Mont Terri Project

Numerical simulation of damage evolution around the PF/PF-A experiment borehole in faulted Opalinus Clay

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Numerical modelling strategy

Short-term (hours to days)

Long-term (months to years)

Not to scale

- Free surface creation
- Mechanical unloading
- Stress redistribution
- Rock mass deformation
- Damage evolution
- …

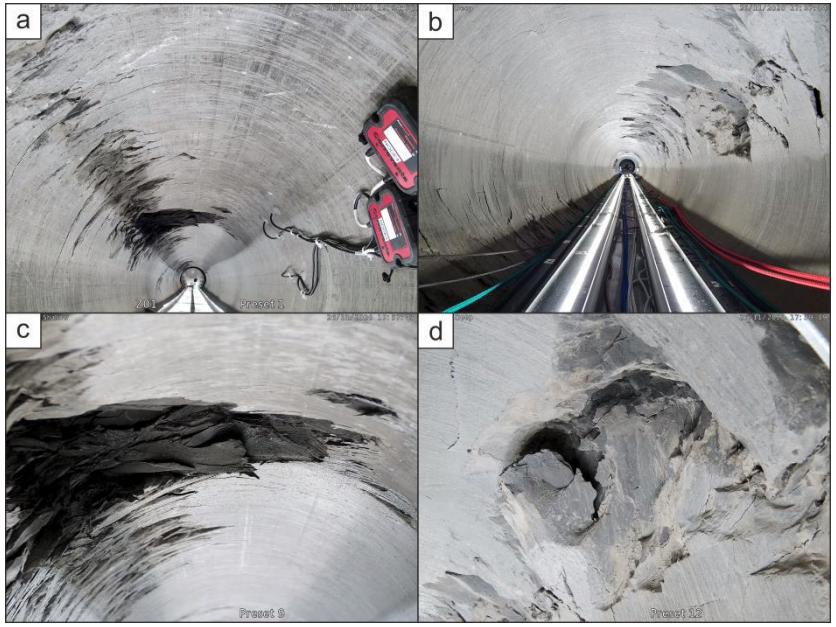
Geomechanical modelling

- Pore pressure diffusion
- Poroelasticity
- Saturation evolution
- Suction
- Swelling
- Creep
- Damage
- …

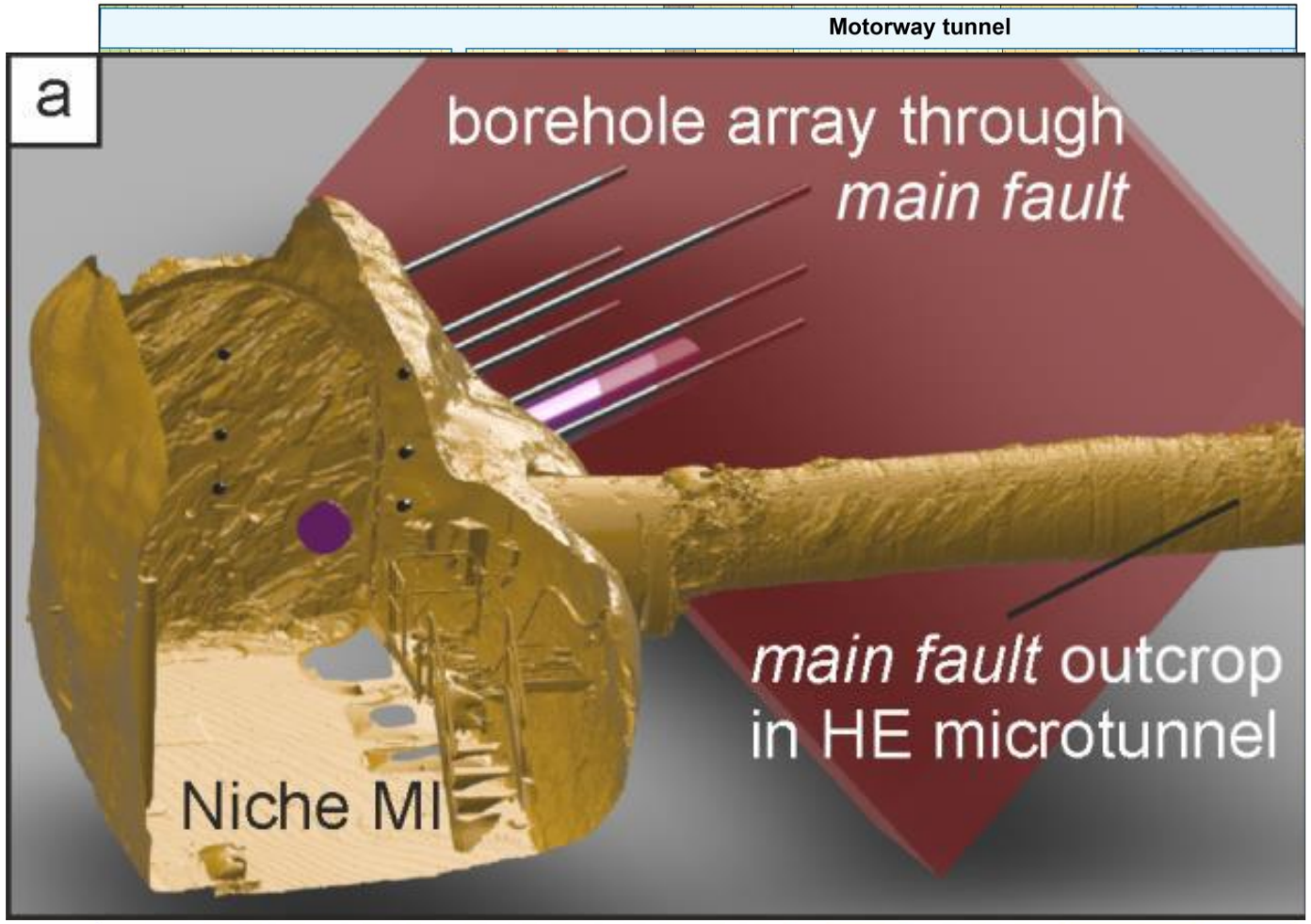
Hydromechanical modelling

PF/PF-A experiment

- Located in Mont Terri Rock Laboratory
- 1 experiment borehole
- 6 monitoring boreholes
- Structurally-controlled overbreaks

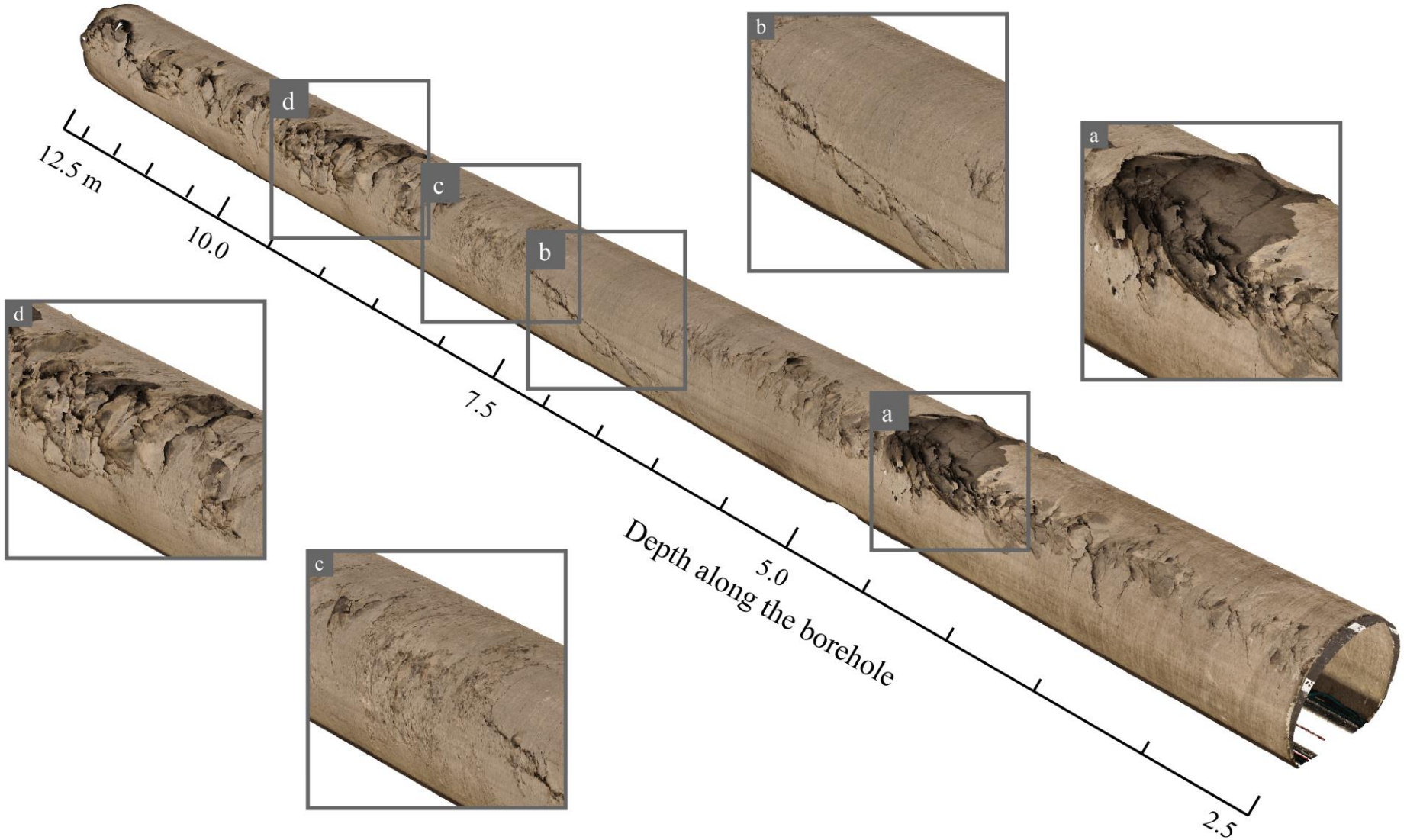


Martin and Loew (2021)



Martin and Loew (2021)

Overbreak pattern (shortly after drilling)



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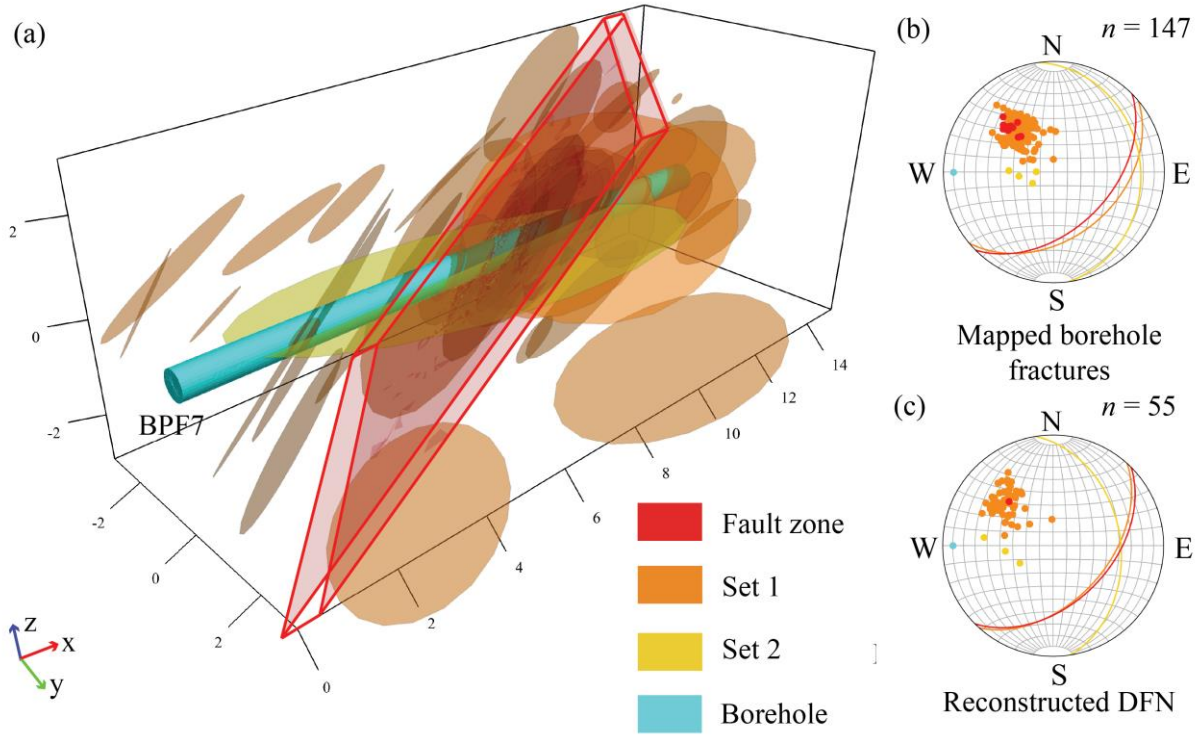
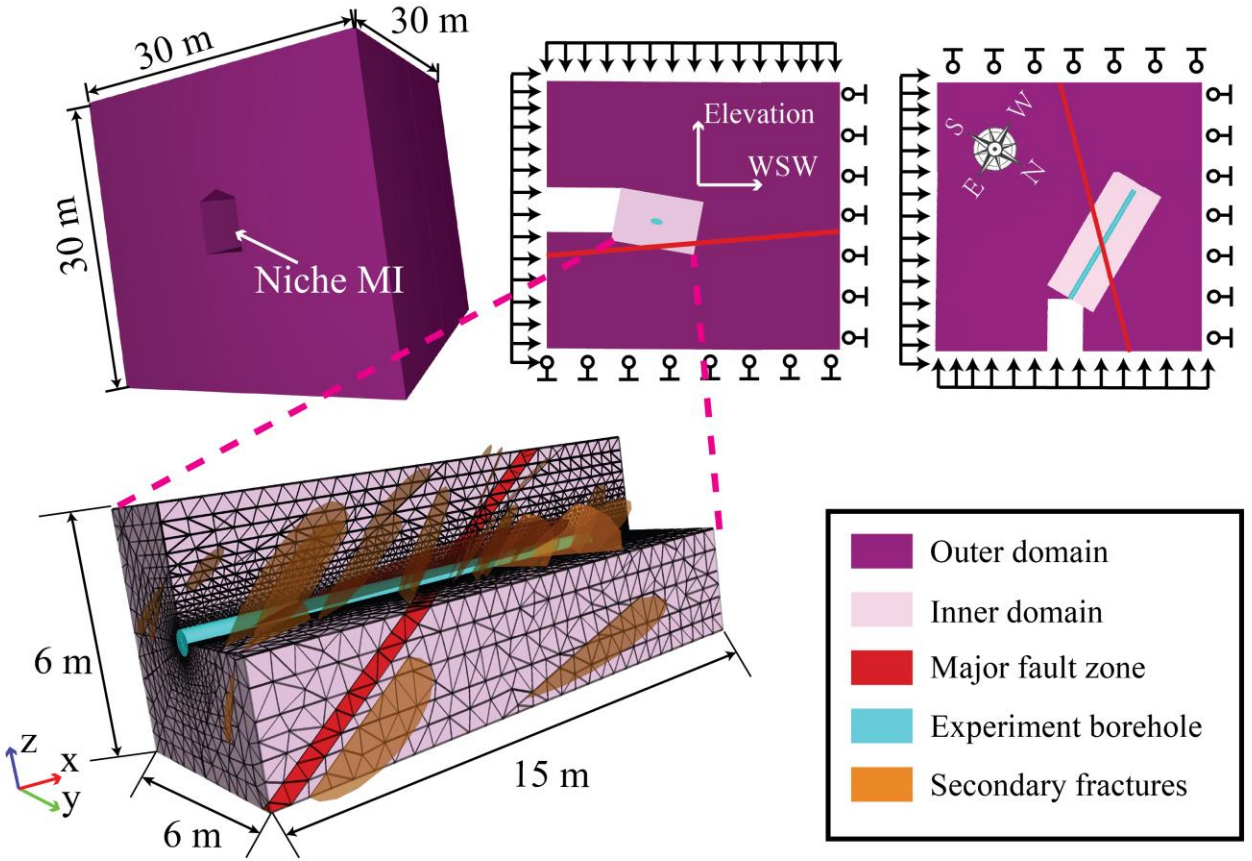
Model setup (geomechanical model)

Fracture network reconstruction



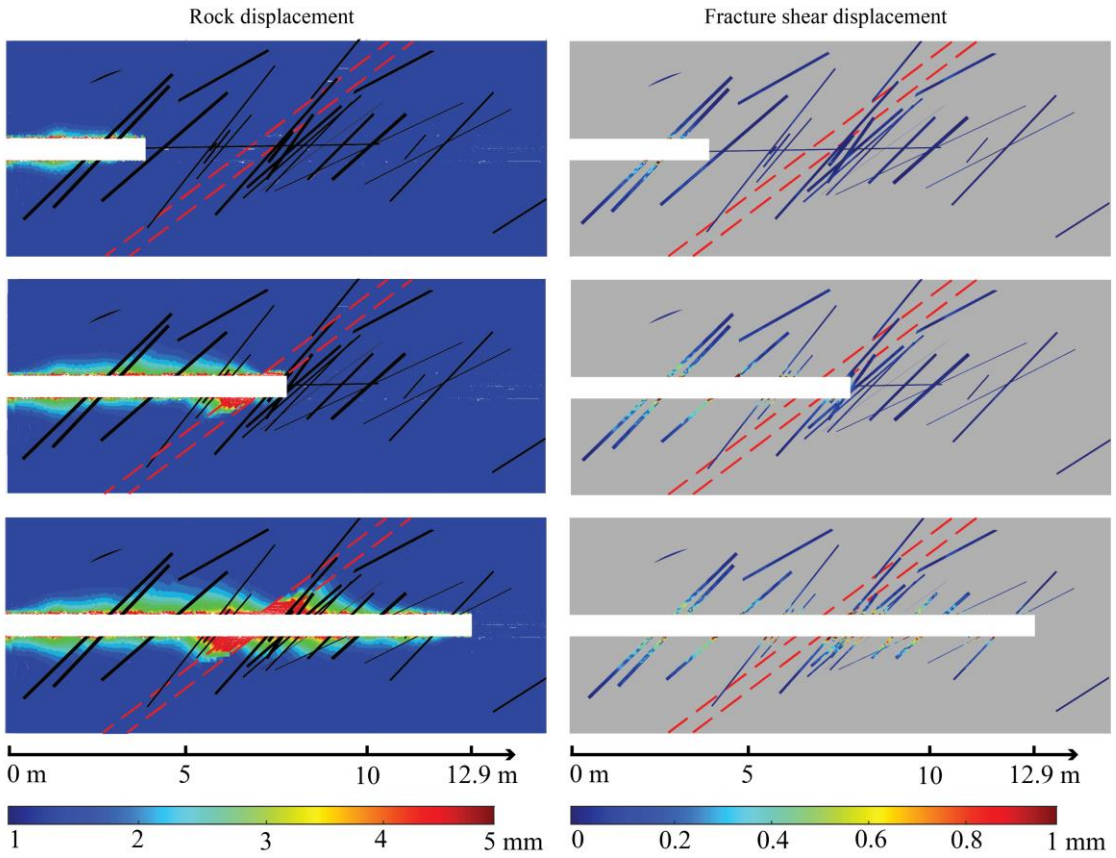
Generated using Fracman

Numerical model construction

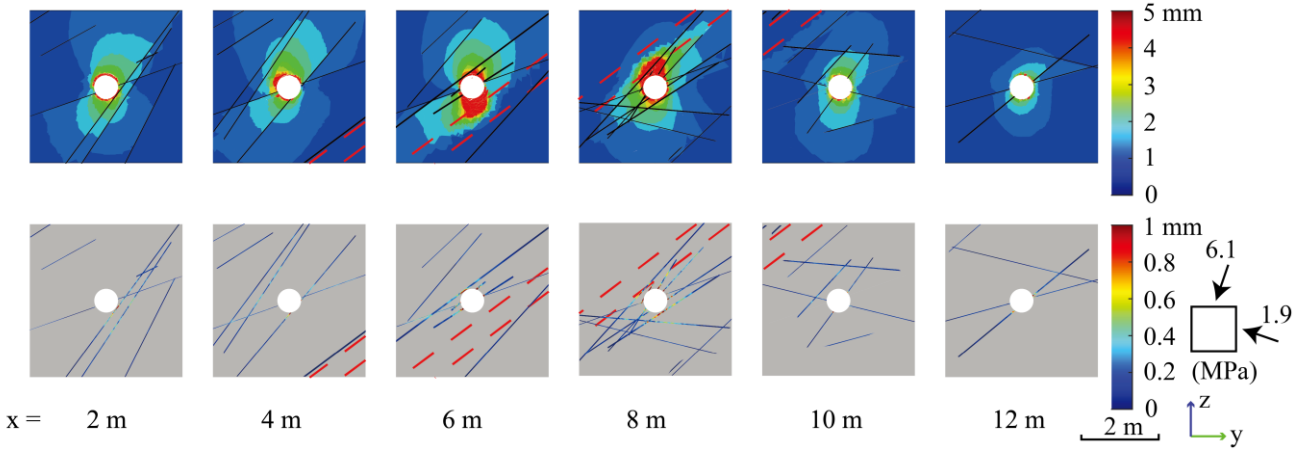


Simulated using 3DEC

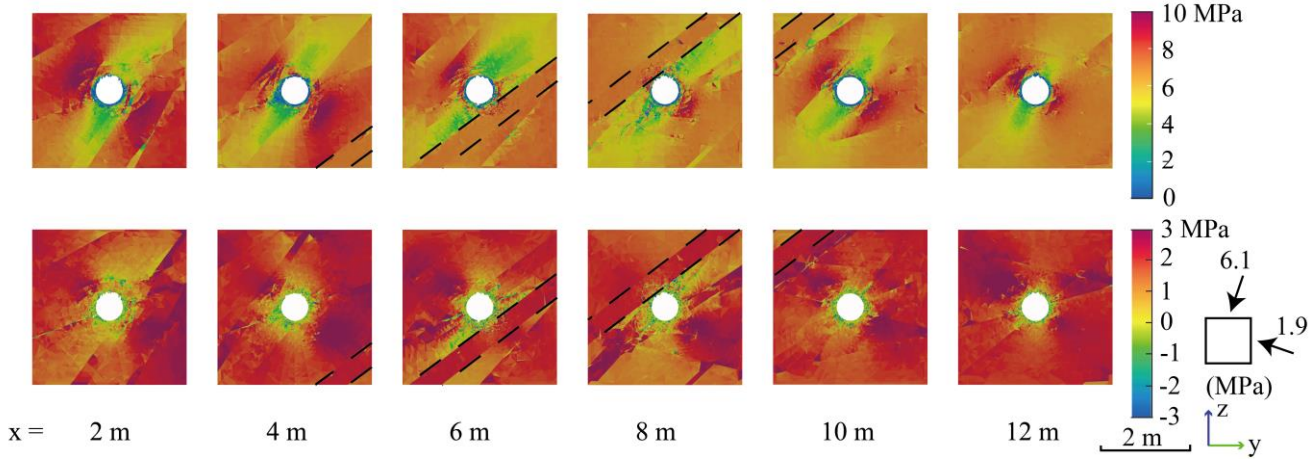
Simulation results



Displacement field



Stress field



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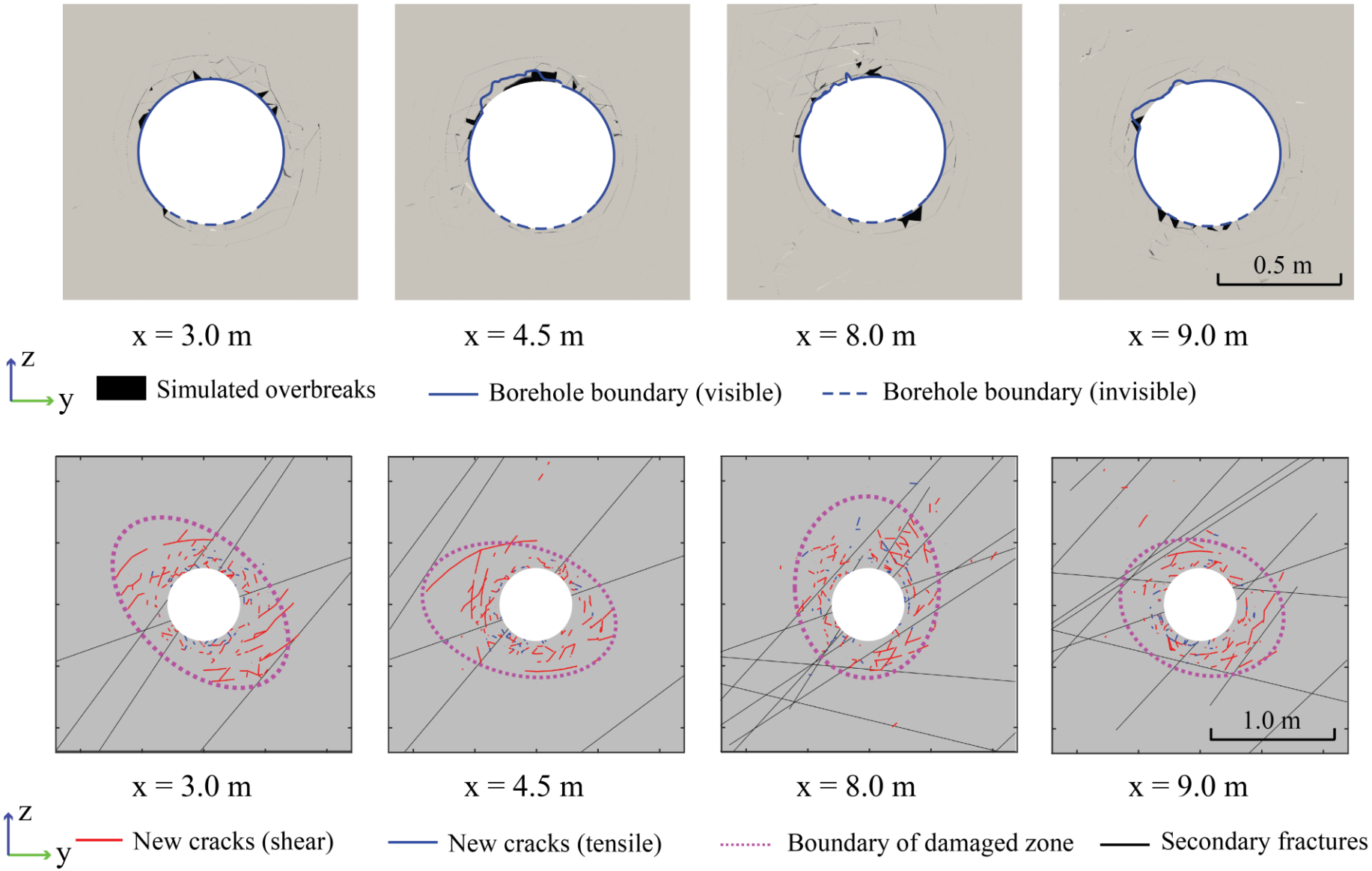
Simulation results



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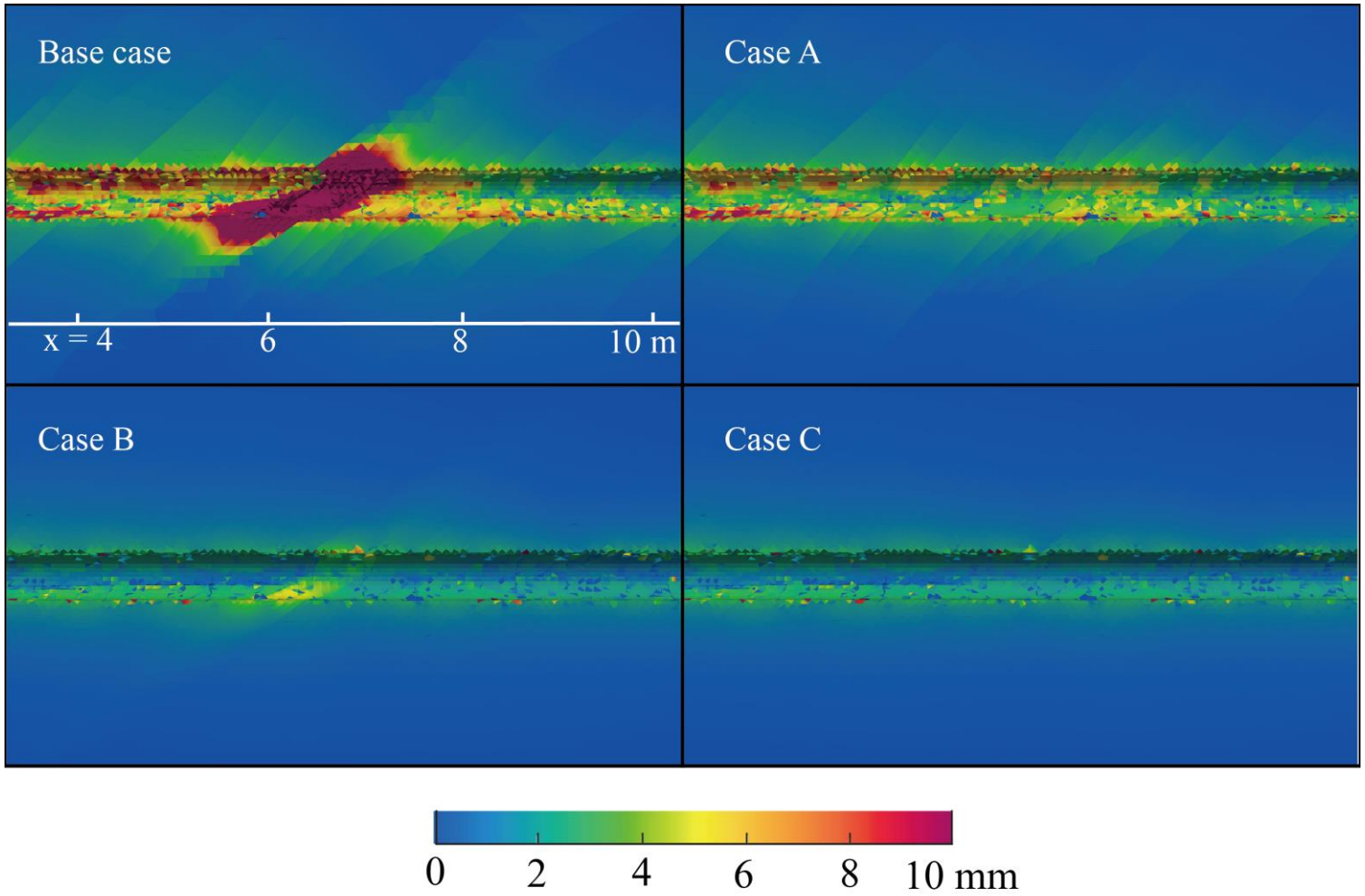
Simulation results

Base case: with fractures and fault zone; **Case A:** with fractures but without fault zone

Case B: with fault zone but without fractures; **Case C:** without fault zone and fractures



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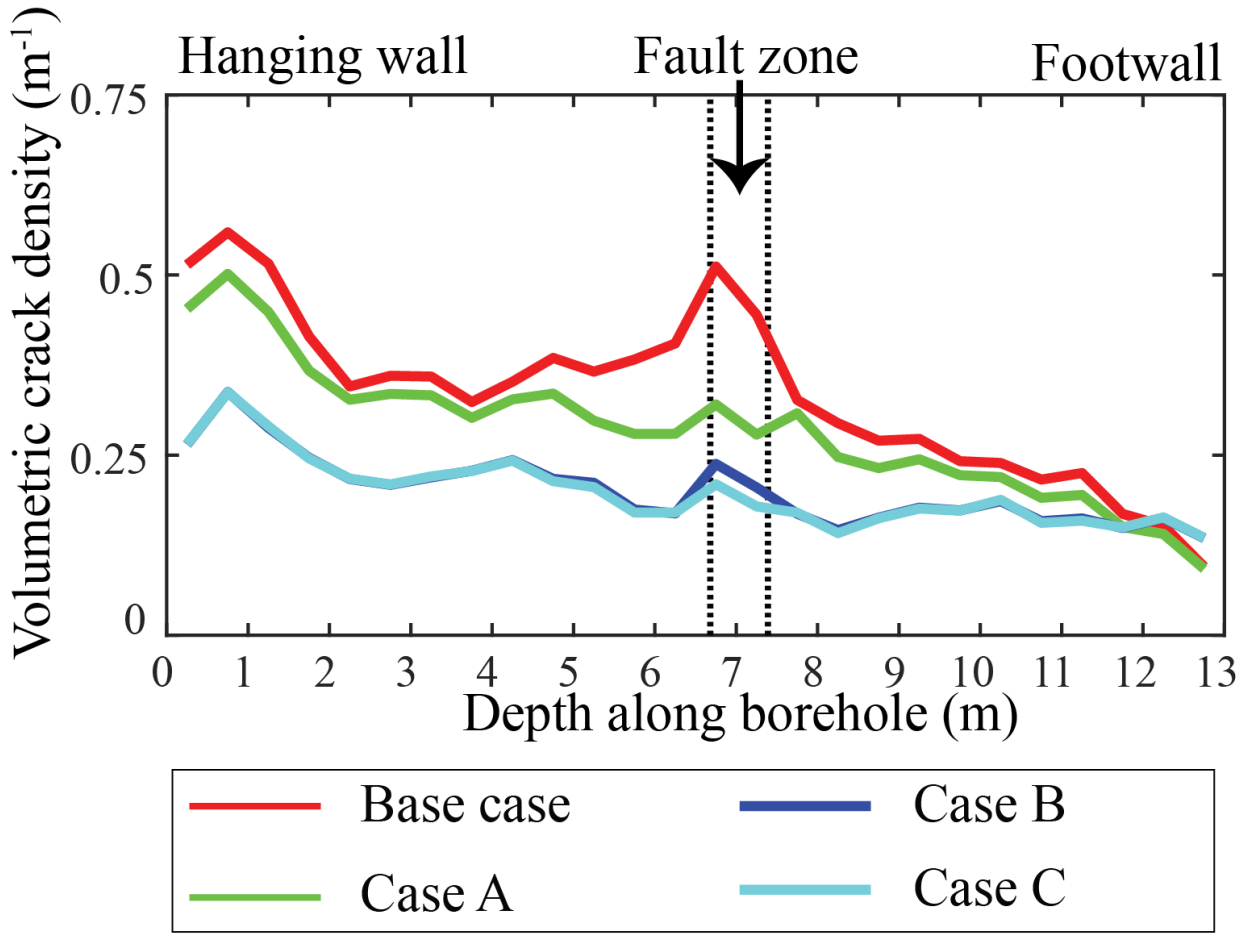
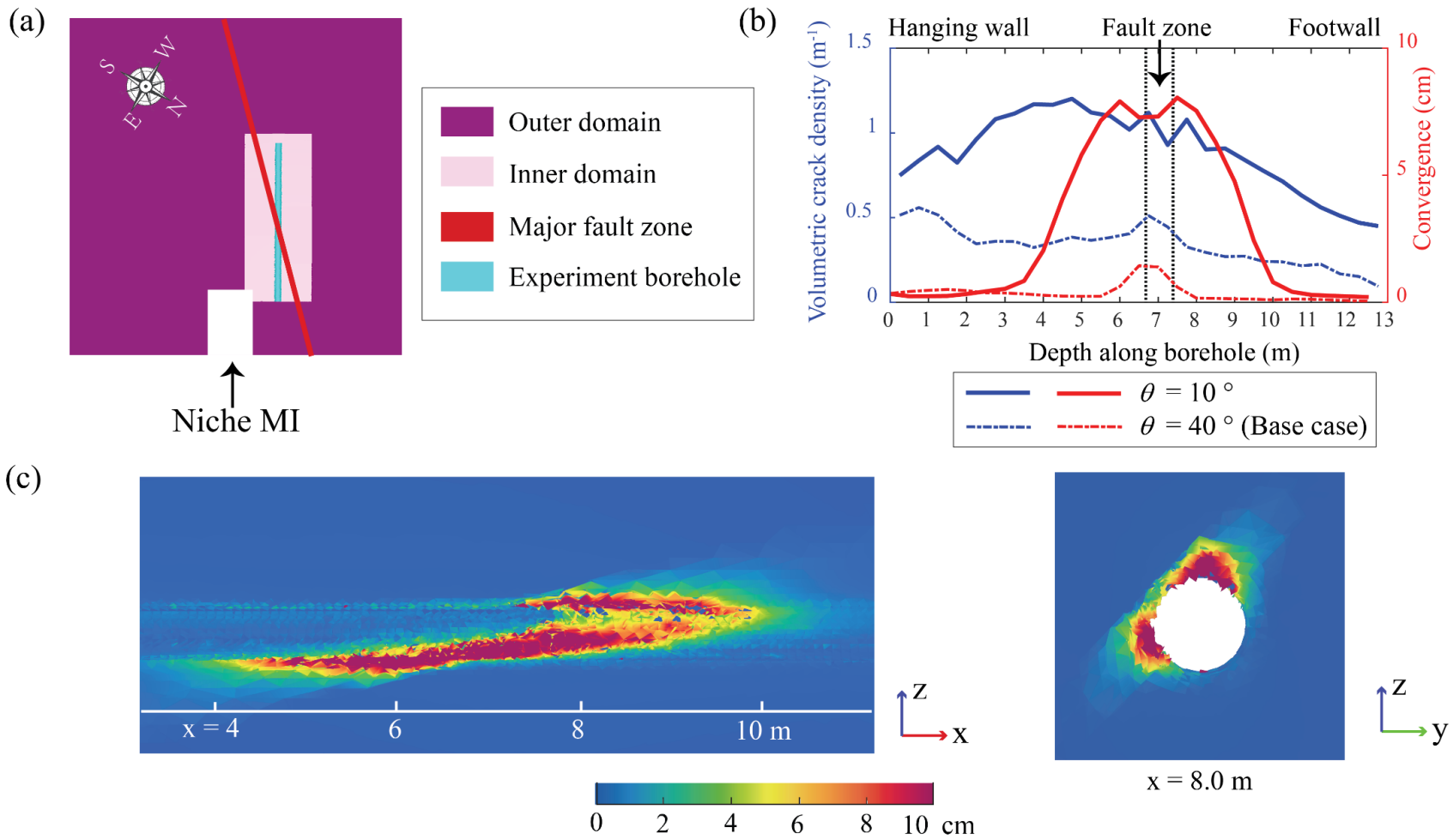


Simulation results

Acute intersection angle (10 deg) between fault zone and borehole

Stronger overbreaks, more new cracks and squeezing ground behaviour are observed



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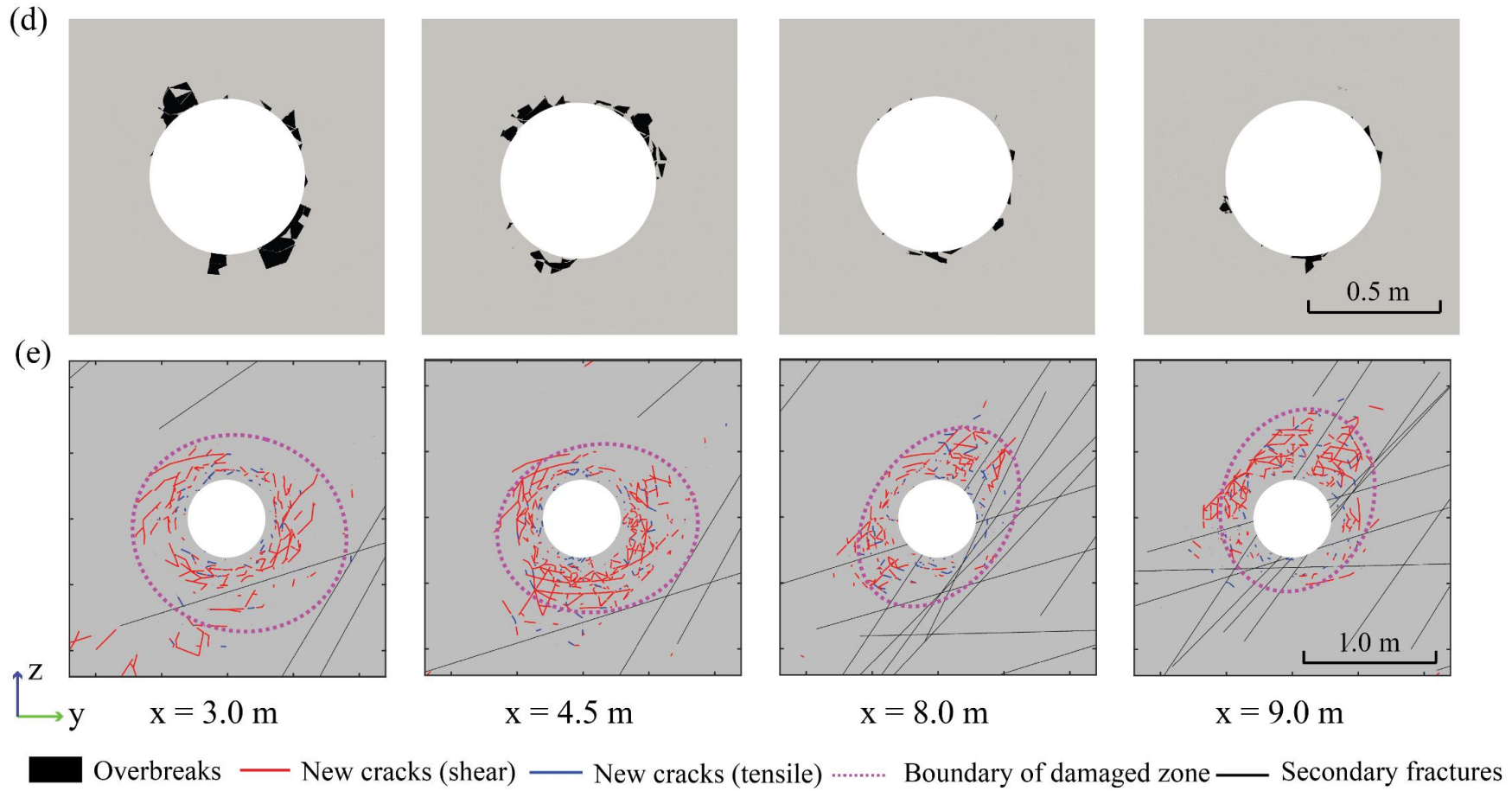

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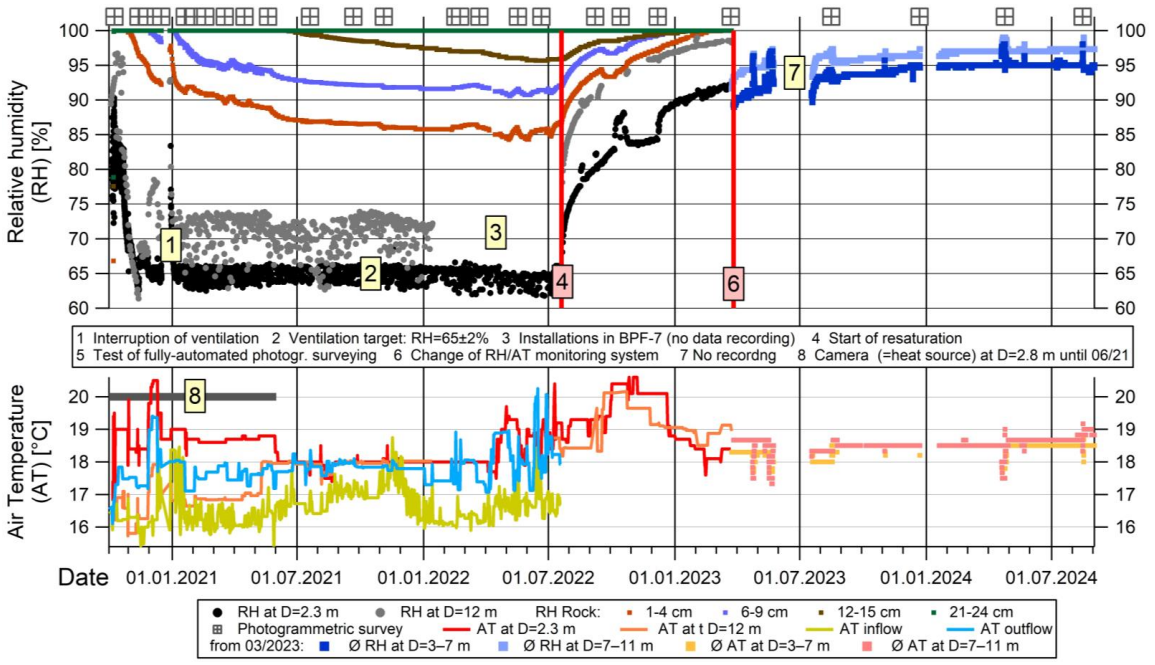
Long-term overbreak evolution in the PF-A experiment

Borehole relative humidity and temperature evolution

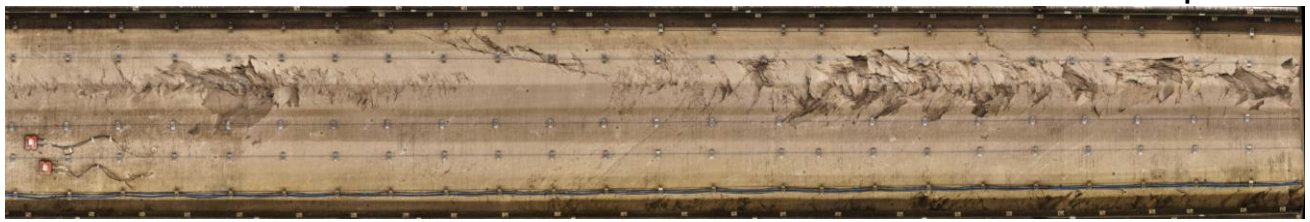


Ventilation | Resaturation | Resaturated

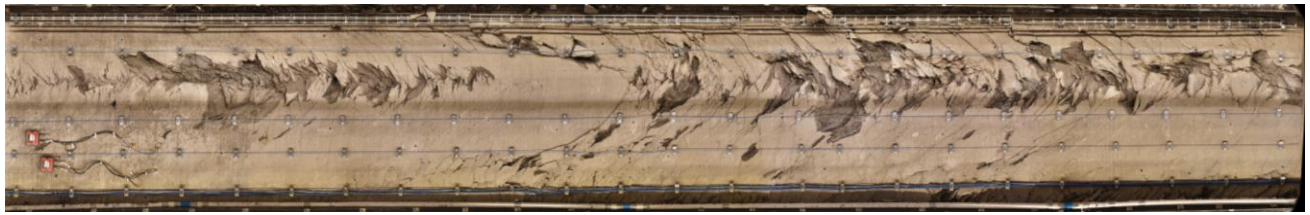
Evolution of overbreaks along the experiment borehole

Start of ventilation phase

End of ventilation phase

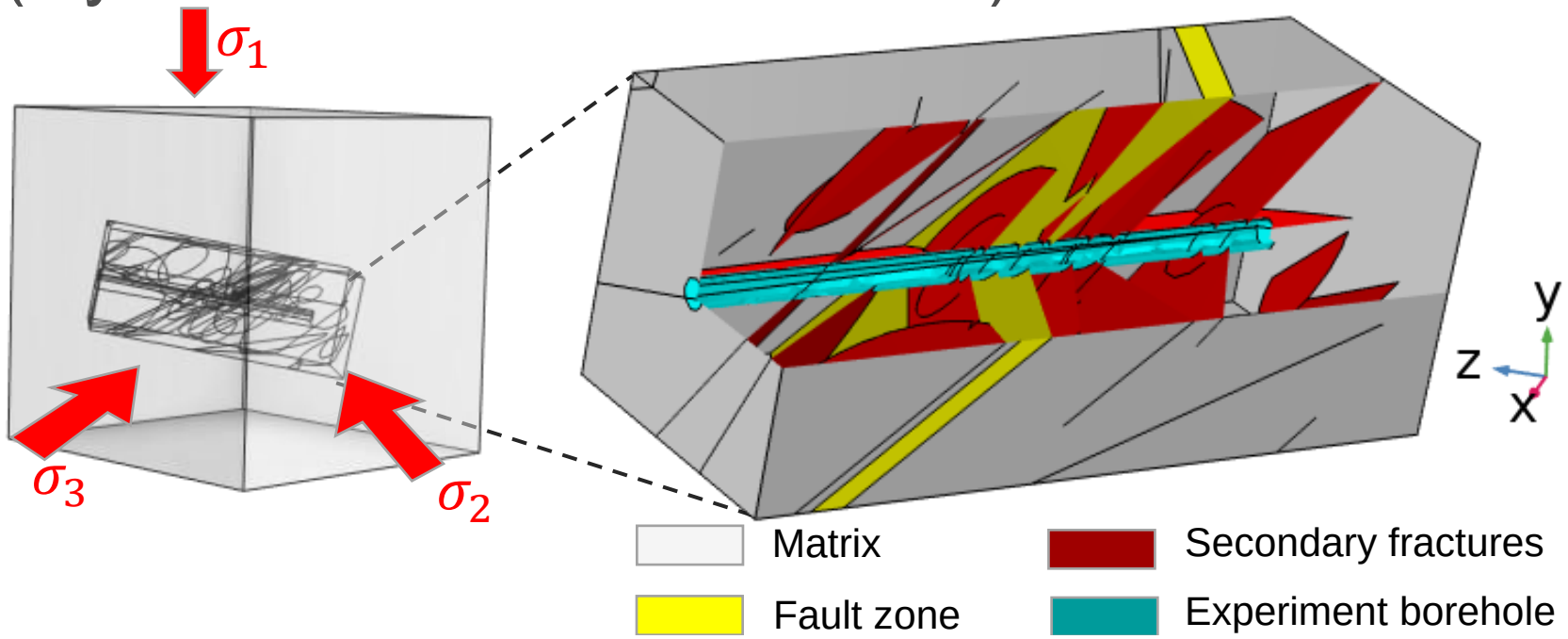


After ~3 years of resaturation



Model setup (hydromechanical model)

Simulated using COMSOL

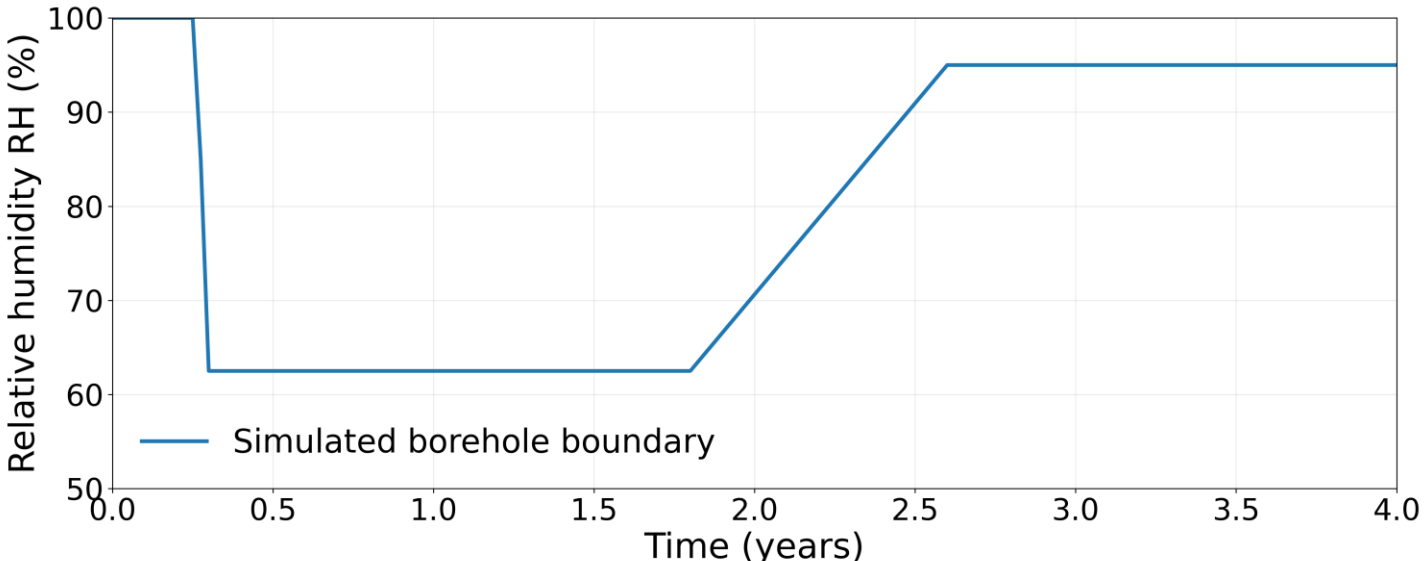


Solid deformation

- Poroelasticity ✓
- Damage ✓
- Swelling✓
- Fracture deformation✓
- Creep×
- Plasticity×

Fluid flow

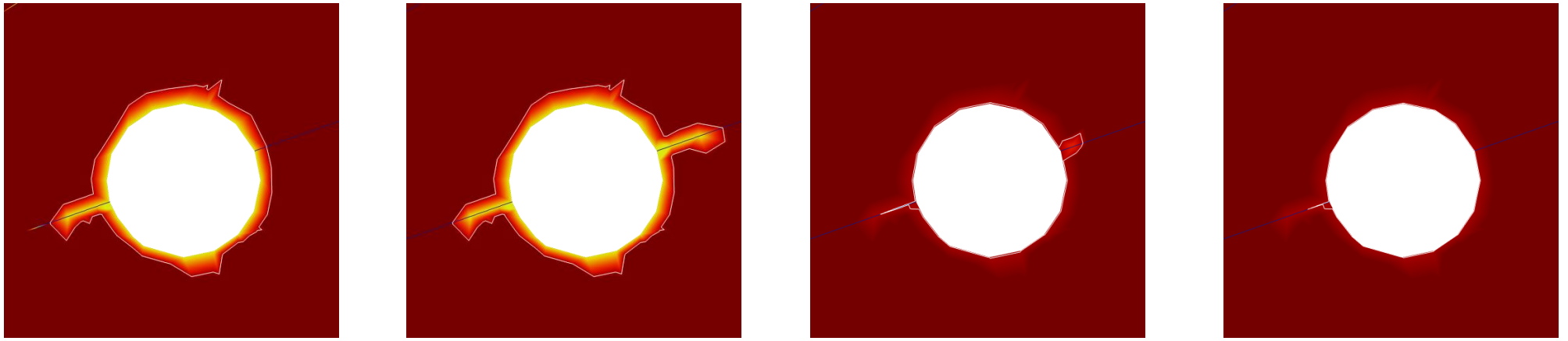
- Unsaturated and saturated flow✓



Preliminary simulation results

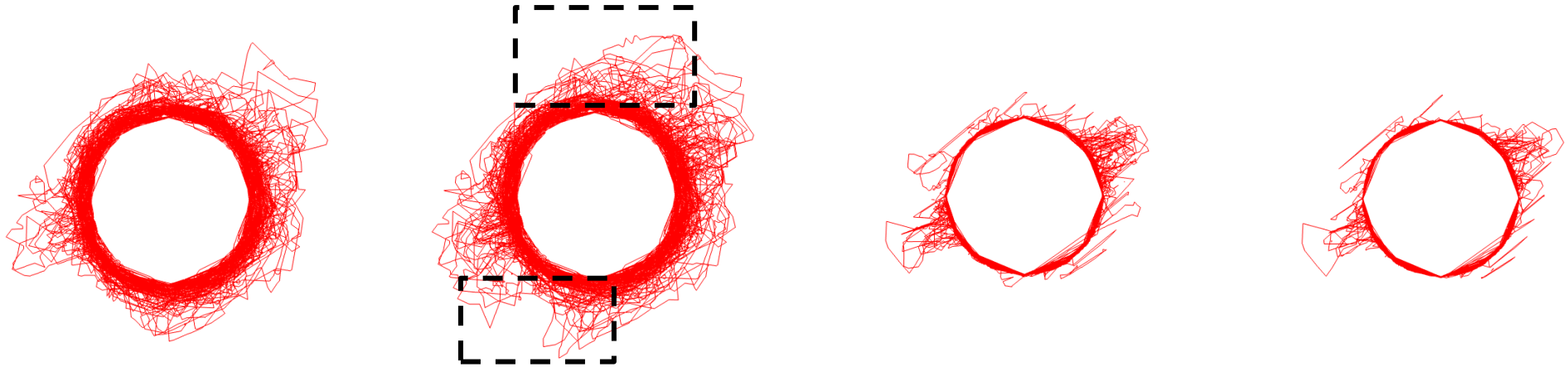
Unsaturated zone evolution

L = 4 m



RH
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

Variation of unsaturated zone



0.5 m

Start of ventilation

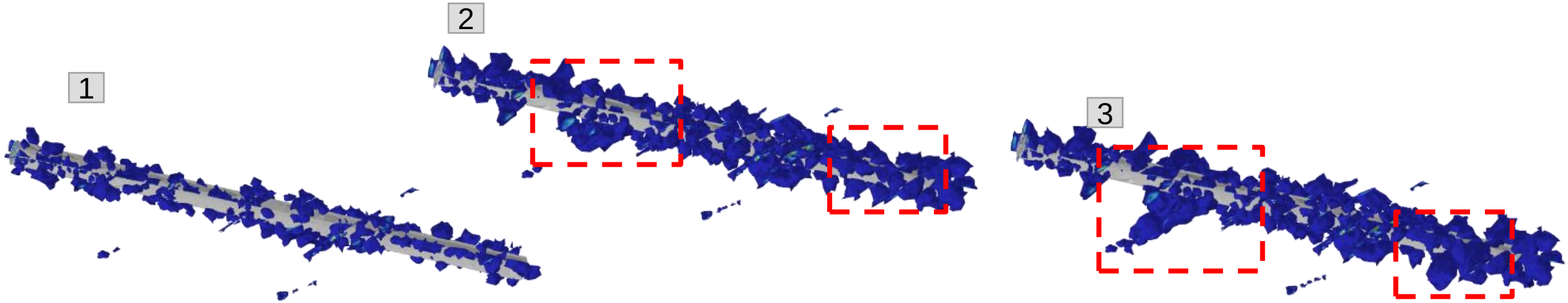
End of ventilation

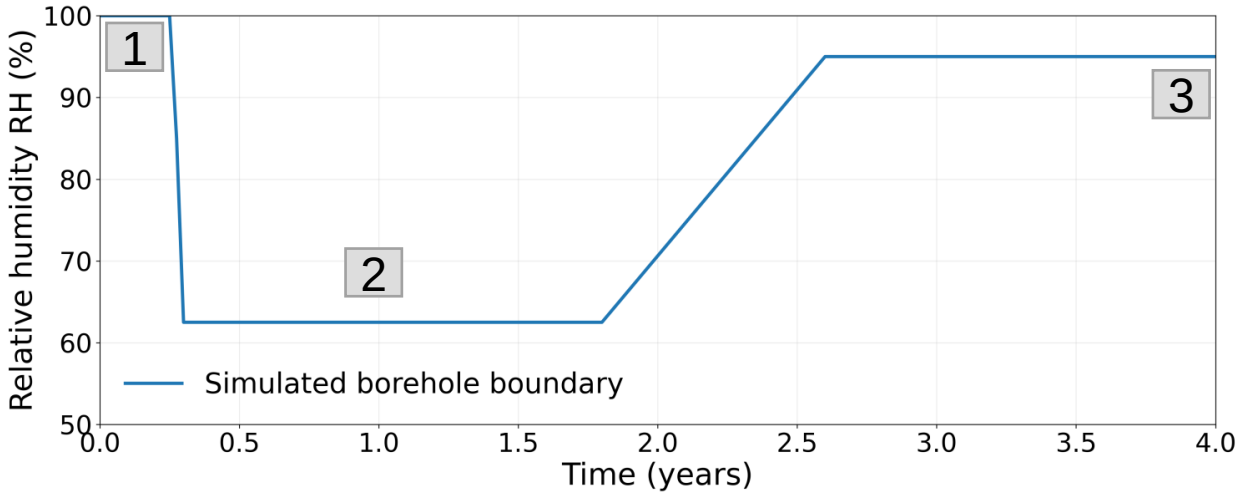
Start of resaturated

End of resaturated

Preliminary simulation results

Damaged zone evolution





Next step plan (hydromechanical modelling)

- Generating new DFN with conditioned simulation.
- Adjusting parameters based on the current updates from the lab team.
- Benchmarking of key model components.
- Validation against experimental observation data (e.g. strain measurements, overbreak pattern and evolution).
- Use the model to understand the interplay and relative importance of different processes (suction, swelling, poroelasticity, creep, etc.) in driving time-dependent overbreak and damage evolution.

Concluding remarks

- A 3D framework has been developed to simulate progressive failure around the PF/PF-A borehole in faulted Opalinus Clay
- The geomechanical model captures short-term damage and overbreak formation, highlighting the effects of fault zone and fracture networks
- The hydromechanical model incorporates realistic hydraulic boundary conditions and coupled processes including unsaturated flow, swelling, suction, and damage
- Future work will extend the framework to drift-scale modelling

Acknowledgement

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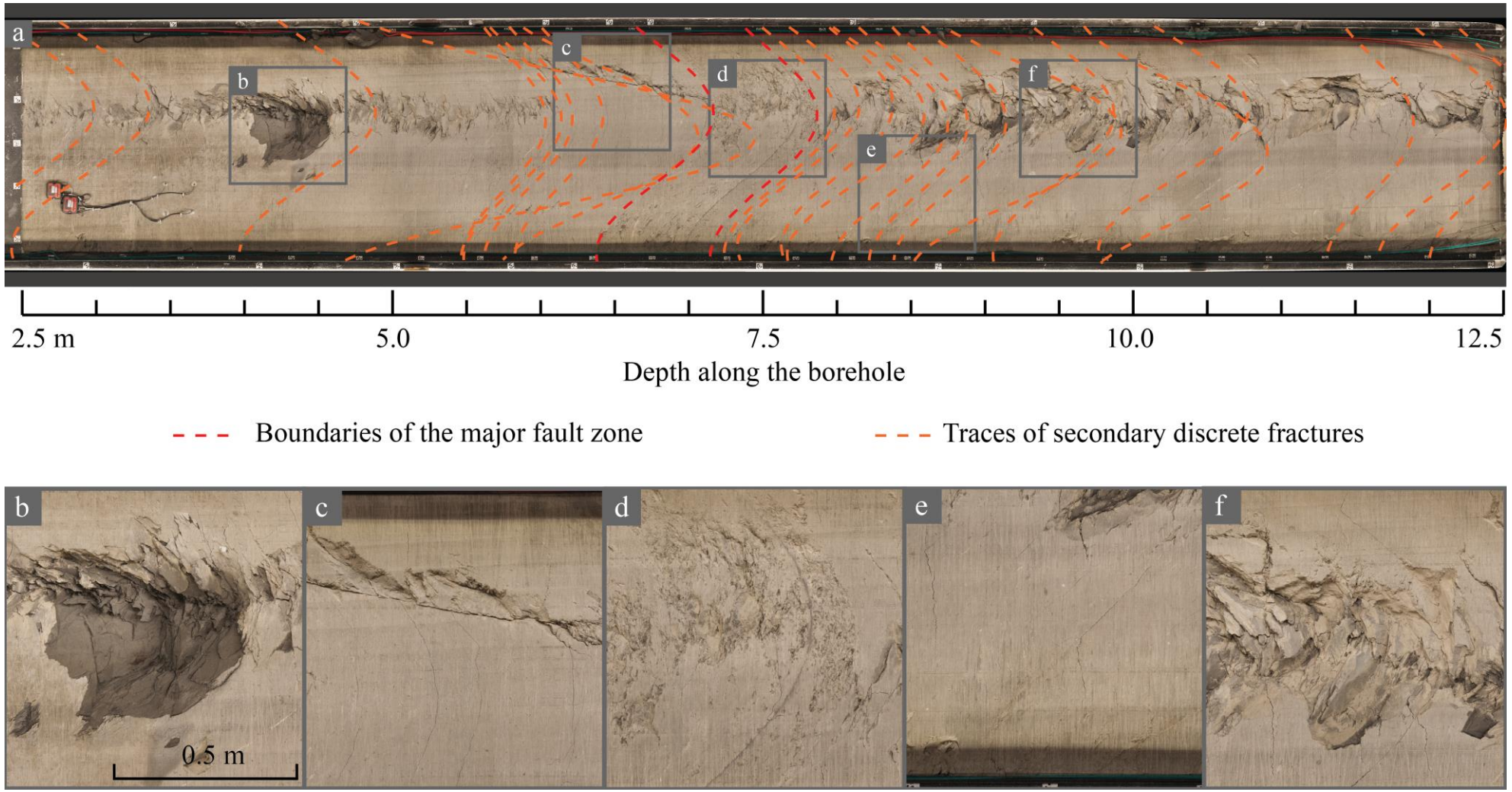
Backup slides

Overbreak pattern along the experiment borehole



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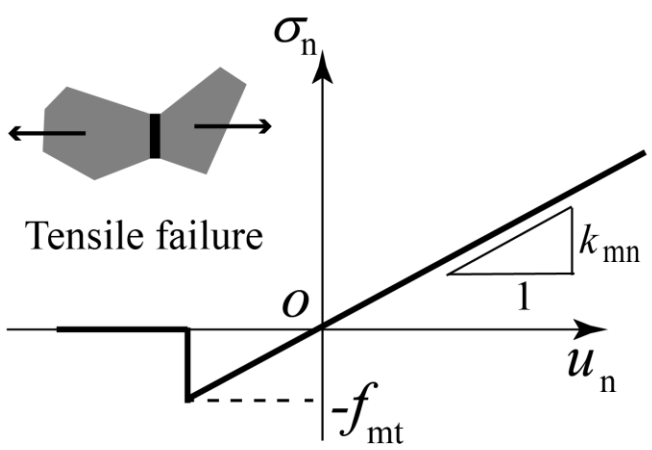
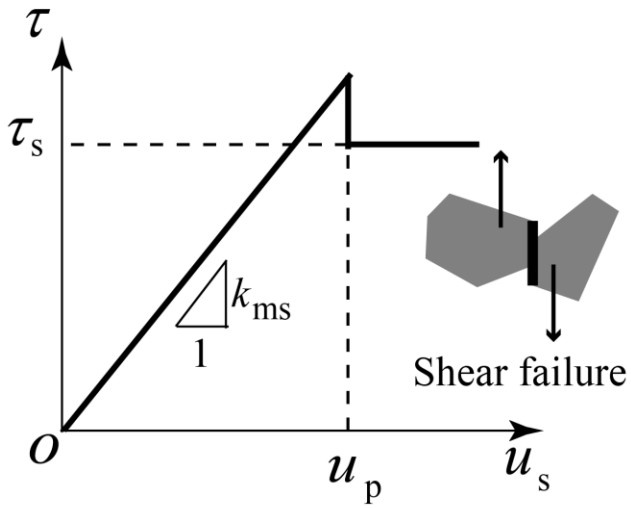
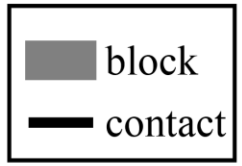
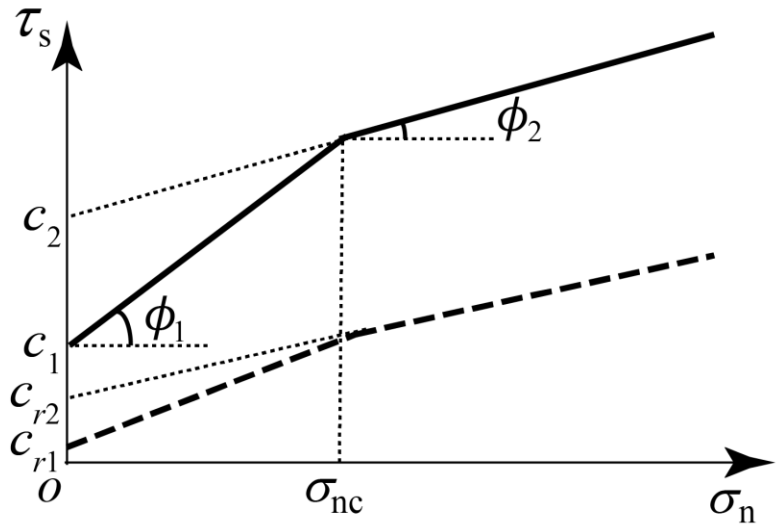
Constitutive models

- Crack growth driven by tensile or shear failure
- Bilinear Mohr-Coulomb criterion









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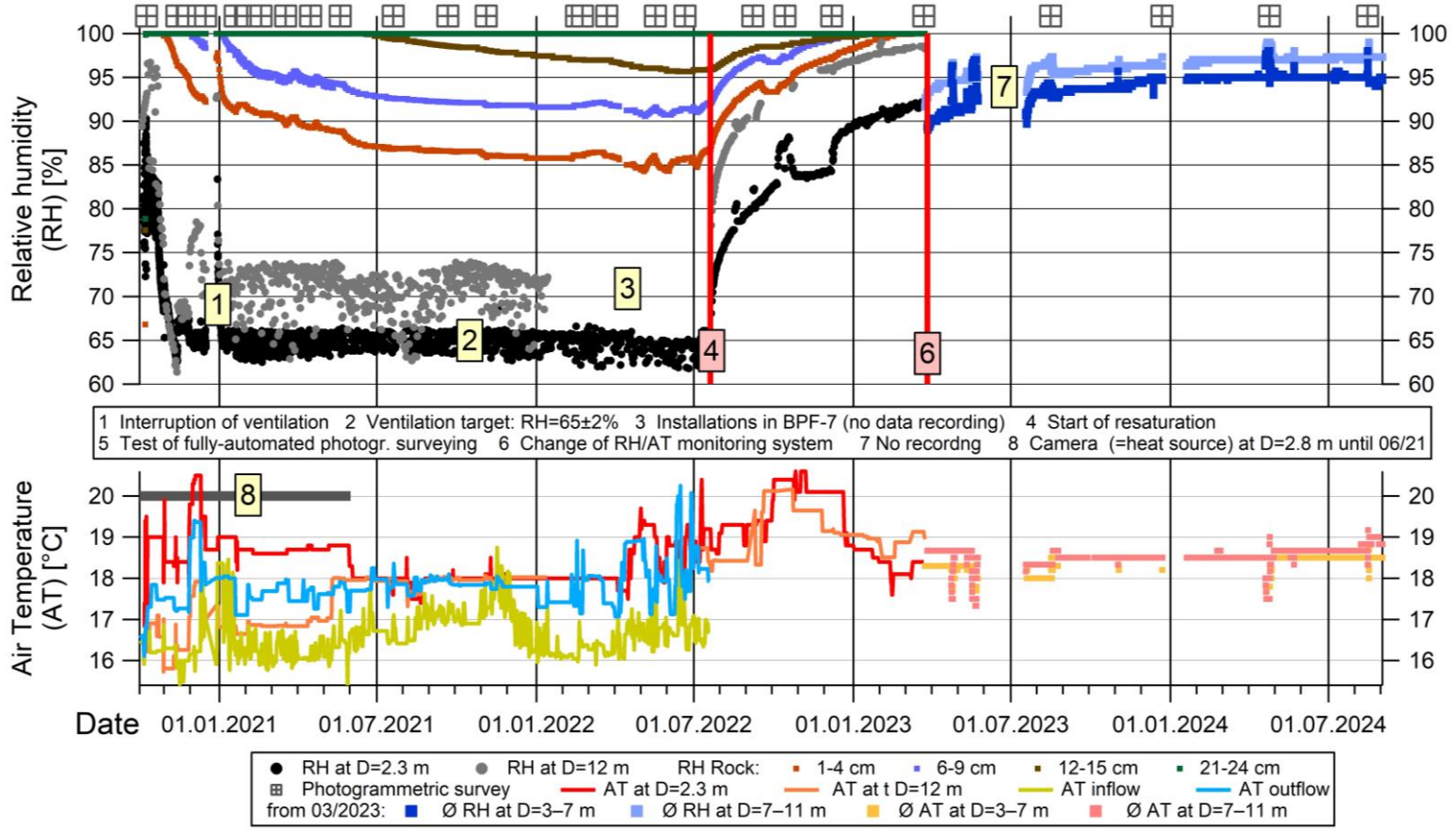
Borehole relative humidity and temperature evolution

- RH during ventilation between 62 and 74 %
- Time-dependent rock desaturation
- Resaturation from 07/2022
- Since 01/2024, the experiment borehole is at >95 % RH
- The unsaturated zone was observed at a distance of 15–21 cm from the tunnel.
- The boundary condition for the tunnel in the model was set based on observed relative humidity data.

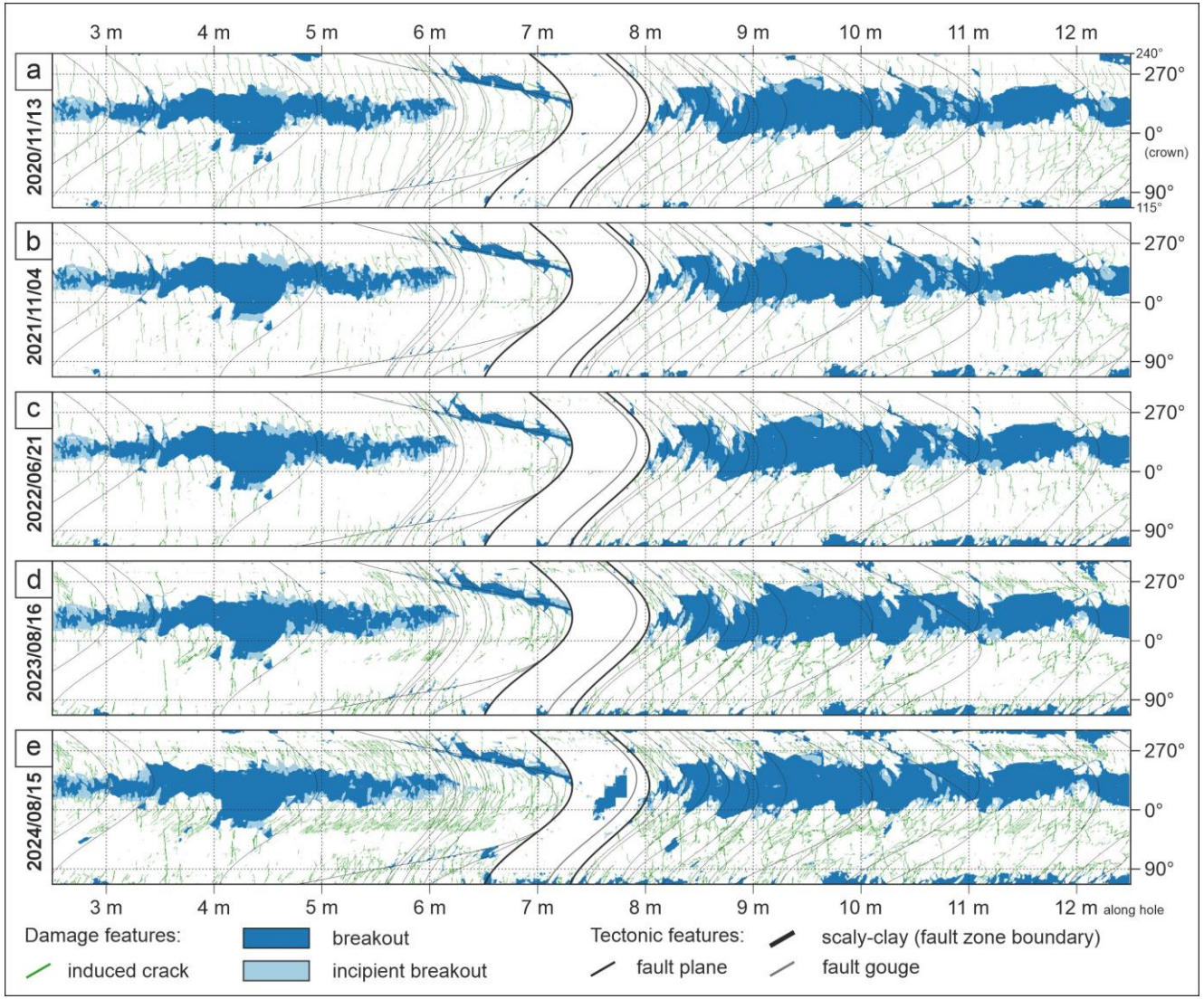


Ventilation

Resaturation

Ziegler et al. 2025

Evolution of induced cracks and breakouts



Ziegler et al. 2025

- New cracks and breakouts developed during the ventilation period and grew extensively during the resaturation period.

a = before the ventilation start
b = halfway through the ventilation period
c = end of ventilation period
d = after resaturation ramp
e = end of resaturation period

Governing equations

Mechanical equilibrium

$$\nabla\sigma + F = 0$$

Total stress

$$\sigma = (1-D)\mathbf{C}\colon(\varepsilon - \varepsilon_{hs}) - \alpha p\mathbf{I}$$

Damage

$$D(\varepsilon) = \begin{cases} 1 - \dfrac{\varepsilon_0}{\varepsilon}\exp\left(-\dfrac{\varepsilon-\varepsilon_0}{\varepsilon_f-\varepsilon_0}\right), & \varepsilon \geq \varepsilon_0 \\ 0, & \varepsilon < \varepsilon_0 \end{cases}$$

$$\varepsilon_f = \frac{G_f}{\sigma_{ts} h_{cb}} + \frac{\varepsilon_0}{2}$$

Swelling

$$\varepsilon_{hs} = \beta_h\left(c_m - c_{m,ref}\right)$$

$$c_m = \rho_w\theta$$

Fracture deformation

$$v_n = \frac{k_{n0} v_m^2}{k_{n0} v_m + \sigma_{eff}}$$

$$\tau_s = \begin{cases} k_s u_s, & u_s < u_p \\ \tau_p, & u_s \geq u_p \end{cases}$$

$$v_s = \begin{cases} -tan\phi_i\, u_s, & u_s < u_p \\ -v_{s_{max}}, & u_s \geq u_p \end{cases}$$

$$b = b_0 - v_n - v_s$$

Richard's equation (matrix)

$$\rho_w\left(\frac{C_m}{\rho_w g} + S_e S_p\right)\frac{\partial p}{\partial t} - \nabla\cdot\left(\rho_w\frac{k_m k_{rm}}{\mu}\left(\nabla_T p - \rho_w \boldsymbol{g}\nabla D\right)\right) = Q_m$$

Richard's equation (fracture)

$$b\rho_w\left(\frac{C_m}{\rho_w g} + S_e S_p\right)\frac{\partial p}{\partial t} - \nabla_\tau\cdot\left(-b\rho\frac{k_f k_{rf}}{\mu}\nabla_\tau p\right) = \rho(q^+ + q^-)$$

Fracture permeability

$$k_f = \frac{b^2}{12}$$

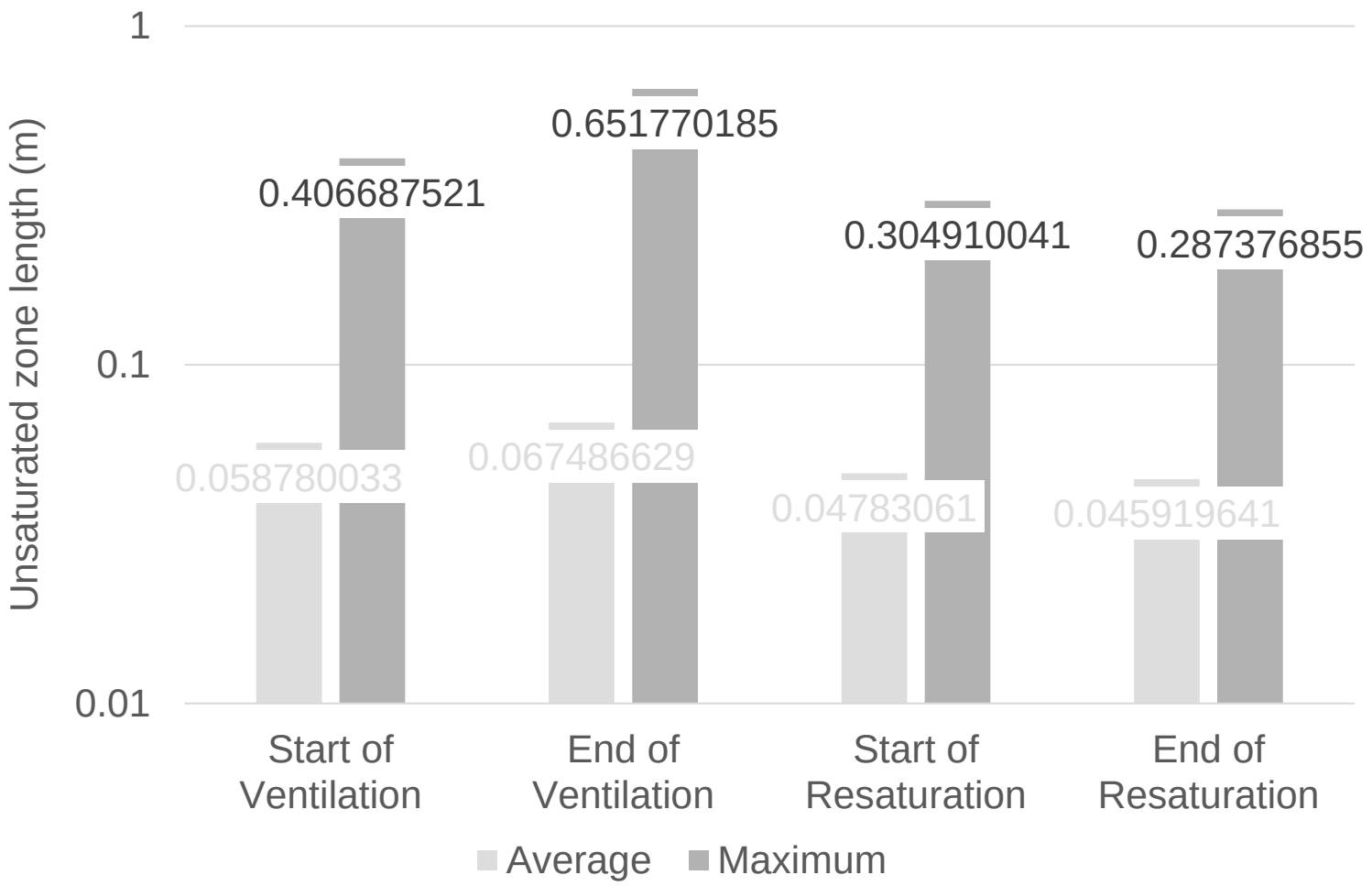
Brooks-Corey retention model

$$S_e = \begin{cases} \dfrac{1}{|\alpha h|^n}, & h < -\dfrac{1}{\alpha} \\ 1, & h \geq -\dfrac{1}{\alpha} \end{cases} \qquad k_r = \begin{cases} S_e^{\frac{2}{n}+l+2}, & h < -\dfrac{1}{\alpha} \\ 1, & h \geq -\dfrac{1}{\alpha} \end{cases}$$

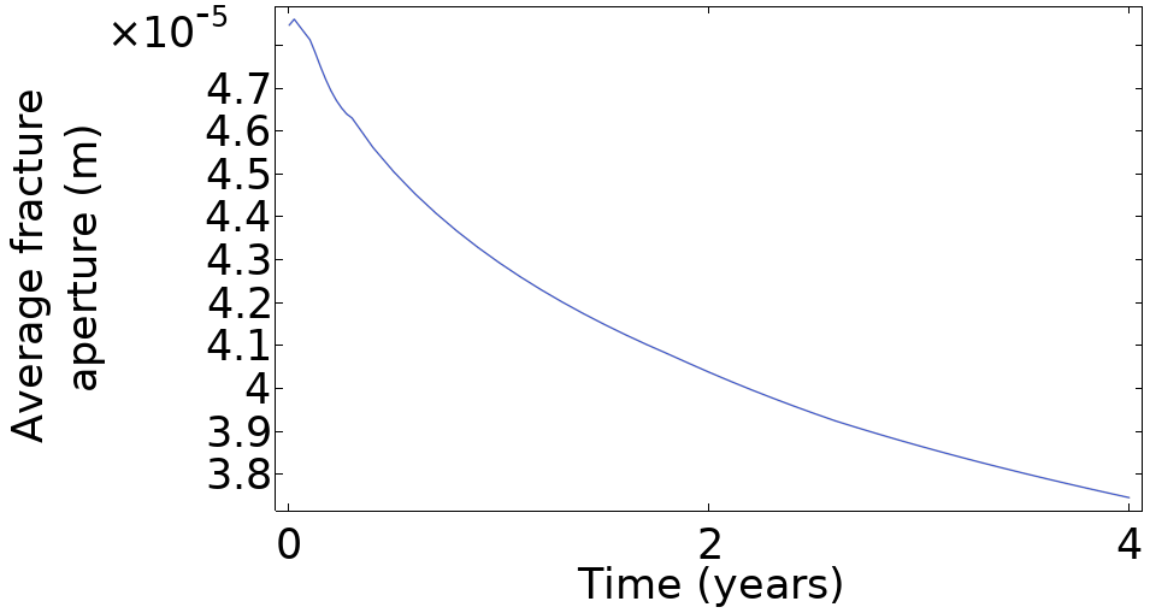
$$C_m = \begin{cases} -\dfrac{n}{H_p}(\theta_s - \theta_r)\dfrac{1}{\left|\alpha H_p\right|^n}, & h < -\dfrac{1}{\alpha} \\ 0, & h \geq -\dfrac{1}{\alpha} \end{cases} \qquad \alpha_f = \frac{b}{2\sigma_w\, cos\,\theta}\rho g$$

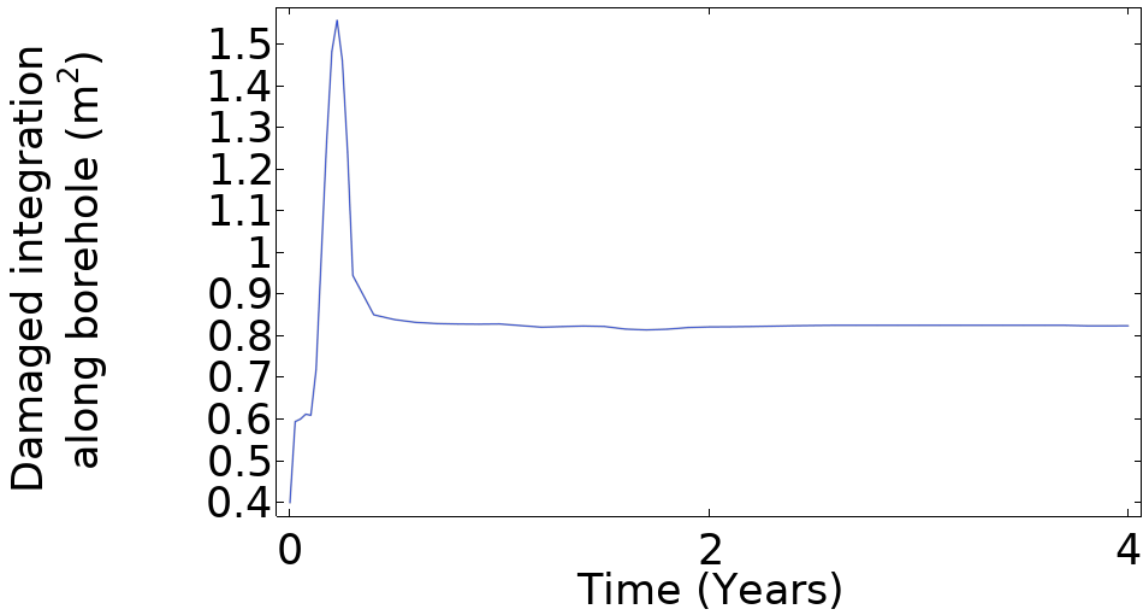
$$\theta = \begin{cases} \theta_r + S_e(\theta_s - \theta_r), & h < -\dfrac{1}{\alpha} \\ \theta_s, & h \geq -\dfrac{1}{\alpha} \end{cases}$$

Unsaturated zone



Evolution of damage





- Aperture evolution mostly driven by the suction effect.
- Damage integration along borehole is almost constant along the borehole during the ventilation and resaturation period.