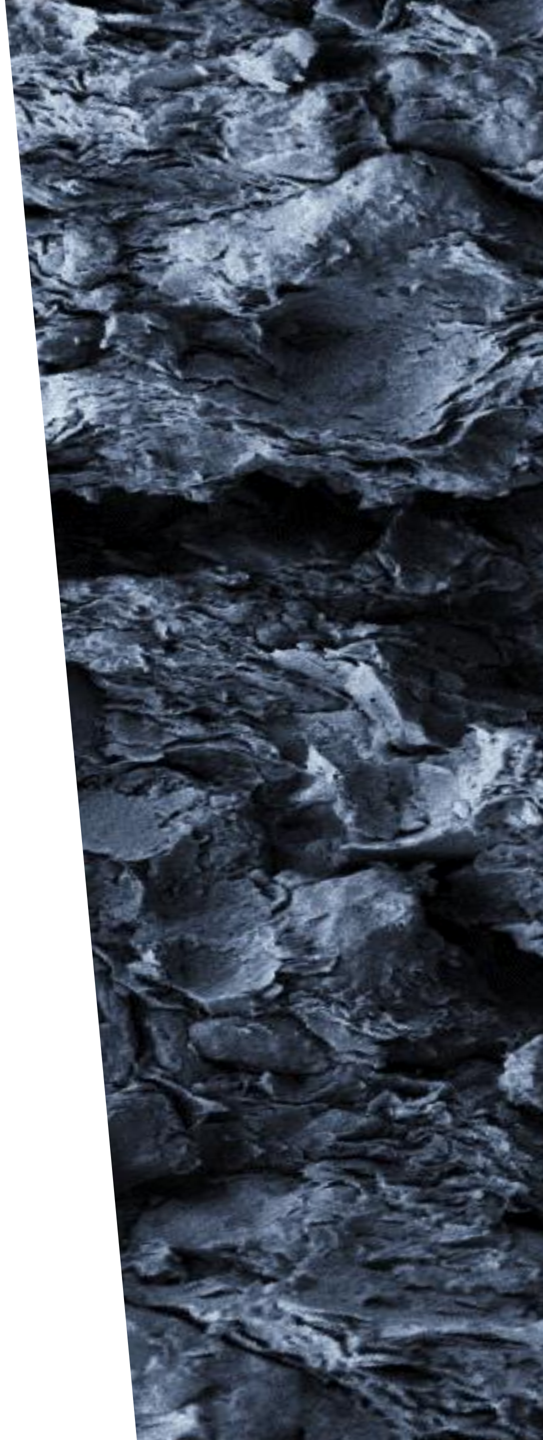
Anisotropic characteristics of claystone under mechanical and thermal loads

Philipp Braun

Siavash Ghabezloo, Pierre Delage



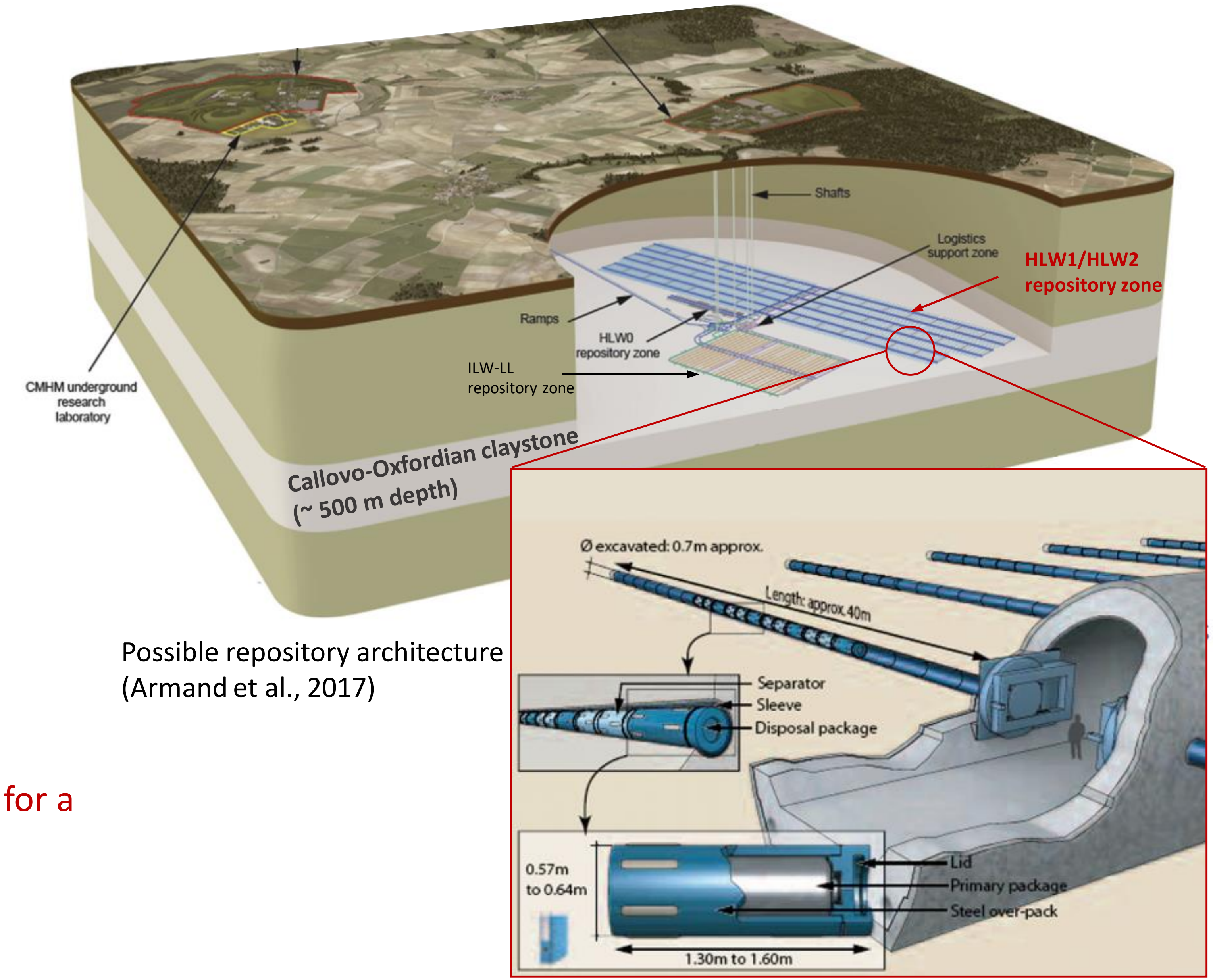
Cigéo Project

Deep geological radioactive waste repository, investigated by Andra

Clay rock acts as natural barrier

- Ability to retain radionuclides
- Low permeability

Understanding the rock behaviour for a safe design of the galleries and microtunnels



Possible repository architecture (Armand et al., 2017)

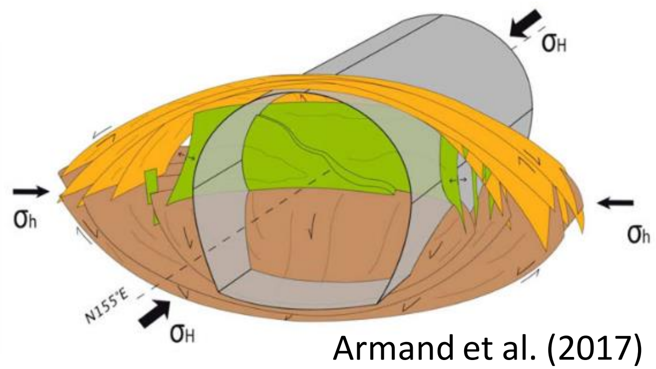
Behaviour of the rock formation

Loading types

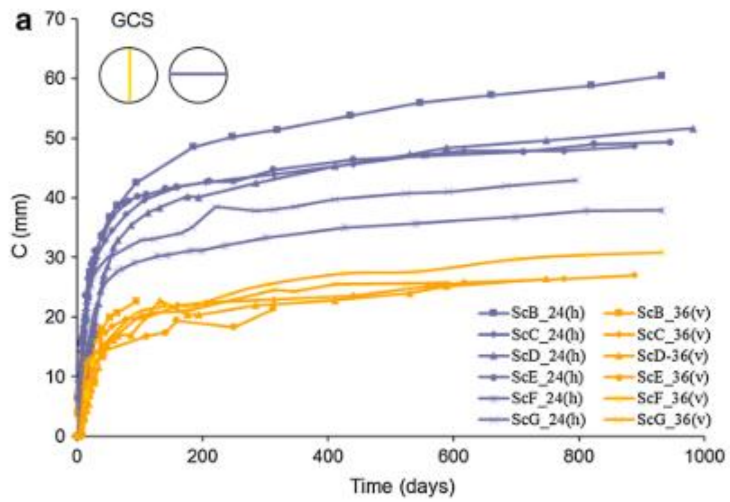
- Mechanical
- Hydraulic
- Thermal

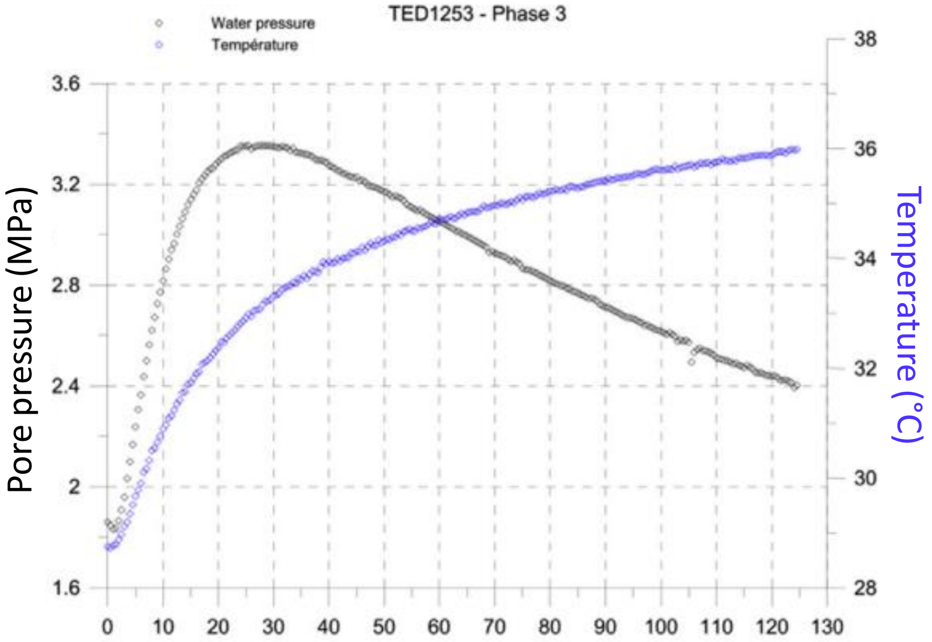
Response

- Instantaneous/elastic: (Thermo-) Poro-elastic
- Irreversible: Plasticity, damage
- Time dependent: Fluid and heat dissipation, viscosity of solid matrix



Armand et al. (2017)

Guayacán-Carrillo et al. (2016)




Conil et al. (2012) Time (days)

Material properties

Callovo-Oxfordian claystone

- Solid matrix of around
  - 42% clay matrix
  - 30% carbonates
  - 25% quartz
  - < 4% feldspar

(Gaucher et al., 2004; Conil et al., 2018)

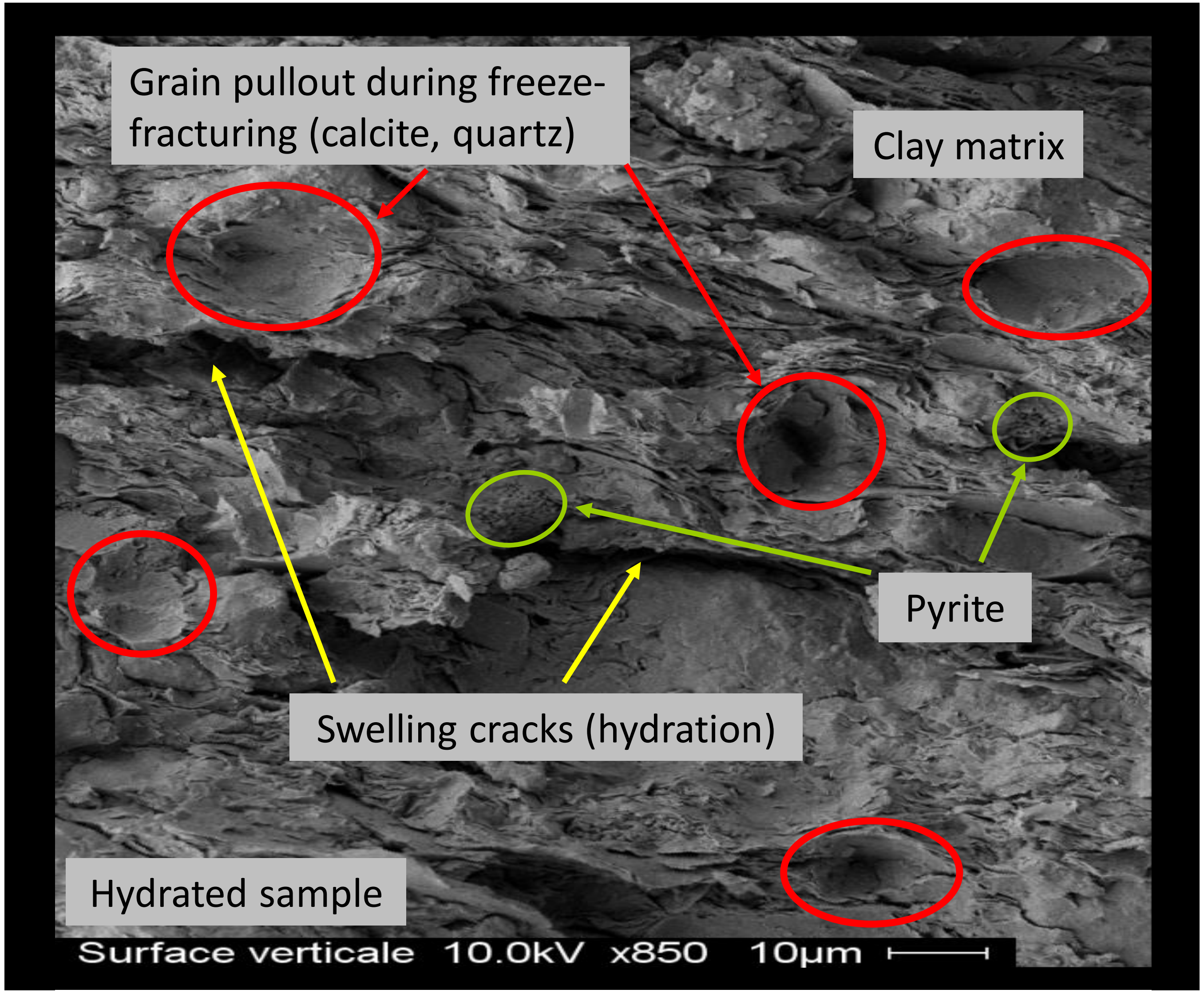
- Porosity of around 18% (Yven et al., 2007; Conil et al., 2018)

➢ Very low permeability

➢ Sensitivity to water:
- Stiffer when desaturated
- Swelling under resaturation

➢ Transverse isotropy in:
- Hydromechanical properties
- Thermal properties
- Permeability

Menaceur (2014)



Transversely isotropic thermo-poro-elasticity

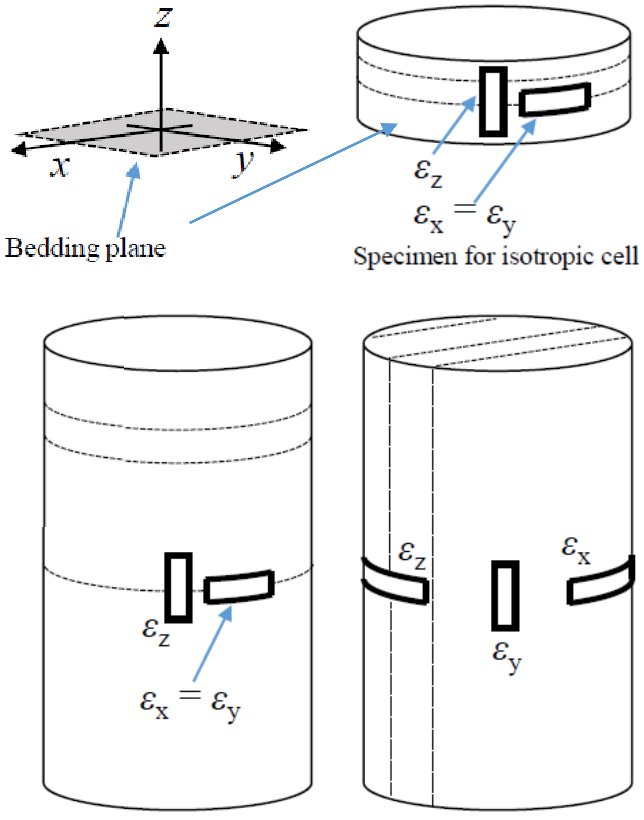
$$d\varepsilon_i = C_{ij} d\sigma_j - C_{ij} b_j dp_f - \alpha_{d,i} dT$$

- Mechanical behaviour:

$$C_{ij} = \begin{pmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/2G' & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/2G & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/2G \end{pmatrix}$$

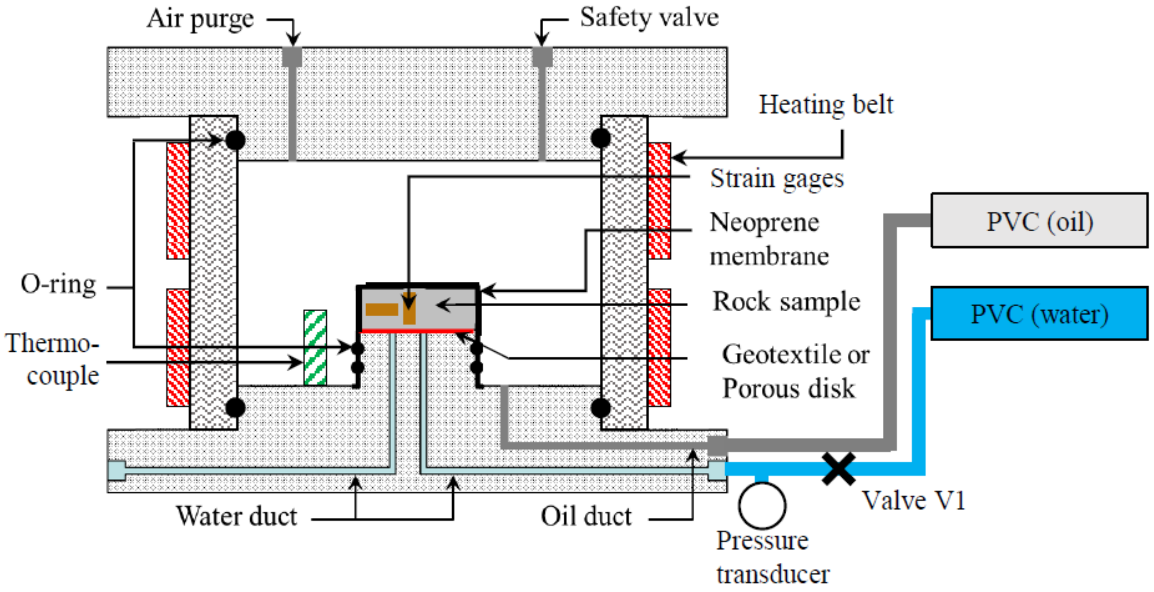
$$\begin{aligned} C_{11} &= 1/E_h \\ C_{12} &= -\nu_{hh}/E_h \\ C_{13} &= -\nu_{zh}/E_z \\ C_{33} &= 1/E_z \\ G' &= E_h/(1+\nu_{hh}) \end{aligned}$$

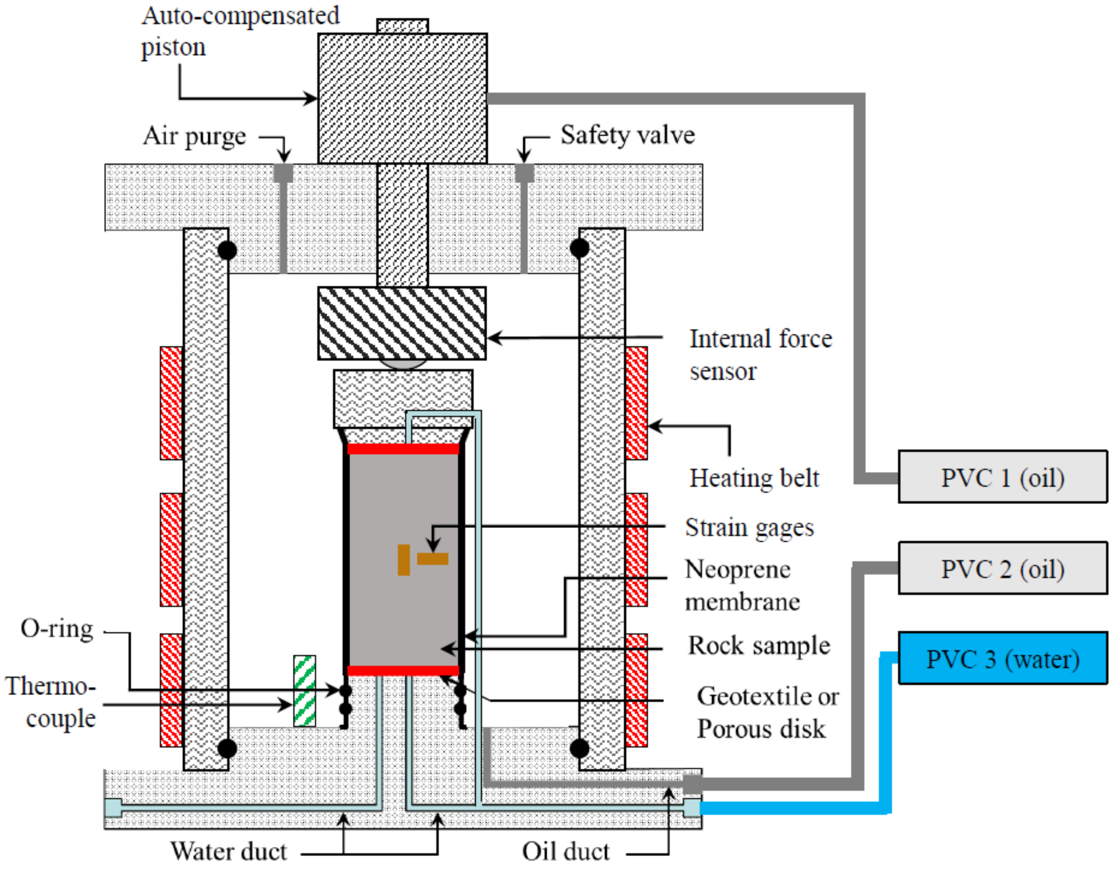
- HM coupling: $b_i = [b_h, b_h, b_z, 0, 0, 0]^\top$
- Thermal strains: $\alpha_{d,i} = [\alpha_{d,h}, \alpha_{d,h}, \alpha_{d,z}, 0, 0, 0]^\top$



Temperature controlled high pressure cells

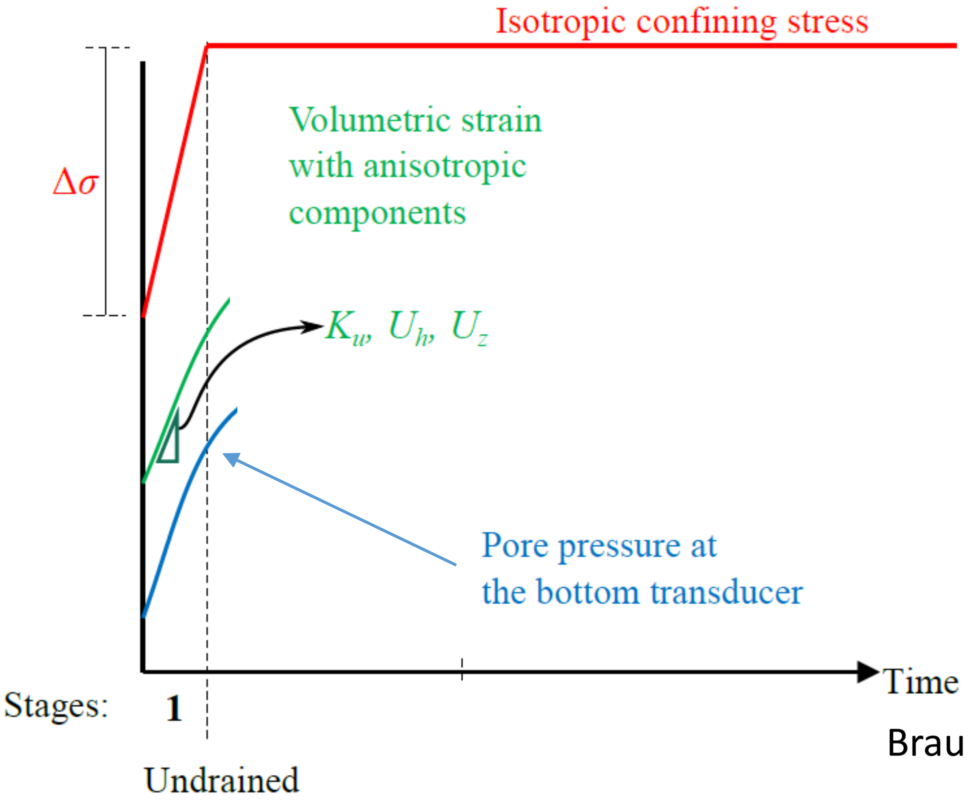
Confining pressure	up to 40 MPa
Temperature control	20 – 90 °C



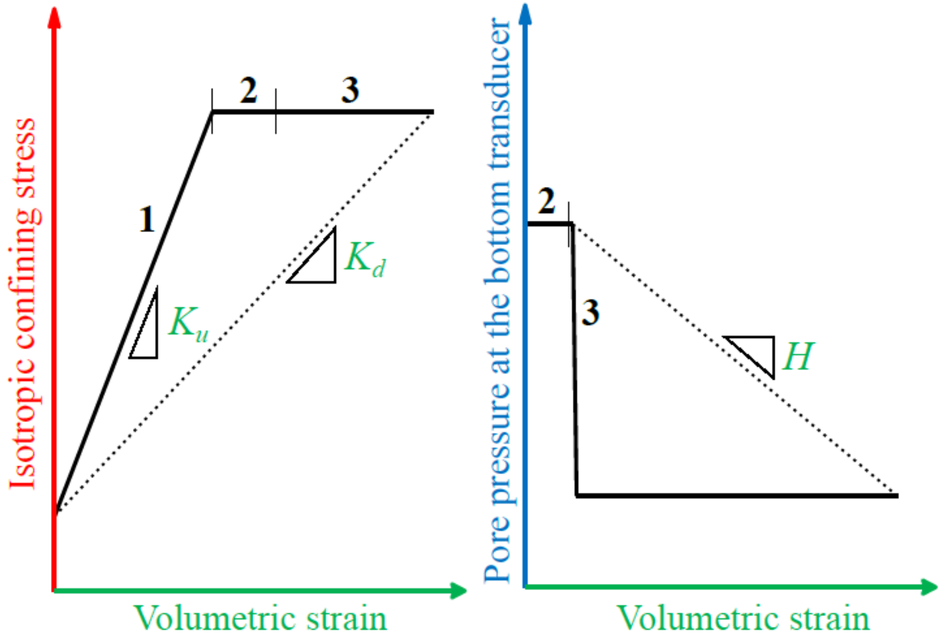


- Under-stress resaturation
- Reduction of drainage length (geometry, geotextile)
- Adapted new testing protocols

New testing protocol



Braun et al. (2019)



- Assuring drained conditions under minimum time necessary
- Measurement of multiple elastic parameters and permeability

Experimental results

$$d\sigma_{ij} = C_{ijkl} d\varepsilon_{kl} - b_{ij} dp - C_{ijkl} \alpha_{kl} dT$$

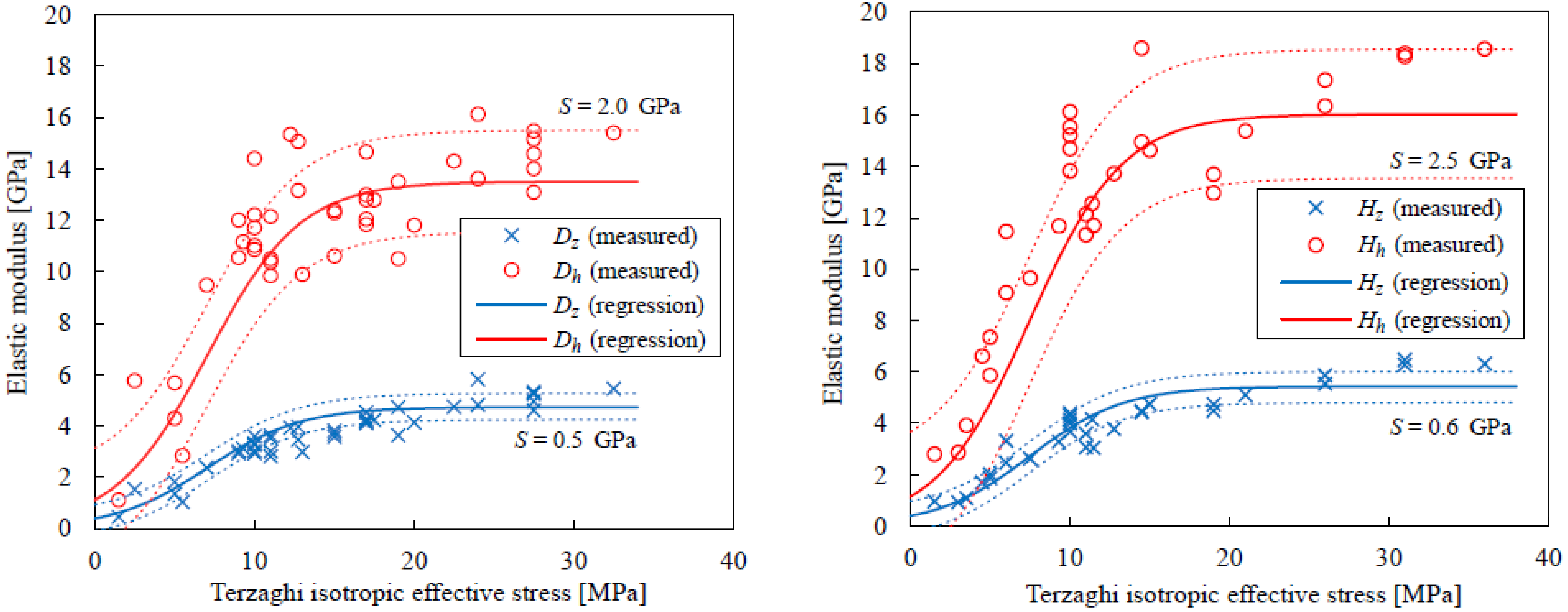
$$\frac{dm_f}{\rho_f} = b_{ij} d\varepsilon_{ij} + \frac{1}{M} dp - 3\alpha_m dT$$

(Braun et al., 2021a,b)

Drained triaxial compression (two directions)	• Measurement of 14 parameters (stress dependent) • Multivariate fitting of transversely isotropic framework (stress dependent) with 9 parameters
Drained isotropic compression	
Undrained triaxial compression (two directions)	
Undrained isotropic compression	
Pore pressure loading	
Drained heating tests	• Observation of anisotropic thermal strains • Thermoplastic characteristics
Undrained heating tests	

Isotropic test response

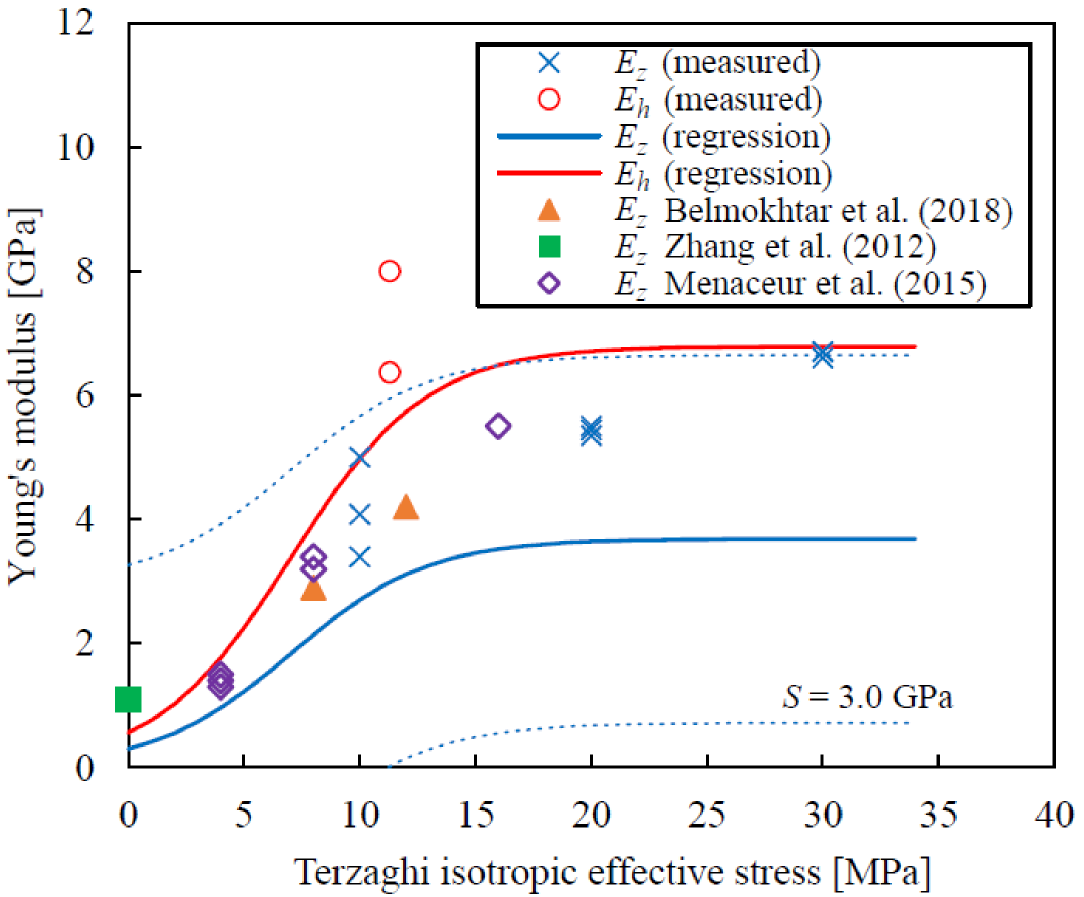
Braun et al. (2021a)

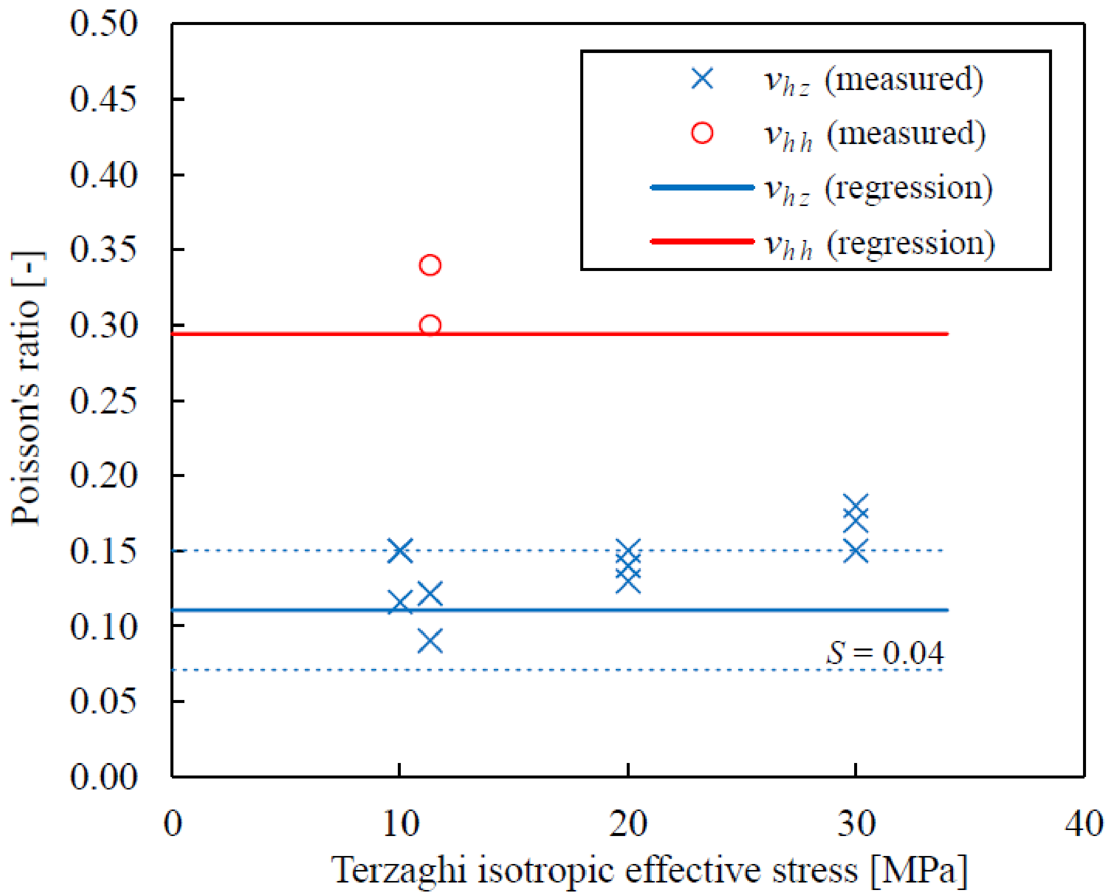


- Significant stress dependency and anisotropy
- Good fit with constant isotropic unjacketed modulus K_s = 19.7 GPa (21.7 GPa, Belmokhtar et al., 2017)

Triaxial test response

Braun et al. (2021a)

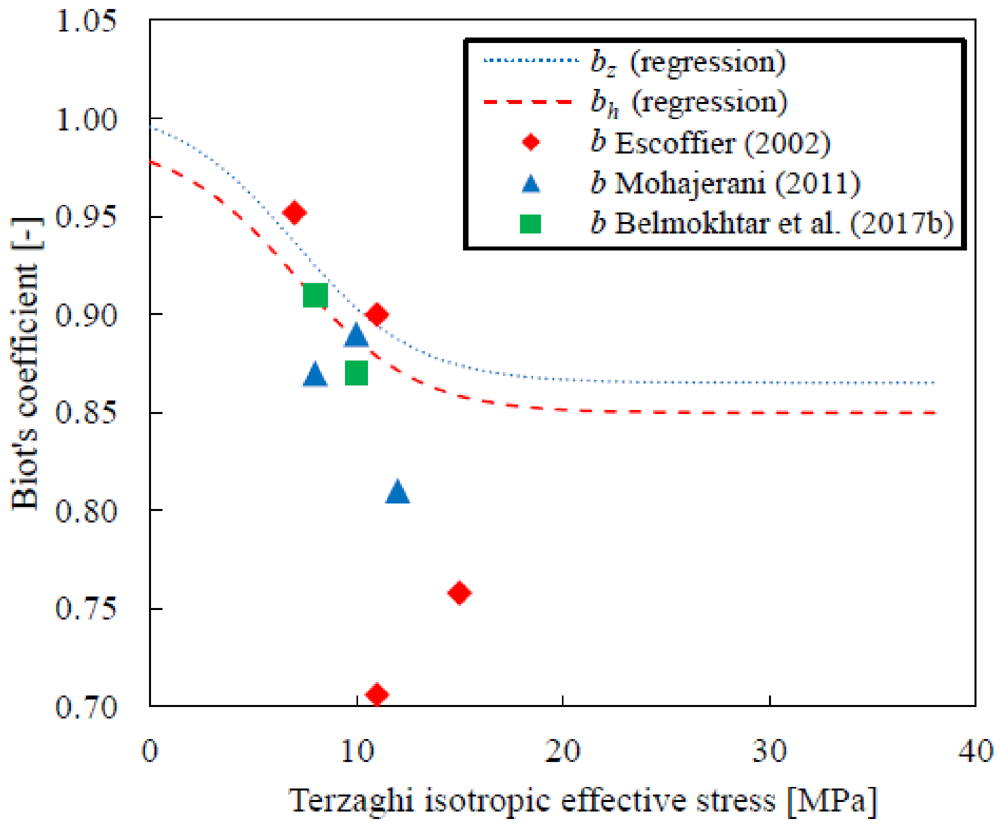


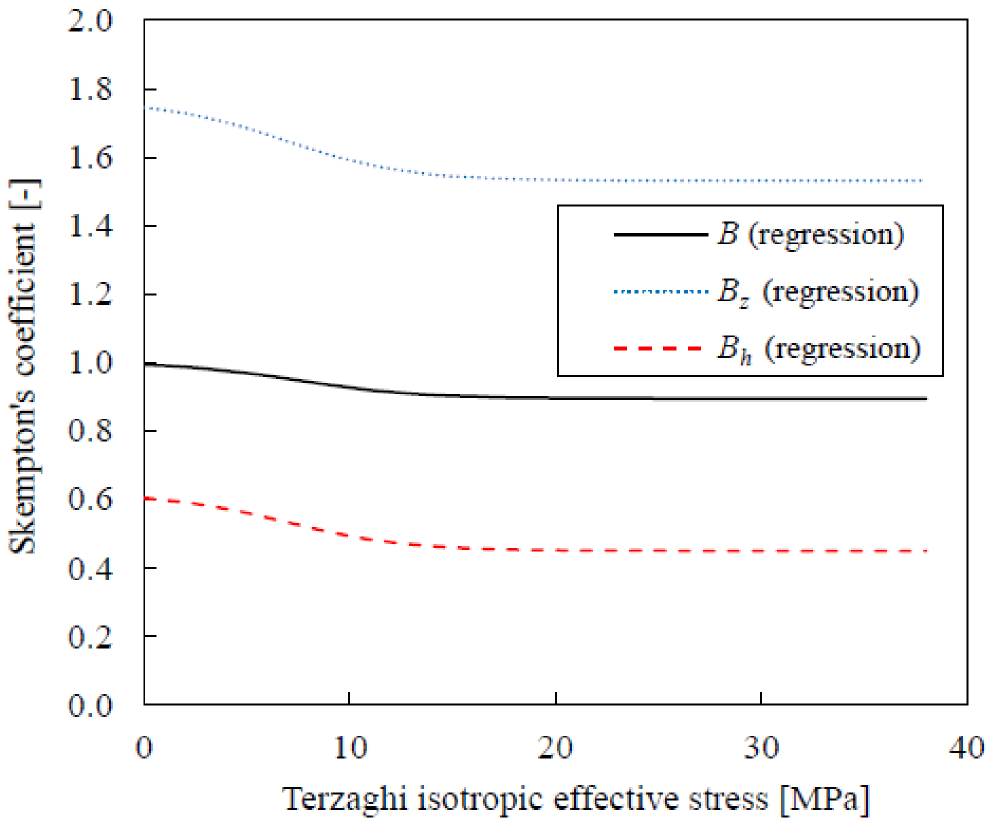


- Significant stress dependency and anisotropy
- Youngs modulus underestimated by the regression model

Back-calculated parameters

Braun et al. (2021a)





- Small stress dependency and anisotropy on *b*
- Anisotropic Skempton coefficient: compare excavation overpressure

Drained thermal strains

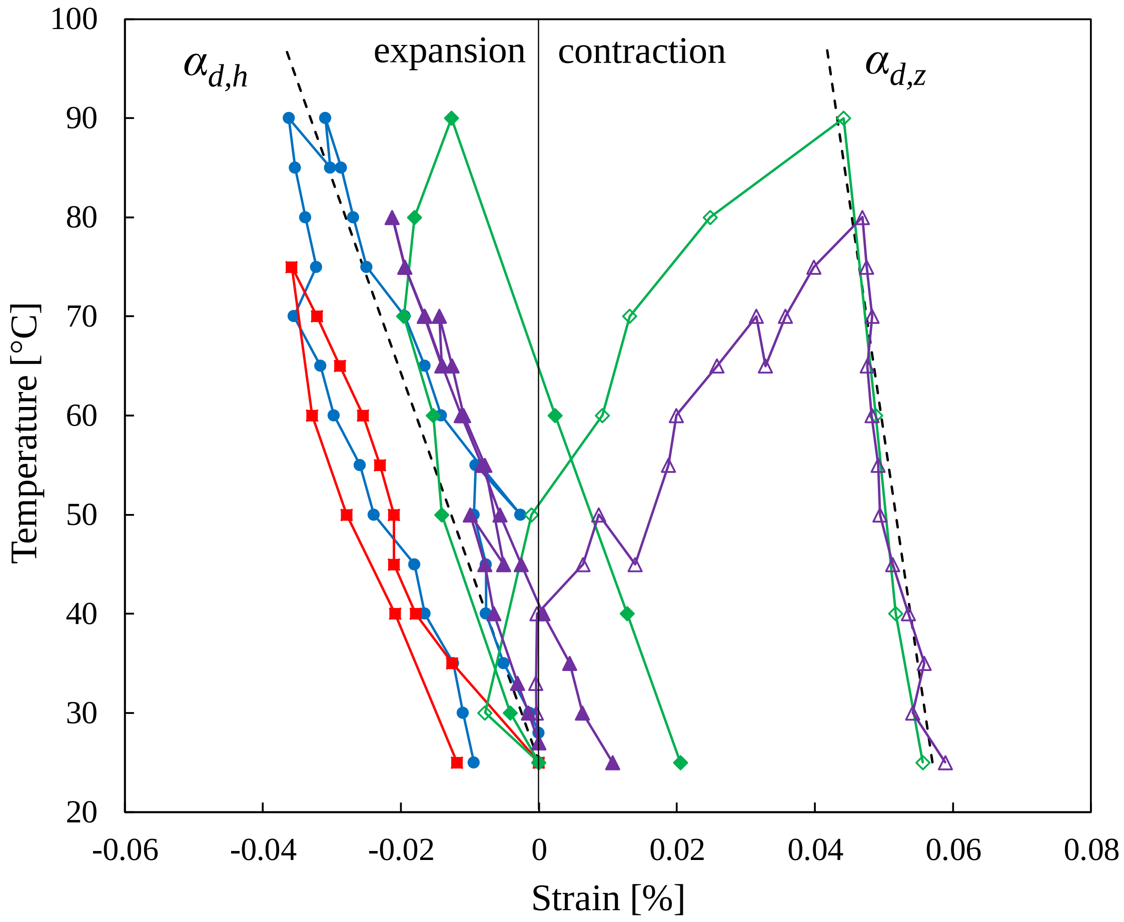
- 4 COx samples tested under heating and cooling at constant (in situ) stress
- Reversible strains parallel to bedding
  - ➢ Compared with mineral properties:

Mineral	Mass-fraction P_i (%)	Thermal expansion coefficient α_i (10^{-5} /°C) volumetric	⊥	∥
Muscovite	42	2.48	1.78 [1]	**0.35** [1]
Calcite	30	1.4 [2]		**0.5**
Quartz	25	3.3 [3]		**1.1**
Feldspar	3	1.1 [2]		**0.4**

[1]McKinstry (1965), [2]Fei (1995), [3]Palciauskas and Domenico (1982)

$$\alpha_{d,h}^{m} = \sum_1^4 \alpha_i \, P_i$$

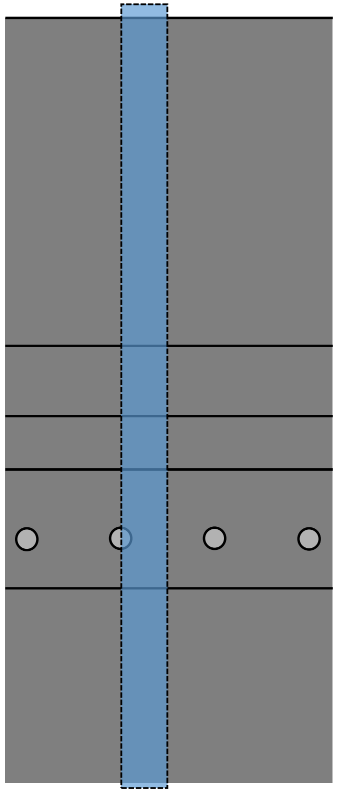
- Irreversible strains upon heating perpendicular to bedding (confirmed in various works on clay based materials)



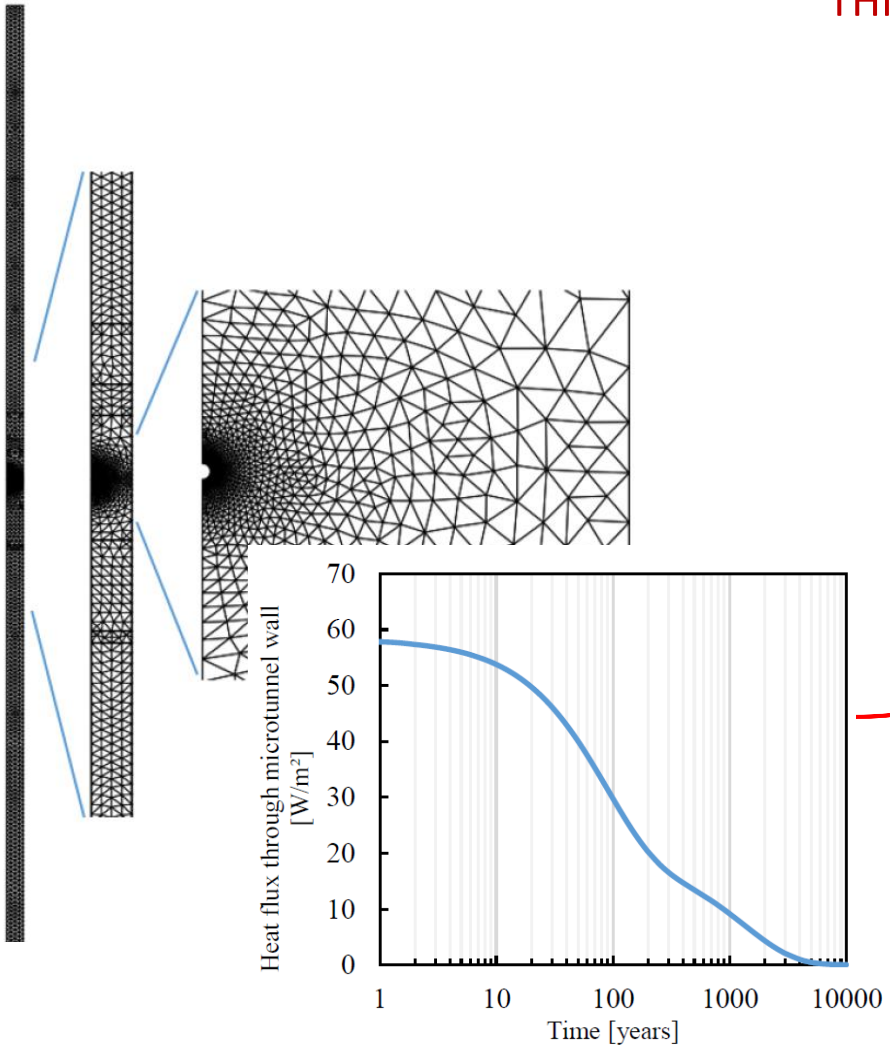
Braun et al. (2020,2021b)

Simulation of a repository scenario

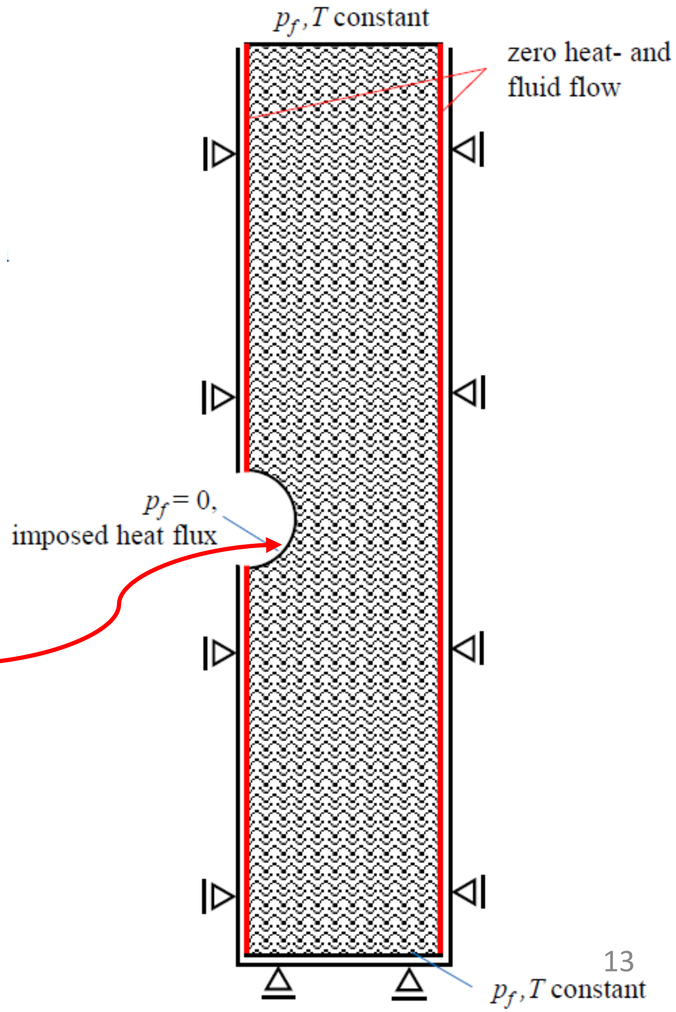
Simulation in FreeFem++ (Hecht, 2012)



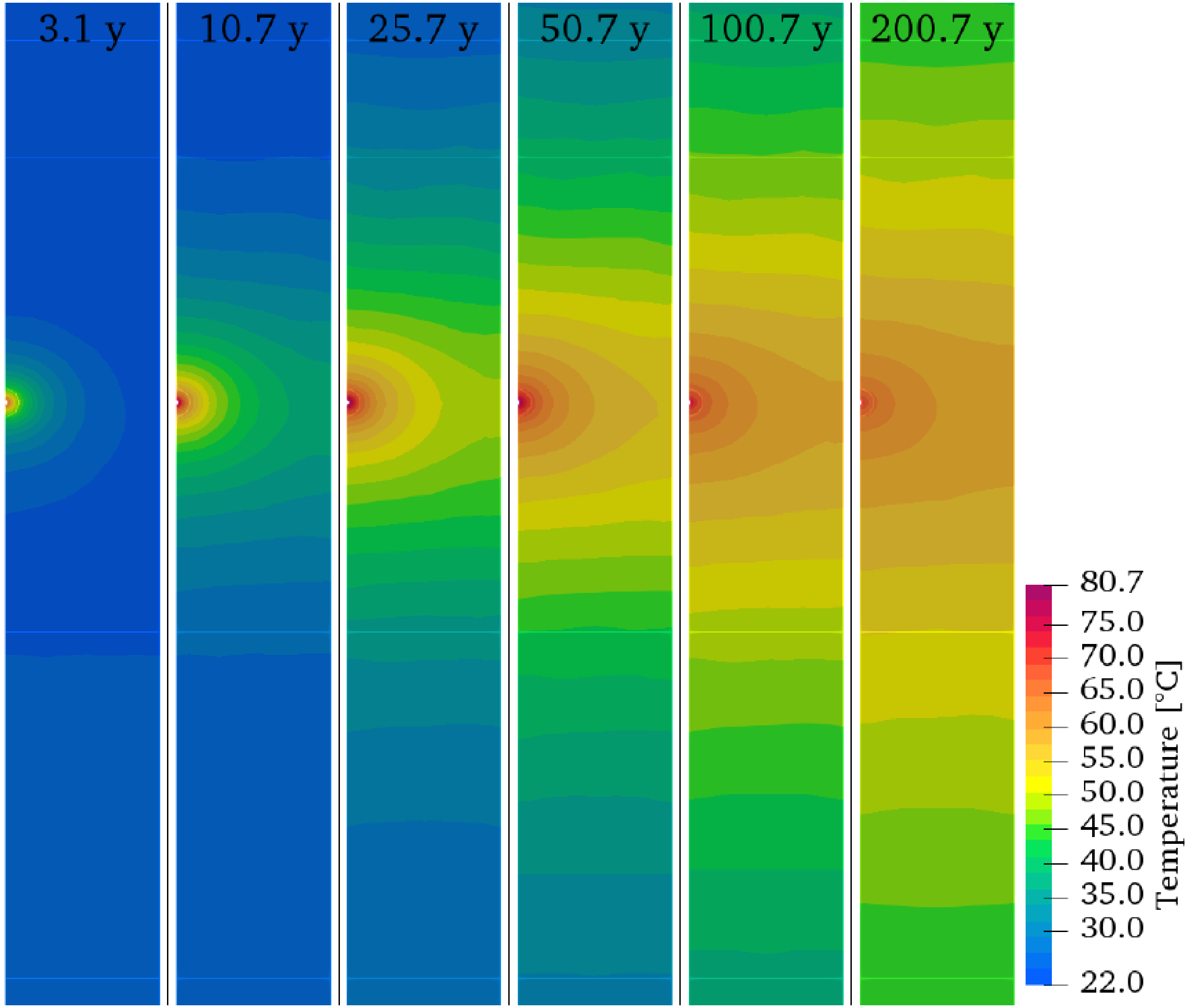
(not to scale)



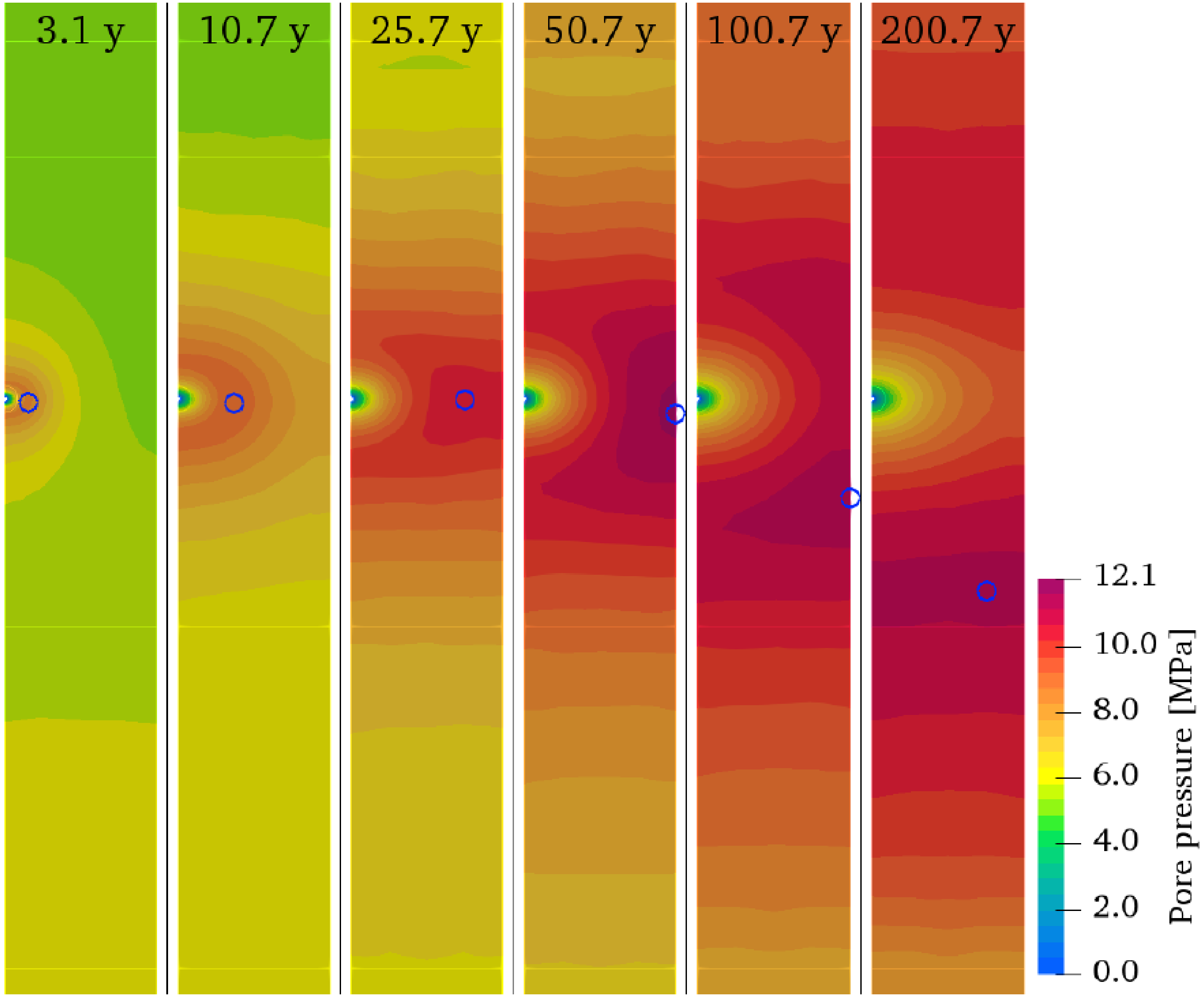
- Imaginary scenario to understand THM processes



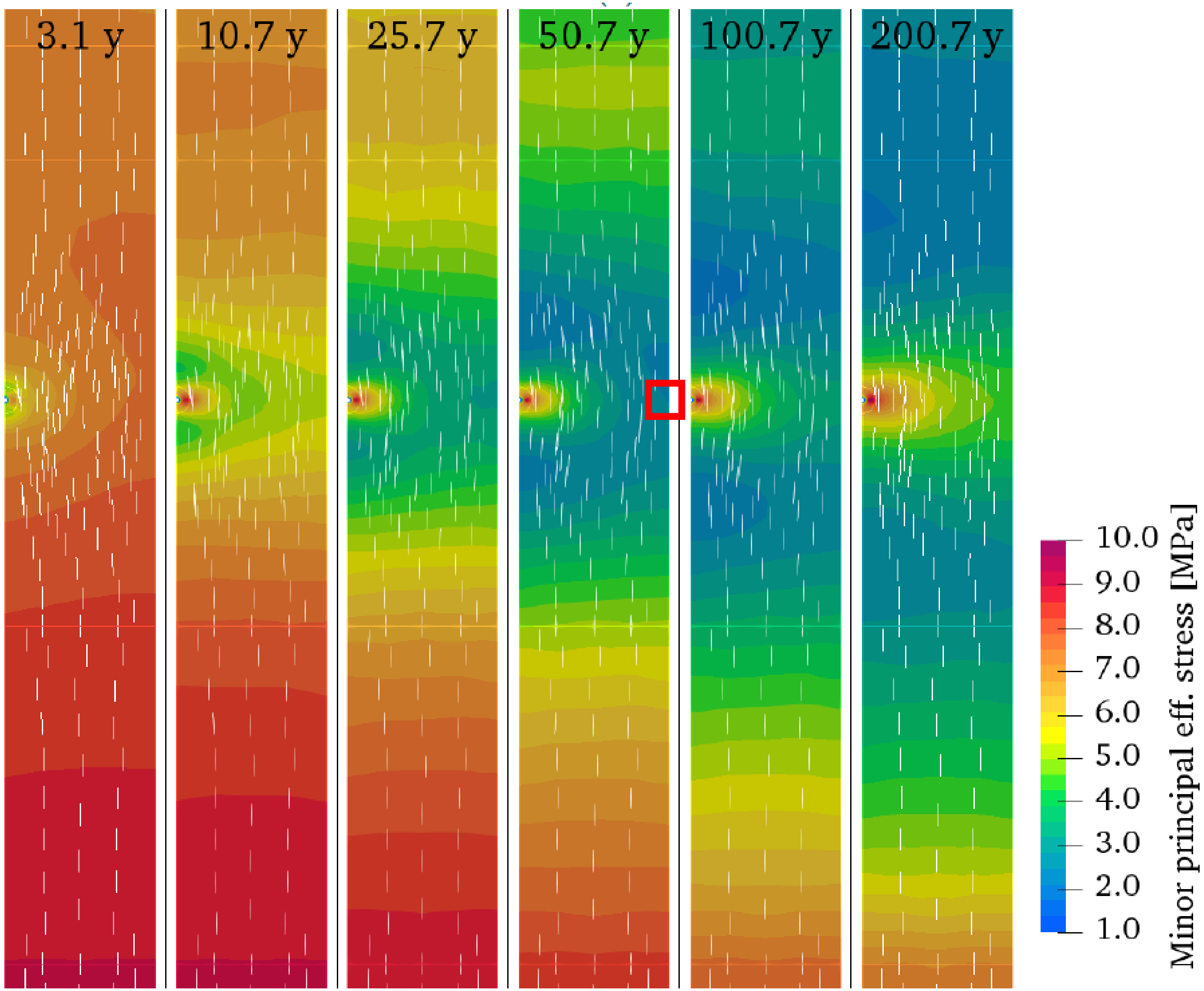
Simulated temperature evolution

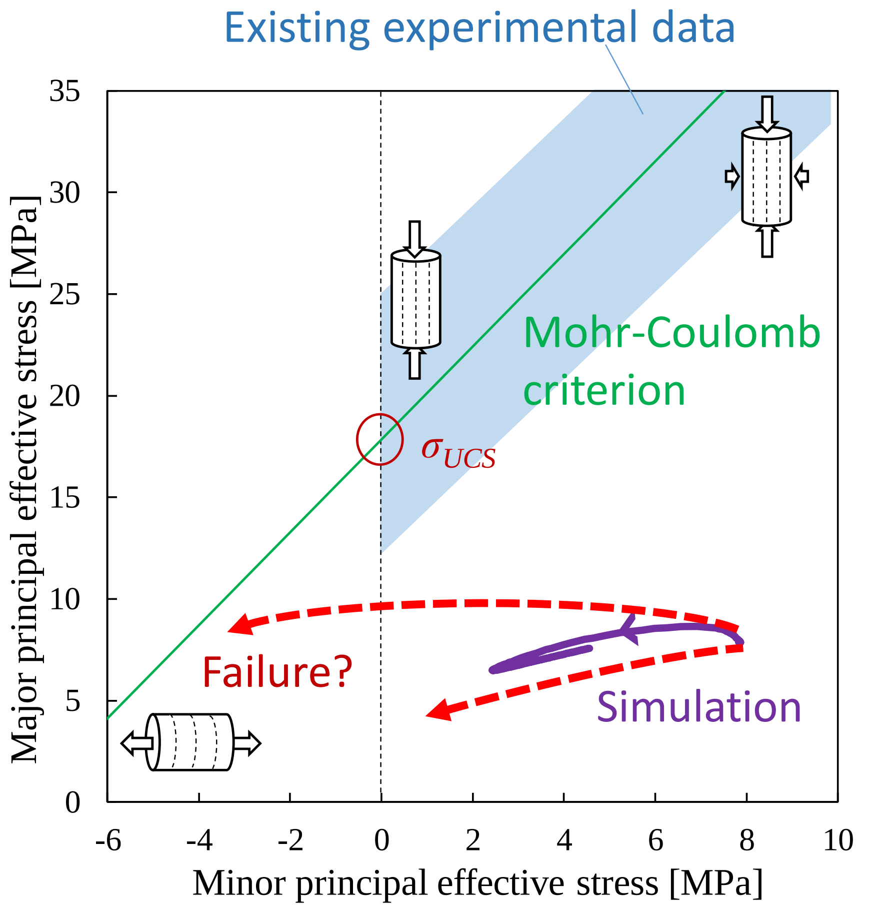


Simulated thermal pressurization



Effective stress changes



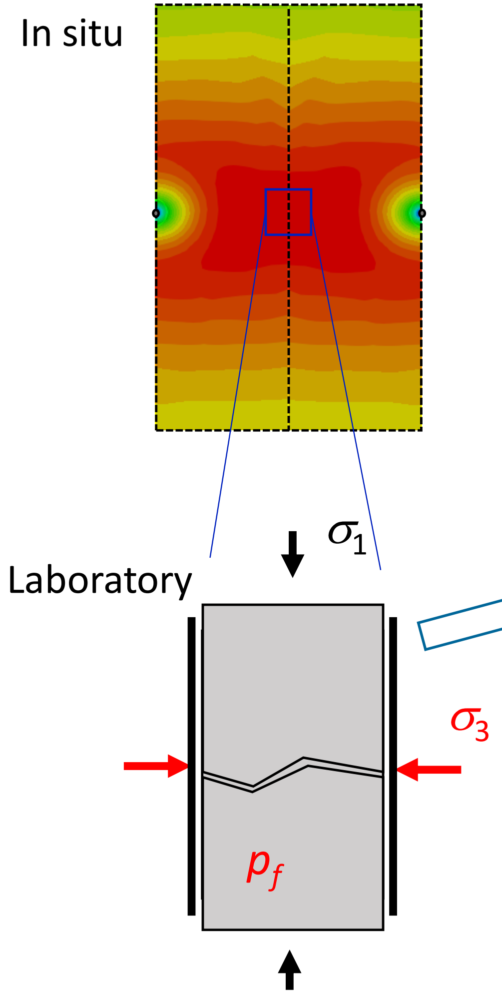


Novel testing device for thermal extension

THM loading paths expected for a REV under highest sollicitations:

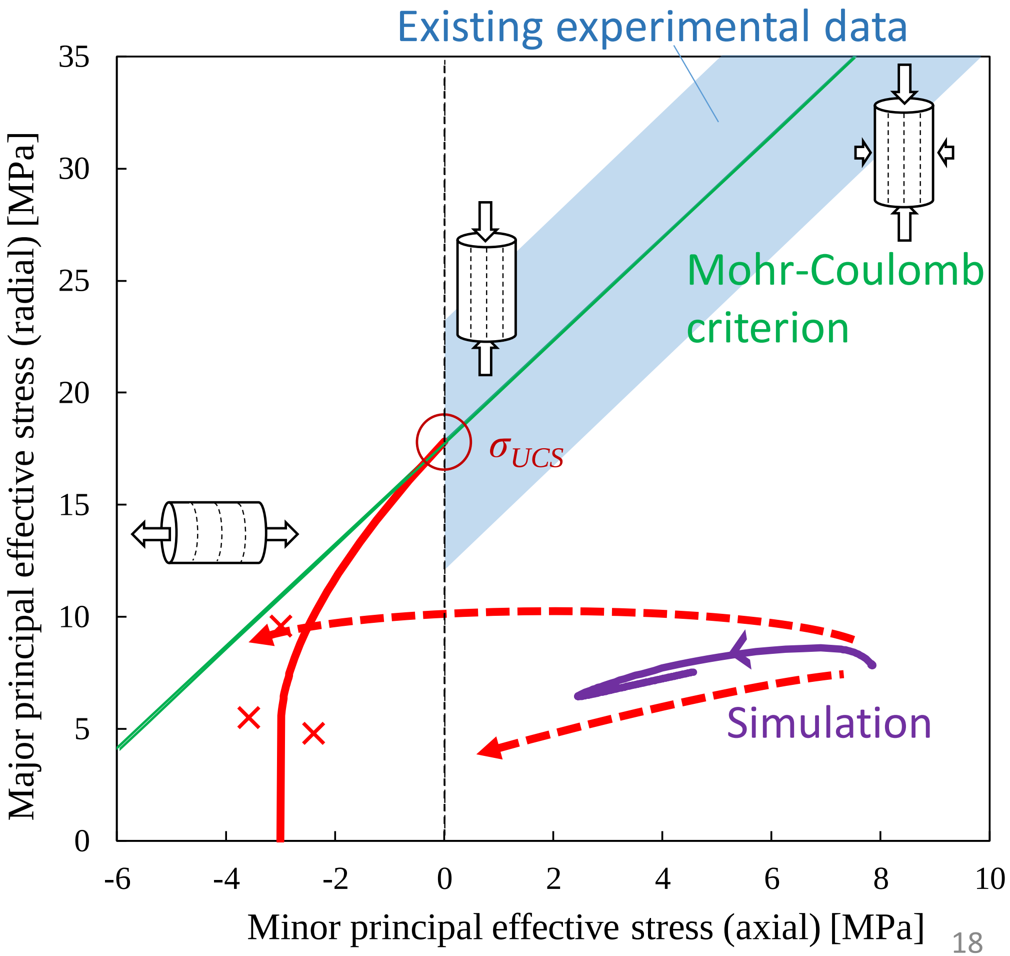
- Constant vertical stress
- Zero lateral strain
- Undrained heating
- Effective tension

➢ Implemented in a new triaxial system



Tensile failure

- Horizontal fractures confirm tensile failure in the weak bedding plane
- Heterogenieties (fossils, burrows) affect failure
- Measurement of failure criterion (Fairhurst modified Griffith)



Conclusions

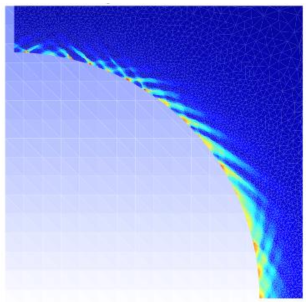
- New time-efficient testing techniques for measuring various HM or THM parameters
- Due to anisotropy large number of experiments and complex analysis required

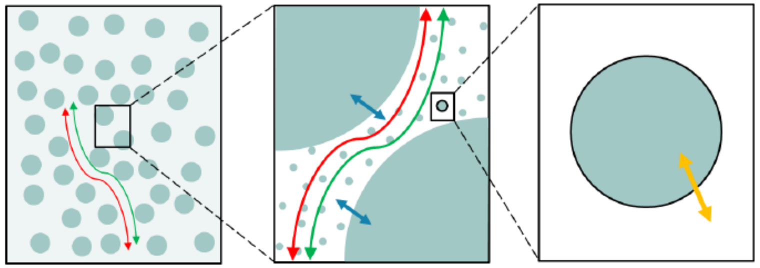
- Significant anisotropy of certain thermo-poromechanical properties (E, υ, B, α, …), less important for b
- Isotropic stress dependency of certain properties
- Compatibility issues for parameters from deviatoric tests, probable deviatoric stress dependency

- Design of a novel triaxial device for thermal extension tests
- Measurement of the tensile resistance during thermal pressurization

Perspectives

- Simulation of thermo-plastic behaviour through an adequate constitutive model
- Implementation of plastic anisotropy
- BIL: FEM code developed by Patrick Dangla
  - Open source, highly adaptable
  - Large number of existing models (multiphase, multiphysics)
  - 1D, 2D and 3D problems
  - In-house development

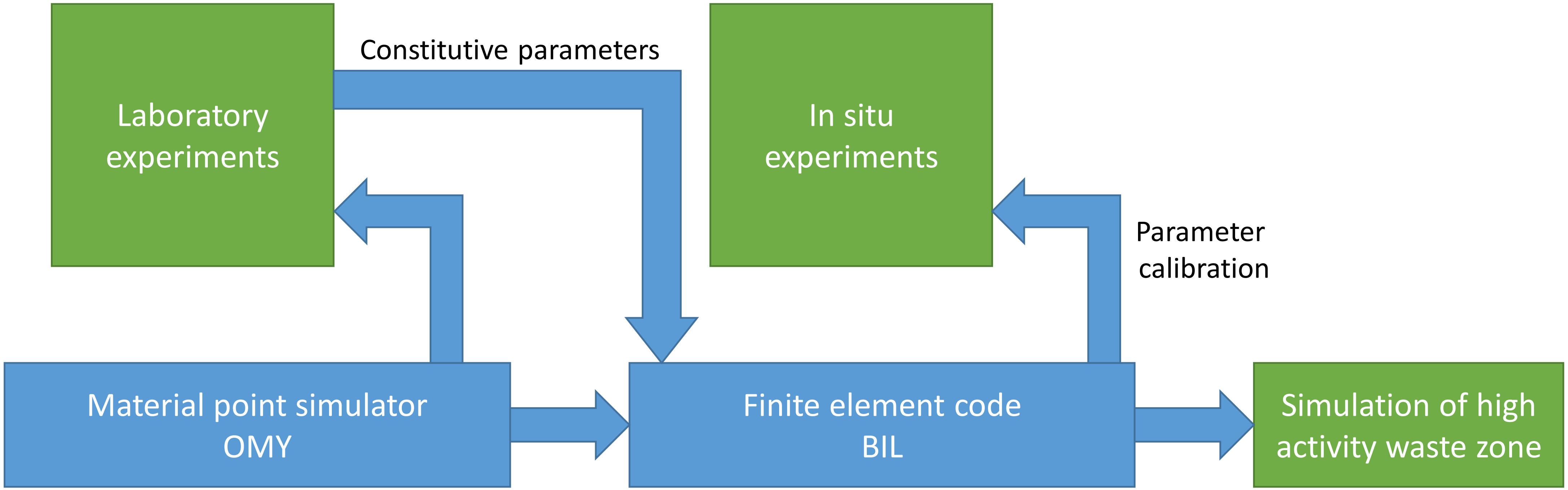




Some examples:

- ❑ Shear band formation during excavation (Poroplasticity with softening)
- ❑ Atmospheric carbonation of cement, Thiery et al. (2007)
- ❑ Diffusion of chlorides in cement-based materials, Baroghel-Bouny et al. (2009)
- ❑ Bentonite pellet-powder mix, Dardé (2019)
- ❑ Multiscale modelling of gas-hydrate bearing soils, Alavoine et al. (2020)

Numerical modeling



Required for plastic behaviour:

- Constitutive modelling
- Parameter calibration

Code developed in-house by P. Dangla