

Shrinkage-induced cracking in Opalinus Clay: investigation of crack modeling parameters and response in the Cyclic Deformation (CD-A) experiment

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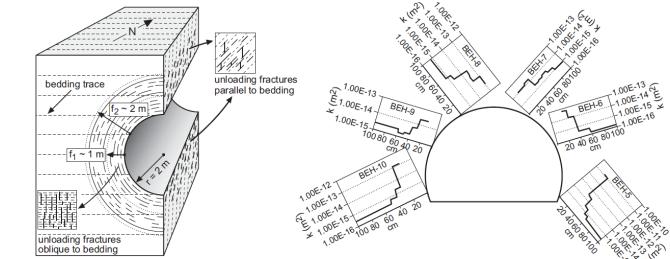
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Motivation & Aims

- Motivation

- Radioactive waste needs to be stored in a safe and sustainable manner
- The integrity of the rock, i.e. its containment capabilities, must be ensured
- Numerical methods are mostly developed at laboratory scale
- Understanding the coupled phenomena that lead to cracking and take place in the rock needs, ideally, to occur at the in-situ scale



[Tsang et al. 2012]

- Aims

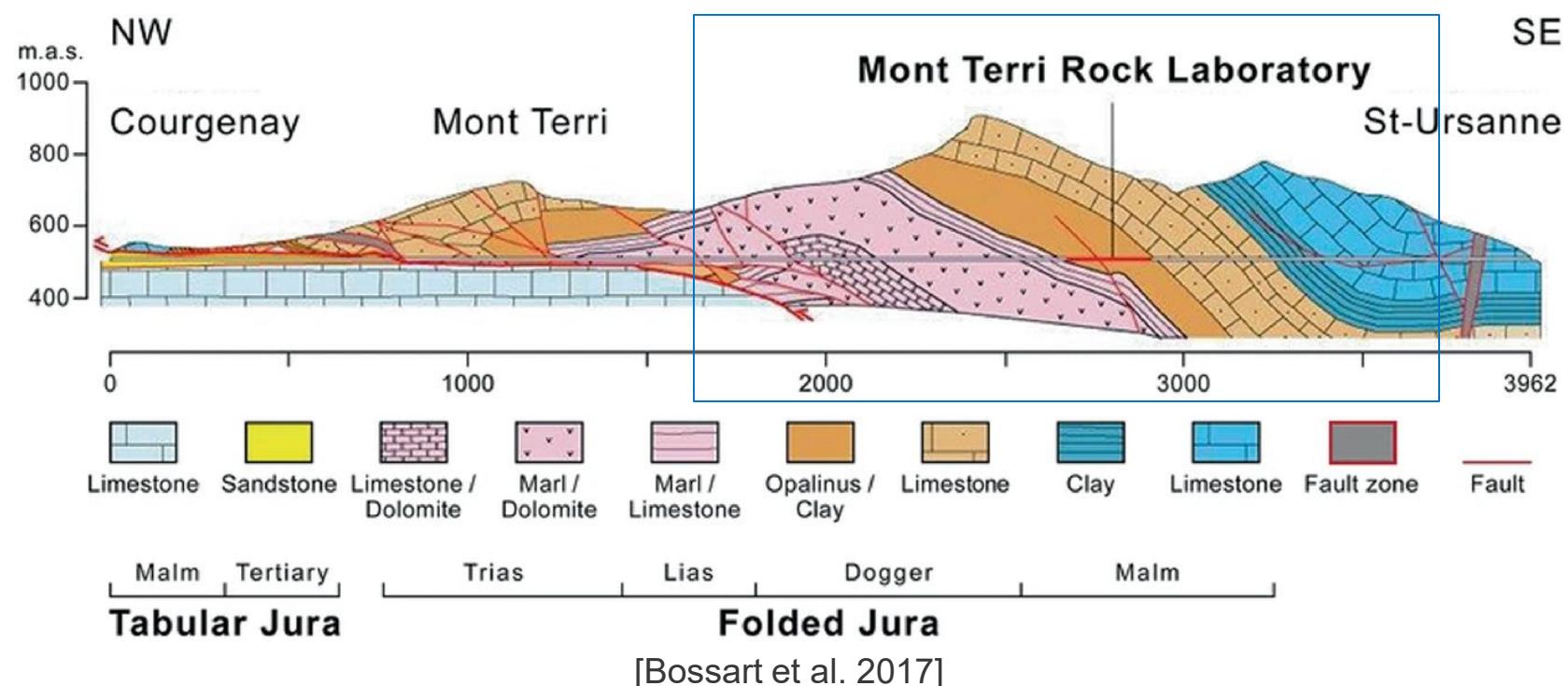
- Provide a methodology for modeling crack due to hydro-mechanical processes in the in-situ scale
- Verify the response of the methodology within the Cyclic Deformation (CD-A) experiment in the Mont Terri Rock Laboratory (Switzerland)

In-situ cracking

1. Initial state (undisturbed rock)

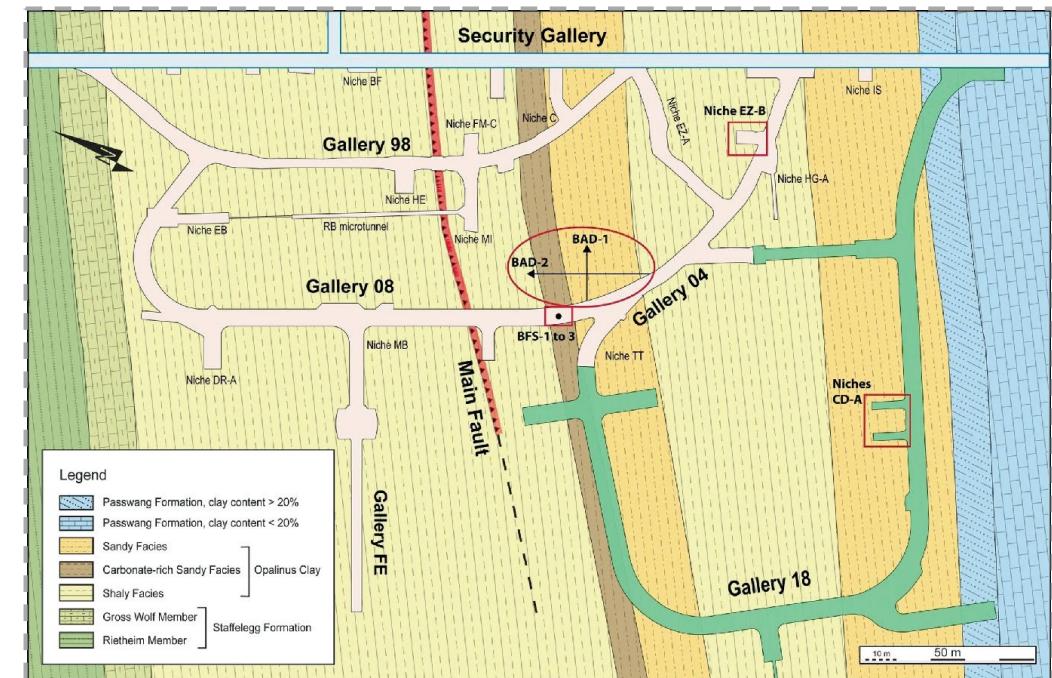
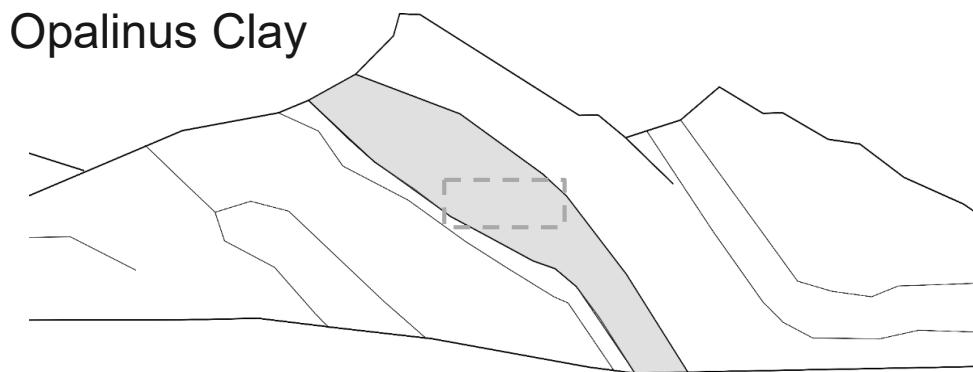
- Example:

- Folded Jura, Opalinus Clay



In-situ cracking

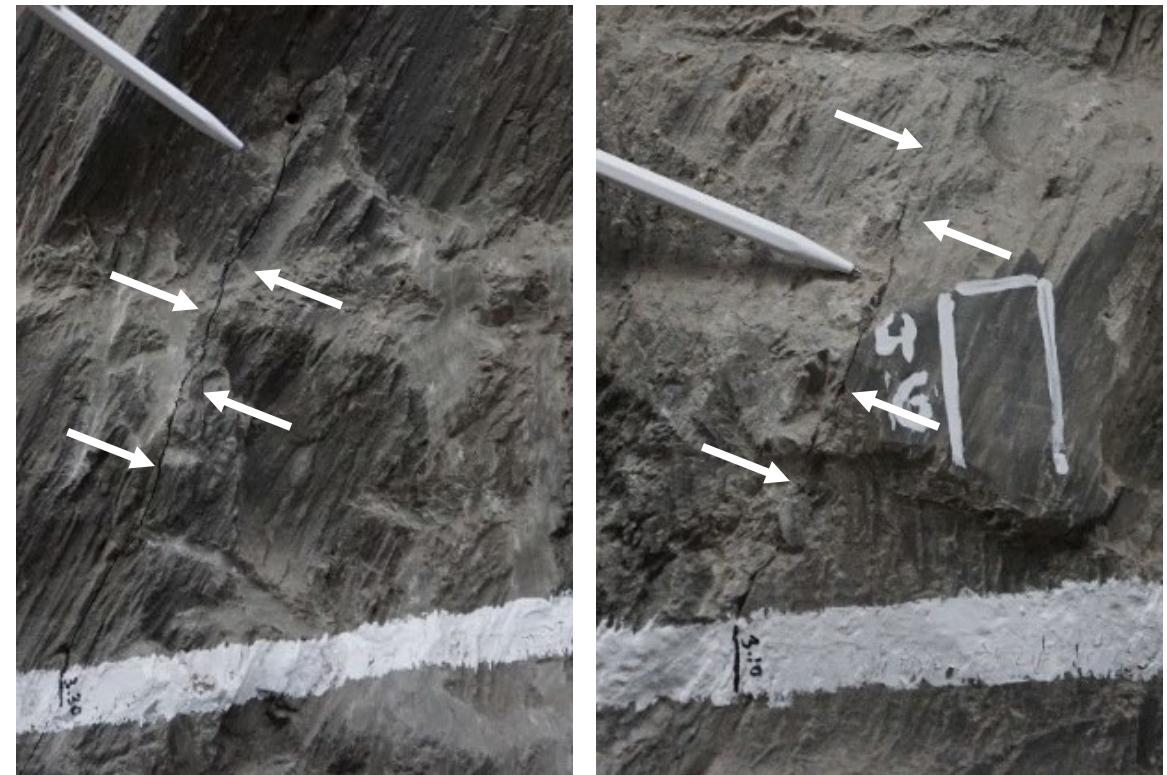
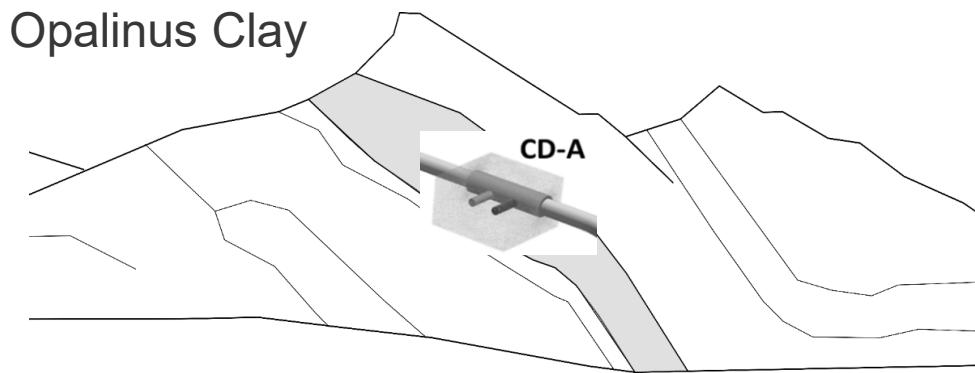
1. Initial state (undisturbed rock), Opalinus Clay
2. Excavation
 - Stress redistribution
 - Plastic behavior (shear / compressive strength criterion)
 - EDZ development (cracks, permeability increase)



[Based on Bossart et al. 2017]

In-situ cracking

1. Initial state (undisturbed rock), Opalinus Clay
2. Excavation
3. Functional/ventilation period
 - Wetting and drying (seasonal changes)
 - Further degradation and/or increase of EDZ, e.g. cracks due to drying



Drying / shrinkage-induced cracks in
Opalinus Clay

Cyclic Deformation (CD-A) experiment

- Investigation of hydro-mechanical (HM) effects due to saturation changes in Opalinus Clay
- Comparison between twin niches with (i) long-term direct and indirect measurements e.g., resistivity, water content, suction and crack development and (ii) numerical simulations.



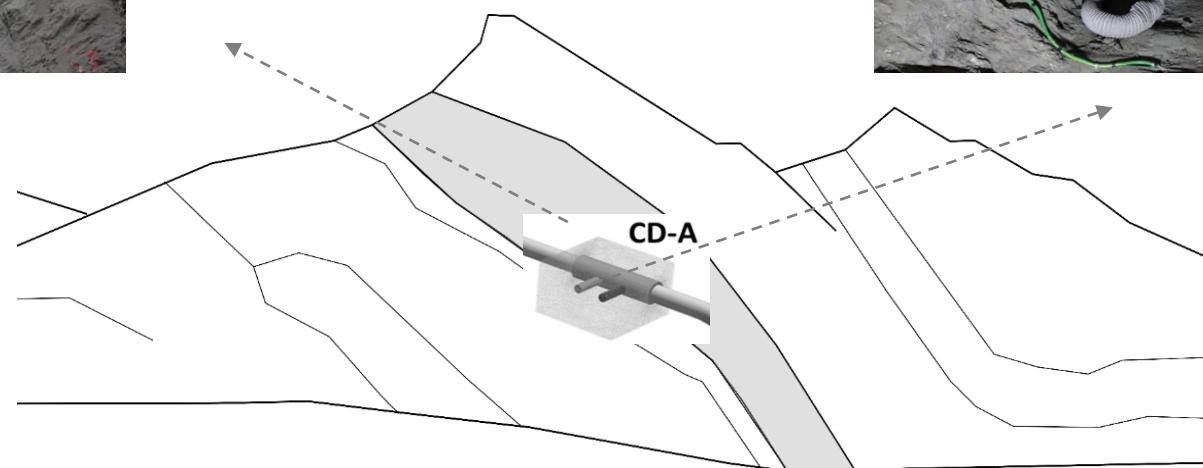
Open niche

- Seasonal humidity variations
- Shrinkage/swelling
- Desiccation cracks



Closed niche

- Controlled high humidity
- Reduced influence of seasonal effects



Cyclic Deformation (CD-A) experiment

- Investigation of hydro-mechanical (HM) effects due to desaturation in Opalinus Clay
- Comparison between twin niches with (i) long-term direct and indirect measurements e.g., resistivity, water content, suction and crack development and (ii) numerical simulations.



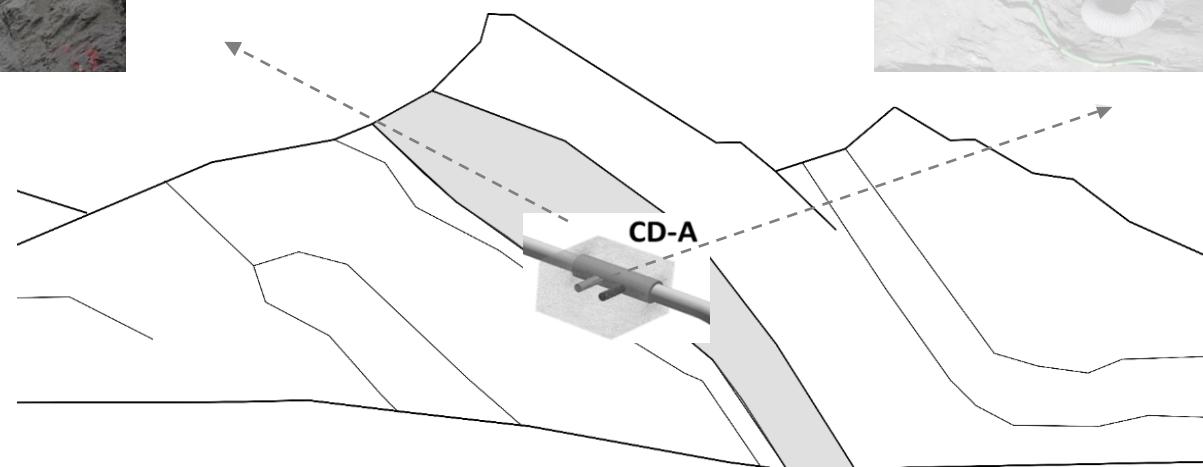
Open niche

- Seasonal humidity variations
- Shrinkage/swelling
- Desiccation cracks



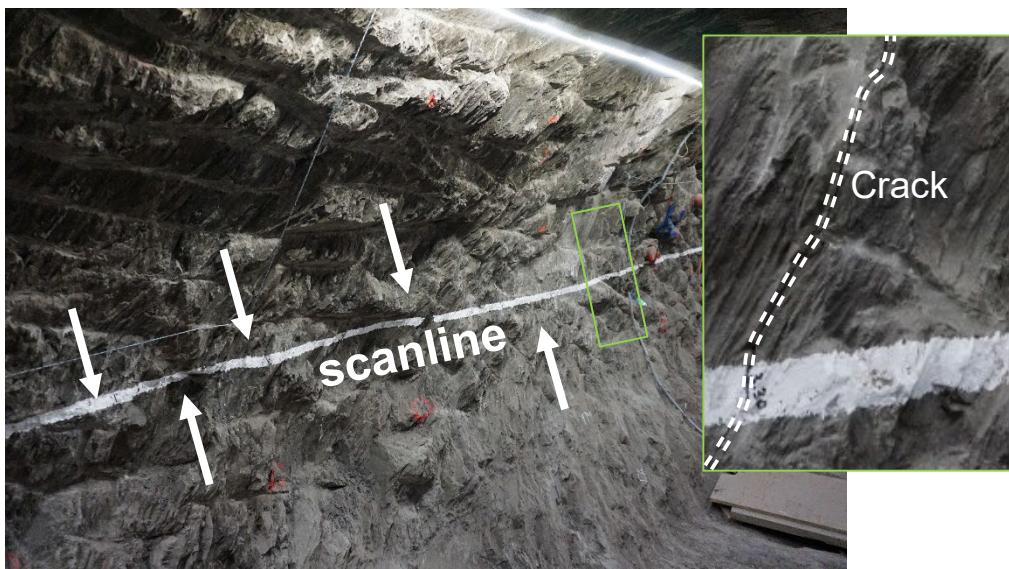
Closed niche

- Controlled high humidity
- Reduced influence of seasonal effects

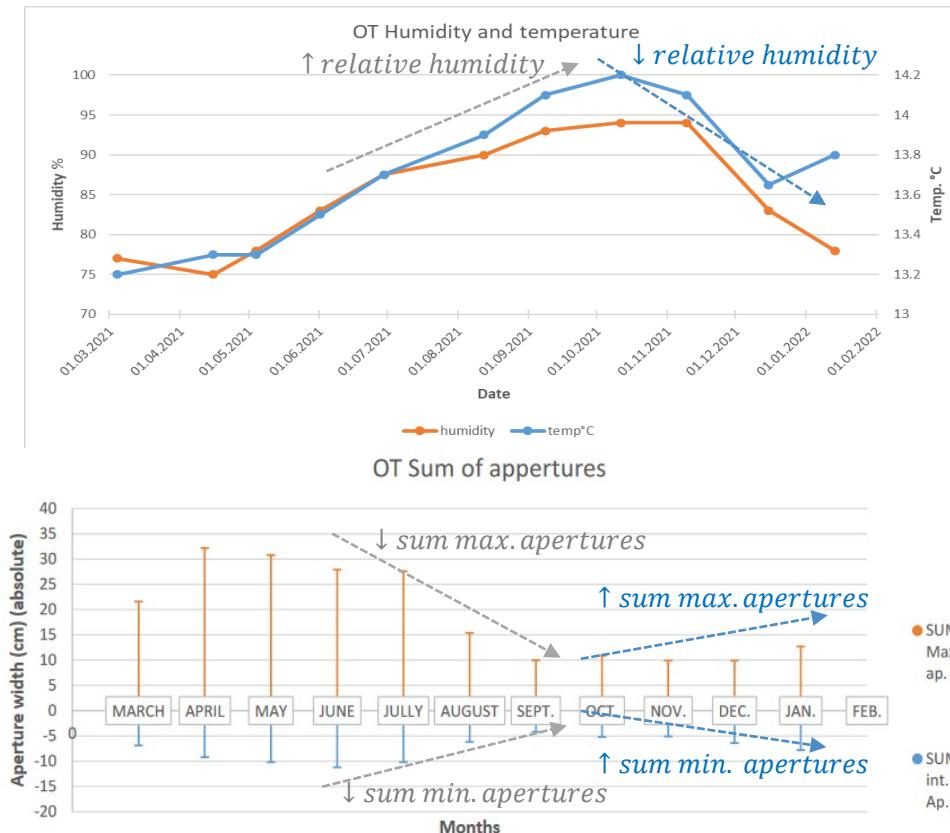


Cyclic Deformation (CD-A) experiment: shrinkage-induced cracking

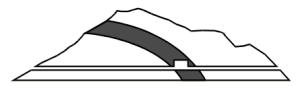
- Approximately 33 cracks registered in March 2021 (more than 90% parallel to the bedding)
 - ~ 3 cracks per meter (niche length = 11 m)
- Aperture between 0.2 and 0.6 mm



- Measurement of crack position and its attributes are challenging



INDRA BASE BGE BGR CHERON CRIPI DOE ENRESA ENSI ETH FANC GRS
HELMHOLTZ IRSN JAEA NAGRA NWMO OBAYASHI RWM SCK•CEN SWISSTOPO TOTAL



Mont Terri Project

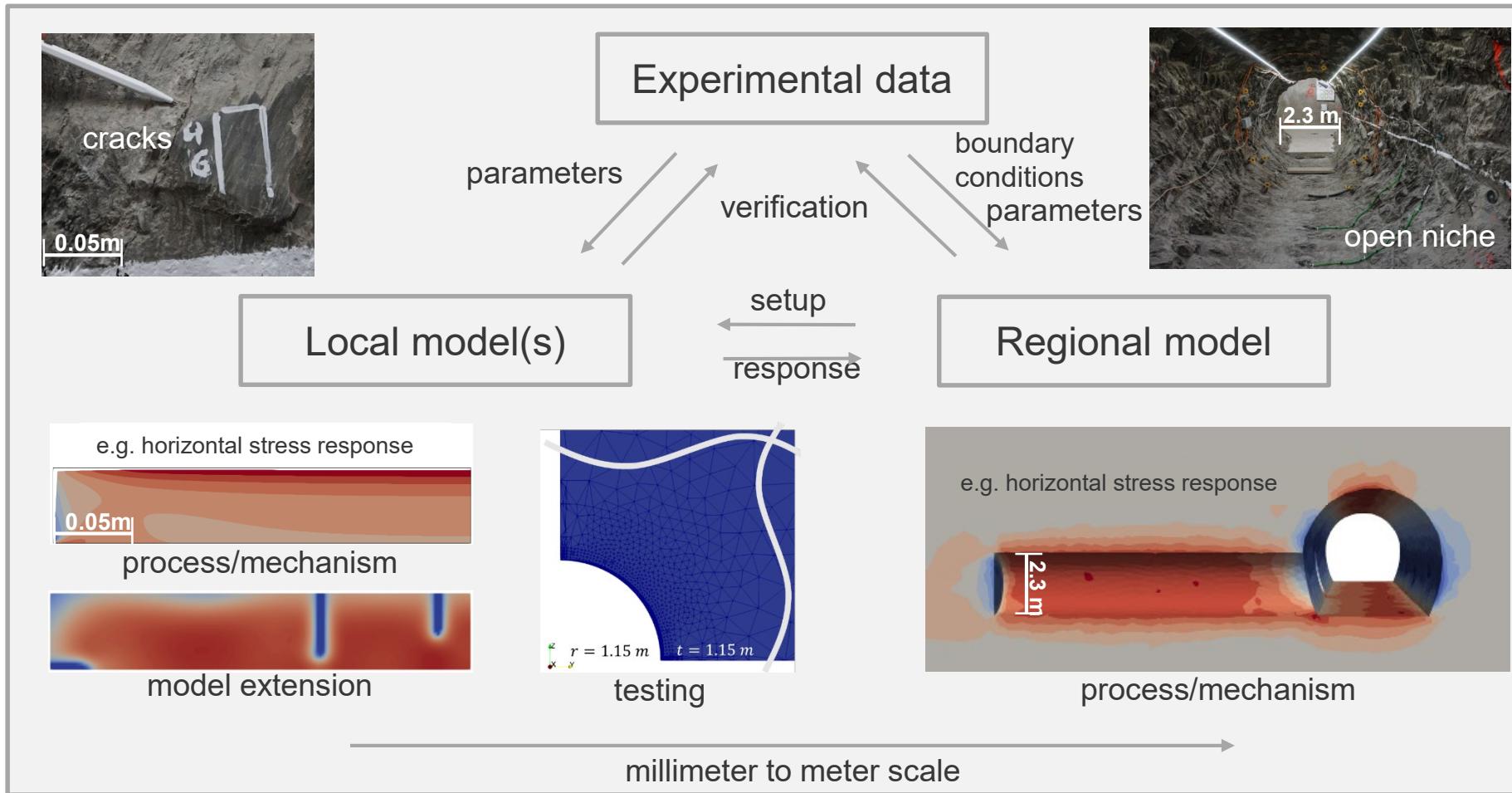
TECHNICAL NOTE 2021-63
February 2022

CD-A Experiment:
Seasonal Crack Mapping in Twin Niches

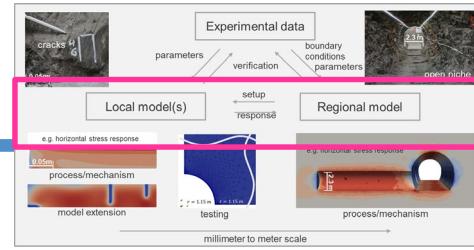
V. Regard, S. Schefer, P. Steiner & D.Jaeggi
swisstopo, Switzerland

[Regard et al. 2022]

Shrinkage-induced cracking: methodology



Modeling methodology



- Mass balance equations

$$\nabla \cdot (nS_I \mathbf{v}_{ls}) + \rho_I \left[C_s \frac{\partial p_I}{\partial t} + S_I \alpha \frac{\partial \text{tr}(\nabla^s \mathbf{u})}{\partial t} \right] = 0$$

$$\nabla \cdot (\sigma' - \alpha S_I p_I \mathbf{I}) + n S_I \rho_I \mathbf{g} + (1-n) \rho_s \mathbf{g} = 0$$

- Further relations and assumptions

- Capillary pressure (Richards assumption)

$$p_c = p_g - p_l$$

$$p_g = p_{atm}$$

- Rate of liquid flow (Darcy's law)

$$n S_I \mathbf{v}_{ls} = -\rho_I k_{rl} \frac{\mathbf{K}_i}{\mu_l} (\nabla p_I - \rho_I \mathbf{g})$$

- Van Genuchten fitting

- Isotropic (!), linear elastic material

- Phase-field evolution equation

$$g'(d)\psi^+ + \frac{G_c}{4c_w} \left(\frac{w'(d)}{\ell} + 2\ell\Delta d \right) = 0$$

$$w(d) = (1-d)^n \text{ and } c_w = \begin{cases} 2/3(n=1)AT1 \\ 1/2(n=2)AT2 \end{cases}$$

- Coupling

$$\nabla \cdot (\sigma' - \alpha S_I p_I \mathbf{I}) + n S_I \rho_I \mathbf{g} + (1-n) \rho_s \mathbf{g} = 0$$

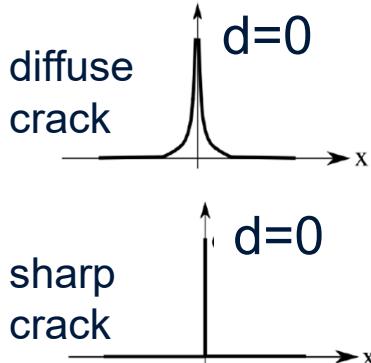
$$\sigma' = g(d)\sigma'_+ + \sigma'_-$$

K. Yoshioka's presentation for further details on the approach (scan code):

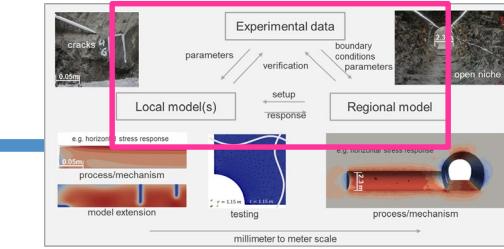


OpenGeoSys

OPEN-SOURCE MULTI-PHYSICS



Experimental data & Model setup



- Parameters from the literature
- Size, setup and boundary conditions based on field observations, e.g. de-saturated zone and cracking



- Calibration of fracture parameters
 - Characteristic length (crack width)

$$\ell_{ch} = \frac{K_I^2}{\sigma_t^2}$$
$$\ell \propto \ell_{ch}$$

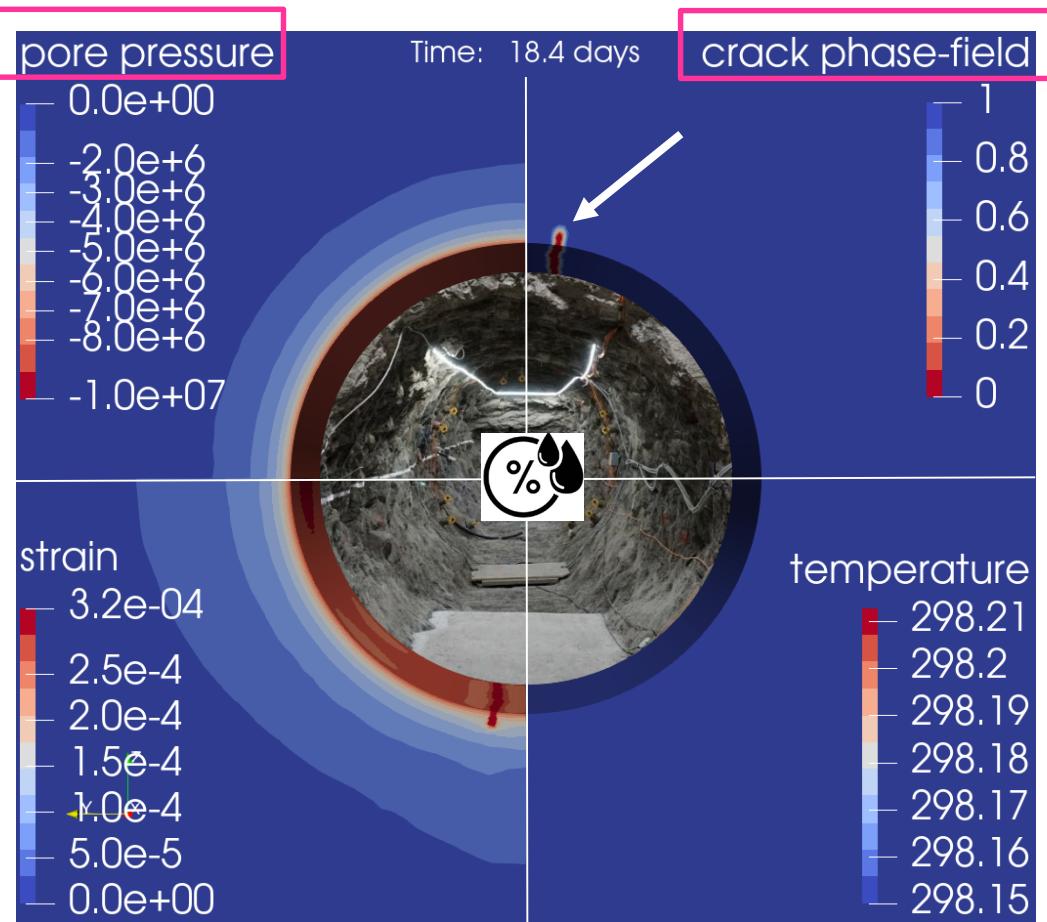
- Fracture energy

$$G_{exp} = \frac{K_I^2}{E}$$
$$G_c \propto G_{exp}$$

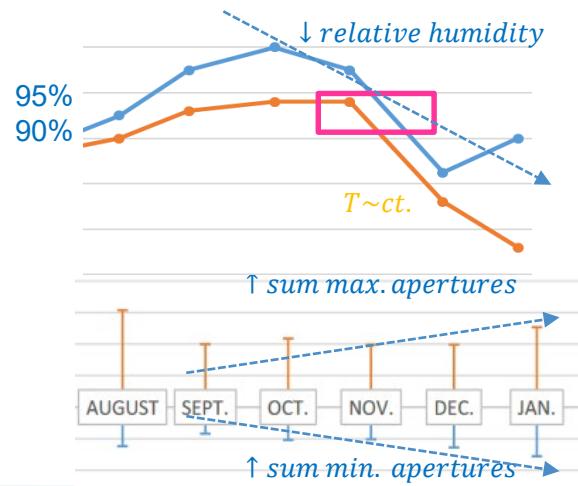


Parameter	Value range [Bock 2009]
Fracture toughness K_I	0.12 – 0.53 MN/ $\sqrt{\text{m}}$
Tensile strength σ_t	0.6 – 1.2 MPa
Elastic modulus E	6 – 13.8 Gpa
Characteristic length ℓ_{ch} *	0.22 – 0.25 m

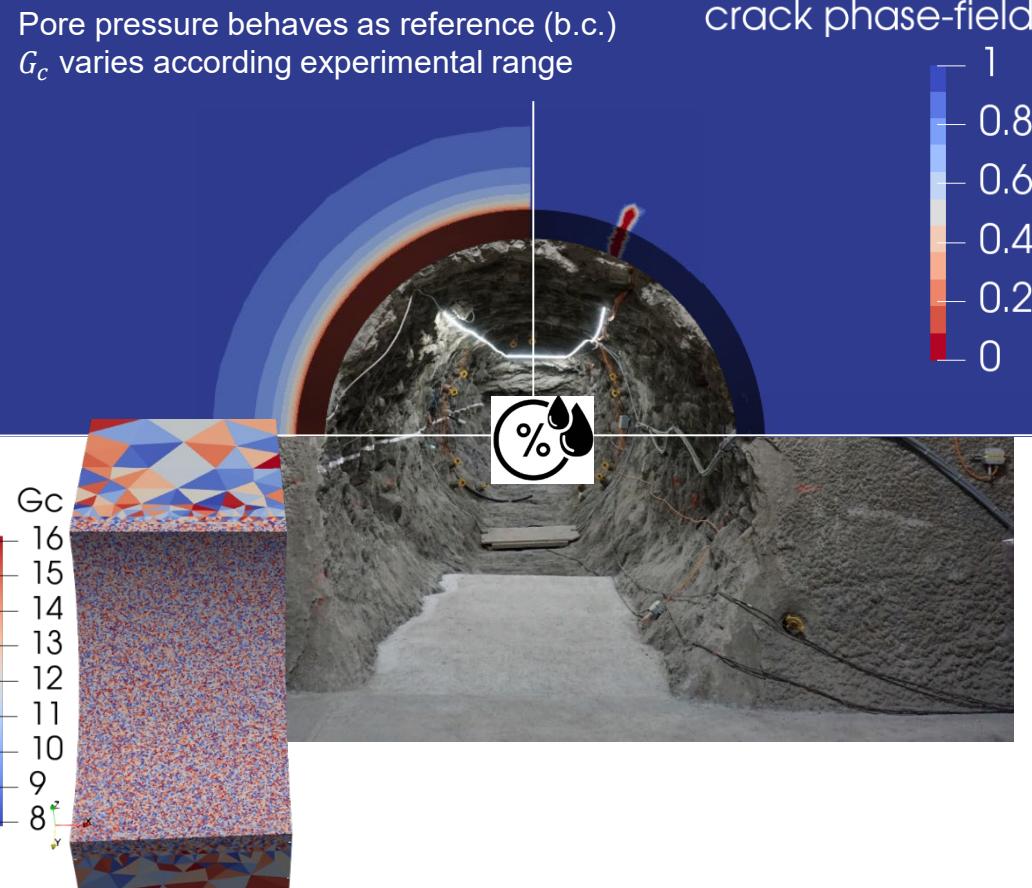
Homogeneous case: reference



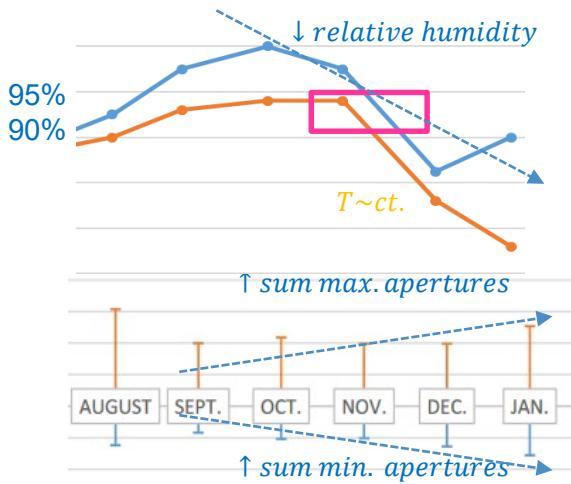
- Crack develops between 93-94 % RH (suction 8-9 MPa), crack front stops due to local mesh refinement
- No further cracks initiate
- Crack opening \sim experimental aperture
- Crack propagation parallel to bedding (ongoing work on anisotropy)
- Number of cracks (symmetry) \sim average experiment, i.e. 3-4 cracks/meter



Heterogeneous case: random fracture energy



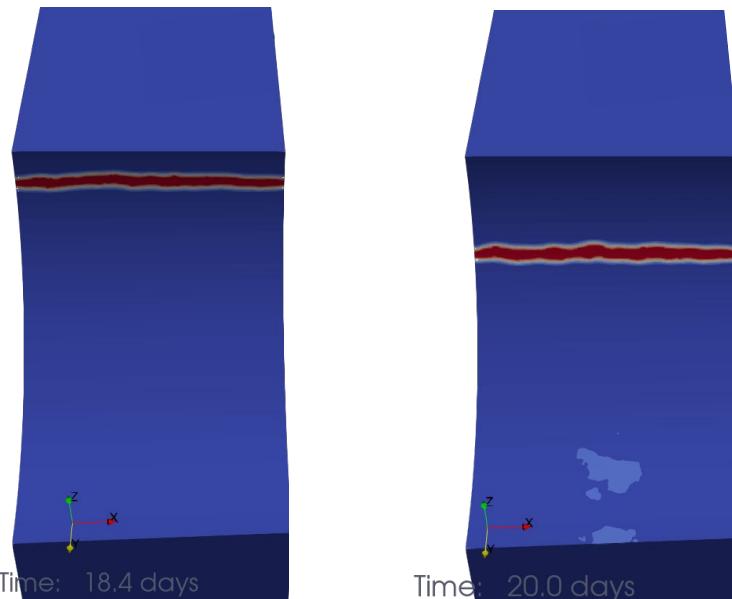
- Crack develops between 93-94 % RH (suction 8-9 MPa), no further cracks initiate
- Crack position shifts, initiates later
- Crack opening \sim experimental aperture
- Crack propagation parallel to bedding (ongoing work on anisotropy)
- Number of cracks \sim average experiment, i.e. 3-4 cracks/meter



Further results

- Restraint increase the number of cracks and complexity of the pattern

Suction between 8-9 MPa (RH 93-94%)

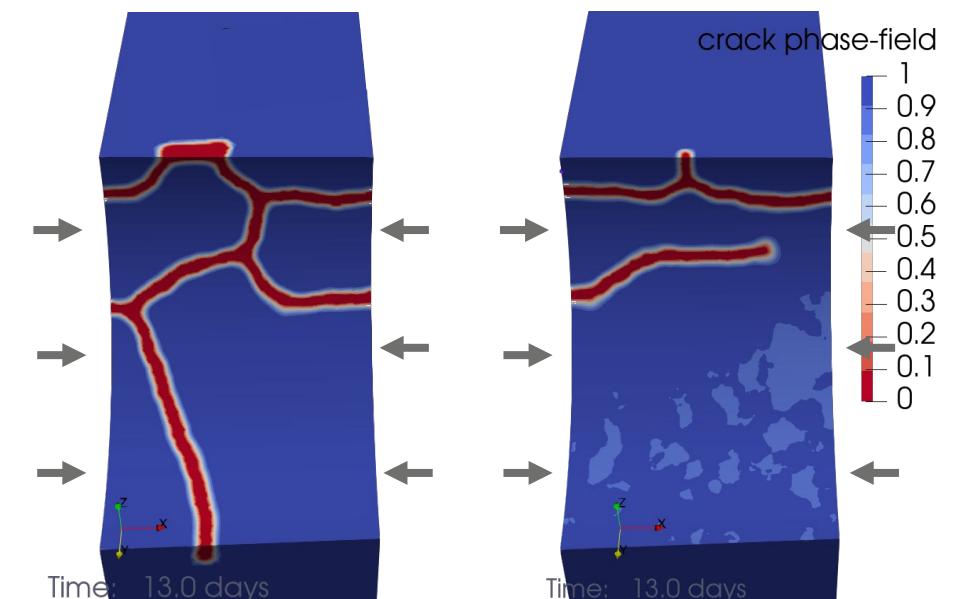


Reference (iso)

Random G_c (iso)

Random G_c ,
 k_i (ani)

Suction between 5-6 MPa (RH 95-96%)



Random G_c ,
 k_i (ani), rest.

Conclusions & Outlook

- Conclusions
 - Methodology for application and calibration of shrinkage-induced cracking at field scale is established [Cajuhi et al. *in prep*]
 - Approach does not require fitting
 - Crack initiation, amount and aperture follow experimental tendency
 - Crack initiation and development (localization) at in-situ scale using homogeneous and random models
- Outlook
 - Account for anisotropy
 - Depth of crack (uniform mesh)
 - Influence of redistribution of in-situ stresses due to excavation and further coupled effects
 - Extension of the framework to account for the wetting path

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