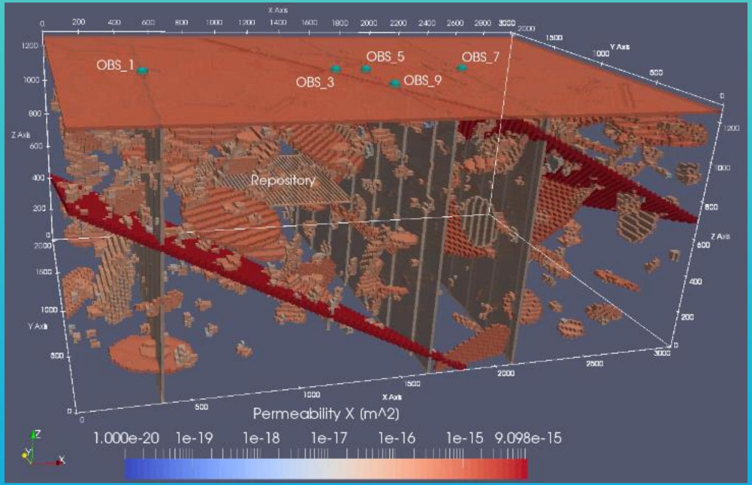


Modeling of the Long-Term Integrity of the Argillite Host Rock Barrier

U.S. Nuclear Waste Technical Review Board
Fact Finding Meeting
July 19, 2022

Jonny Rutqvist
Lawrence Berkeley National Laboratory

Funding was provided by the Spent Fuel and Waste Science and Technology, Office of Nuclear Energy, of the U.S. Department of Energy under Contract Number DE-AC02-05CH11231 with Lawrence Berkeley National Laboratory.

Argillite Coupled Processes Modeling Team

Lawrence Berkeley National Laboratory

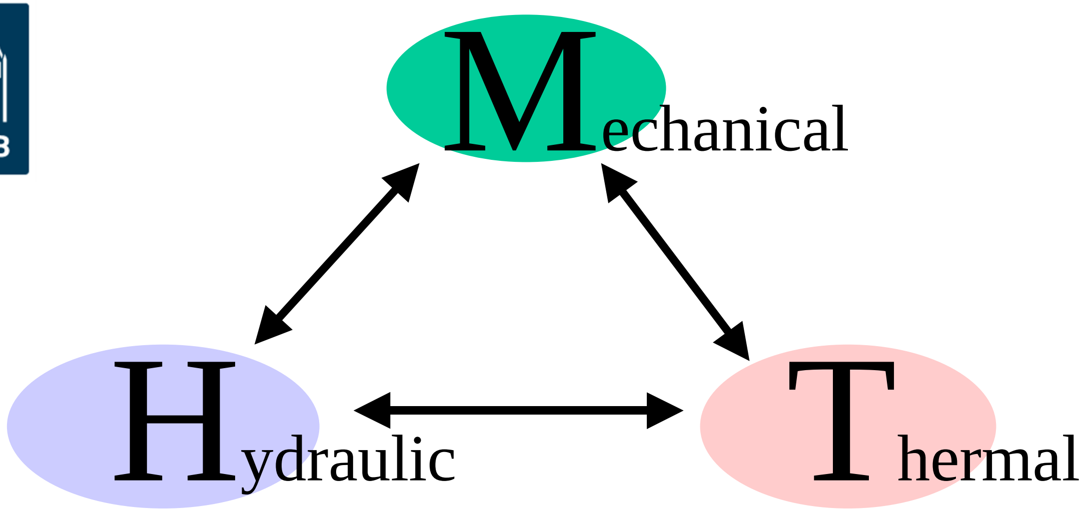
Jonny Rutqvist, Tsubasa Sasaki, Sangcheol Yoon, Mengsu Hu, Keurfon Luu, Yves Guglielmi, Liange Zheng, Jens Birkholzer

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)



T = Thermal

H = Hydraulic

M = Mechanical

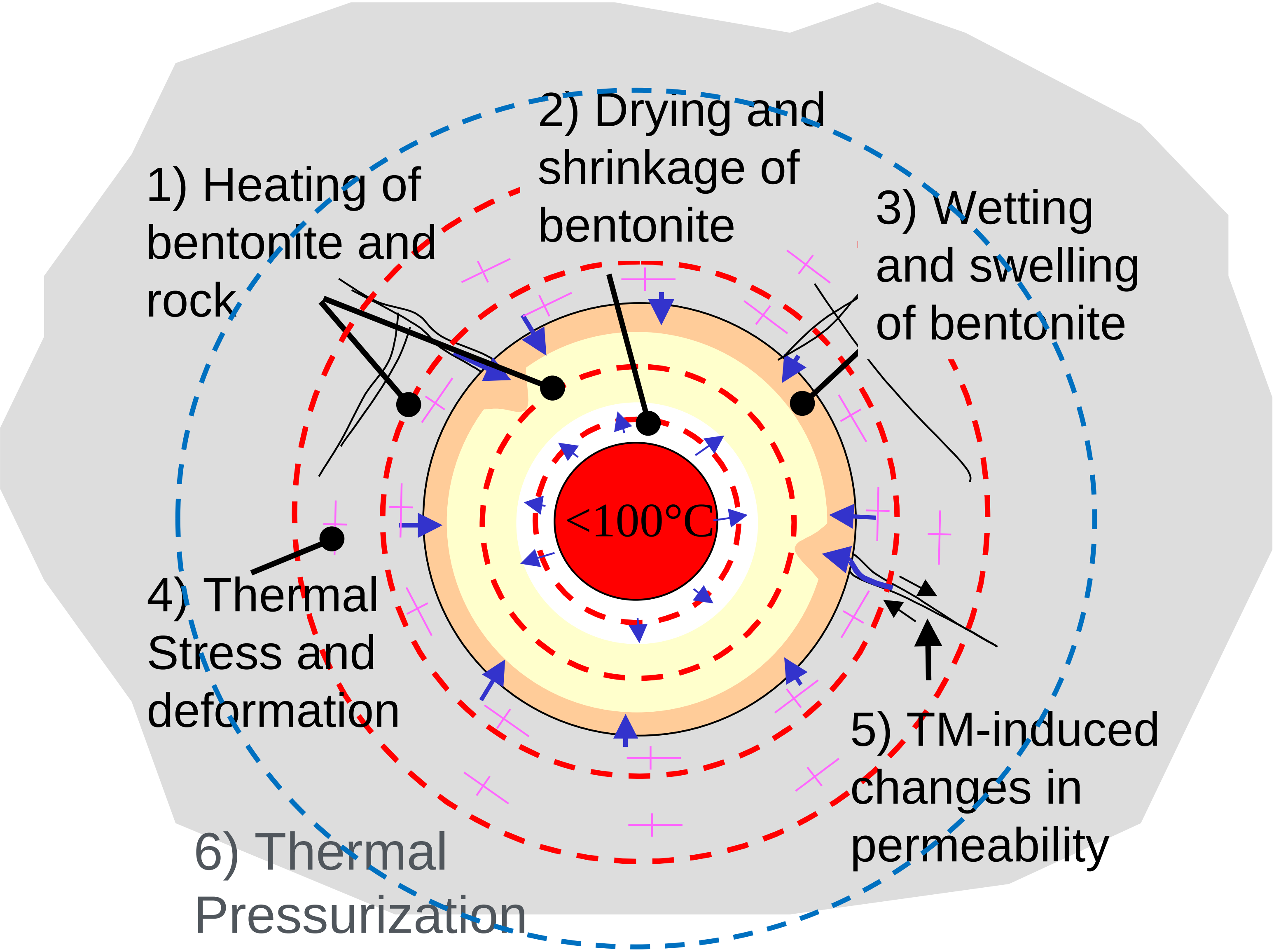
THM = Thermo-hydro-mechanical

P = Pressure

T = Temperature

σ = Stress

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



1) Heating of bentonite and rock

2) Drying and shrinkage of bentonite

3) Wetting and swelling of bentonite

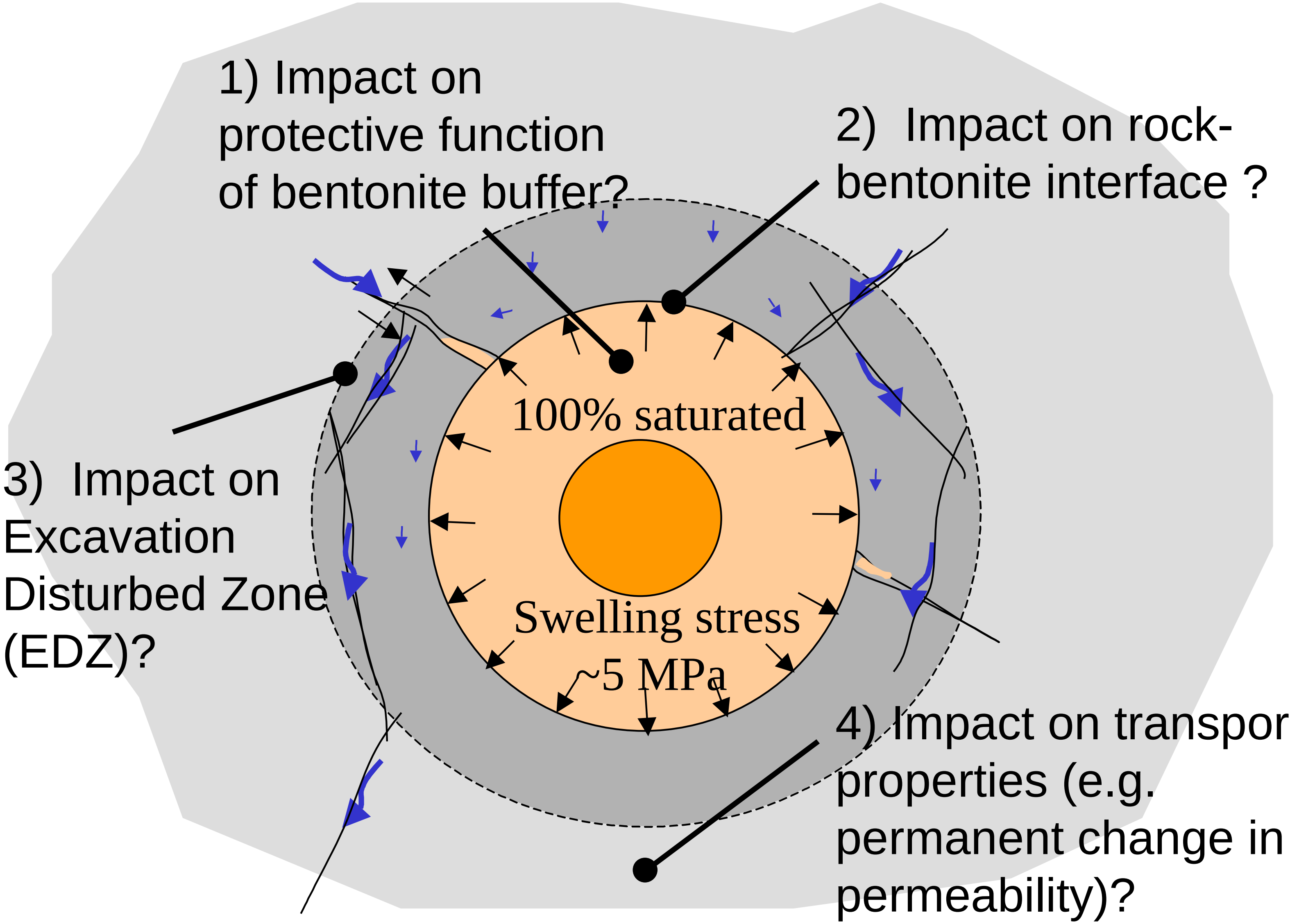
4) Thermal Stress and deformation

5) TM-induced changes in permeability

6) Thermal Pressurization

(Rutqvist, 2015)

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



1) Impact on protective function of bentonite buffer?

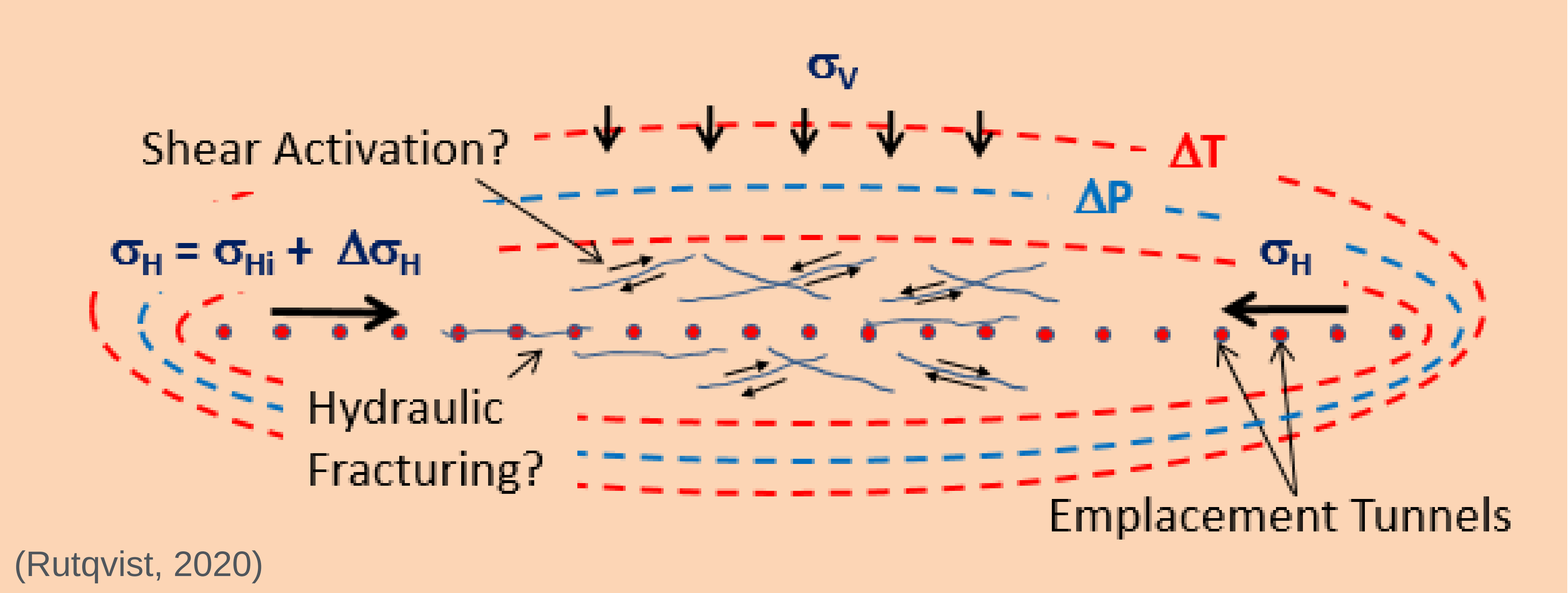
2) Impact on rock-bentonite interface ?

3) Impact on Excavation Disturbed Zone (EDZ)?

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

(Rutqvist, 2015)

Repository THM-Induced Stress Changes



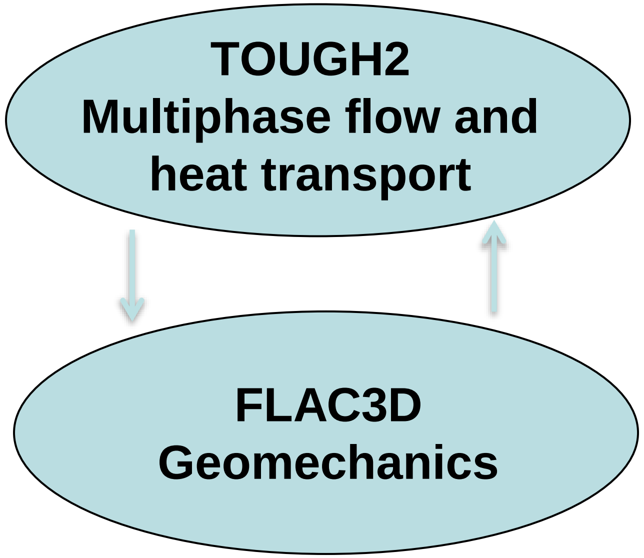
(Rutqvist, 2020)

- 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



TOUGH2
Multiphase flow and heat transport

FLAC3D
Geomechanics

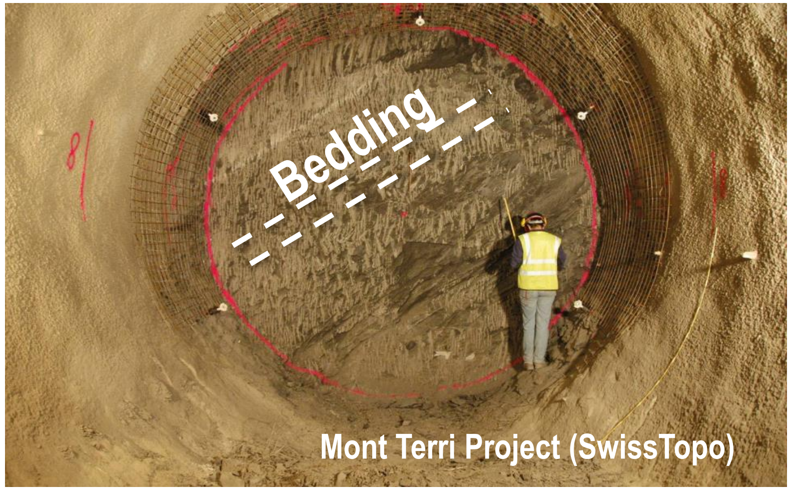
(Rutqvist et al., 2002; Rutqvist 2011; 2017)

- 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)

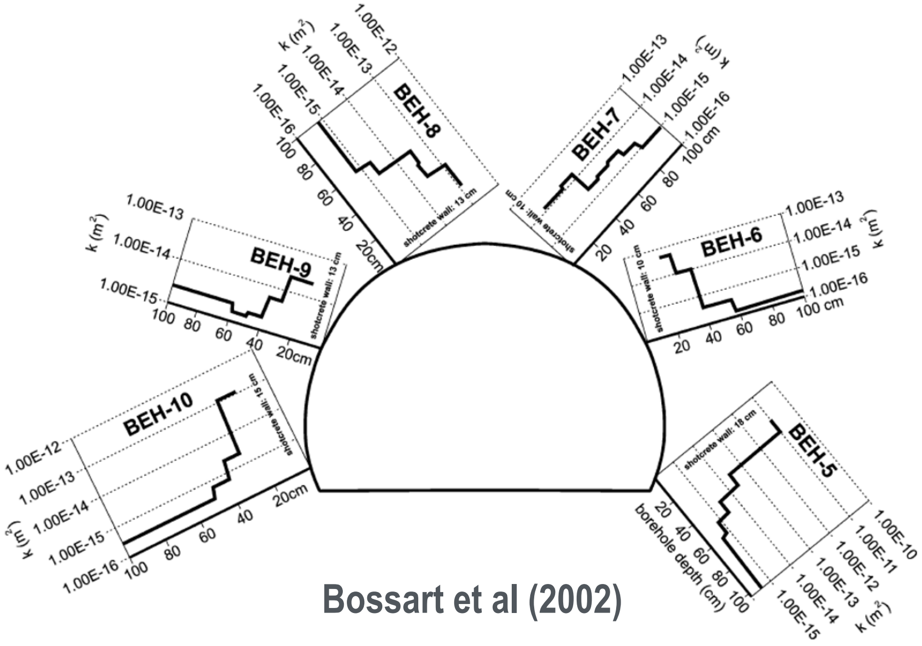
By adding to existing model capability

- 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)

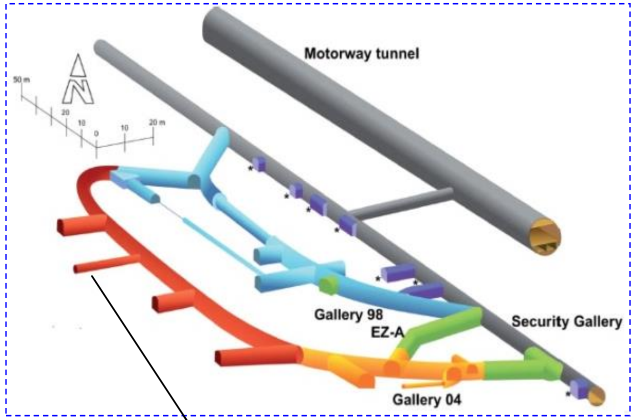
Model Validation

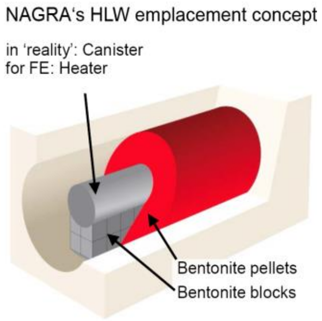
Three examples of modeling of field experiments:

1. Full Scale Emplacement Experiment in Opalinus Clay at Mont Terri Laboratory, Switzerland
2. Heated micro-tunnel experiment in COx Claystone at Bure, France
3. Thermal-pressurization fracturing experiment in Cox Claystone at Bure, France

Modeling Mont Terri Full-Scale Emplacement Experiment (DECOVALEX-2023)

Site

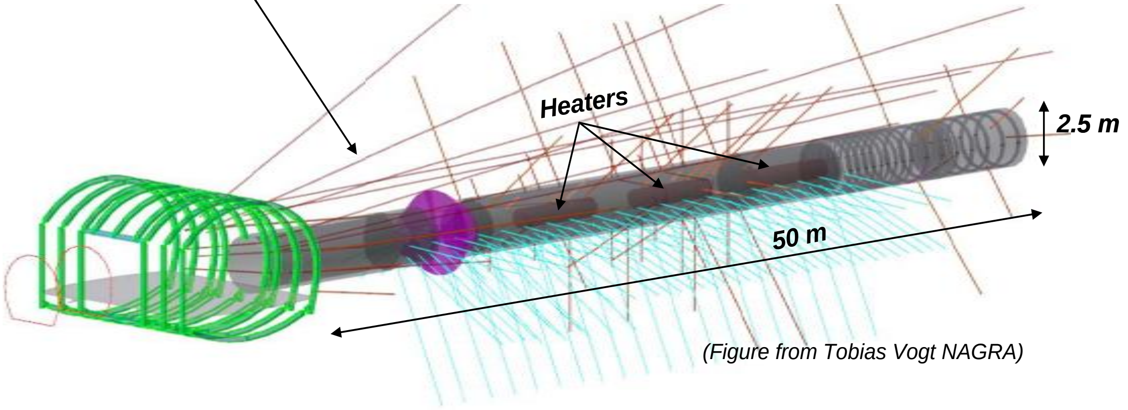




Full-scale

15-20 years of heating

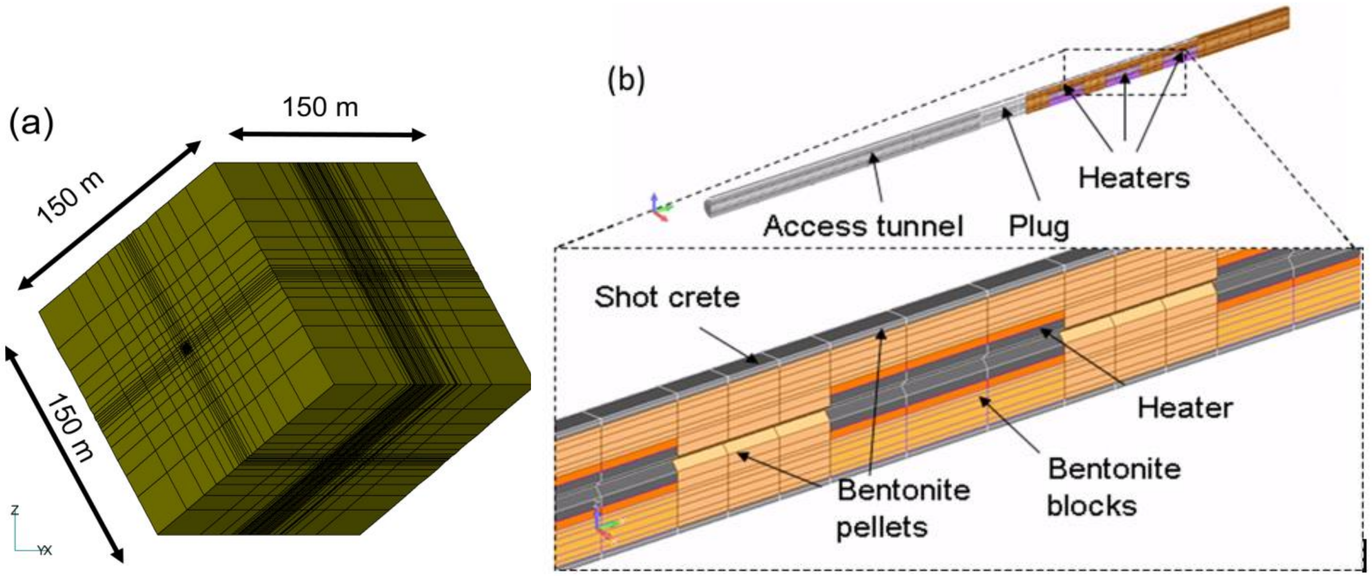
Granular bentonite emplacement



(Figure from Tobias Vogt NAGRA)

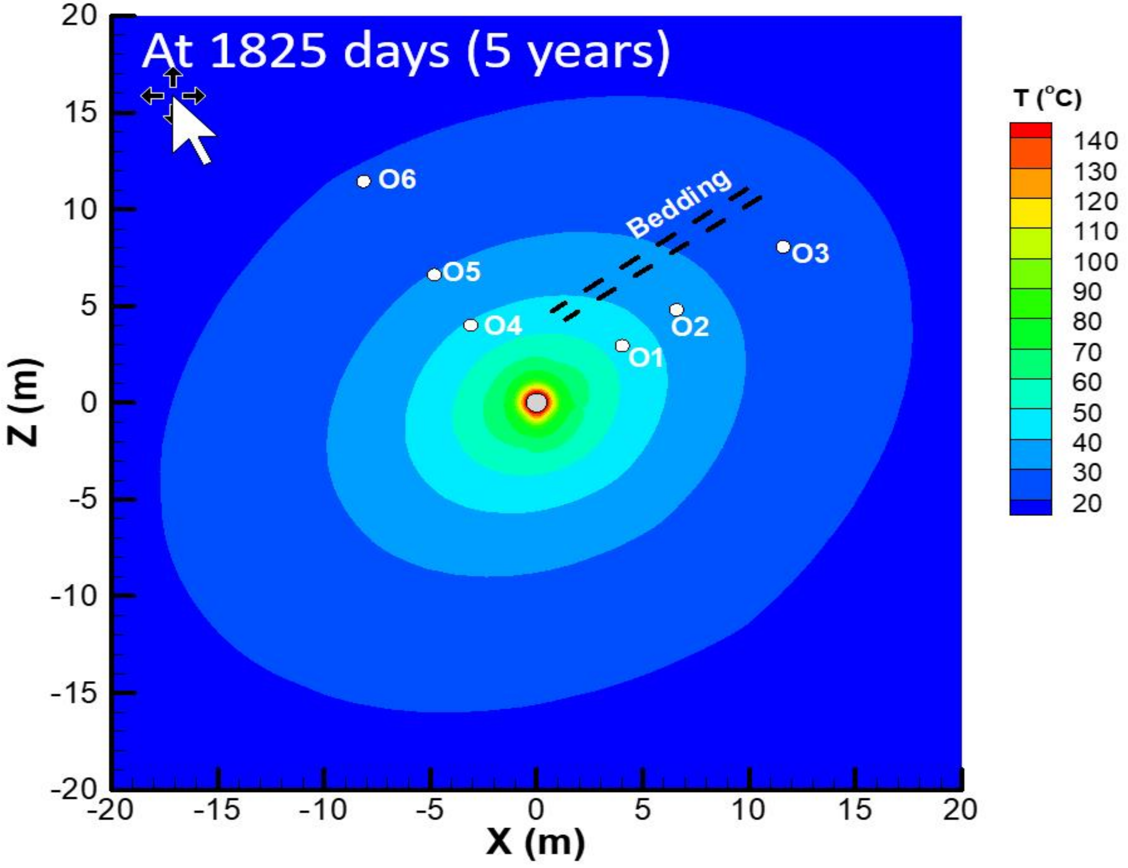
- **15-20 years of heating**
- **Temperature up to 140°C in bentonite**

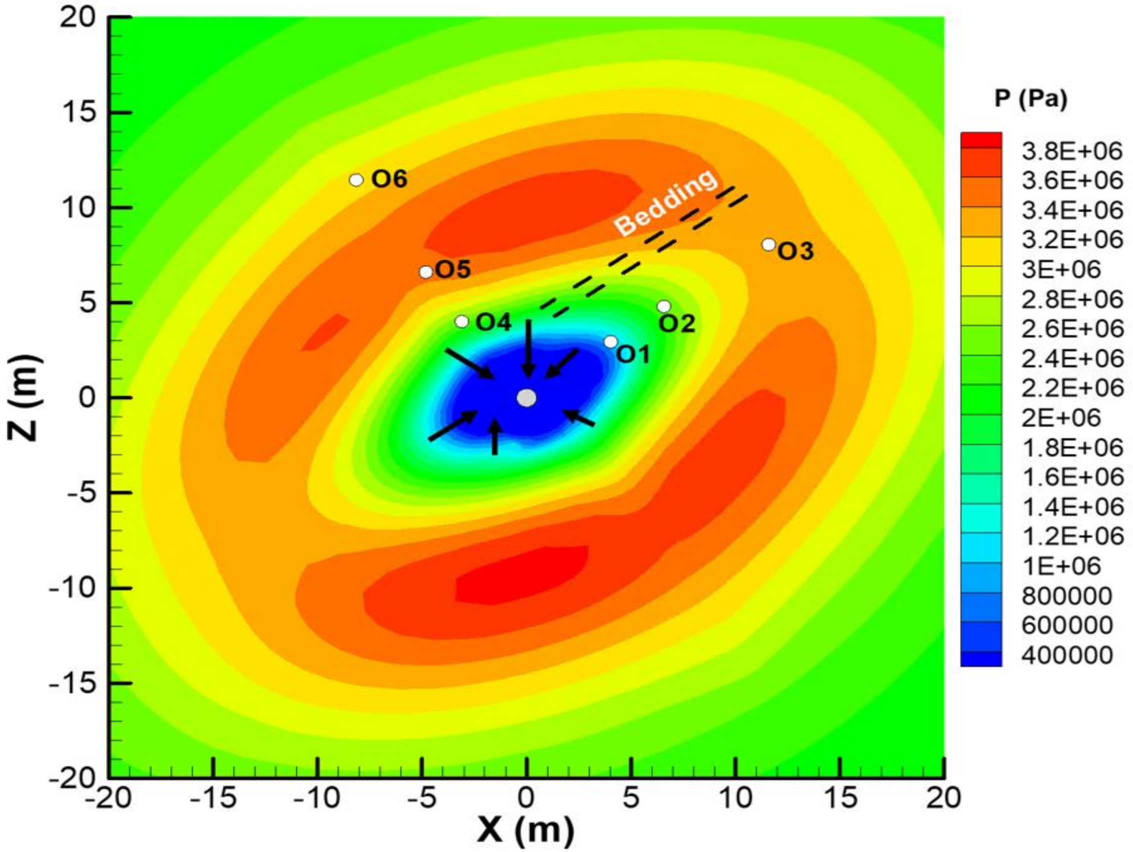
Numerical Model



- **9 Modeling Teams in DECOVALEX-2023**
- **Comparison with five years of field data is ongoing**
- **Predict thermal pressurization and interaction with bentonite buffer**

Modeling Mont Terri Full-Scale Emplacement Experiment (DECOVALEX-2023)

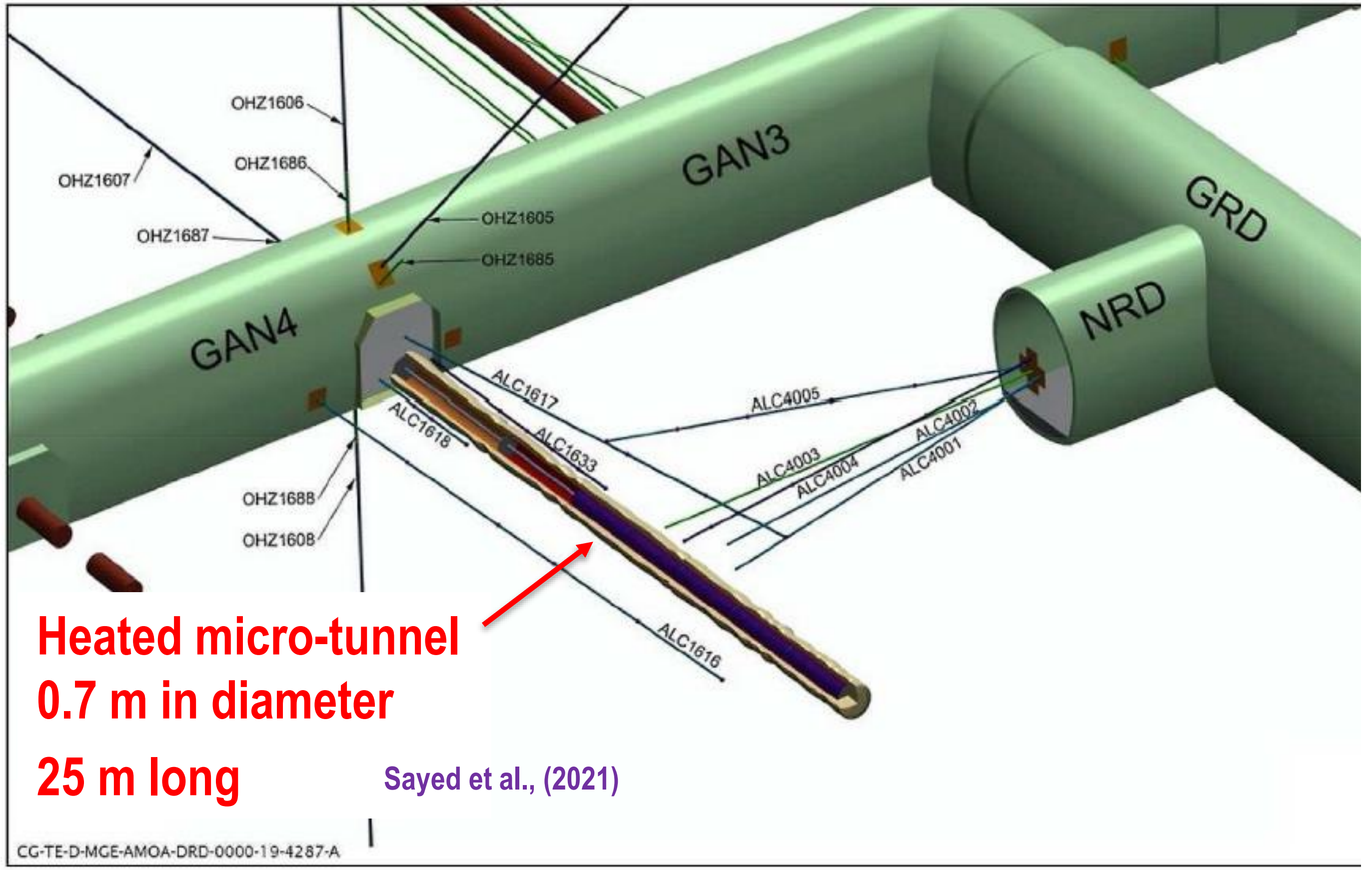




- **Temperature and pressure responses are anisotropic**
- **Flow and suction into bentonite has a significant impact on pressure response near the tunnel**
- **Key parameters: permeability, fluid thermal expansion coefficient, porous media compressibility**

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

The Micro-Tunnel Experiment in Cox Claystone at Bure

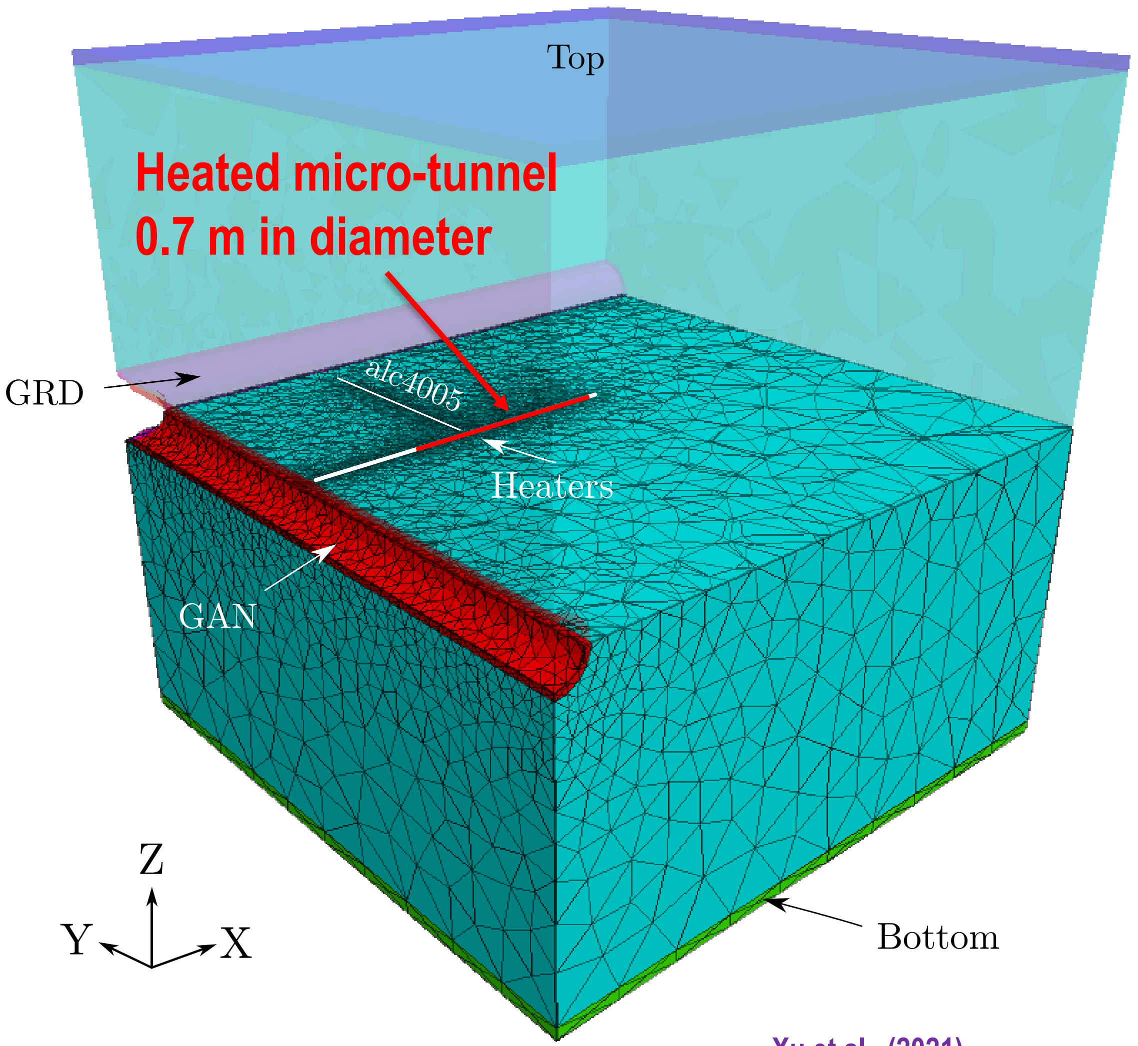


Heated micro-tunnel
0.7 m in diameter
25 m long

Sayed et al., (2021)

- Four years of heating up to about 50°C
- 5 DEOCOVALEX-2019 modeling teams and models
- Compare temperature and pressure responses

Numerical Model

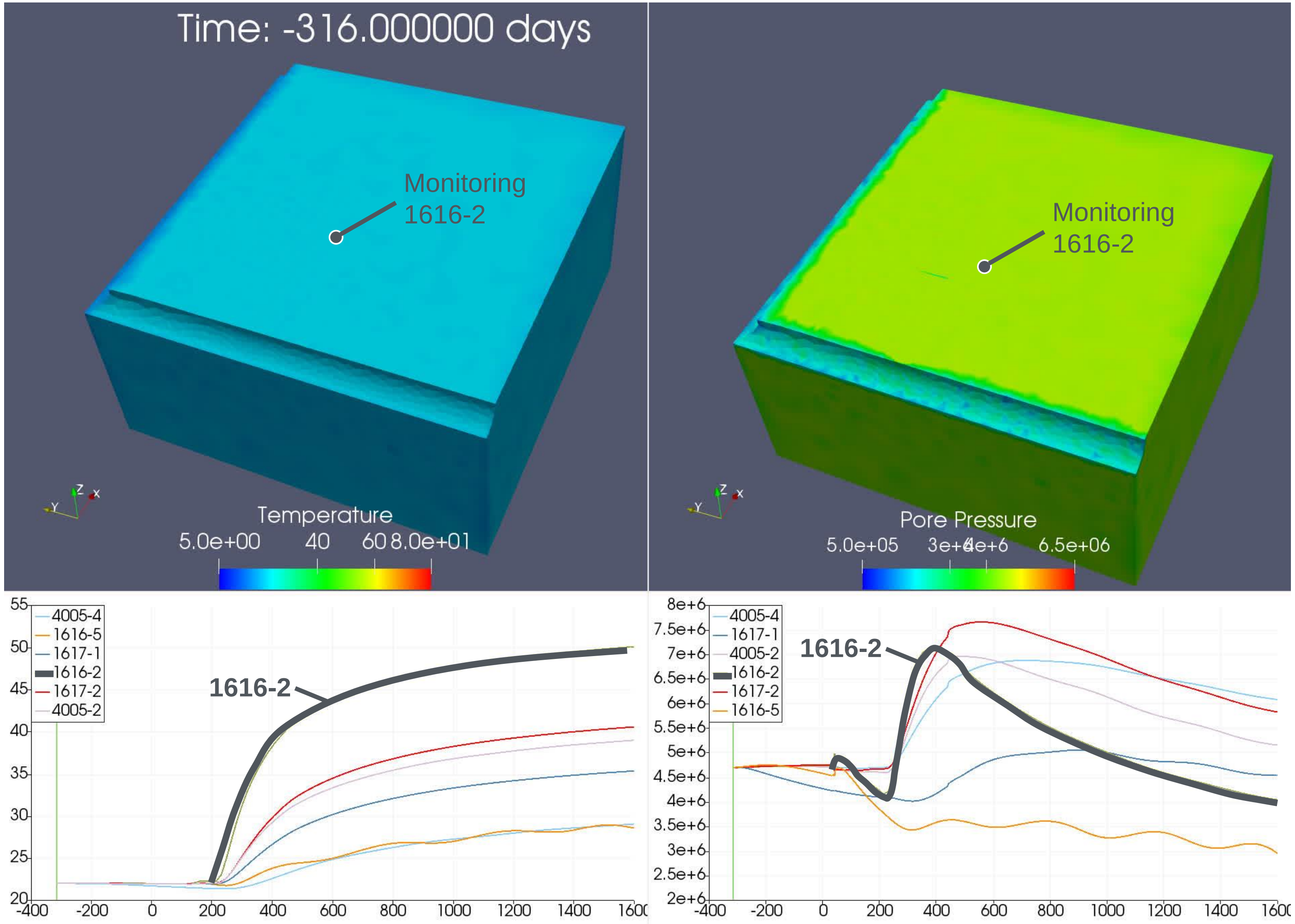


Heated micro-tunnel
0.7 m in diameter

Xu et al., (2021)

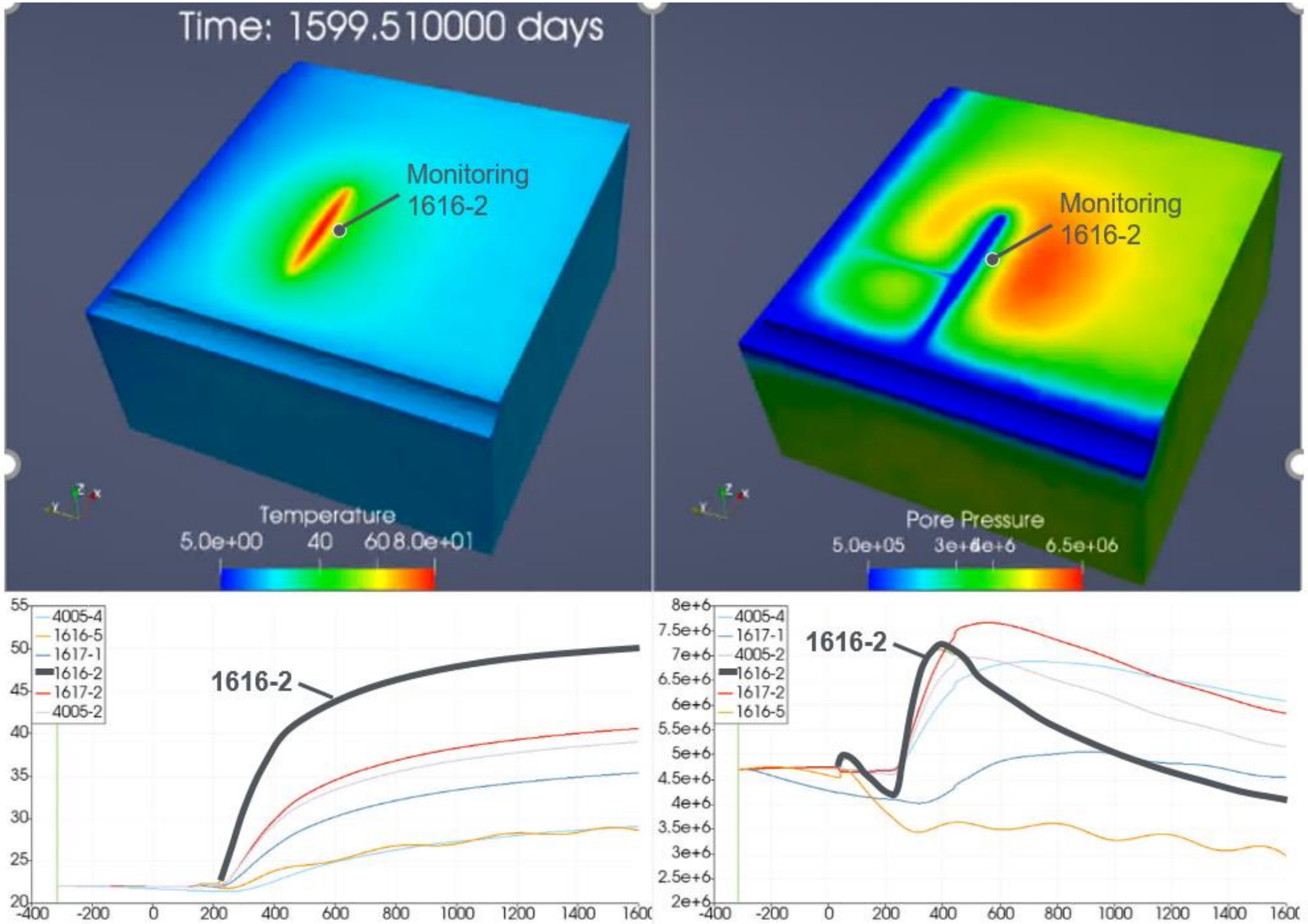
Modeling of Thermal Pressurization Experiment at Bure (DECOVALEX-2019)

A movie of thermal pressurization



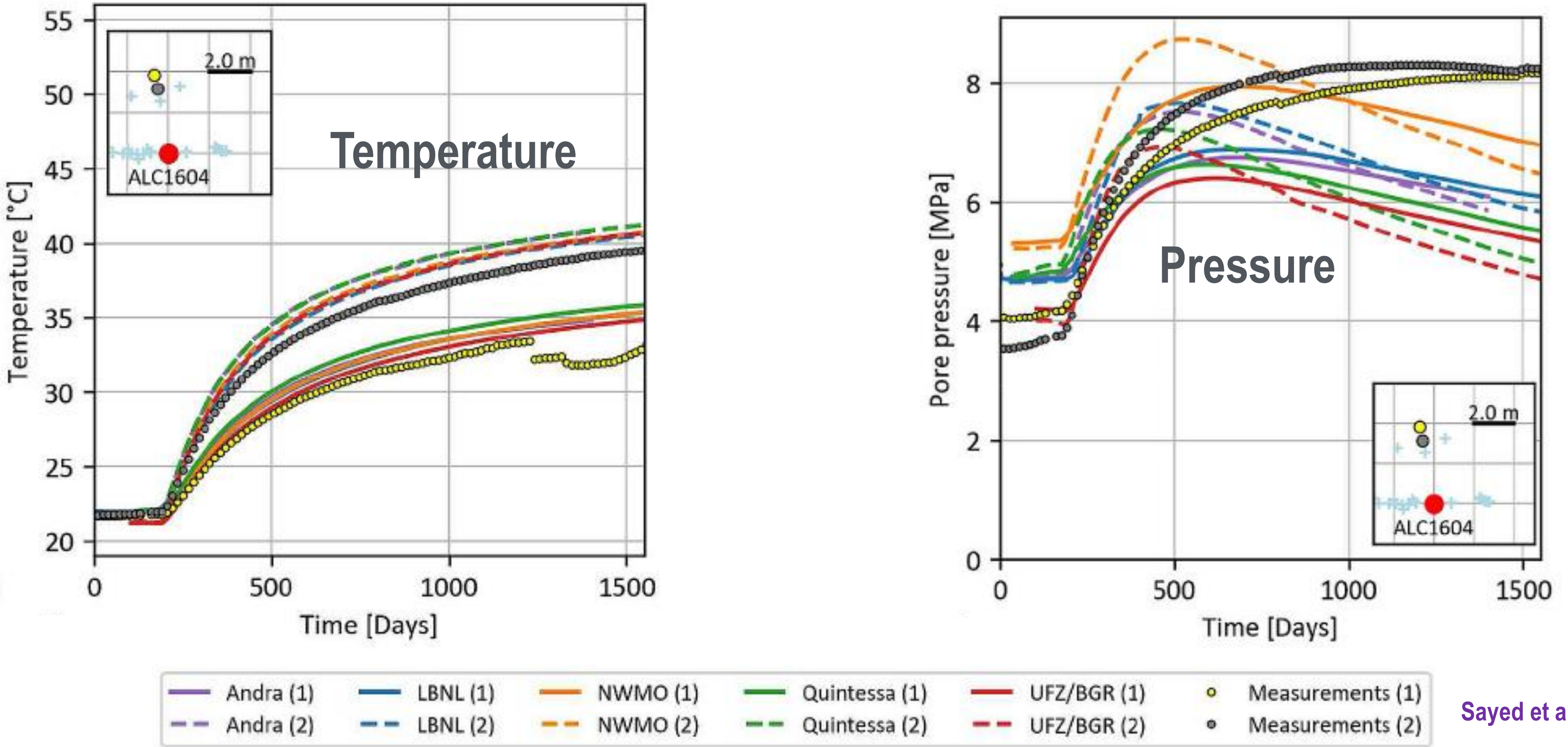
Xu et al., (2021)

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



Xu et al., (2021)

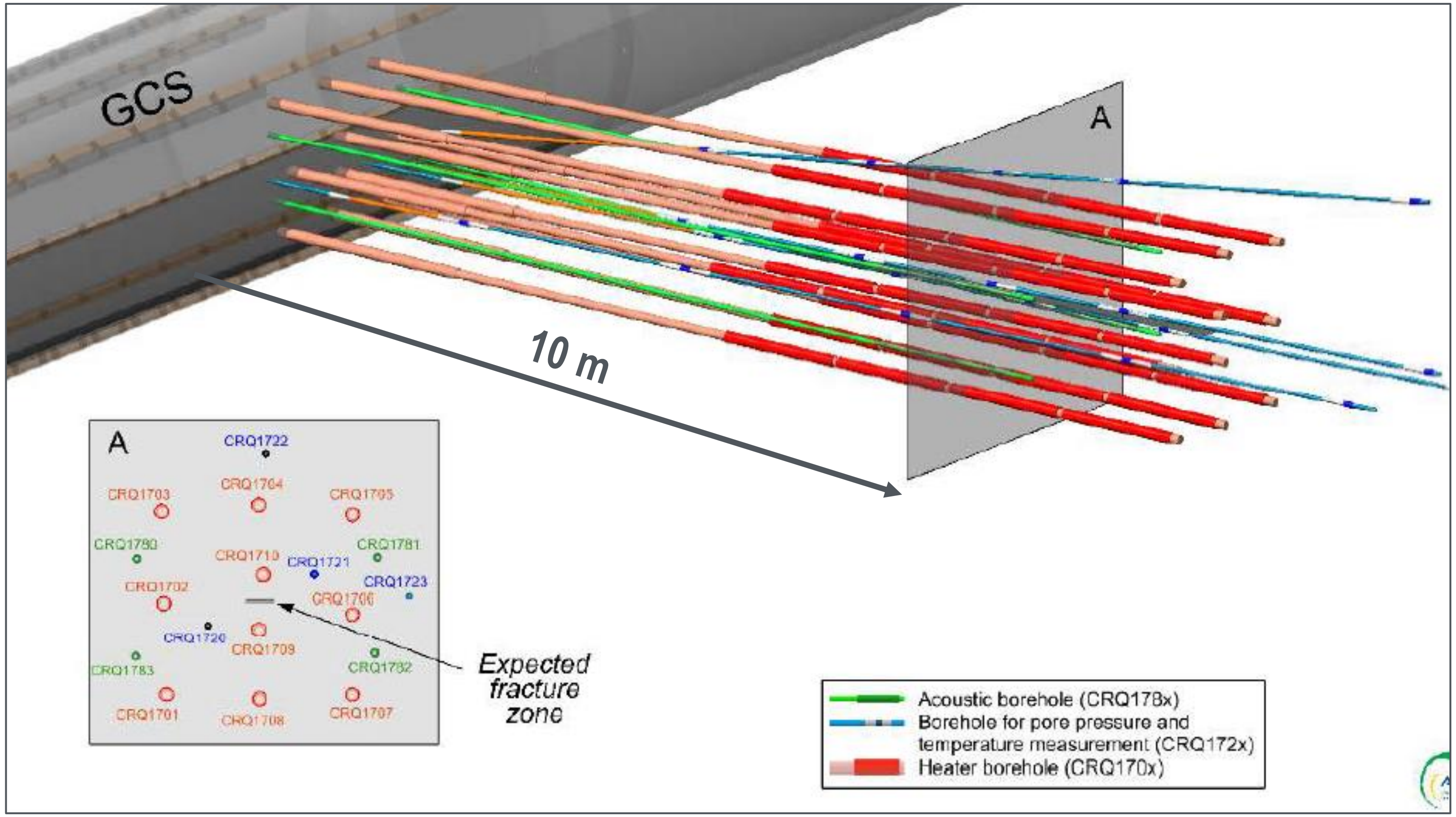
Modeling of Thermal Pressurization Experiment at Bure (DECOVALEX-2019)

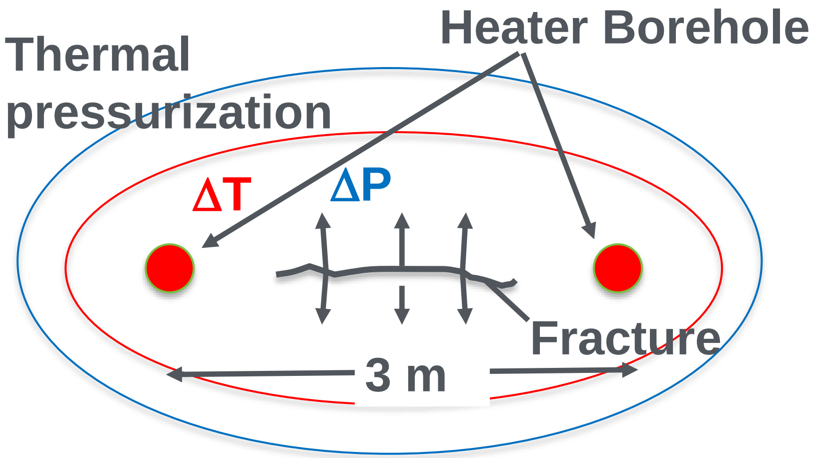


Sayed et al., (2021)

- **Temperature accurately predicted while pressure response deviate at later times for monitoring points located away from the tunnel**
- **Pressure much less than the least principal stress magnitude (far from hydro-fracturing)**

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





Thermal pressurization

Heater Borehole

ΔT

ΔP

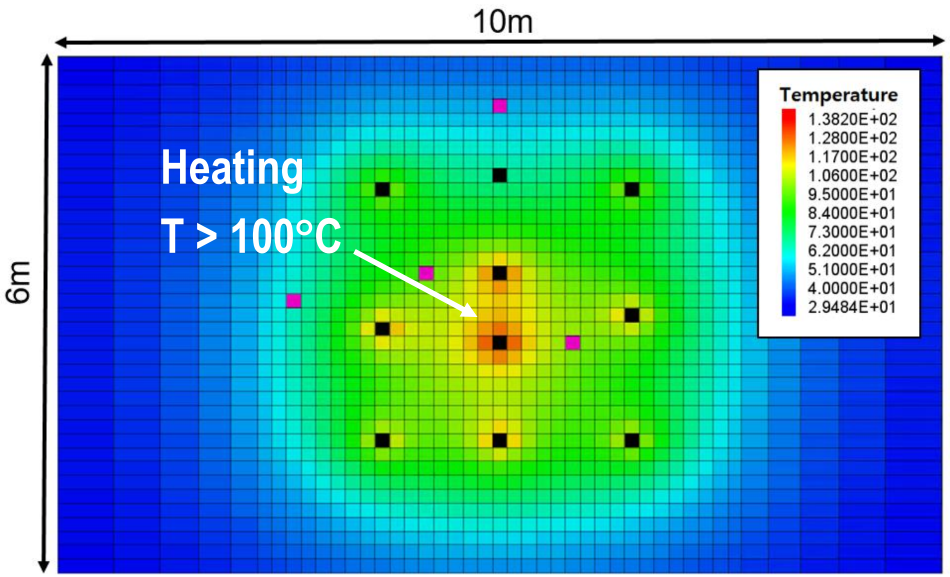
Fracture

3 m

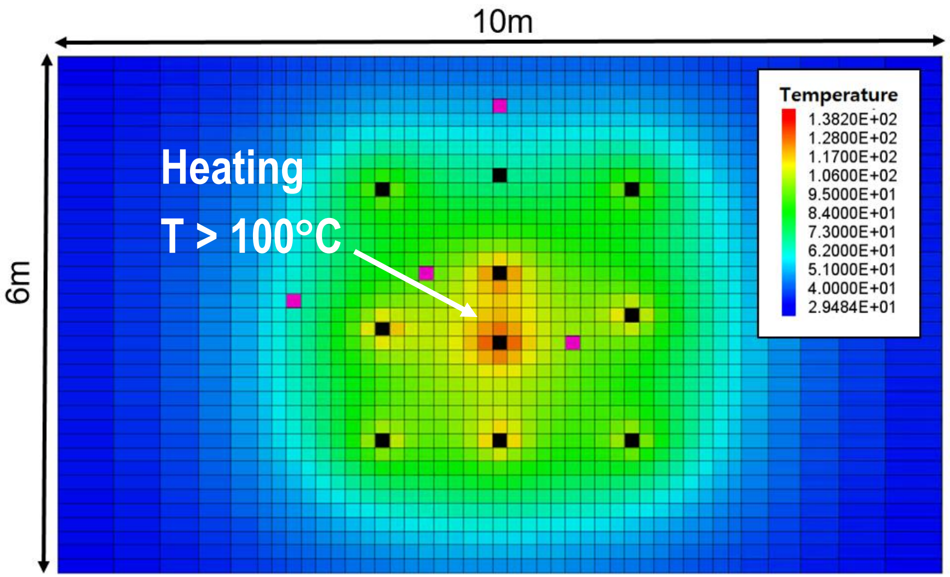
Borehole array on tunnel wall

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

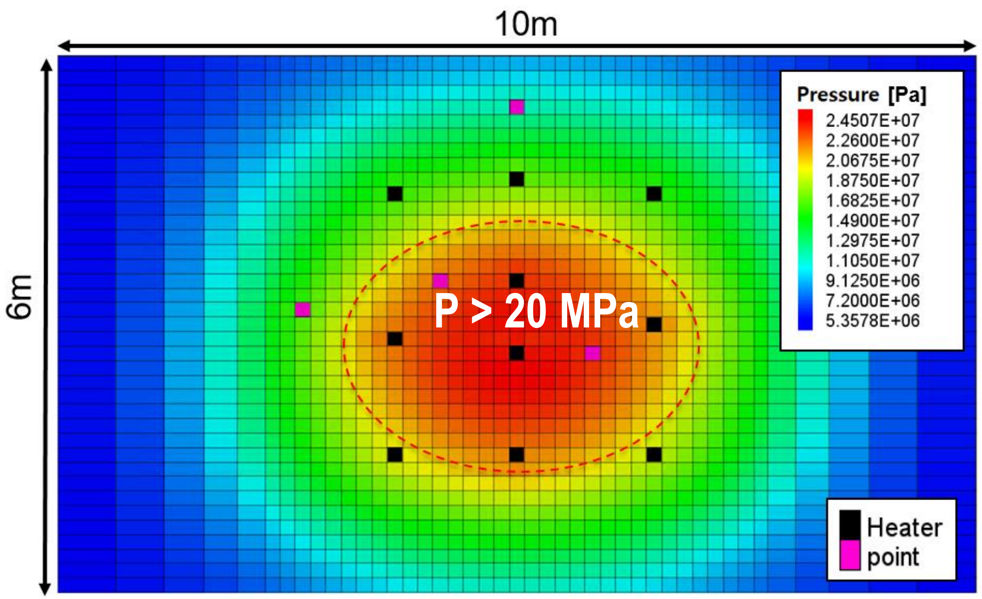
Modeling Thermal-Pressurization Fracturing at Bure in COx claystone (DECOVALEX 2023)



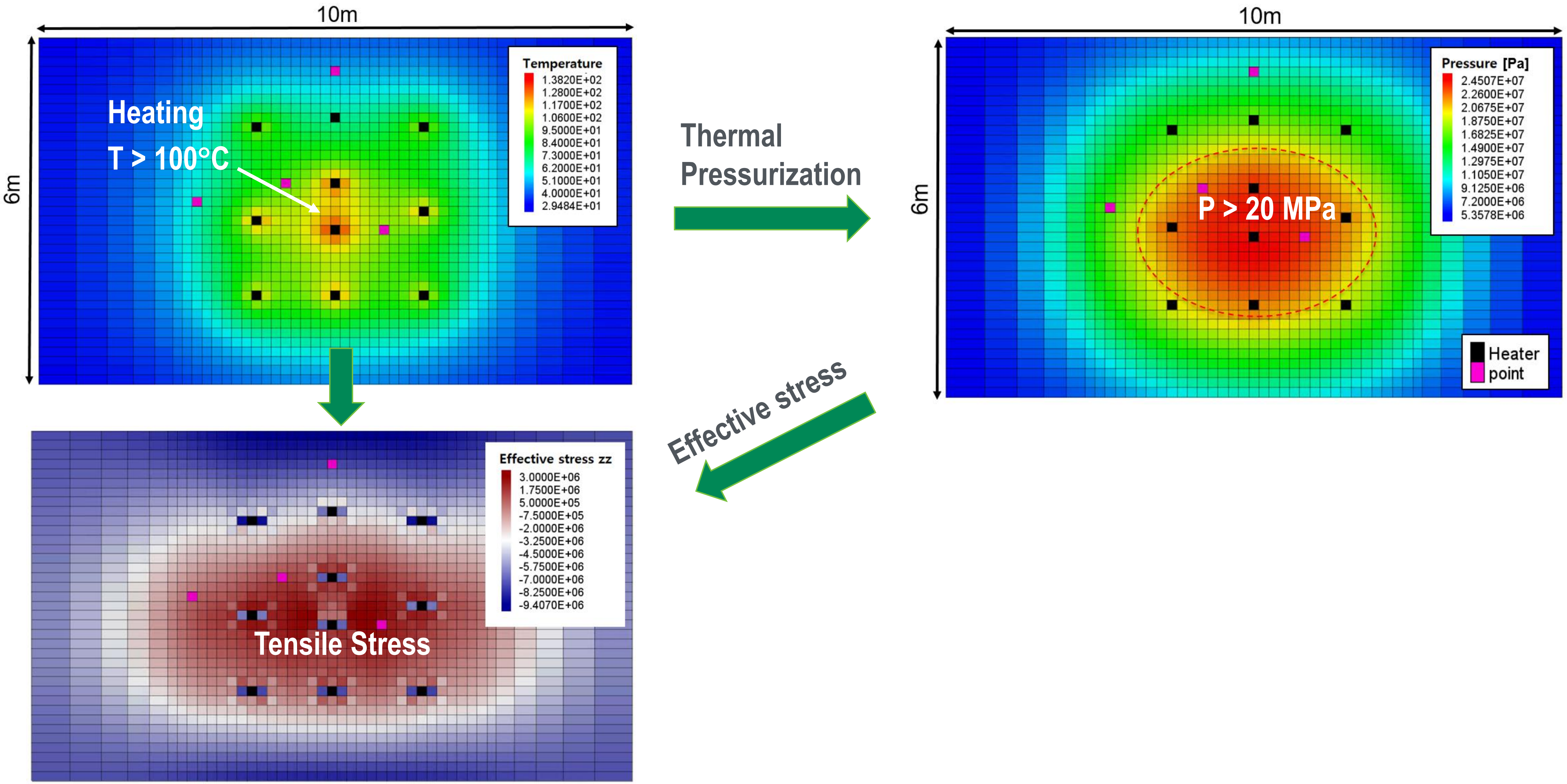
Modeling Thermal-Pressurization Fracturing at Bure in COx claystone (DECOVALEX 2023)



Thermal Pressurization



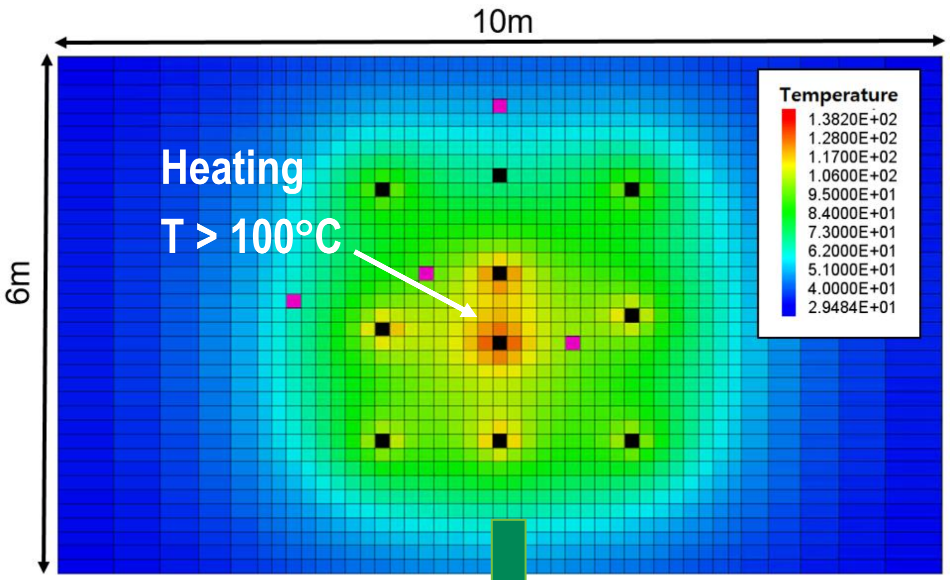
Modeling Thermal-Pressurization Fracturing at Bure in COx claystone (DECOVALEX 2023)



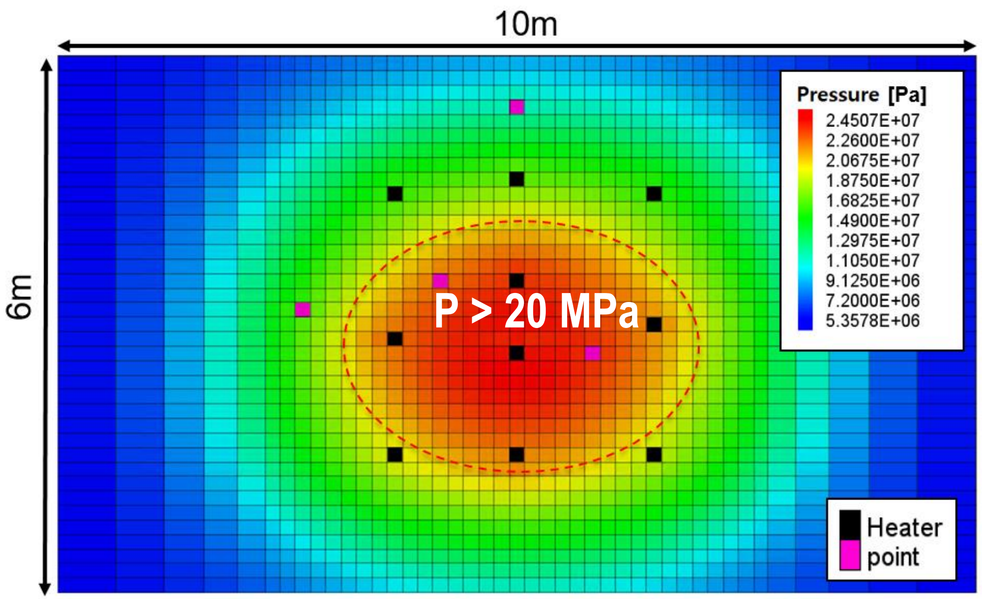
Thermal Pressurization

Effective stress

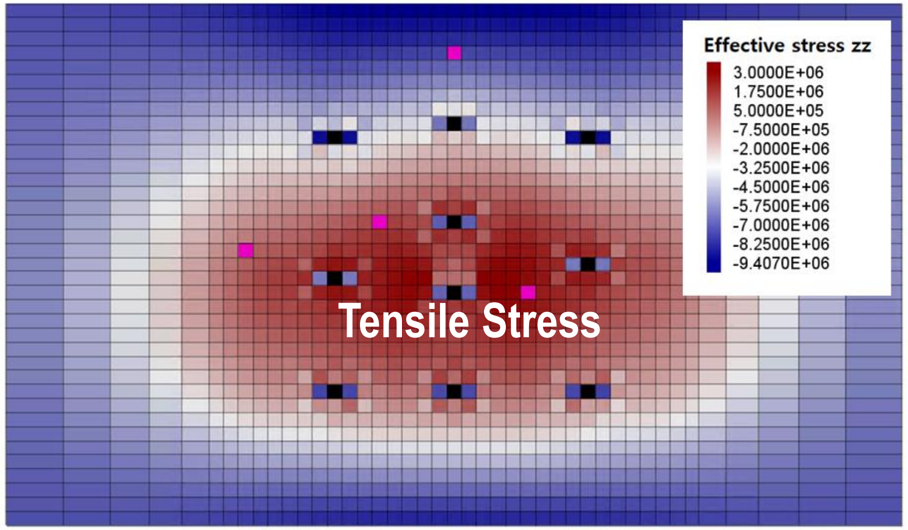
Modeling Thermal-Pressurization Fracturing at Bure in COx claystone (DECOVALEX 2023)



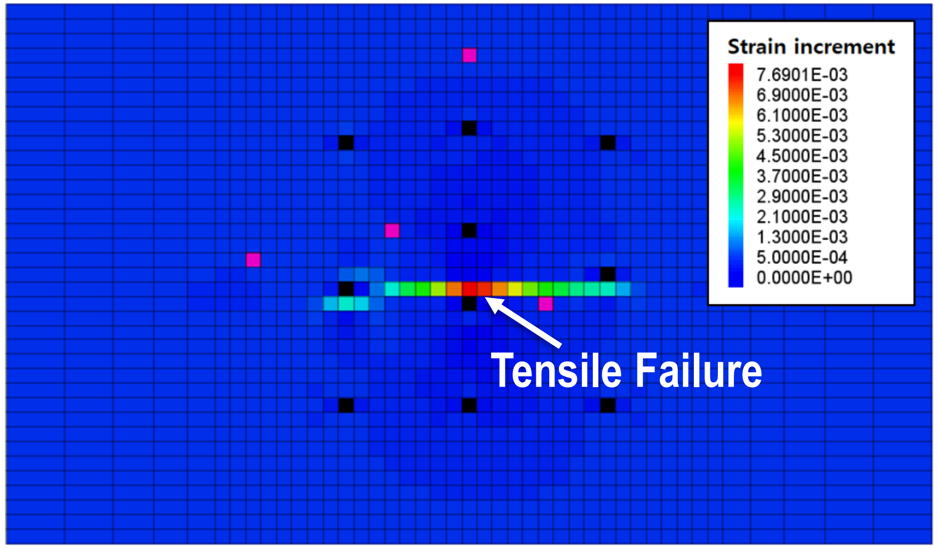
Thermal Pressurization



Effective stress



Fracturing

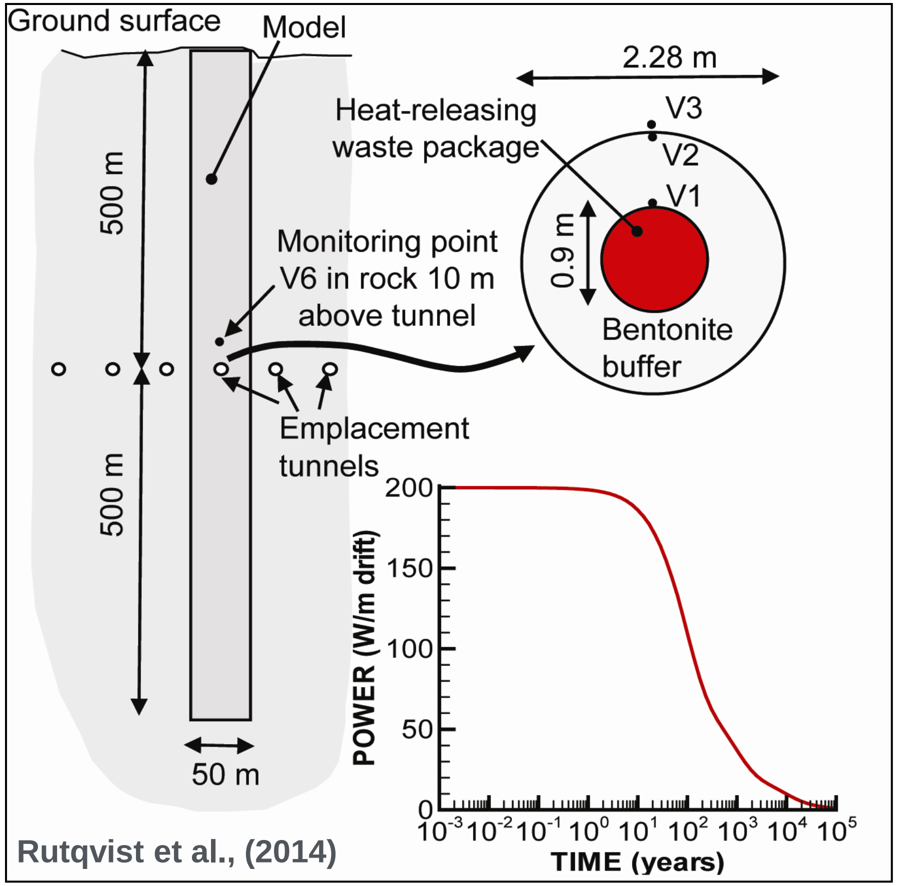


Modeling Long Term Repository Behavior

Three aspects:

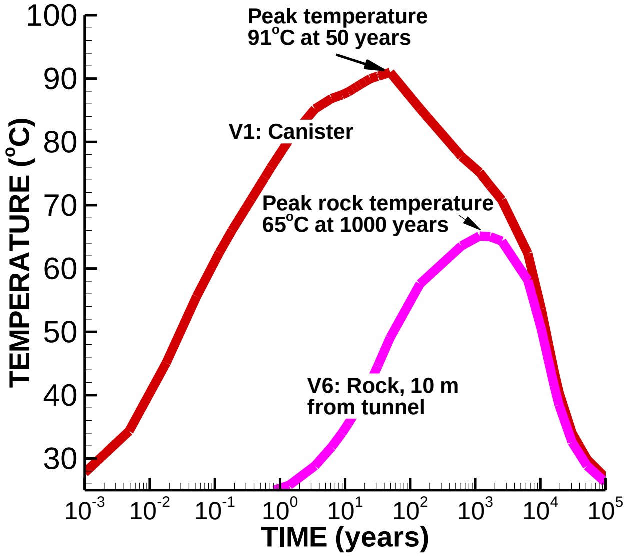
1. **Repository THM responses of the argillite barrier**
2. **Near-field EDZ THM response**
3. **Impact of creep in the argillite barrier (ductile-brittle)**

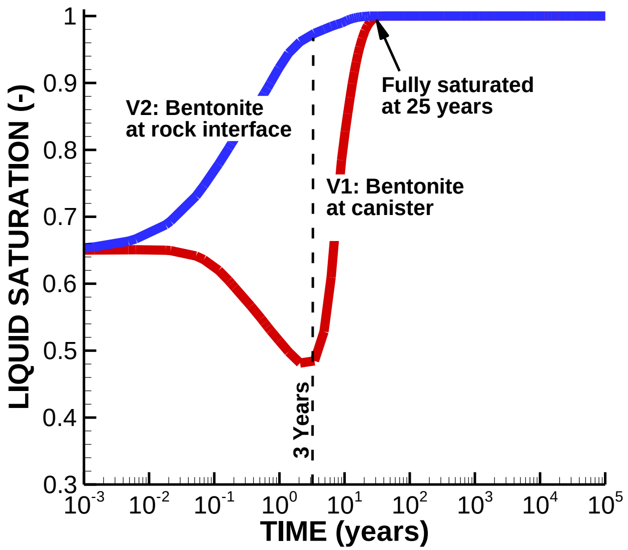
Long-term Coupled Processes Simulation



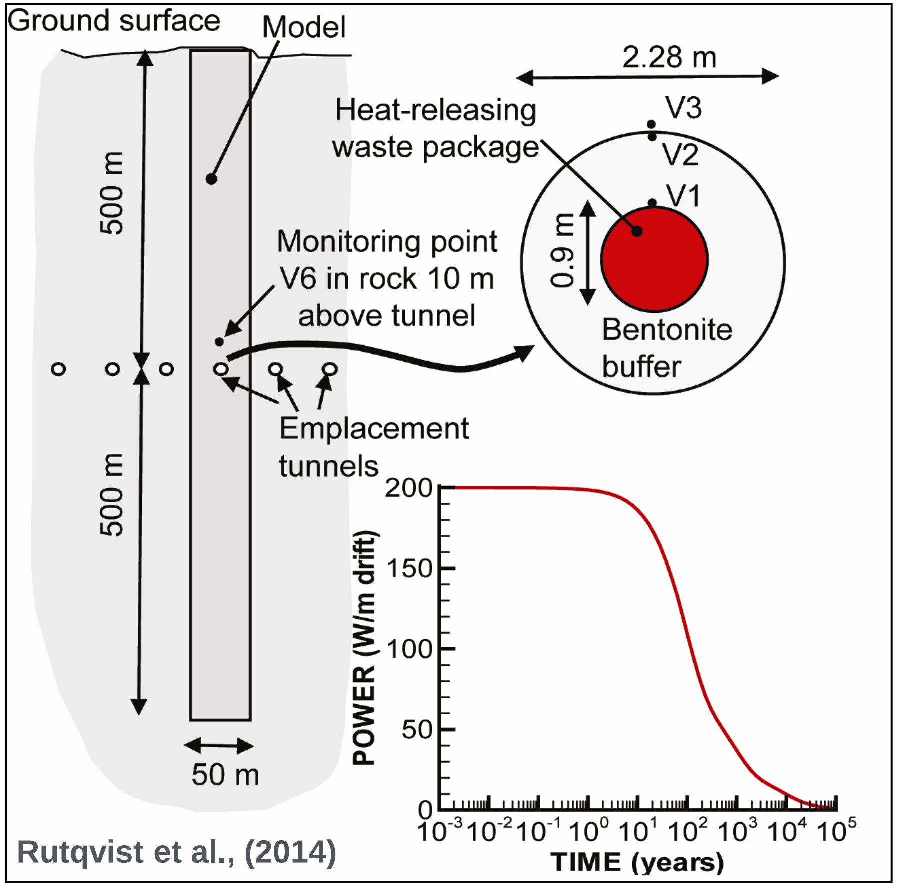
Rutqvist et al., (2014)

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



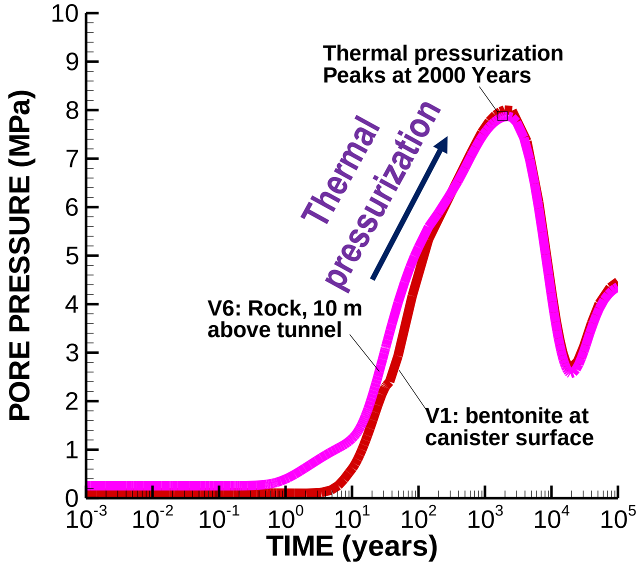


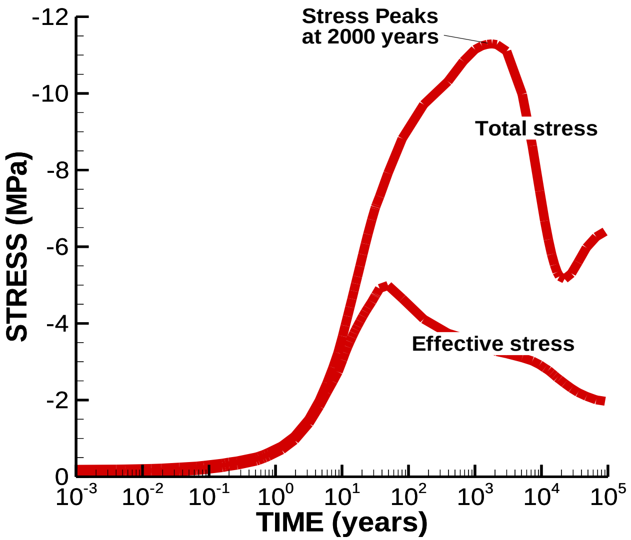
Long-term Coupled Processes Simulation



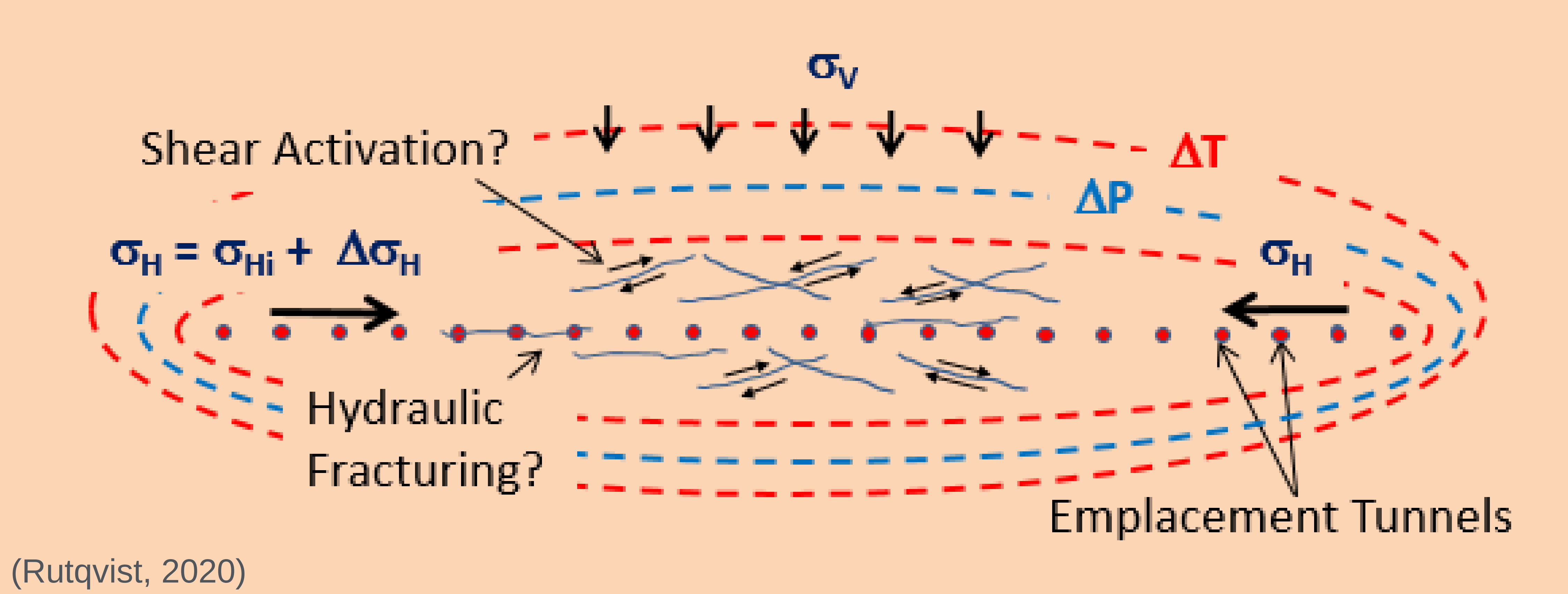
Rutqvist et al., (2014)

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





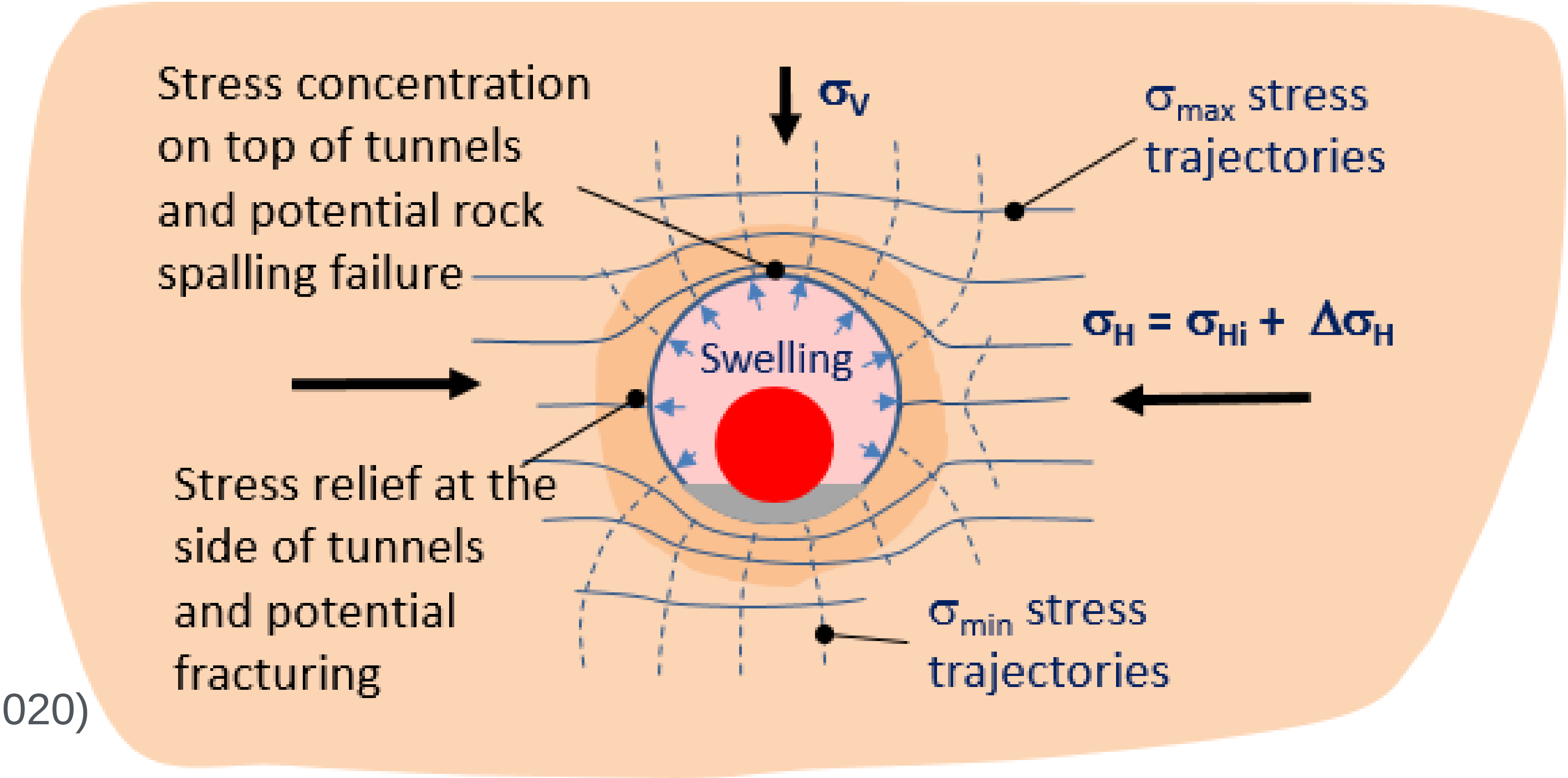
Repository Temperature-induced Stress Changes



(Rutqvist, 2020)

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

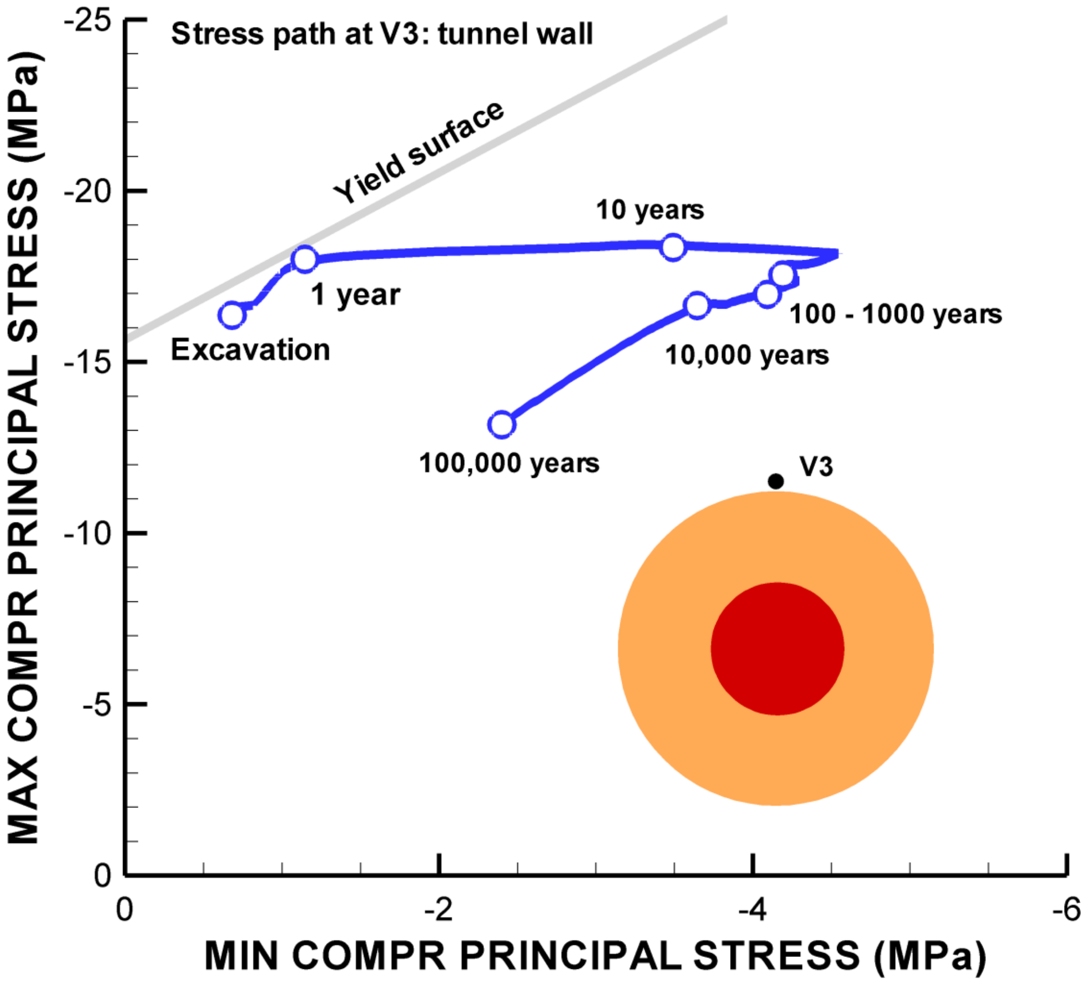
Repository Temperature-induced Stress Changes



(Rutqvist, 2020)

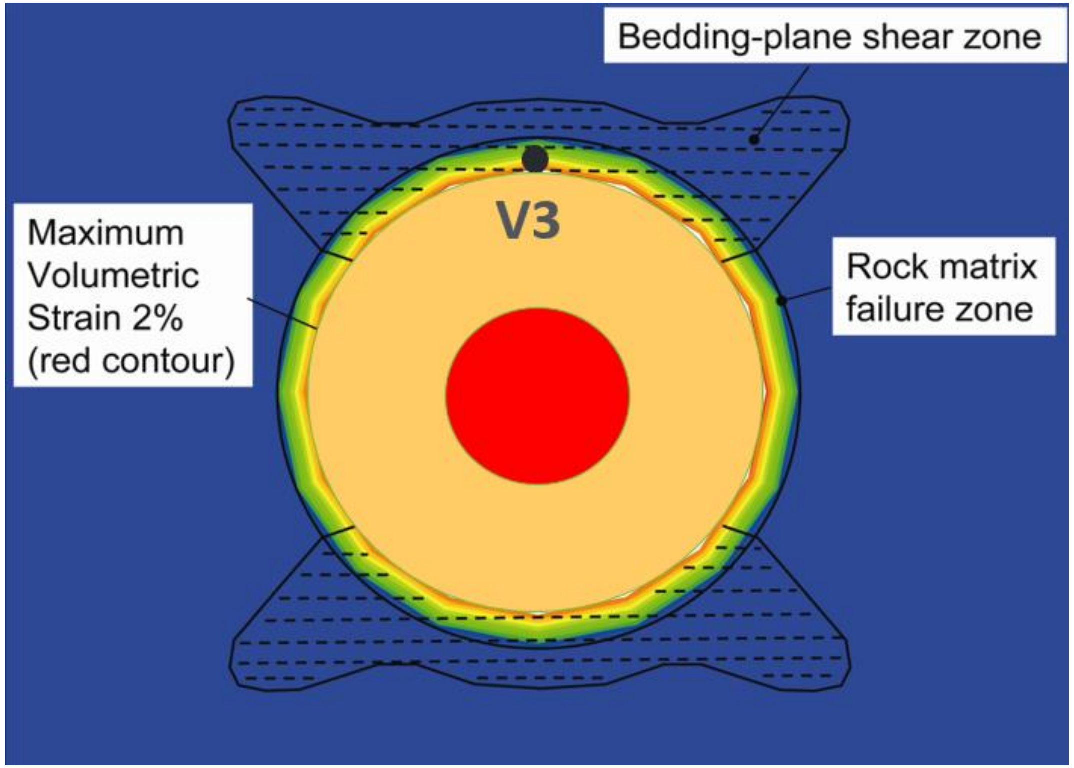
- Can impact EDZ thousands of years after repository closure (when repository temperature peaks)
- Important to have a supporting buffer stress at that time

Long-term Coupled Processes Simulation



Rutqvist et al., (2014)

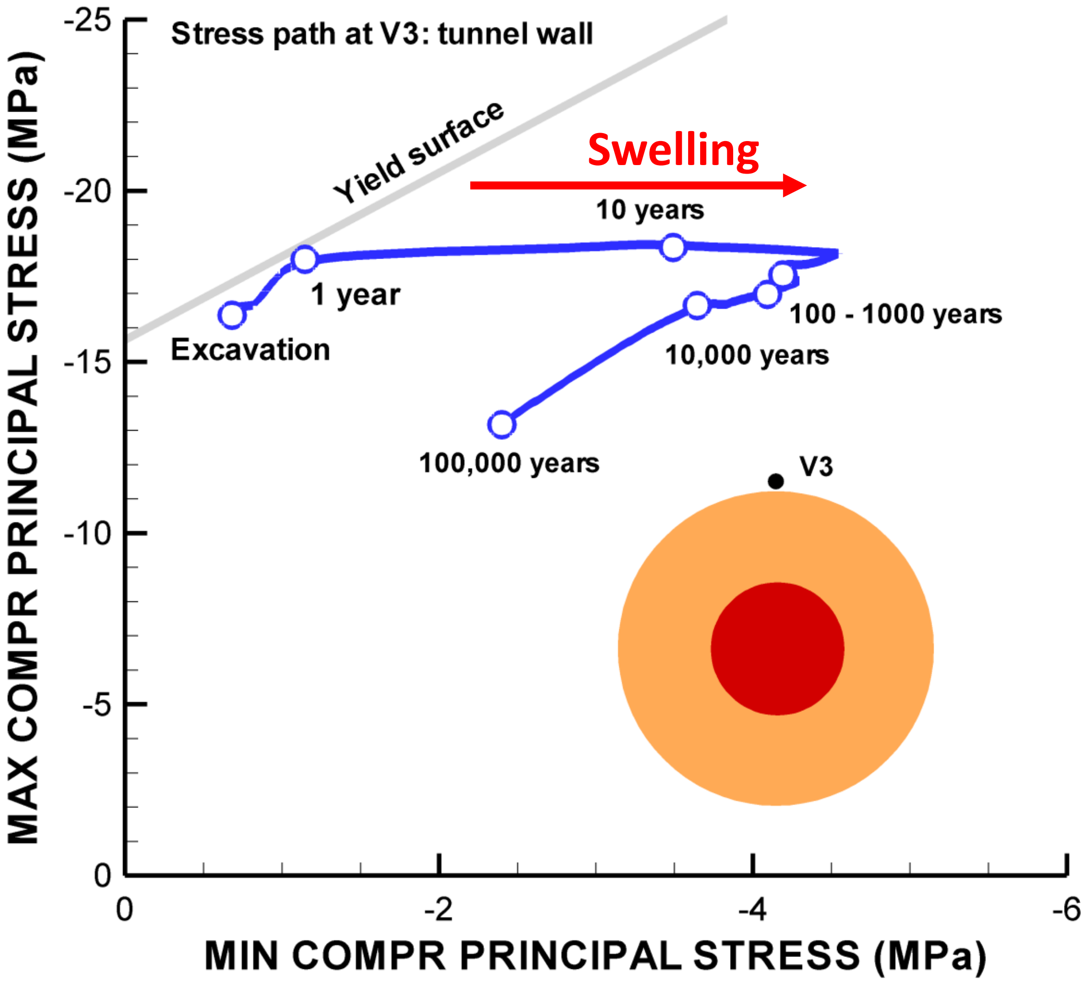
Excavation Disturbed Zone (EDZ) Evolution



EDZ evolution impacted by:

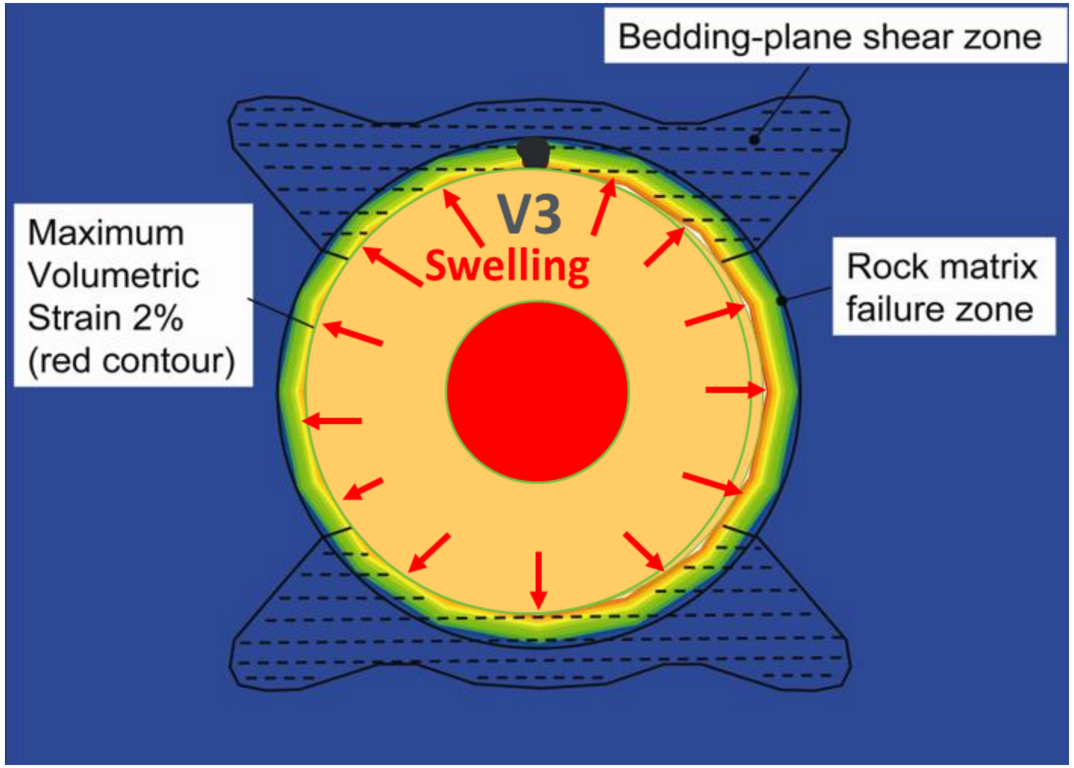
1) Thermal pressurization
2) Thermal stress
3) Wetting-induced bentonite swelling

Long-term Coupled Processes Simulation



Rutqvist et al., (2014)

Excavation Disturbed Zone (EDZ) Evolution



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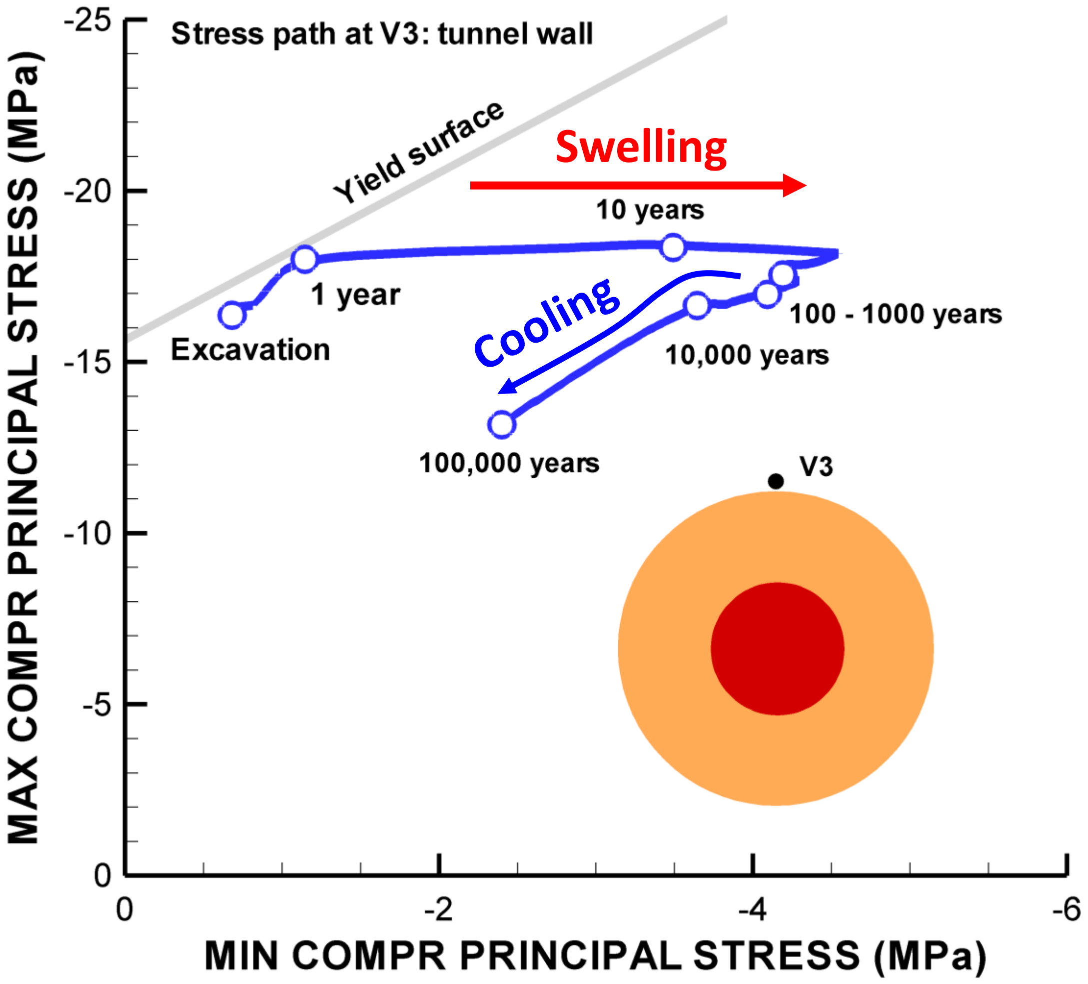
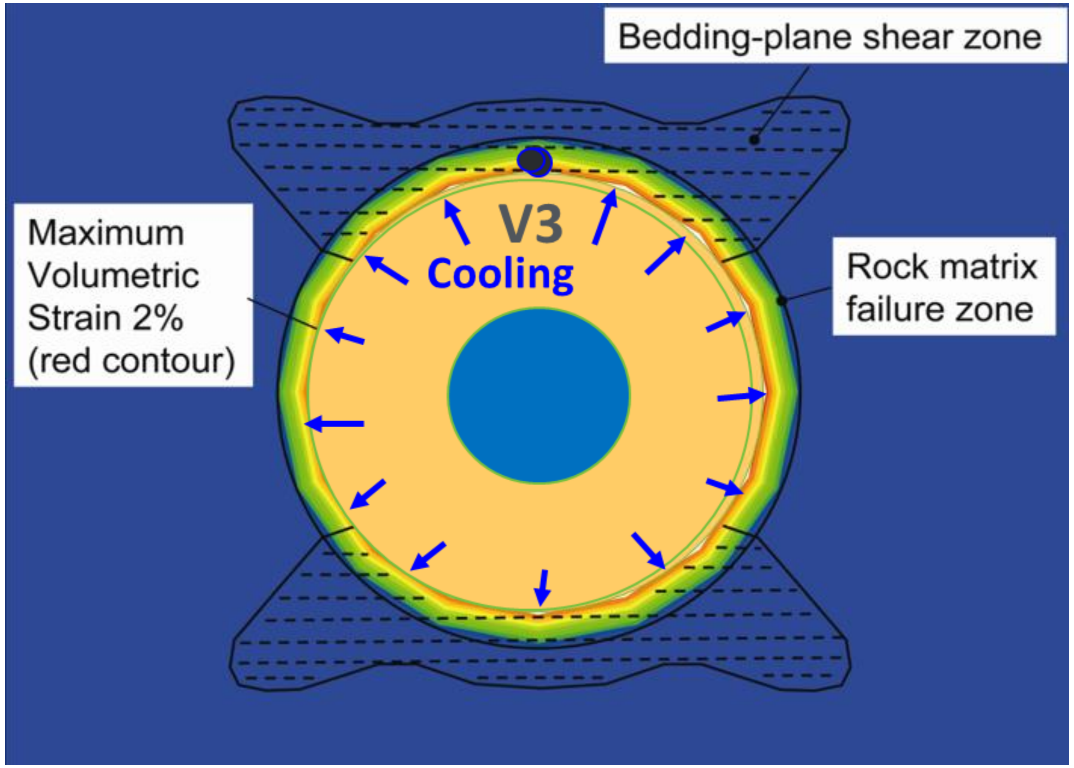
Long-term Coupled Processes Simulation



Rutqvist et al., (2014)

Excavation Disturbed Zone (EDZ) Evolution

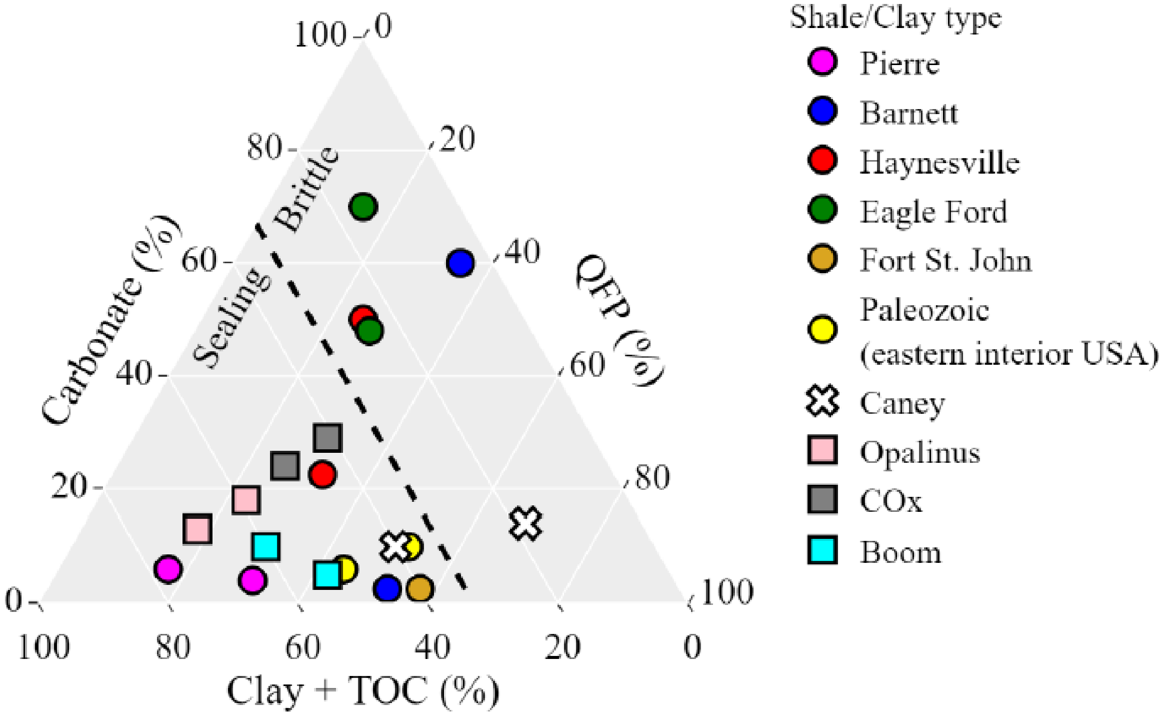


EDZ evolution impacted by:

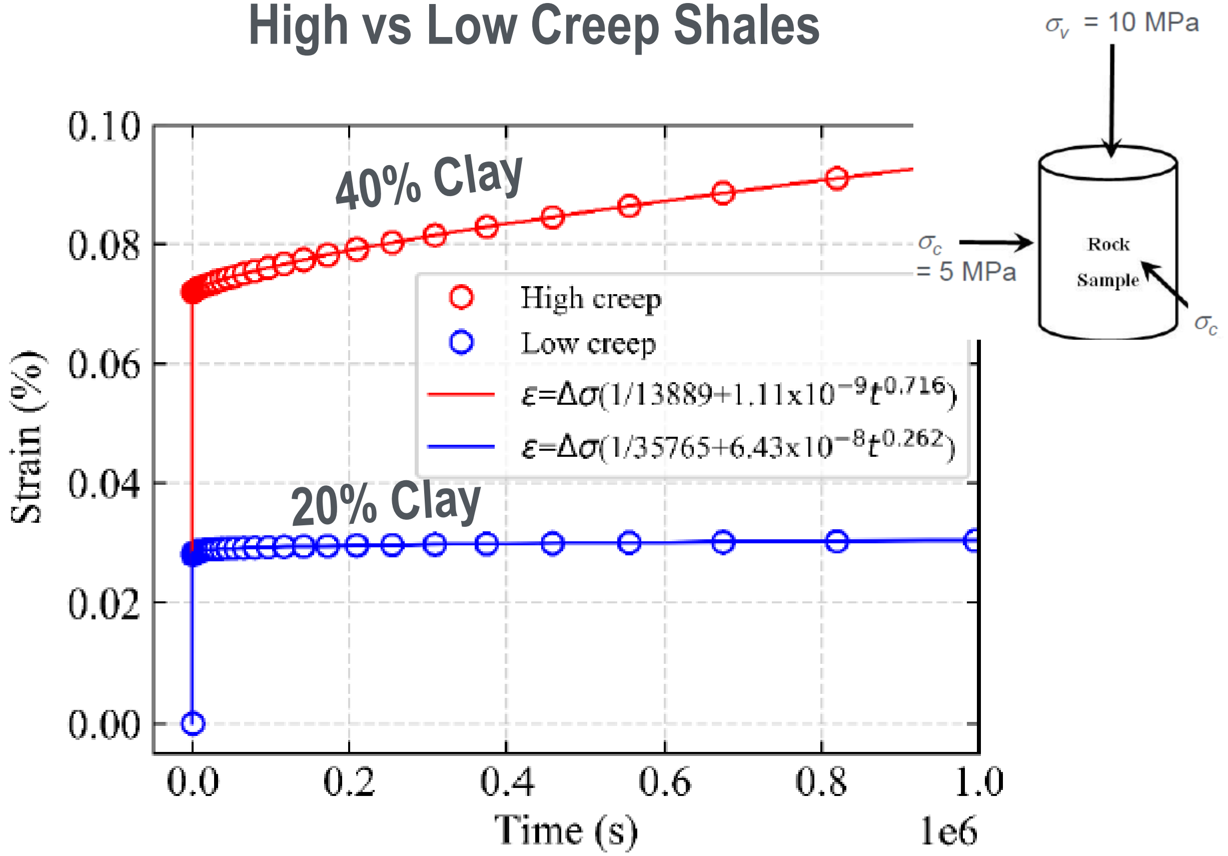
1) Thermal pressurization
2) Thermal stress
3) Wetting-induced bentonite swelling

Impact of Long-Term Creep

Sealing vs Brittle Shales



High vs Low Creep Shales

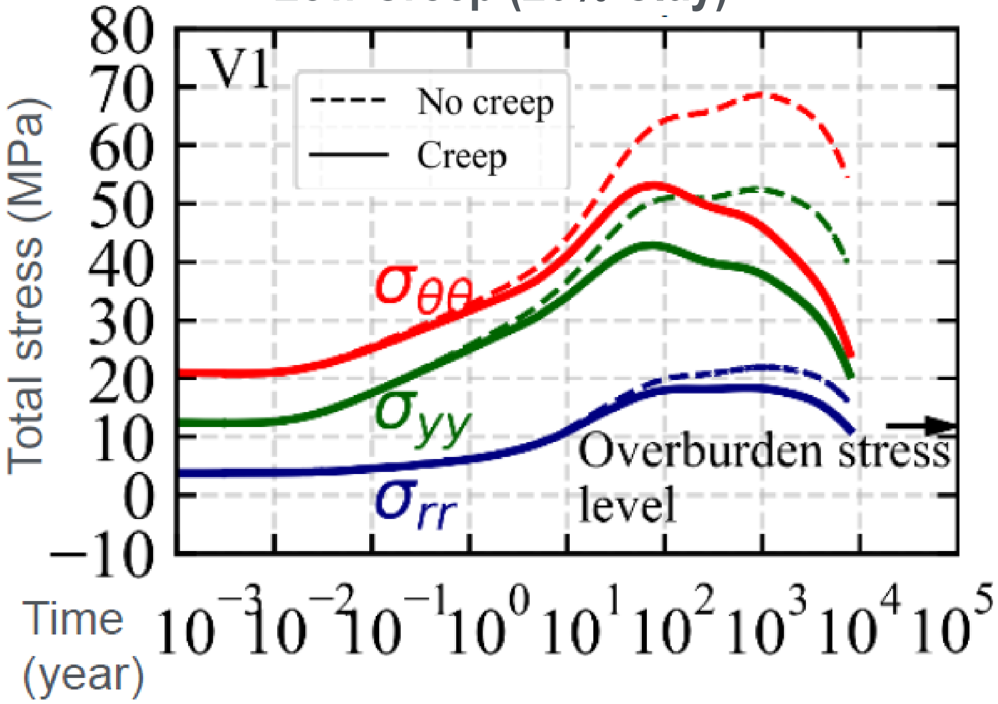


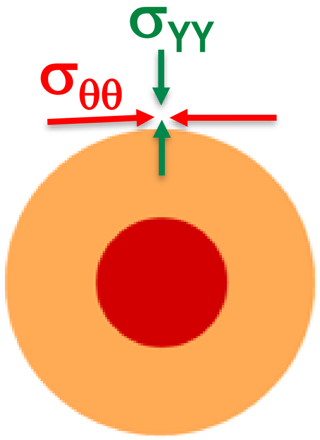
High clay content ⇒ Soft + high creep ⇒ self-sealing

Sasaki and Rutqvist (2022)

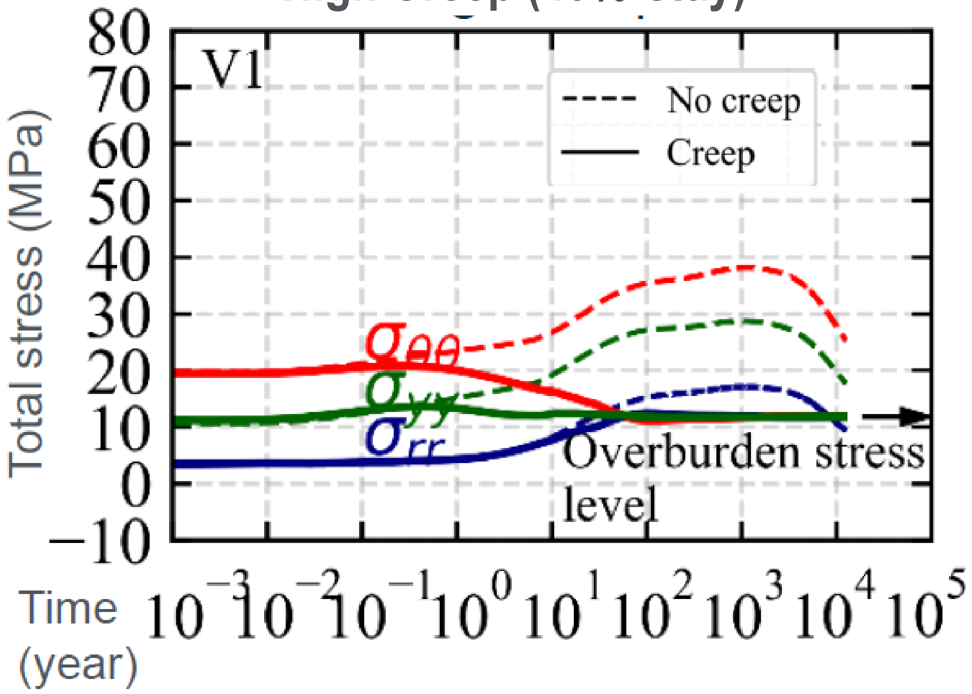
Impact of Long-Term Creep

Low Creep (20% Clay)





High Creep (40% Clay)



Stiffer rock and higher thermal stress

Shear stress remains elevated to 10,000 years

Risk of brittle damage in EDZ

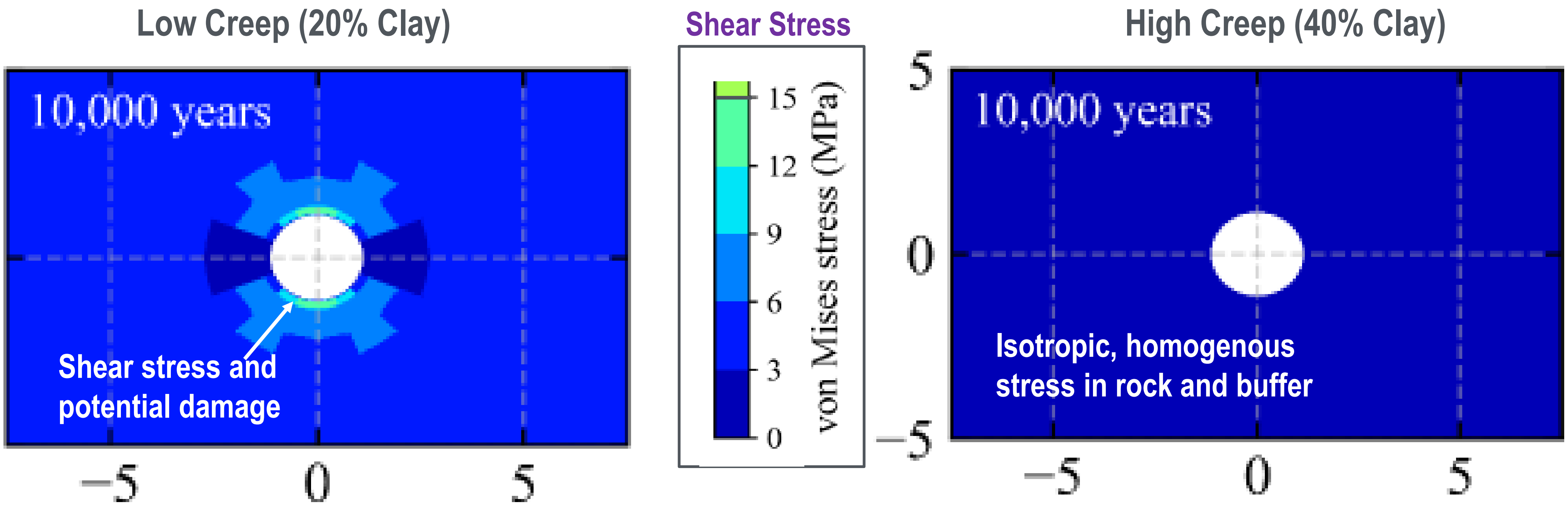
Softer rock and lower thermal stress

Shear stress released by creep in 50 years

Self-sealing EDZ

Sasaki and Rutqvist (2022)

Impact of Long-Term Creep



Low Creep (20% Clay)

Shear Stress

High Creep (40% Clay)

Shear stress and potential damage

Isotropic, homogenous stress in rock and buffer

Stiffer rock and higher thermal stress

Shear stress remains elevated to 10,000 years

Risk of brittle damage in EDZ

Softer rock and lower thermal stress

Shear stress released by creep in 50 years

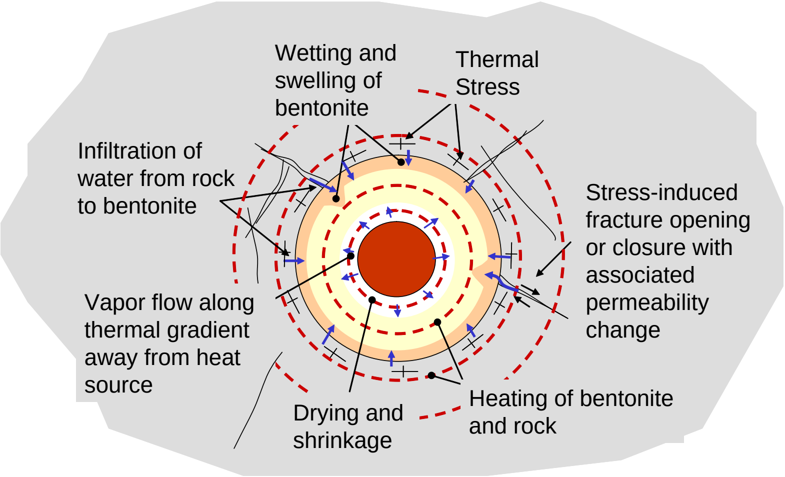
Self-sealing EDZ

Sasaki and Rutqvist (2022)

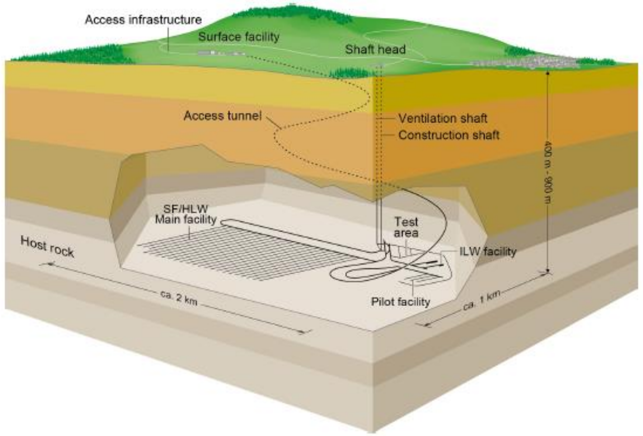
Coupled Processes Model ⇔ Performance Assessment (PA) Model

- N**ear 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 Excavation Disturbed Zone (EDZ), (2) inform PA about local flow created by coupled processes.

Coupled Processes Model of an Emplacement Tunnel



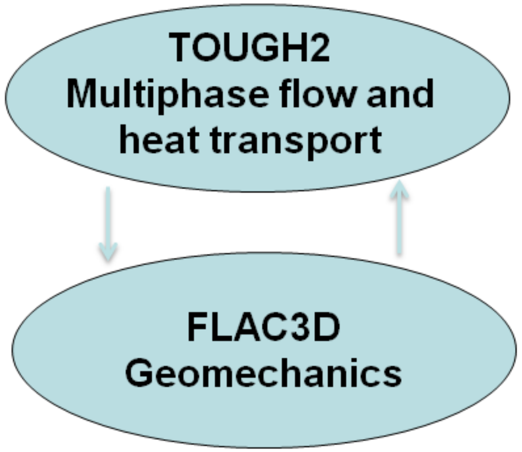
PA Model of Entire Repository



Example layout from the Swiss Concept (Seiphoori, 2015)

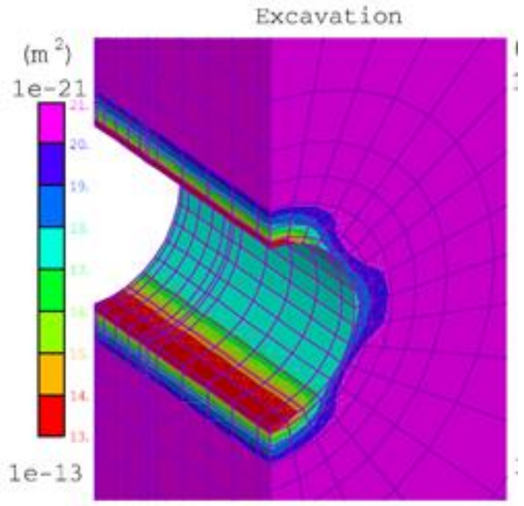
State of the Art and R&D Needs for Argillite THM Modeling

- **THM model framework established (TOUGH-FLAC)**
- **Constitutive THM models for argillite host rocks**
  - Anisotropic shale THM constitutive model validated
  - Thermal pressurization fracturing, fault shear and sealing being investigated
  - Need for creep parameters, such a low stress creep, anisotropic creep
- **Models for EDZ in argillite**
  - 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.,…..
  - Can also learn from shale-gas research



TOUGH2
Multiphase flow and heat transport

FLAC3D
Geomechanics



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
- 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
FEPs	Features, Events, and Processes
FLAC	Fast Lagrangian Analysis of Continua
LBNL	Lawrence Berkeley National Laboratory
NAGRA	Swiss waste management organization
PA	Performance Assessment
Swisstopo	Federal Office of Topography, Switzerland
THM	Thermo-hydro-mechanical
TOUGH	Transport Of Unsaturated Groundwater and Heat