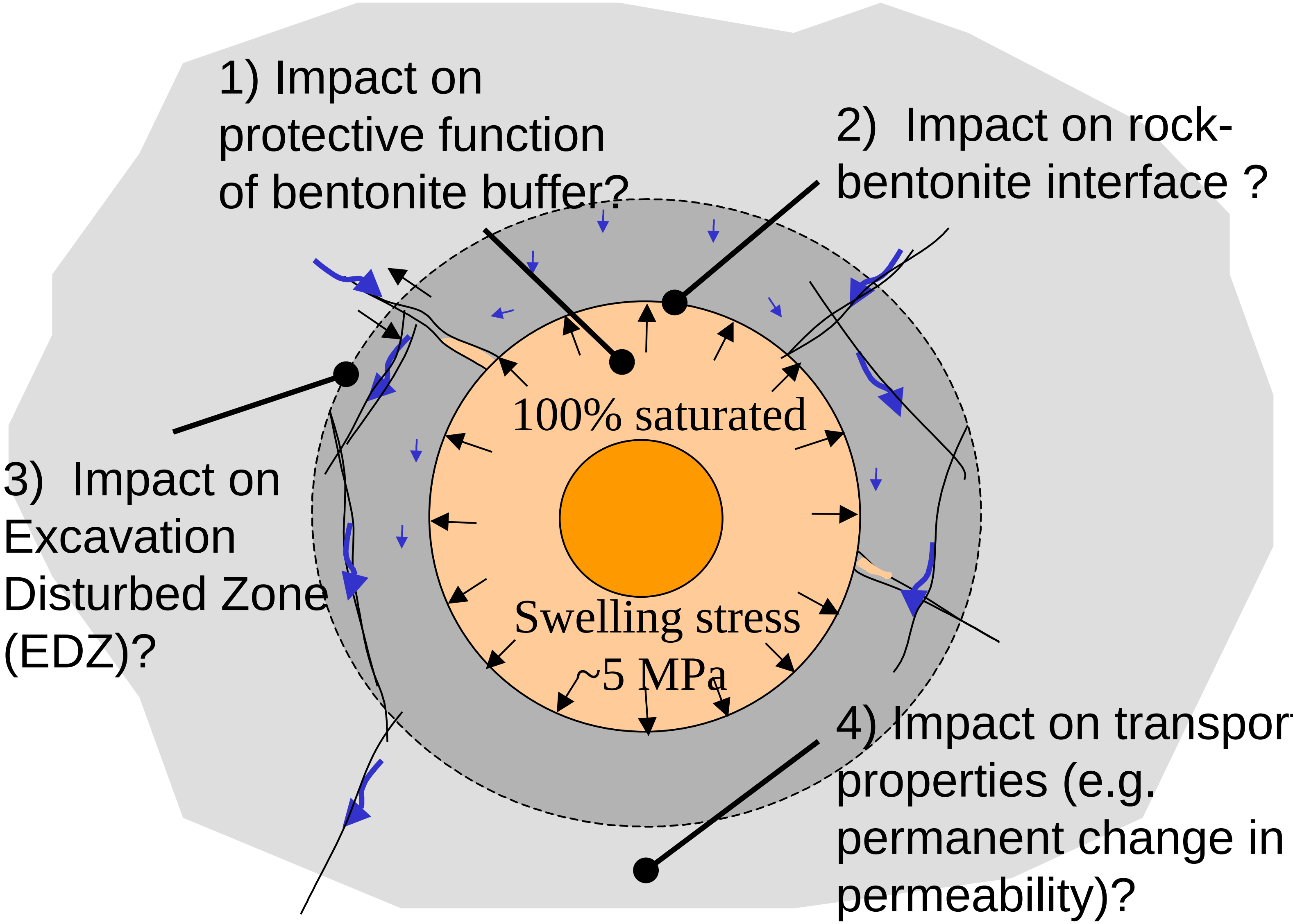
Long Term (1000 to 100,000 years) Impact of Coupled THM Processes

1) Impact on protective function of bentonite buffer?

2) Impact on rock-bentonite interface ?

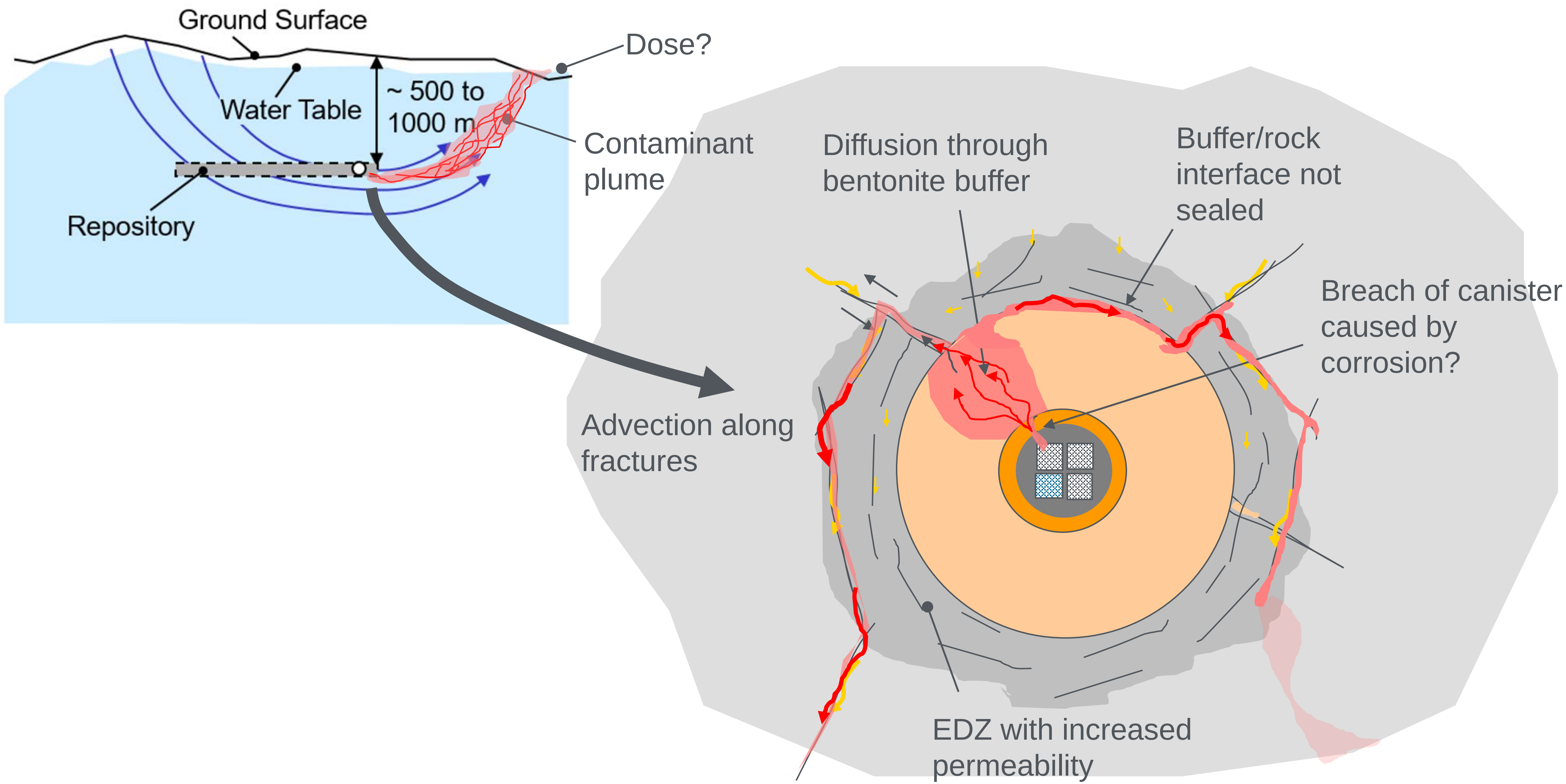
3) Impact on Excavation Disturbed Zone (EDZ)?

4) Impact on transport properties (e.g. permanent change in permeability)?



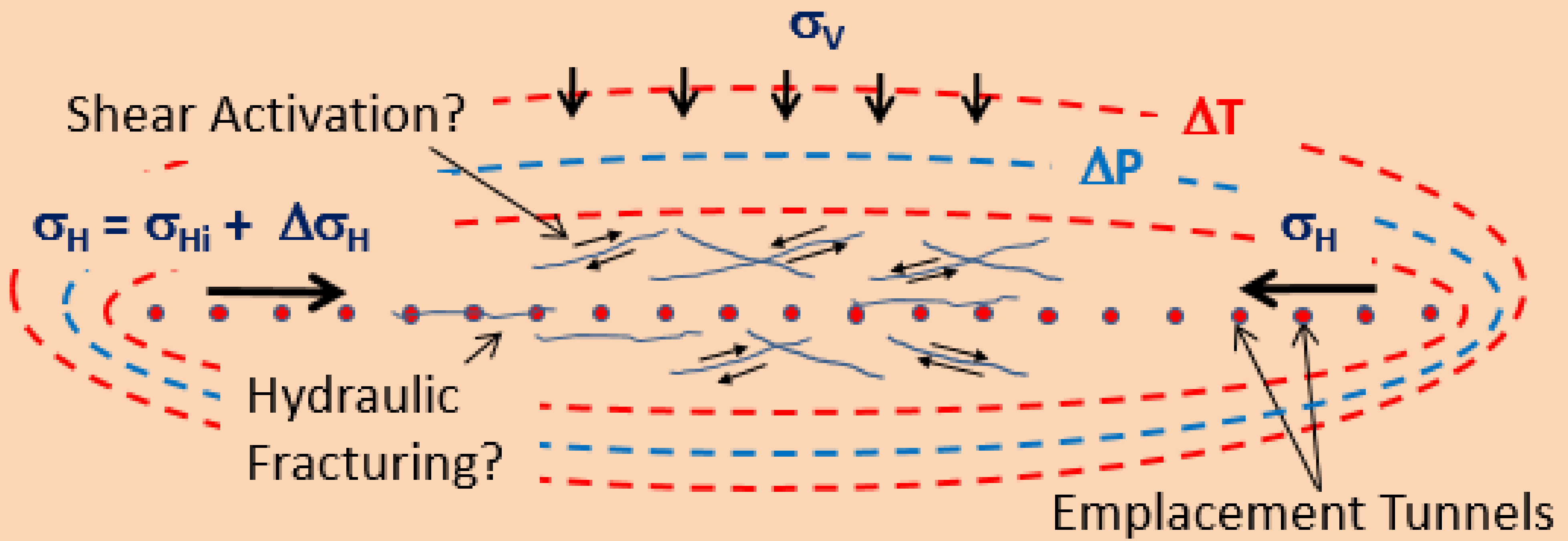
(Rutqvist, 2015)

Breached Barriers (Illustrated)



(Rutqvist, 2015)

Repository THM-Induced Stress Changes



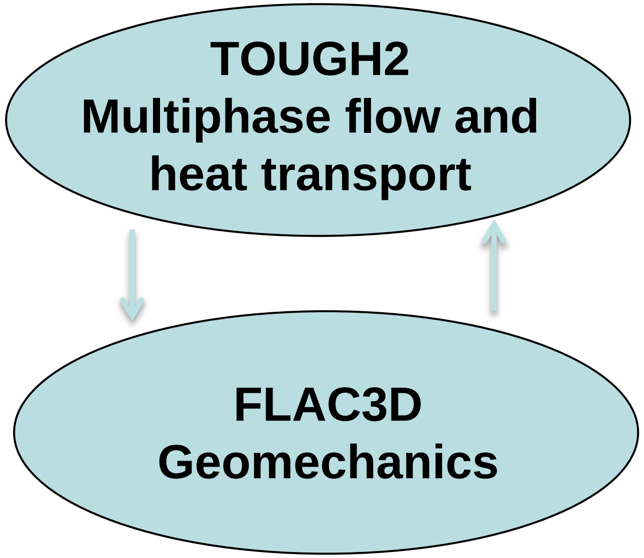
(Rutqvist, 2020)

- Repository temperature change (ΔT) results in thermal pressurization (ΔP)
- ΔT and ΔP results in thermal stress and poro-elastic stress ($\Delta\sigma_H$)
- **Impact on host rock integrity? (Fracturing?, Shear?, Opening of flow paths?)**

A Thermo-Hydro-Mechanical Model Framework

TOUGH-FLAC Simulator:

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



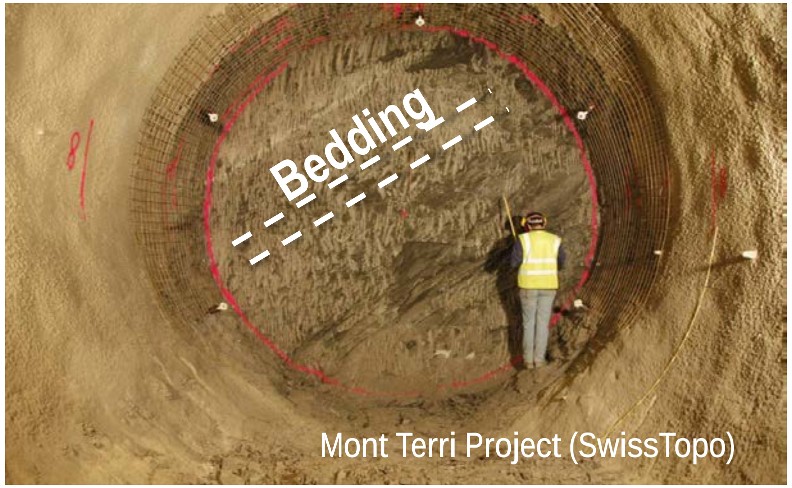
(Rutqvist et al., 2002; Rutqvist 2011; 2017)

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

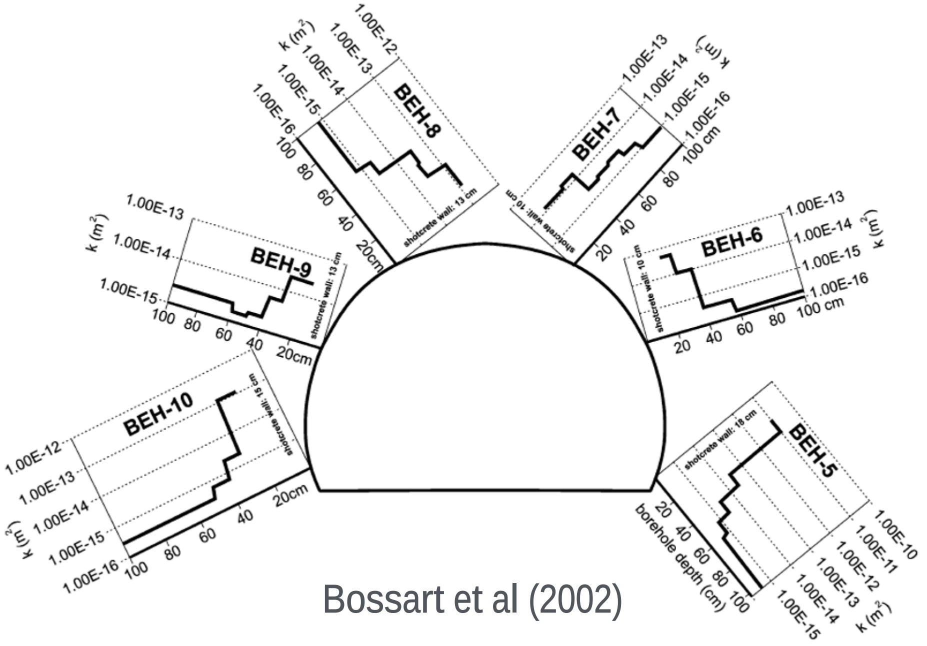
By adding to existing model capability

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

Argillite Host Rock Modeling



Mont Terri Project (SwissTopo)



Bossart et al (2002)

1) Anisotropic THM properties

- Mechanical model considering weak planes along bedding (e.g. reduced shear strength)
- Higher thermal conductivity along bedding
- Higher permeability along bedding

2) Excavation Disturbed Zone (EDZ)

- Anisotropic stress-dependent permeability
- Brittle versus more ductile (sealing) argillite
- Models could be calibrated against field measurements (site specific)

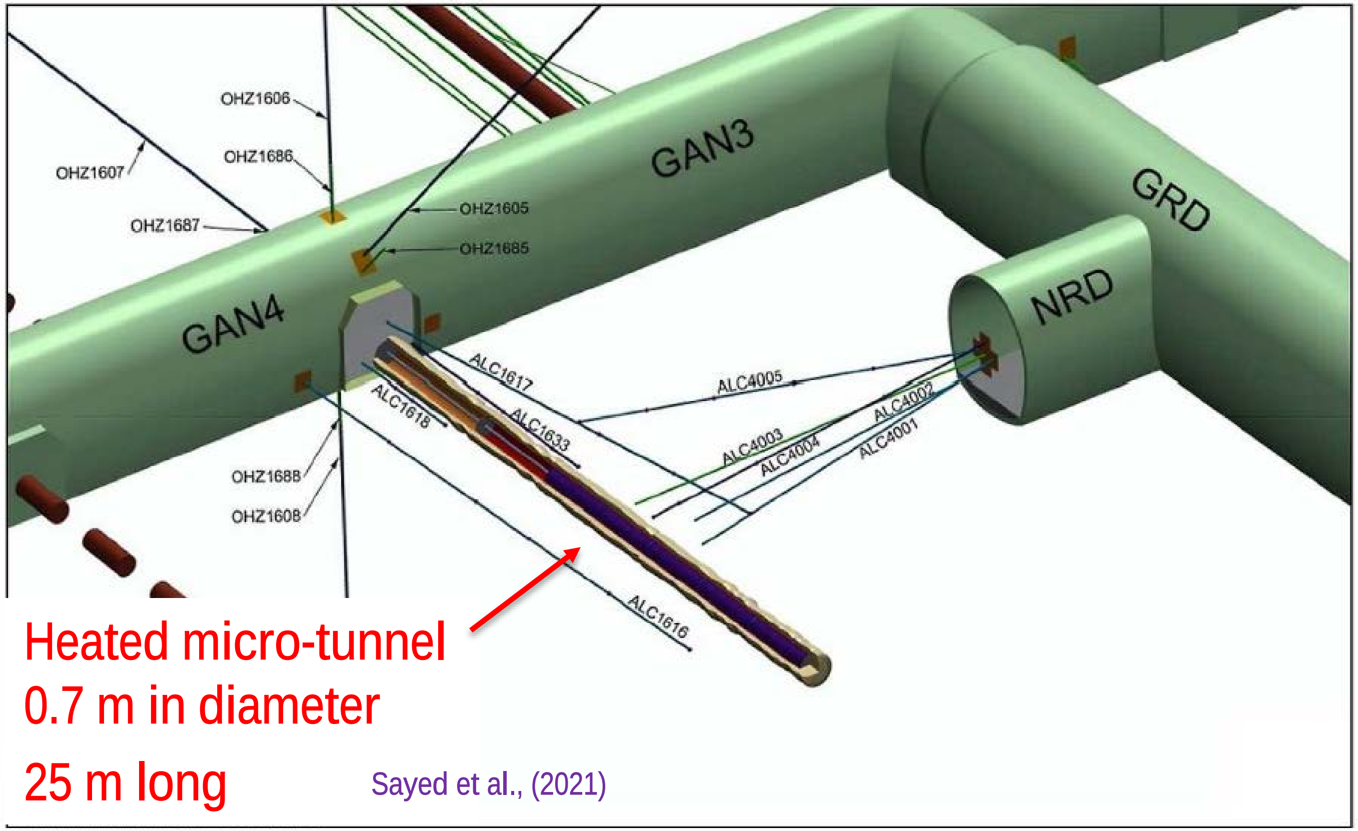
Model Verification and Validation in Argillite

1. Analytical solutions (thermo-poro-elasticity)
2. Laboratory experiments (Argillite THM properties)
3. Experiments at Mont Terri (Opalinus Clay)
    - HE-D thermal-pressurization (DECOVALEX-2015)
    - HE-E half-scale bentonite-argillite interaction (DECOVALEX-2015)
    - Fault slip experiment (DECOVALEX-2019)
    - FE-E Full-scale emplacement (DECOVALEX-2023)
4. Experiments at Bure (Cox Claystone)
    - TED Borehole scale heater thermal-pressurization (DECOVALEX-2019)
    - ALC Micro-tunnel heater thermal-pressurization (DECOVALEX-2019)
    - Thermal and gas fracturing experiments (DECOVALEX-2023)

- TOUGH-FLAC code
- Argillite THM model
- Bentonite THM model
- Compare with data
- Compare with other codes in DECOVALEX
- Compare with other models in DECOVALEX

Modeling of Thermal Pressurization Experiment at Bure (DECOVALEX-2019)

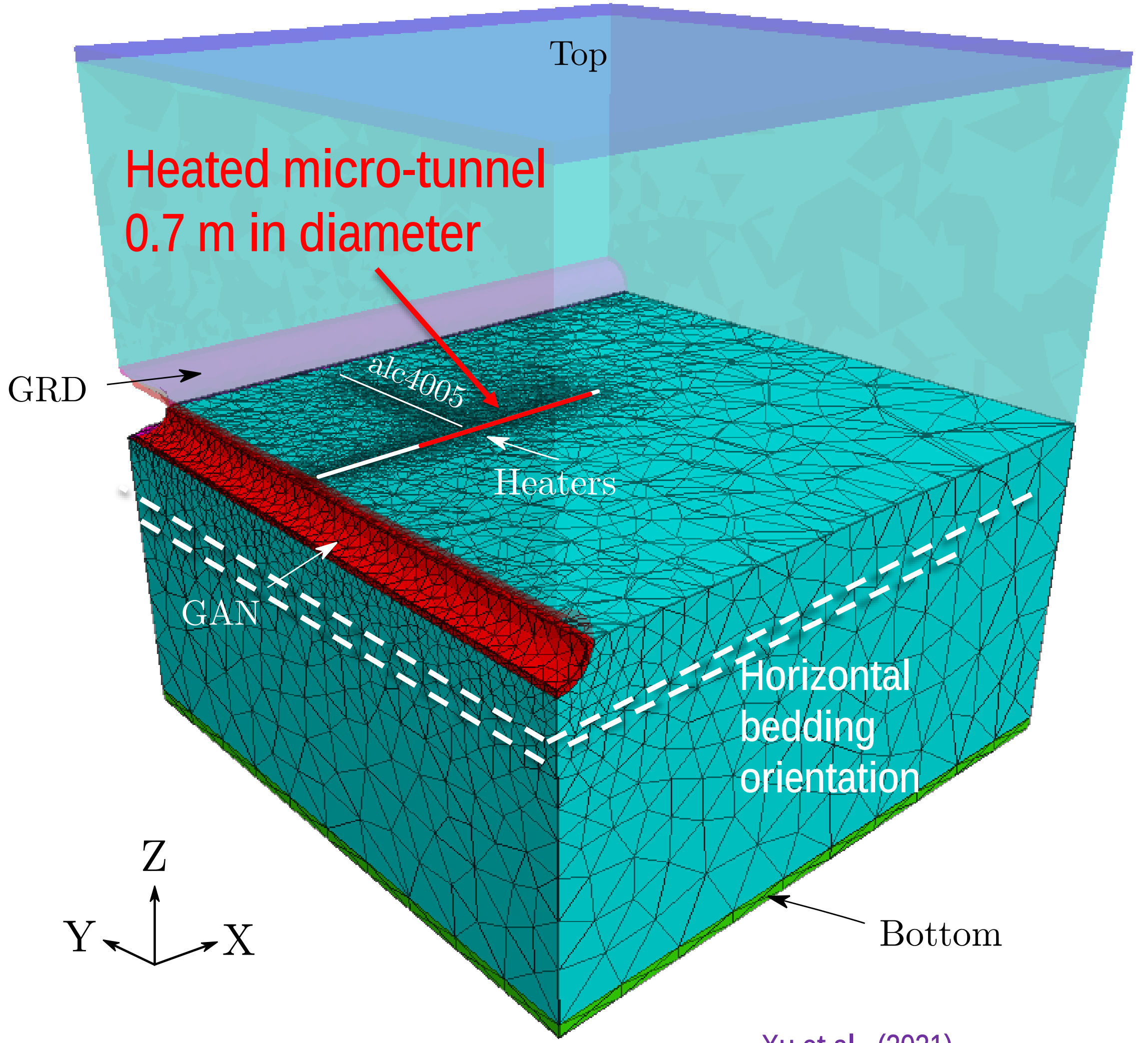
The Micro-Tunnel Experiment in Cox Claystone at Bure



Sayed et al., (2021)

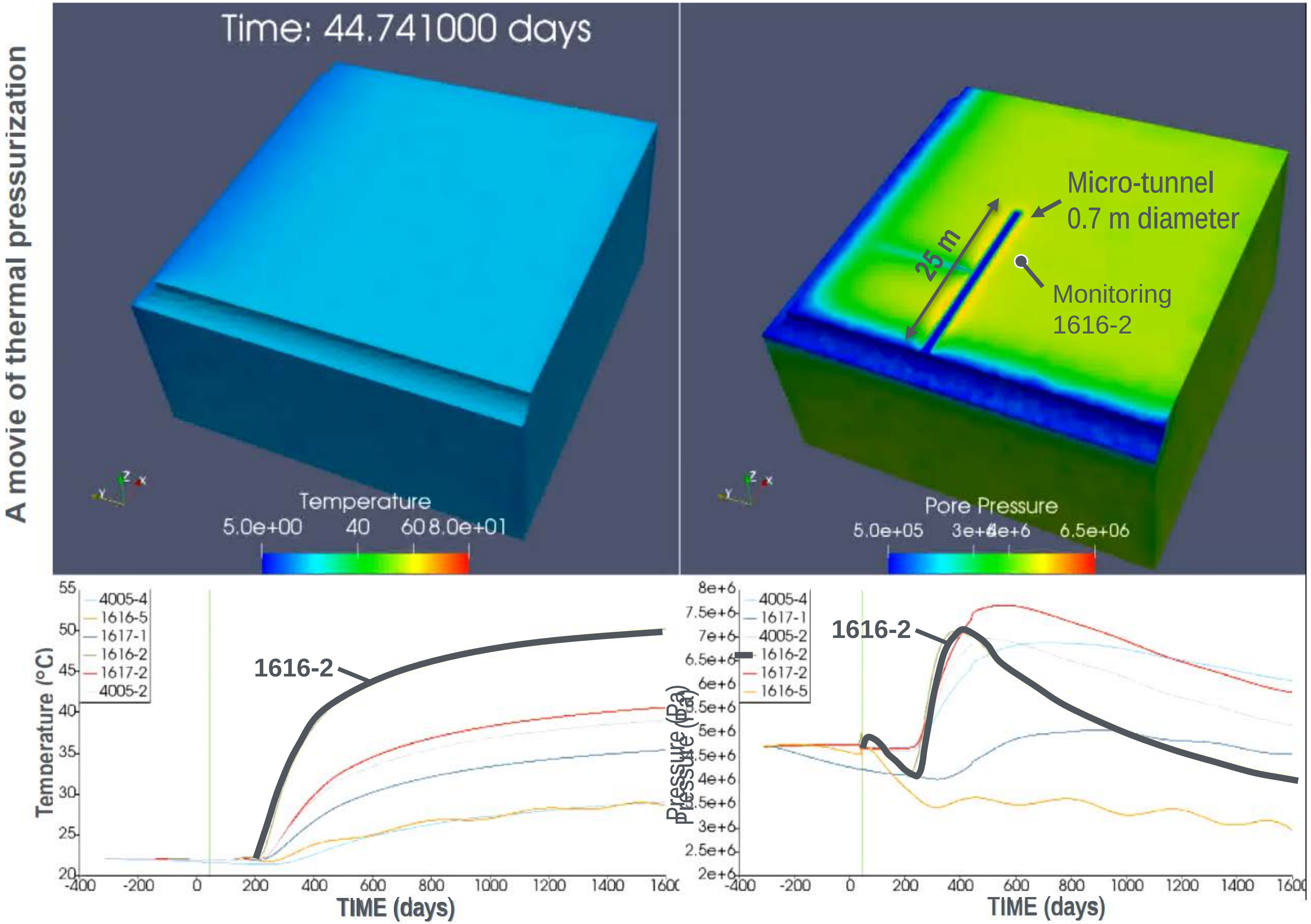
- Four years of heating up to about 50°C
- 5 DECOVALEX-2019 modeling teams and models
- Properties from modeling of previous experiment at Bure
- Compare predicted temperature and pressure responses

Numerical Model



Xu et al., (2021)

Modeling of Thermal Pressurization Experiment at Bure (DECOVALEX-2019)



Xu et al., (2021)

Modeling of Thermal Pressurization Experiment at Bure (DECOVALEX-2019)

A movie of thermal pressurization

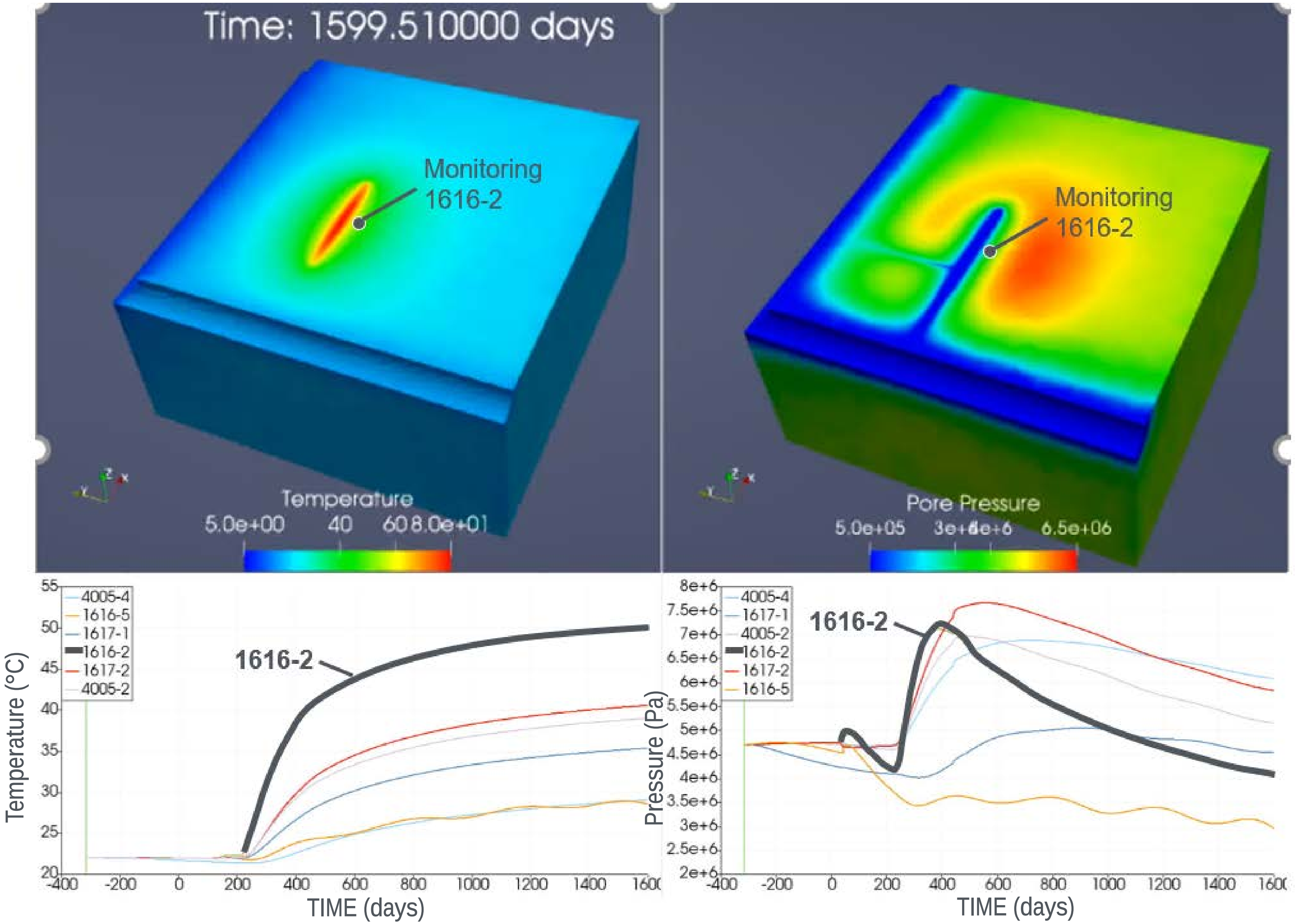
Temperature (°C)

TIME (days)

TIME (days)

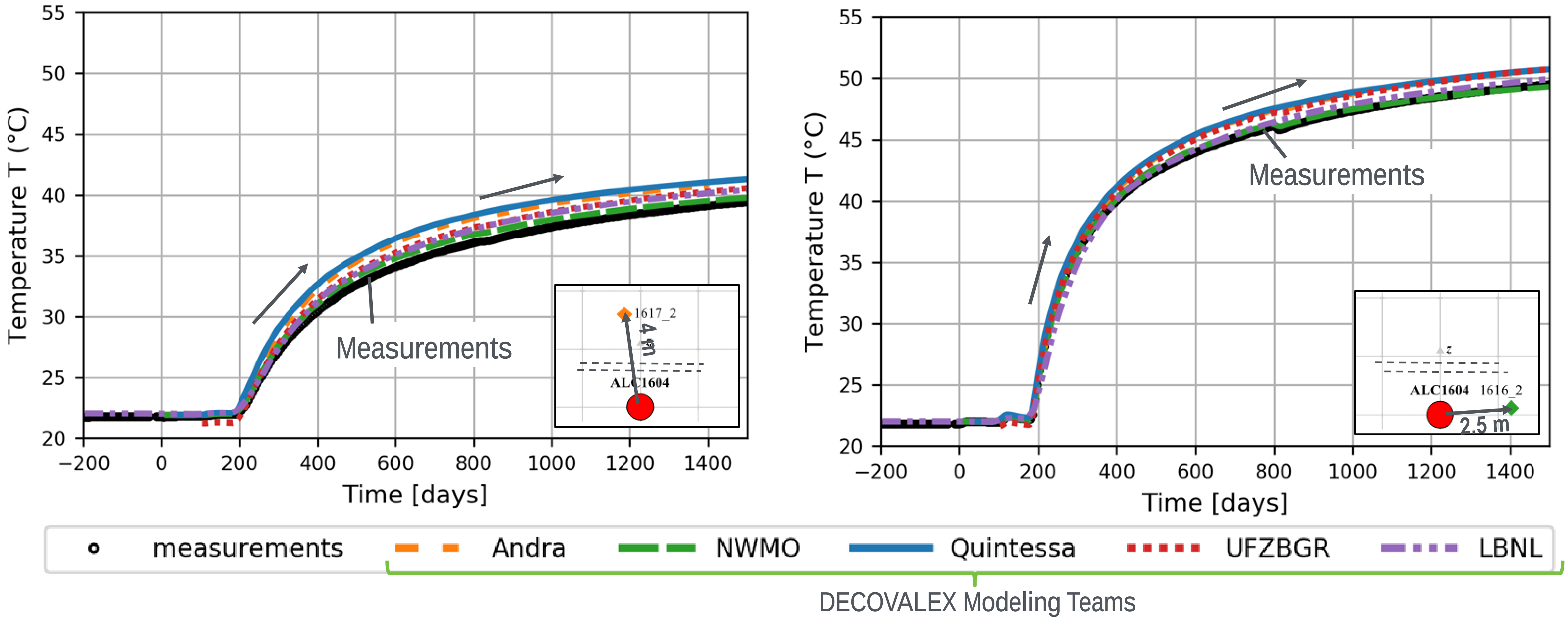
Xu et al., (2021)

Modeling of Thermal Pressurization Experiment at Bure (DECOVALEX-2019)



Xu et al., (2021)

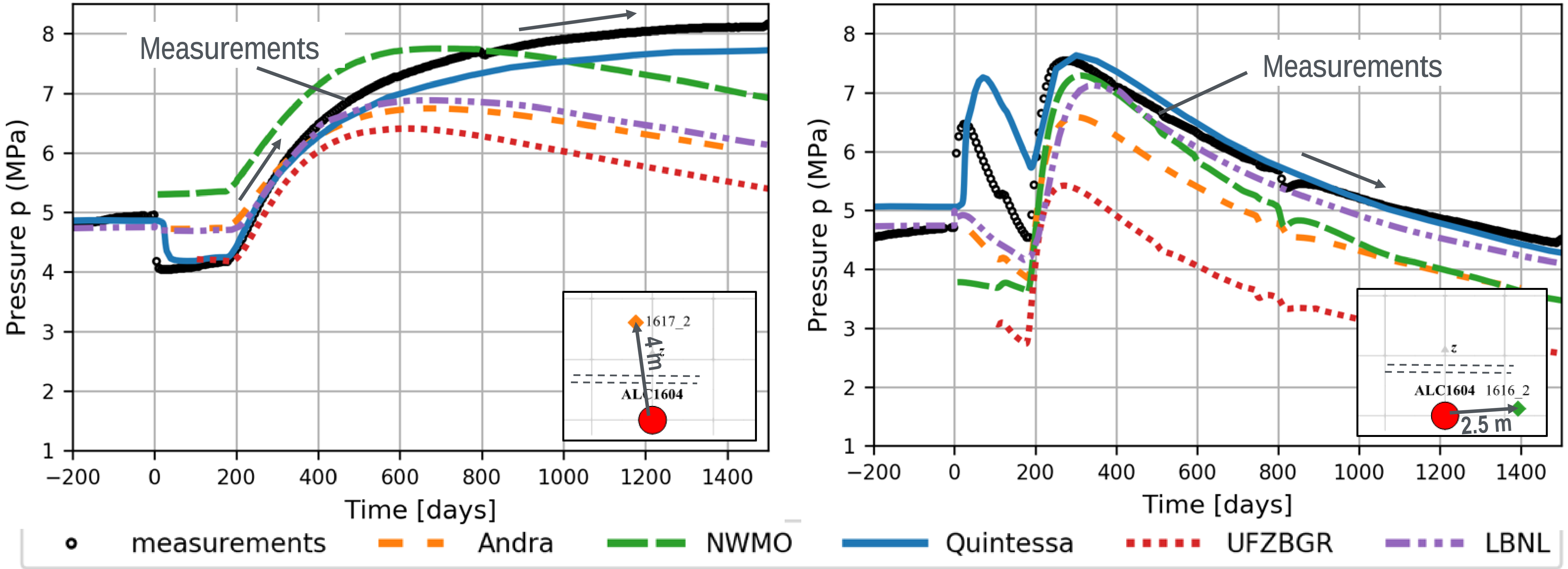
Modeling of Thermal Pressurization Experiment at Bure (DECOVALEX-2019)



- **Anisotropic temperature evolution accurately predicted by all modeling teams**

Sayed et al., (2021)

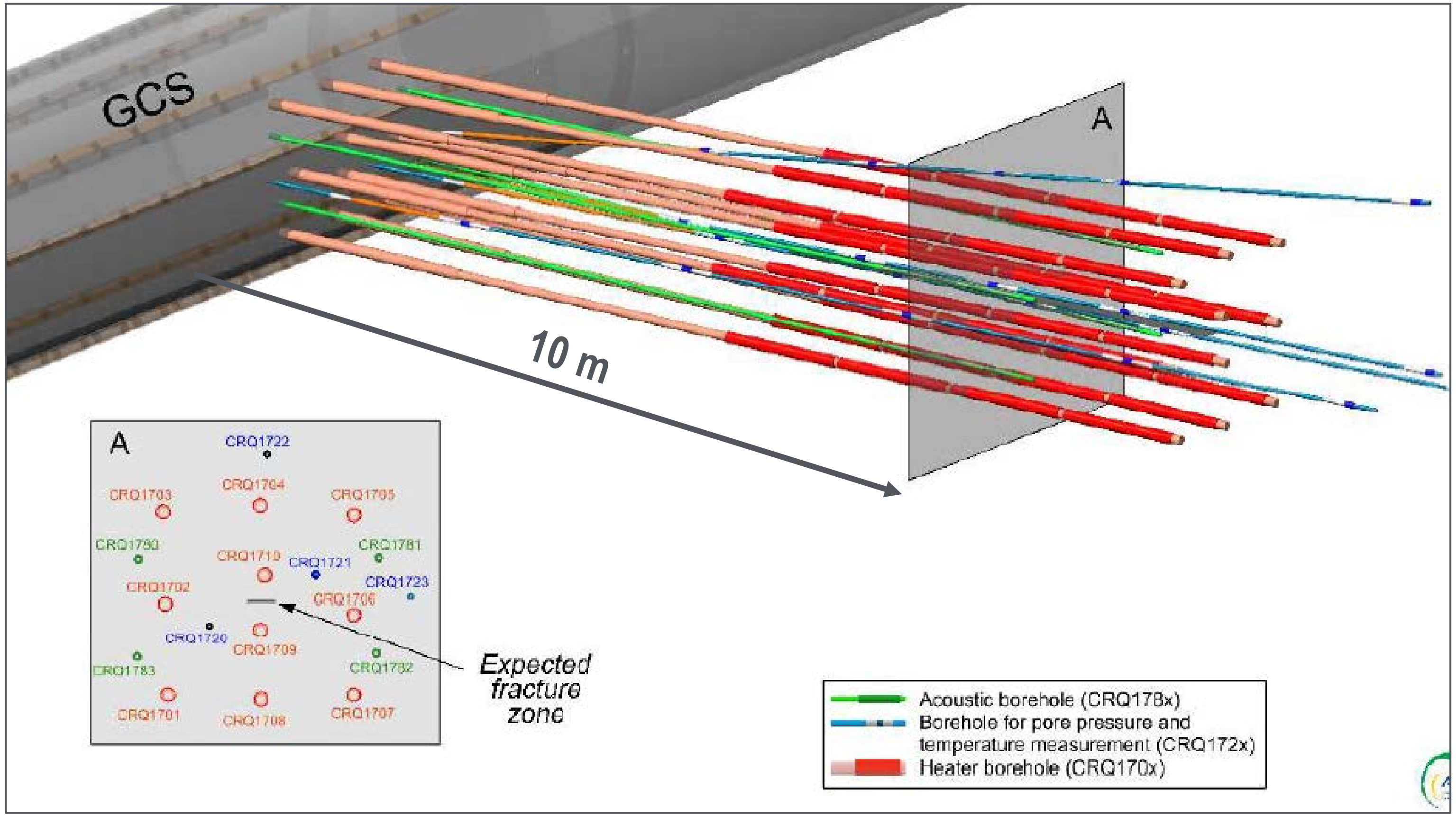
Modeling of Thermal Pressurization Experiment at Bure (DECOVALEX-2019)

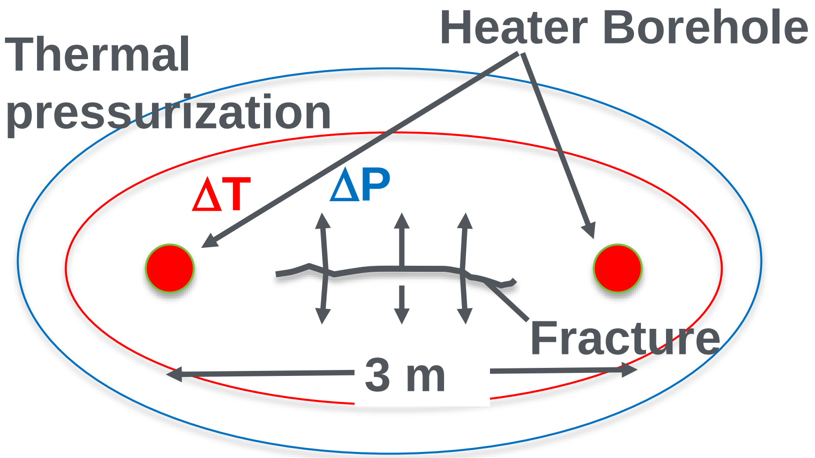


- Some deviations between measured and modeled anisotropic pressure evolution
- Deviations attributed to complex excavation effects and spatial variability in permeability
- Quintessa (blue line) is calibrated model results

Sayed et al., (2021)

Modeling Thermal-Pressurization Fracturing at Bure in COx claystone (Ongoing in DECOVALEX-2023)





Borehole array on tunnel wall

- Two years with heat pulses up to about 100°C
- 5 DECOVALEX-2023 modeling teams and models
- Compare temperature, pressure, stress, fracturing
- Fracturing and fracture sealing?

Summary of Bure Argillite Modeling

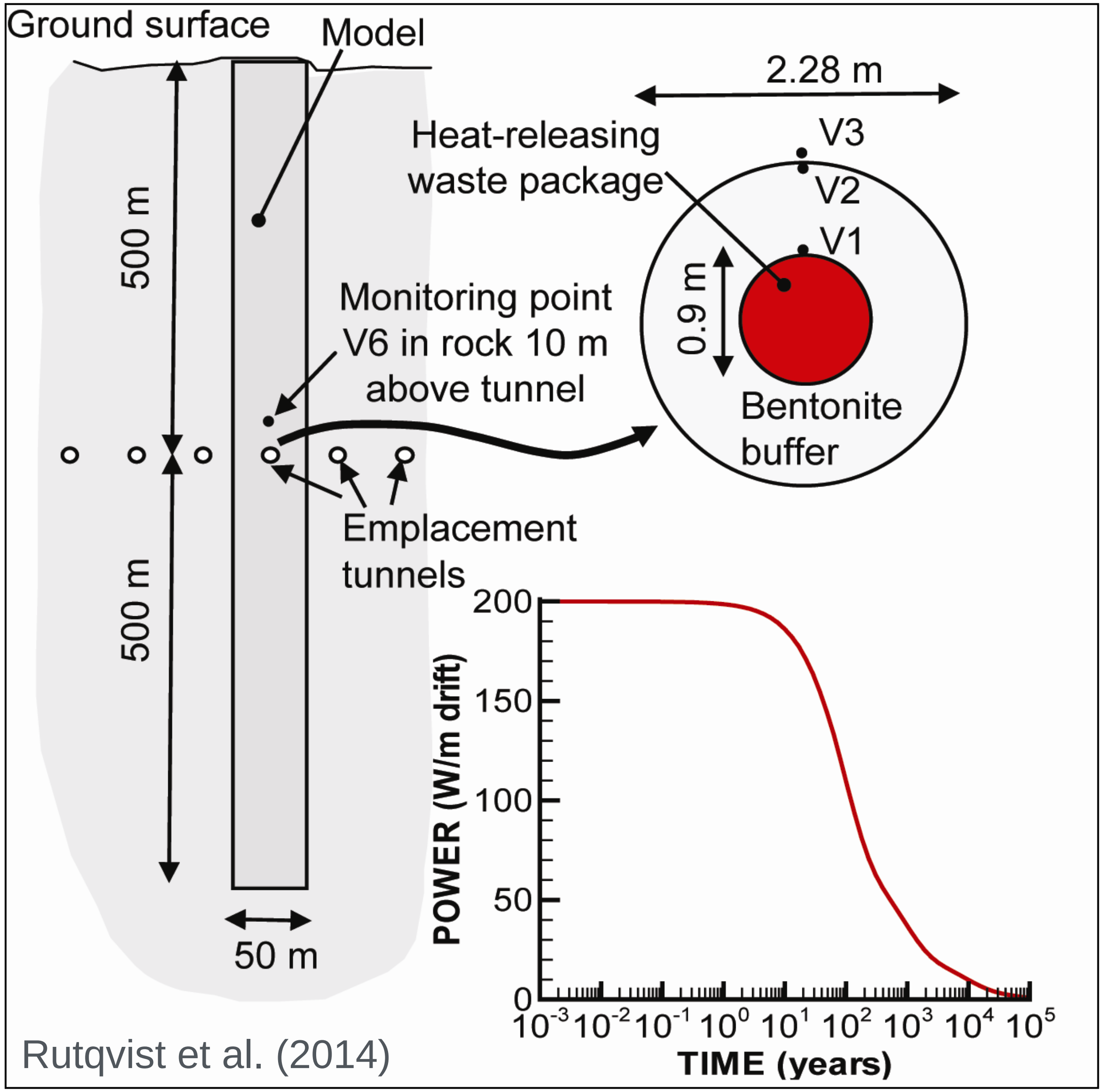
- Key parameters: anisotropic thermal conductivity and permeability, fluid and solid thermal expansion, solid-fluid storage, tensile strength
- Temperature and pressure can be predicted more confidently than mechanical responses
- Sensitivity study quantifies spatial variability in properties
- Such variability in properties can be applied for bounding predictions of the long-term repository response

Modeling Long-term Repository Behavior

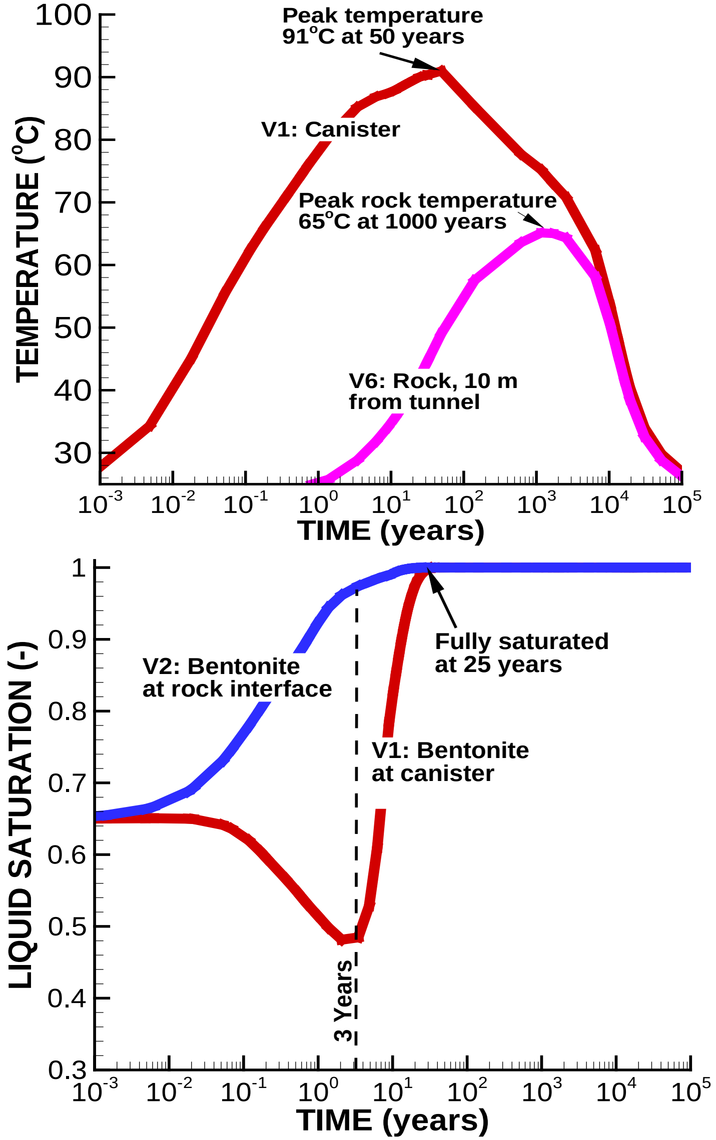
Three aspects:

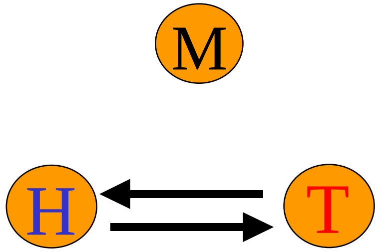
1. Repository THM responses of the argillite barrier
2. Near-field EDZ THM response
3. Impact of creep in the argillite barrier (ductile-brittle)

Long-term Coupled Processes Simulation



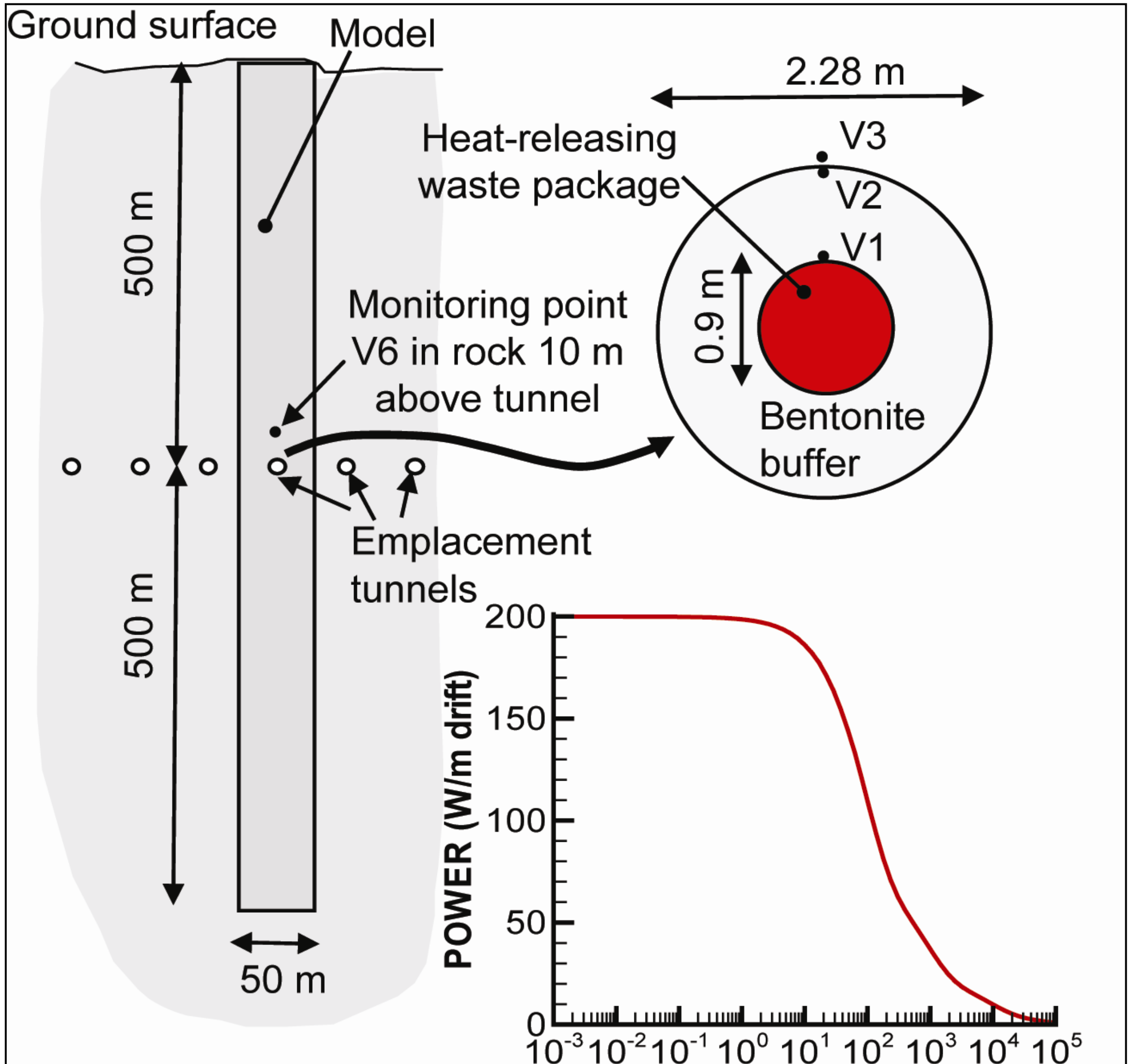
Rutqvist et al. (2014)



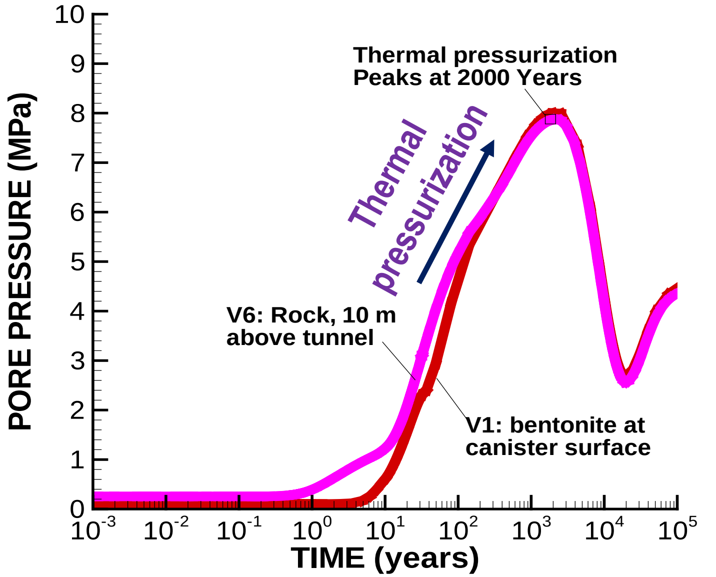


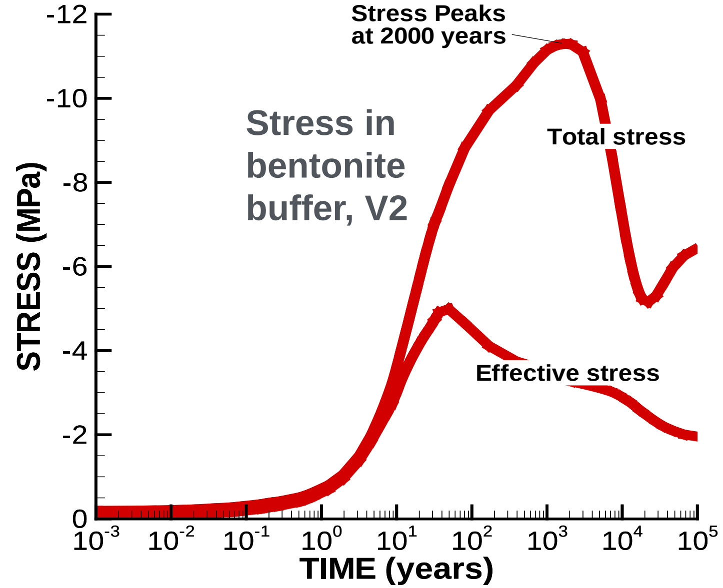
- **Peak temperature?**
- **Time to peak temperature?**
- **Time to full saturation?**

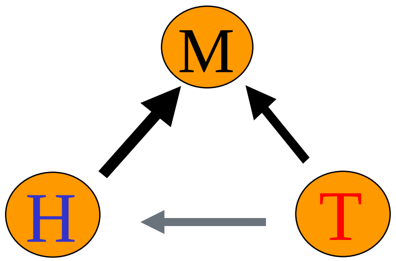
Long-term Coupled Processes Simulation



Rutqvist et al. (2014)

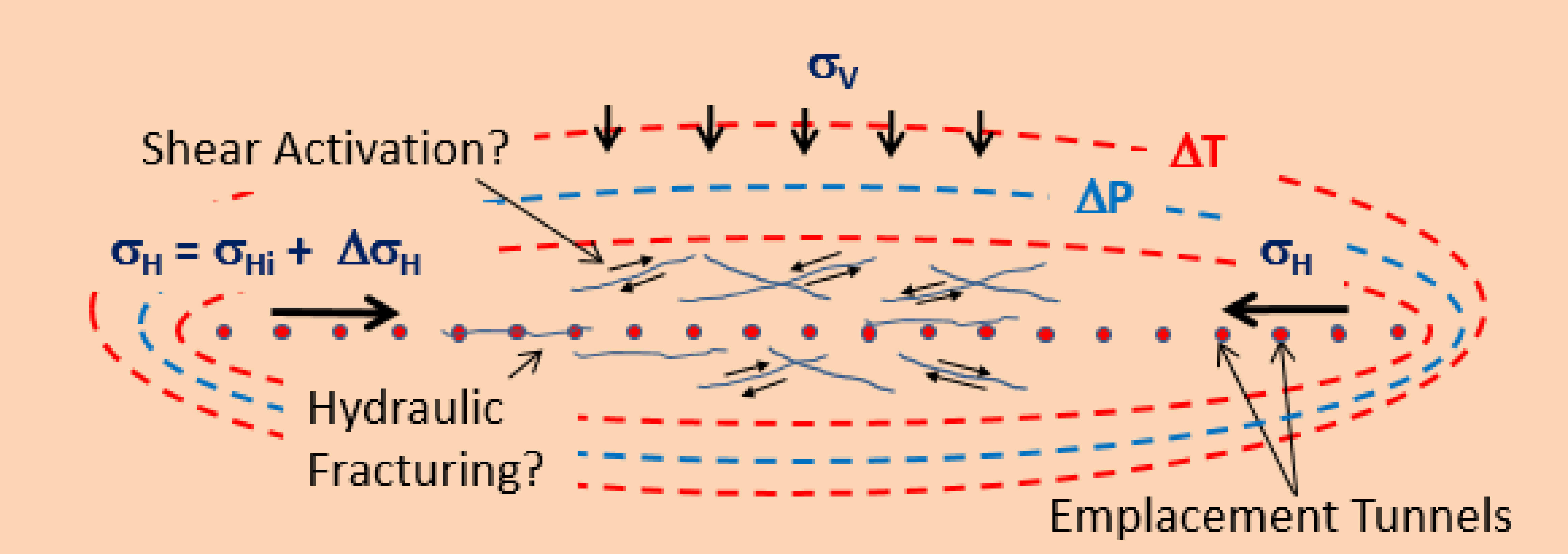






- Peak temperature?
- Time to peak temperature?
- Time to full saturation?
- Peak pressure?
- Time to peak thermal impact?
- Sufficient swelling stress?

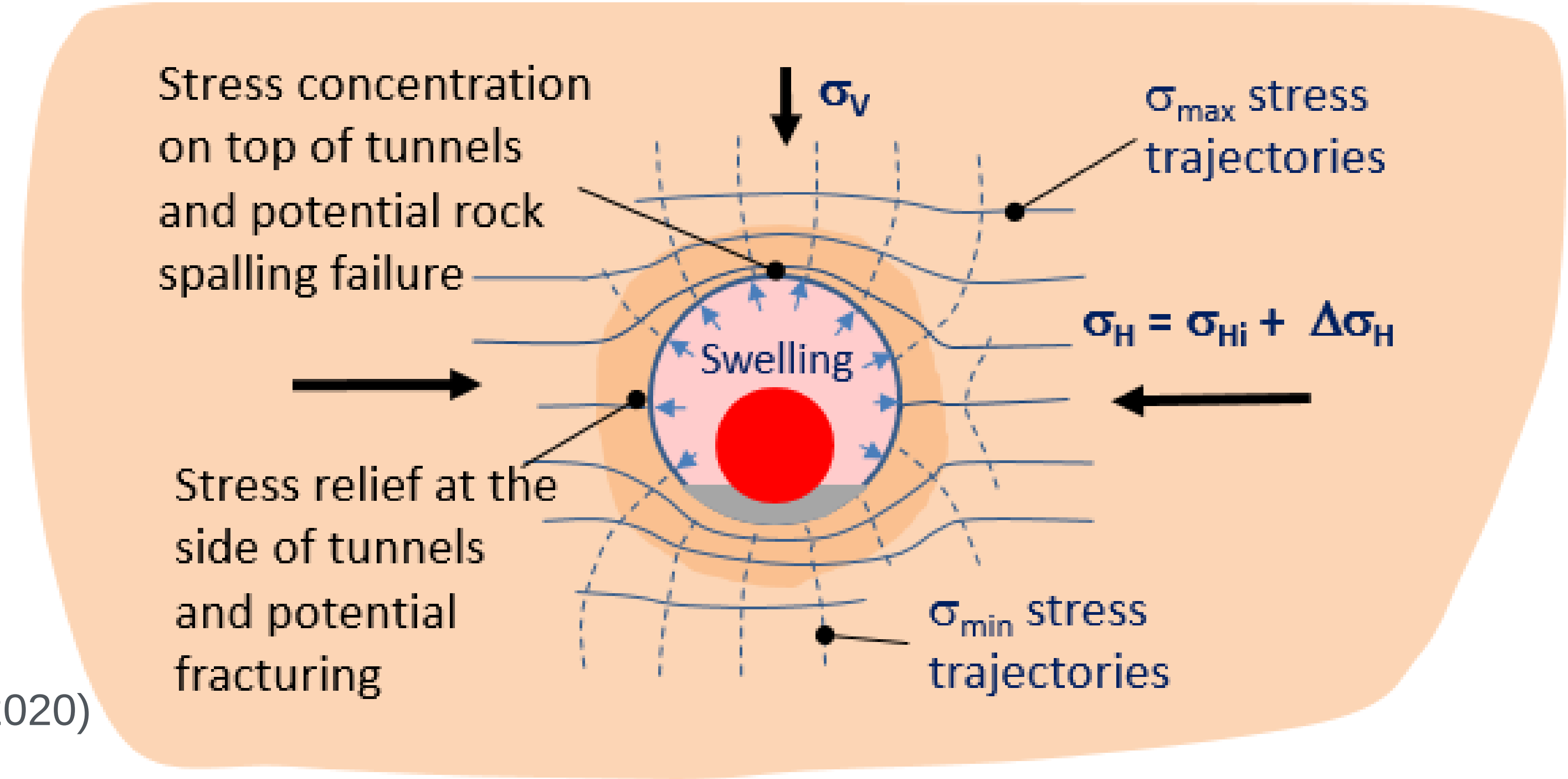
Repository Temperature-induced Stress Changes



(Rutqvist, 2020)

- ΔT can result in high pressure, shear stress, and potential fracturing
- May become the limiting temperature for thermal management

Repository Temperature-induced Stress Changes

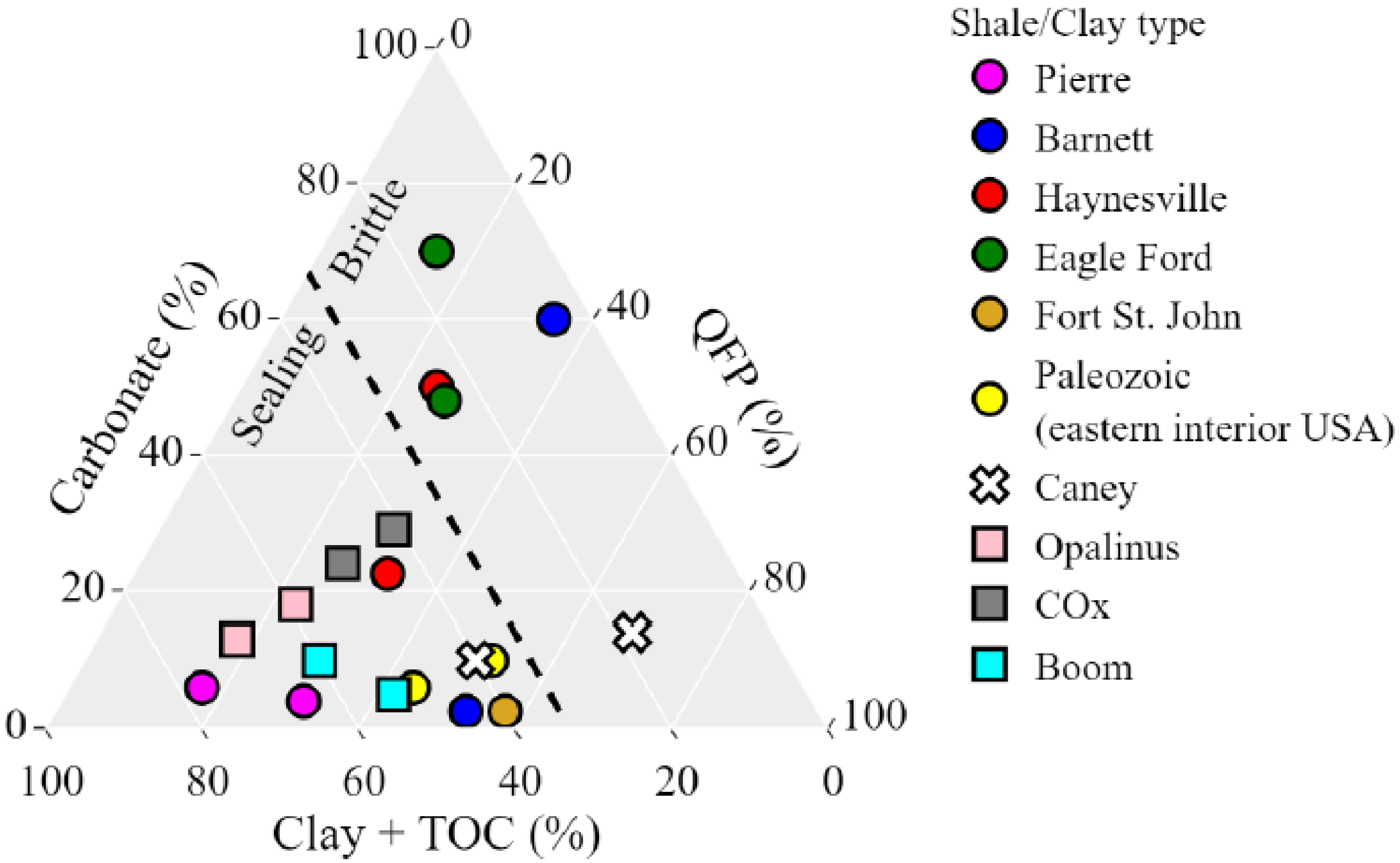


(Rutqvist, 2020)

- Can impact EDZ thousands of years after repository closure (when repository temperature peaks)
- Important to have a supporting buffer stress at that time

Simulating Impact of Long-Term Creep

Sealing vs Brittle Argillite

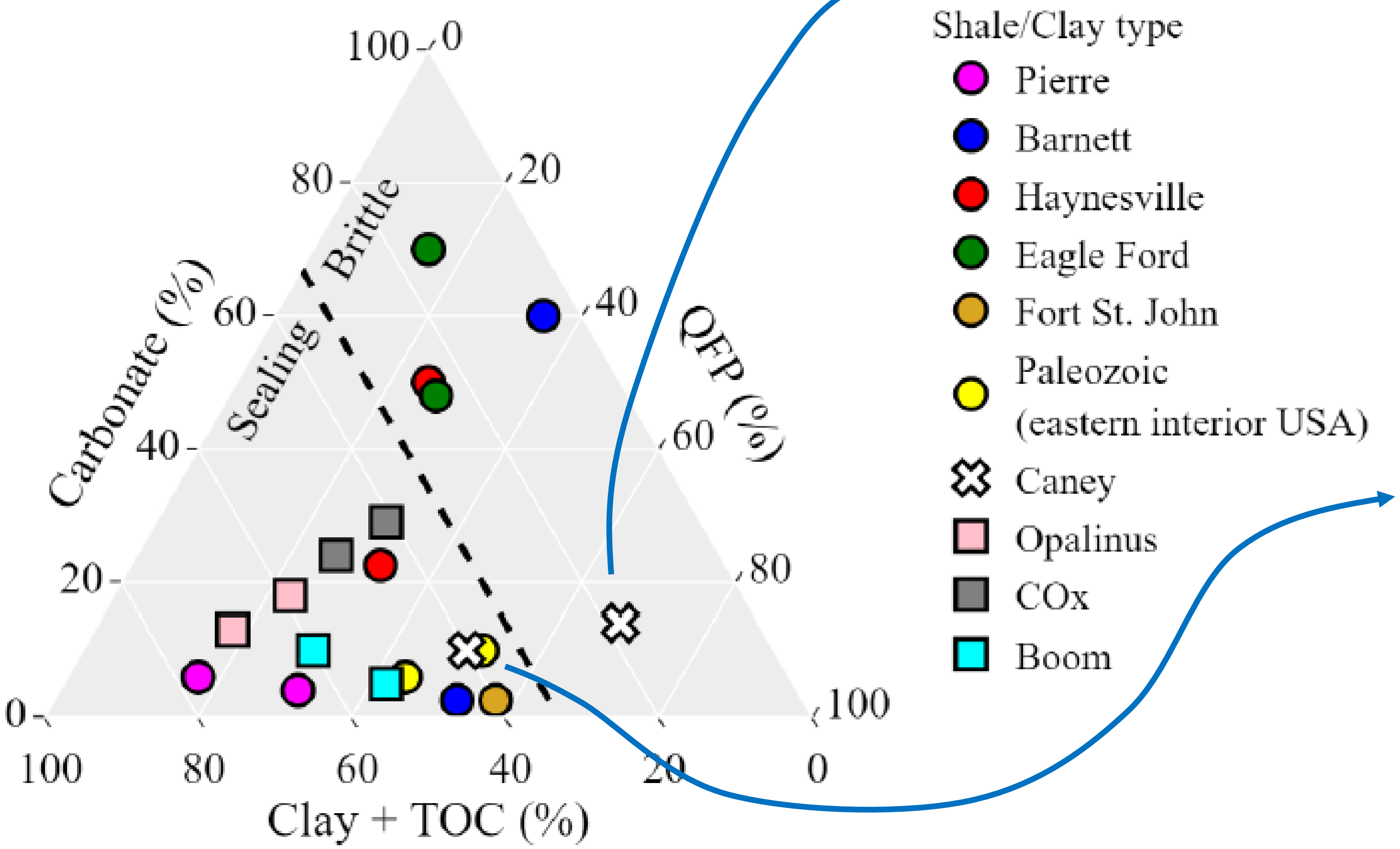


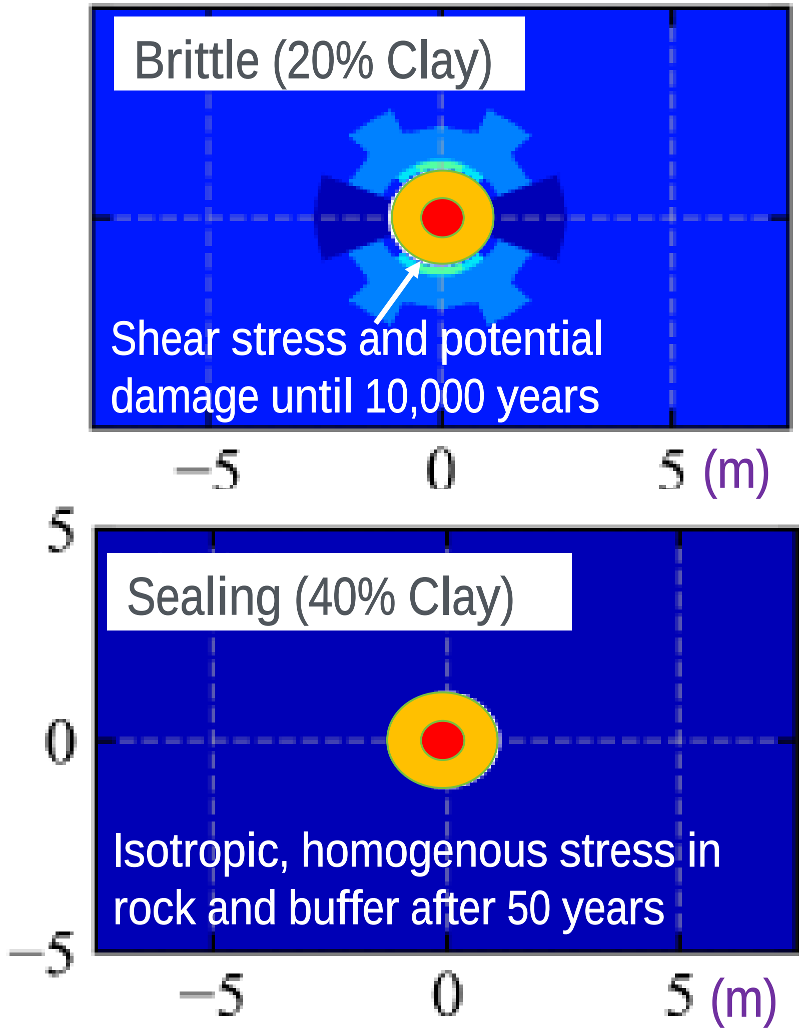
QFP = Quartz + Feldspar + Pyrite
TOC = Total Organic Carbon

Sasaki and Rutqvist (2022)

Simulating Impact of Long-Term Creep

Sealing vs Brittle Argillite





High clay content ⇒ Soft + high creep ⇒ self-sealing

Sasaki and Rutqvist (2022)

Summary

- Repository coupled thermal-hydraulic-mechanical (THM) processes can have a significant impact on the argillite barrier integrity
- Field experiments at underground research laboratories have been designed to study phenomena such as thermal pressurization and fracturing
- Modeling of these experiments in DECOVALEX provides confidence in the models applied to predict these processes for a repository
- The type of argillite, whether more ductile or more brittle, cold have a significant impact on the argillite barrier behavior
- High temperature would cause stronger thermal pressurization, but could also accelerate creep and sealing of clay-rich shale
- Coupled THM modeling can be applied in the thermal management and repository design to assure argillite barrier integrity

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Acronyms and Abbreviations

ALC	Micro-tunnel experiment at Bure
ANDRA	National Radioactive Waste Management Agency (France)
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)
FE	Full-scale Emplacement Experiment at Mont Terri
FLAC	Fast Lagrangian Analysis of Continua
LBNL	Lawrence Berkeley National Laboratory
NAGRA	Swiss waste management organization
NWMO	Nuclear Waste Management Organisation (Canada)
QFP	Quartz + feldspar + pyrite
Swisstopo	Federal Office of Topography (Switzerland)
THM	Thermo-hydro-mechanical
TOC	Total Organic Carbon
TOUGH	Transport Of Unsaturated Groundwater and Heat
UFCBGR	Federal Institute for Geosciences and Natural Resources and Helmholtz Centre for Environmental Research (Germany)