

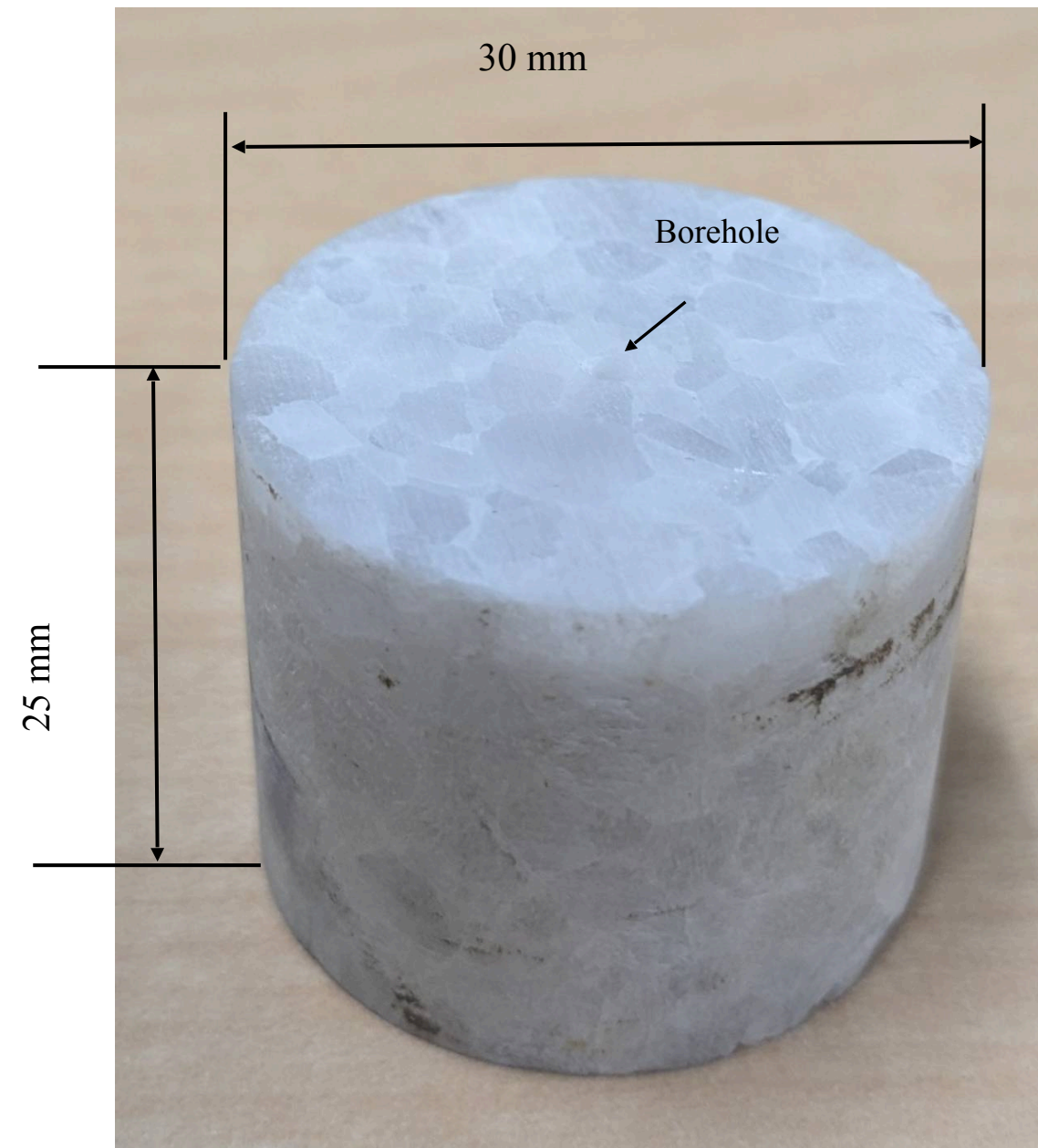
Hydraulic fracturing by supercritical CO₂ injection considering rock microstructure

June 9, 2026, DFN modelling workshop

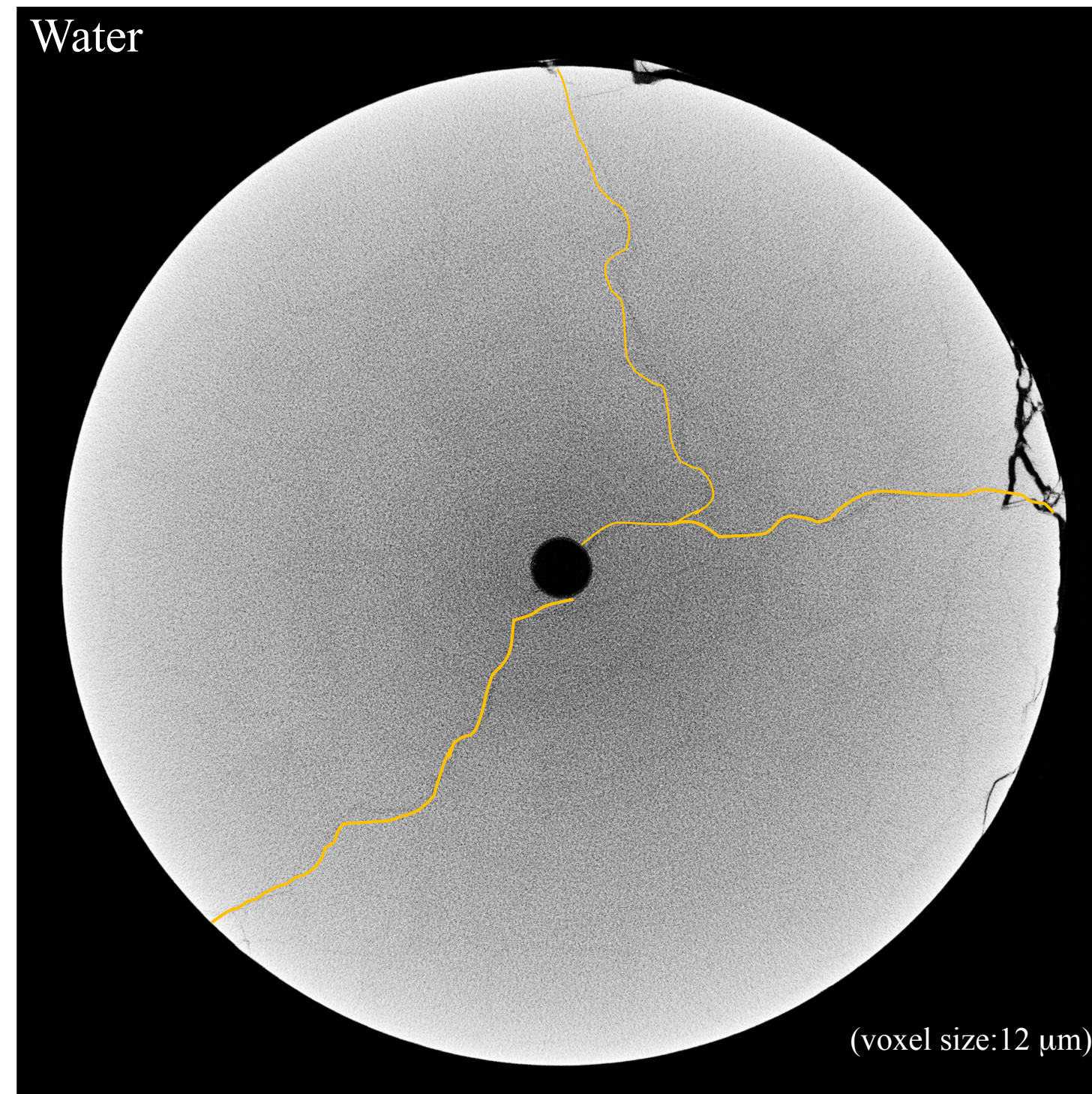
W. Yuan, T. You, K. Yoshioka
Montanuniversität Leoben

Y. Kanemaru, P. Eko, S. Kazumasa, N. Watanabe, and K. Sakaguchi
Tohoku University

Motivation

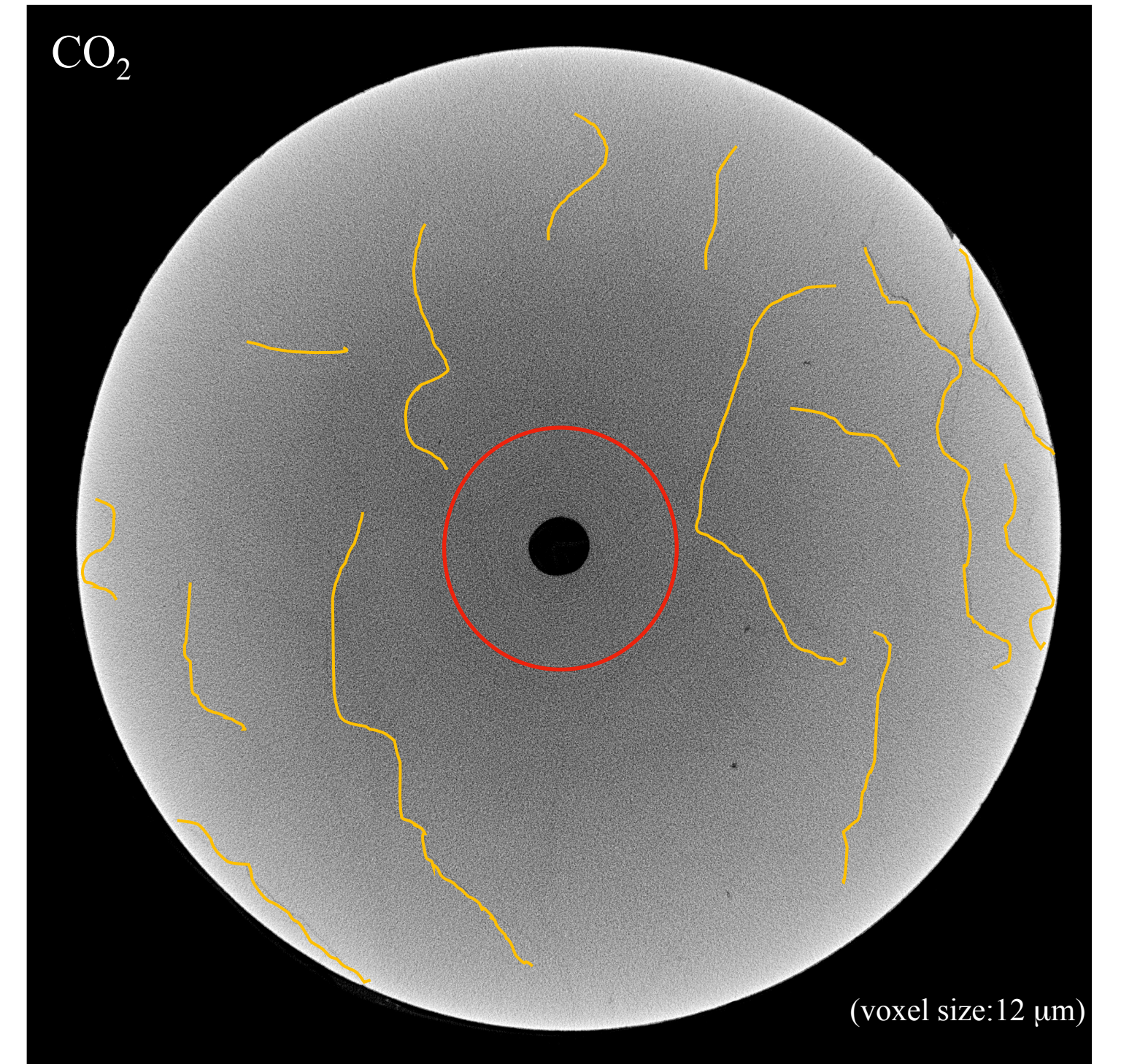


Coarse-grain marble

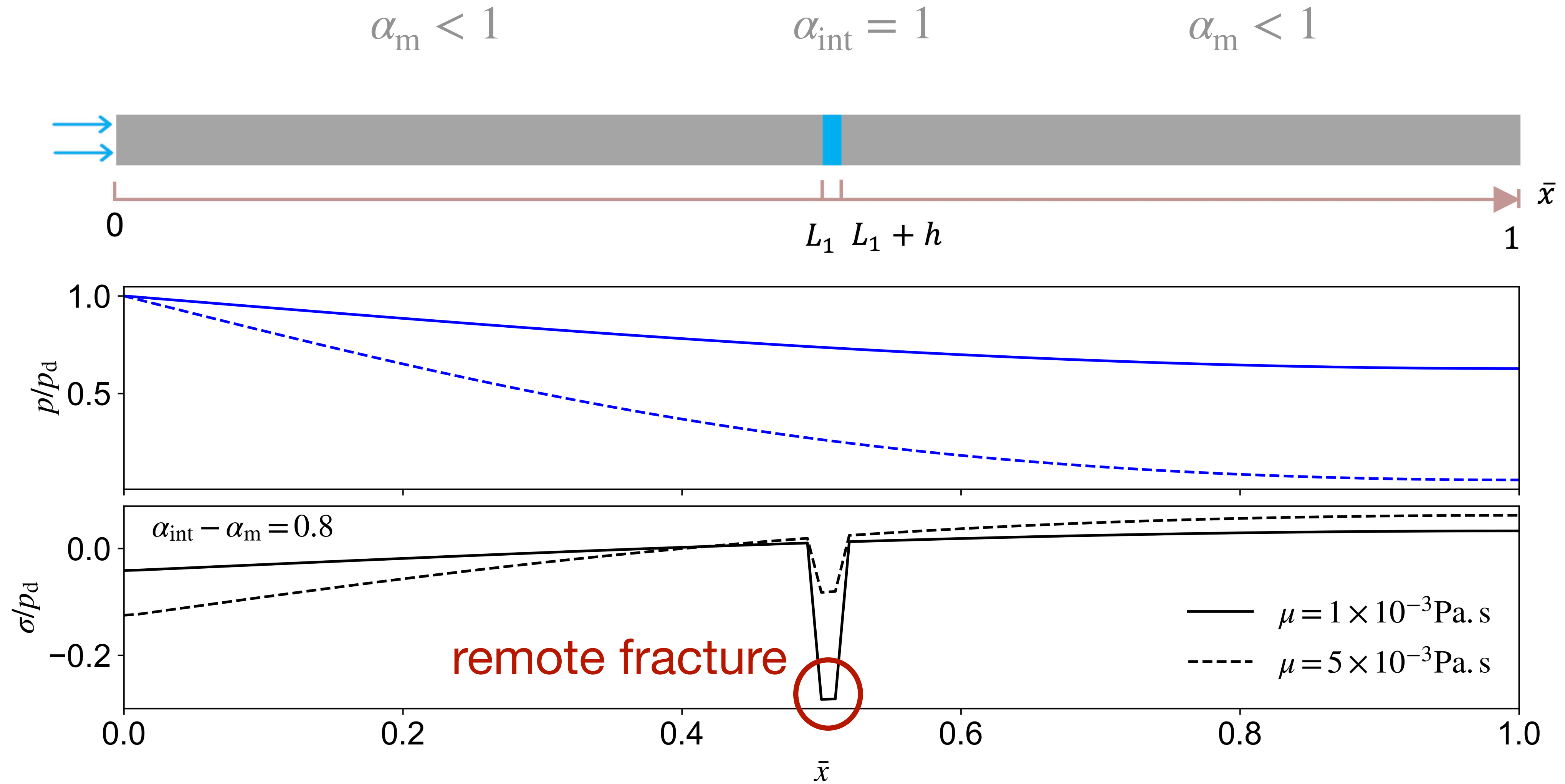


Kanemaru

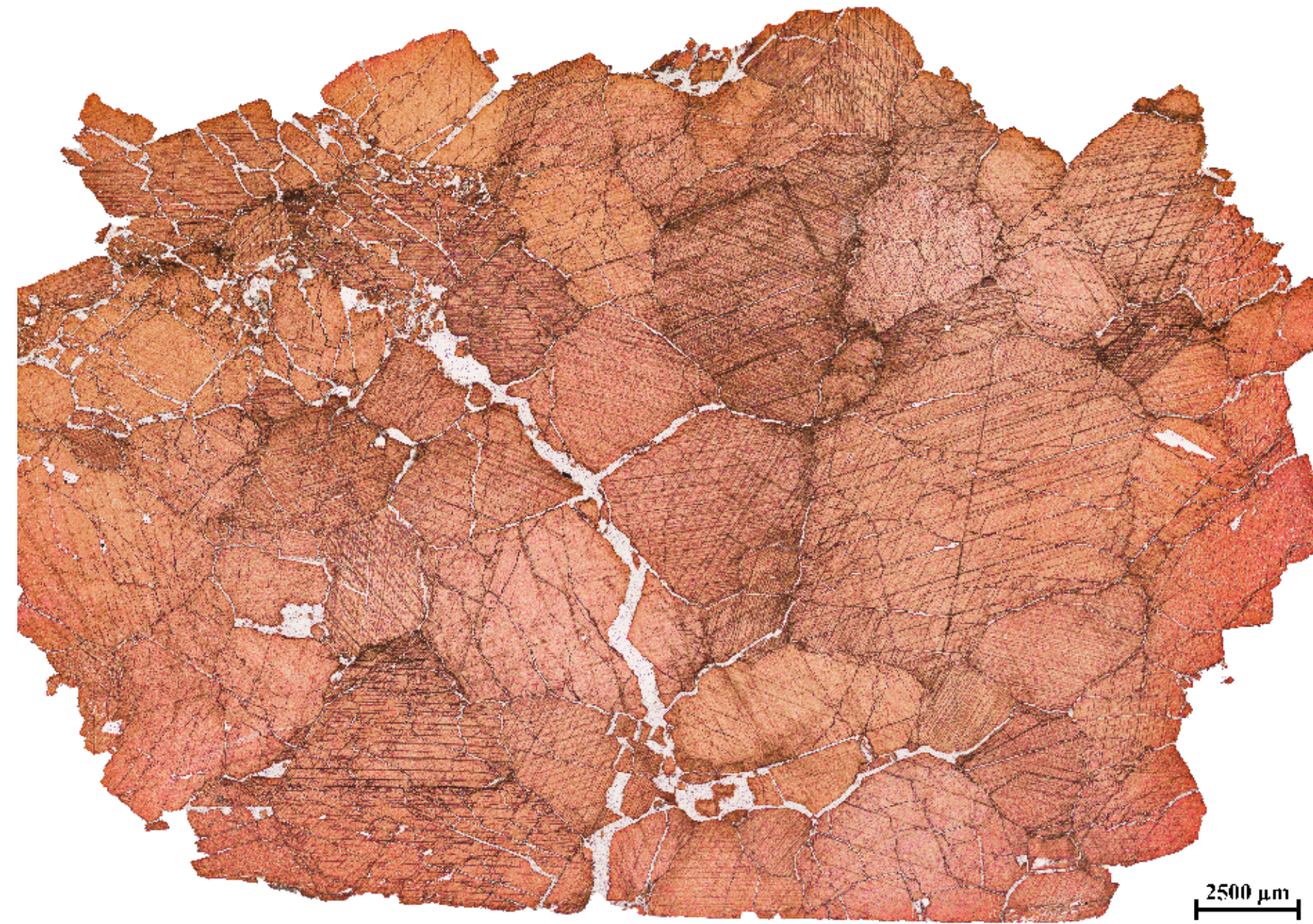
Remote fracture



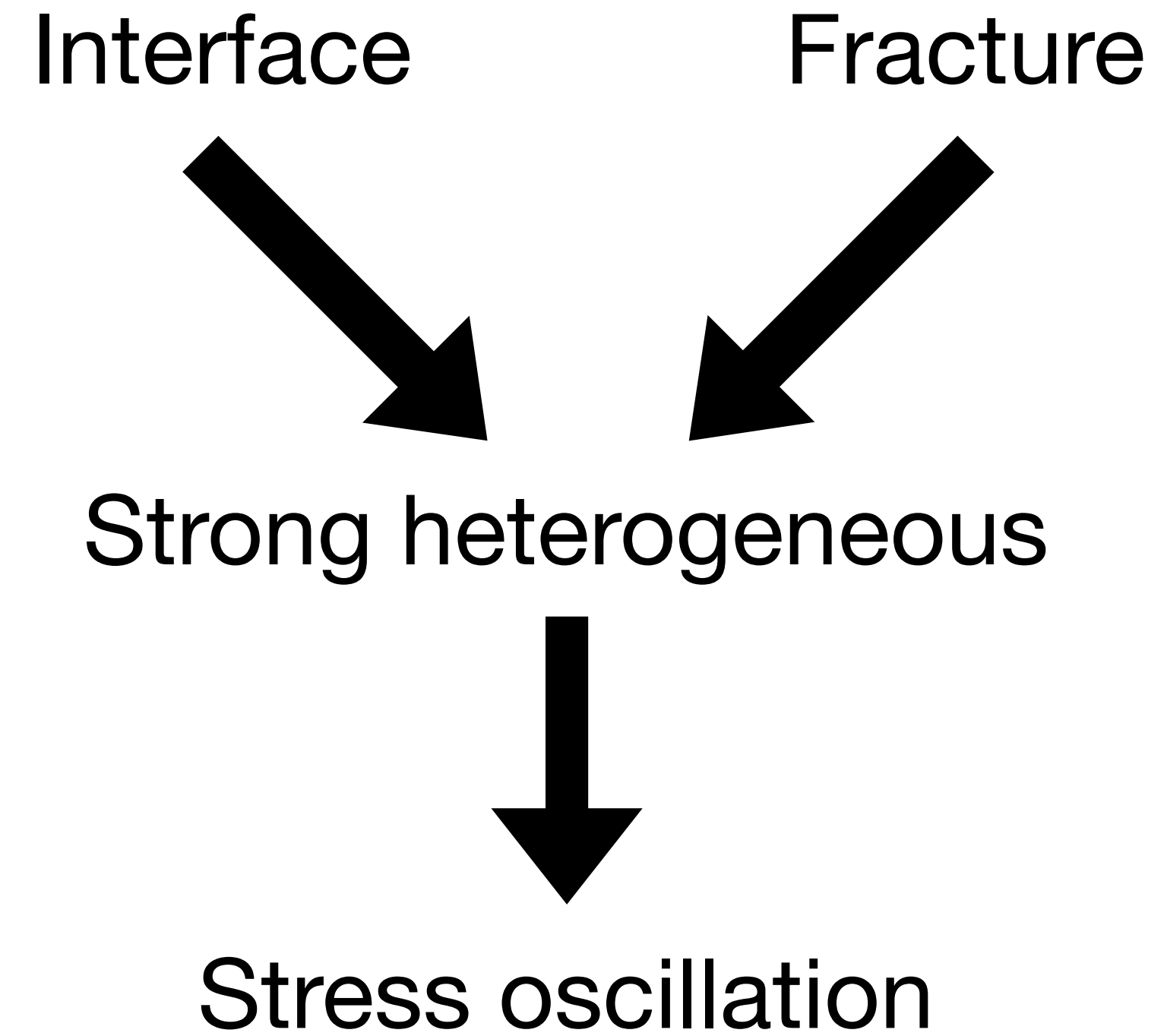
Motivation



Motivation



Marble CT

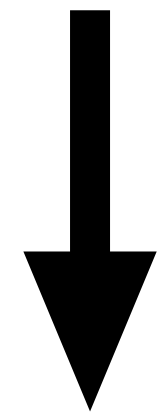


Typical method: enriched Galerkin, discontinuous Galerkin

Additional computation costs

Phase field model

Phase field variable: d $0 \longrightarrow 1$ Intact \longrightarrow Broken



Degradation function $g(d) = (1 - d)^2$

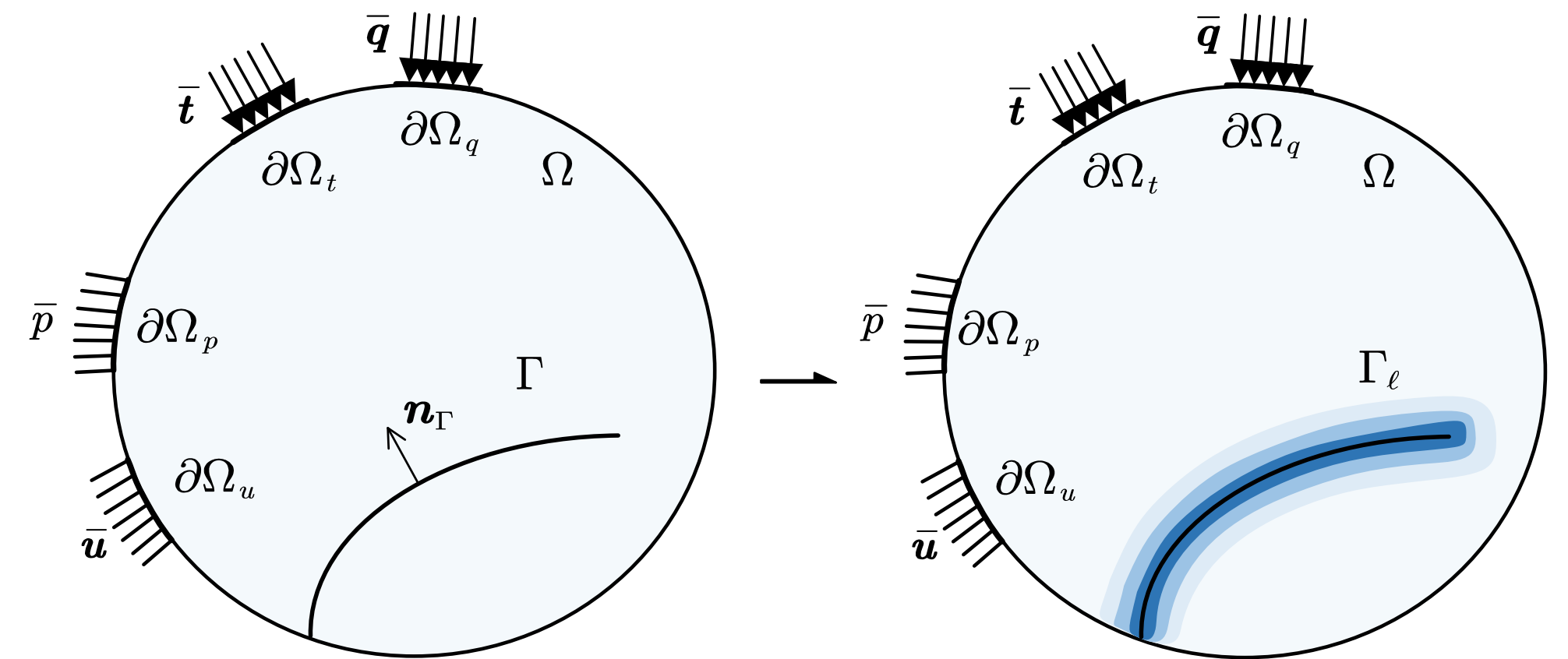
Material stiffness

1D diffuse crack profile $d(x) = e^{-|x|/l_0}$

Crack surface density function

$$\gamma(d, \nabla d) = \frac{1}{2l_0} d^2 + \frac{l_0}{2} |\nabla d|^2$$

Crack surface energy $\Psi^f = \int_{\Gamma} G_c dS = \int_{\Omega} G_c \gamma dV$



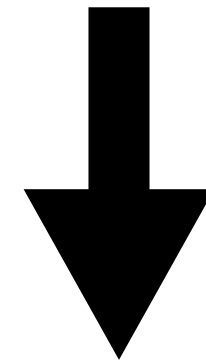
Discrete

Continue

Phase field model

Francfort-Marigo variational principle

Total energy = strain energy + crack surface energy



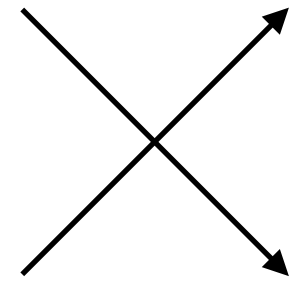
Phase field governing equation

OpenGeoSys has implemented phase field model.

Spatial stabilisation term

HMPPhasefield

Phase field



Hydromechanics

Monolithic scheme

Pressure field residual introduces a new term

$$S_p := \xi h_e^2 \int_{\Omega} \frac{\nabla p^i - \nabla p^{i-1}}{\Delta t} \cdot \nabla w_p dV$$

$$\xi = \frac{1}{4(\lambda + 2\mu)}$$

Rodrigo, CMAME, 2016

Update with consideration of cracks

$$\xi = \frac{1}{6\beta} + \frac{\alpha^2}{4k_{\text{eff}}}$$

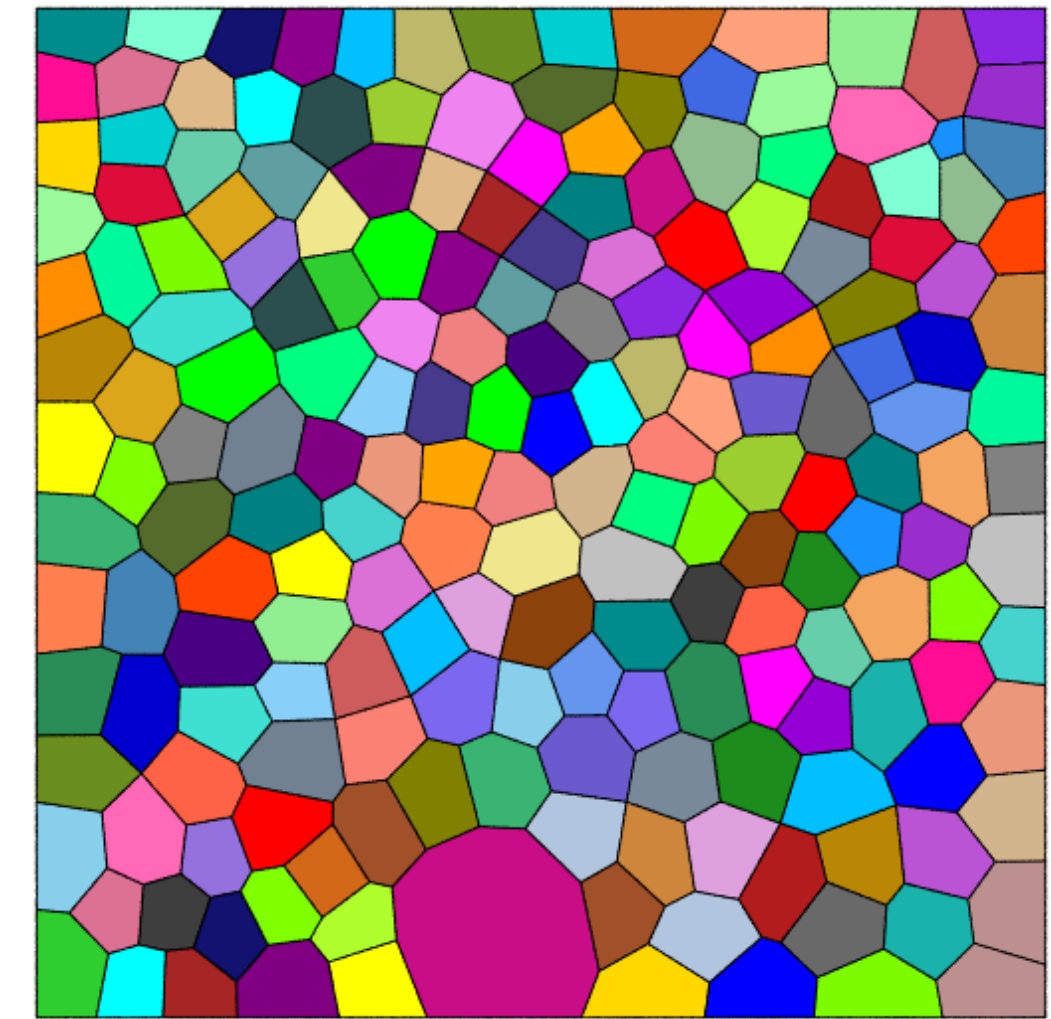
2d model (Coarse-grained Marble)

- Random polycrystalline topology generation (Neper)

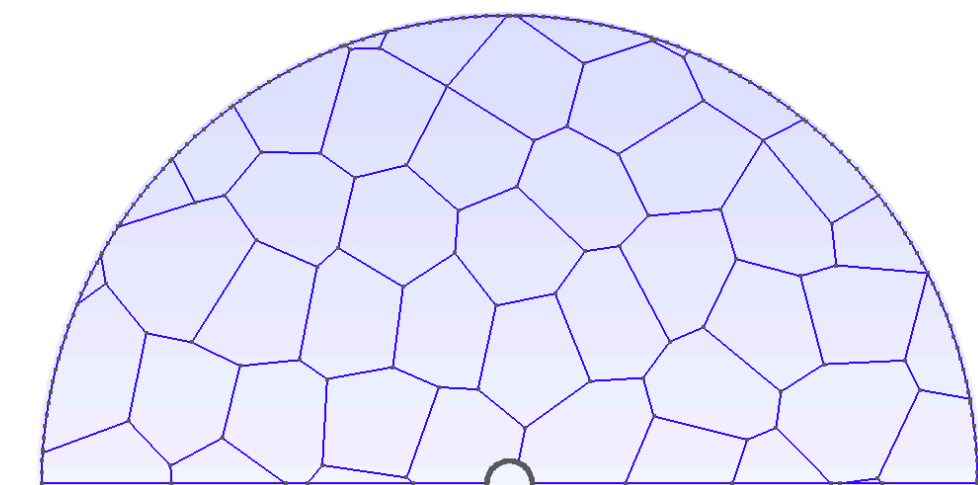
Grain diameter: lognormal(4mm, 0.2)

Grain circularity: 0.95

- Geometric clipping (python scripting)
- Mesh generation (Gmsh) Mesh size: 0.05 mm



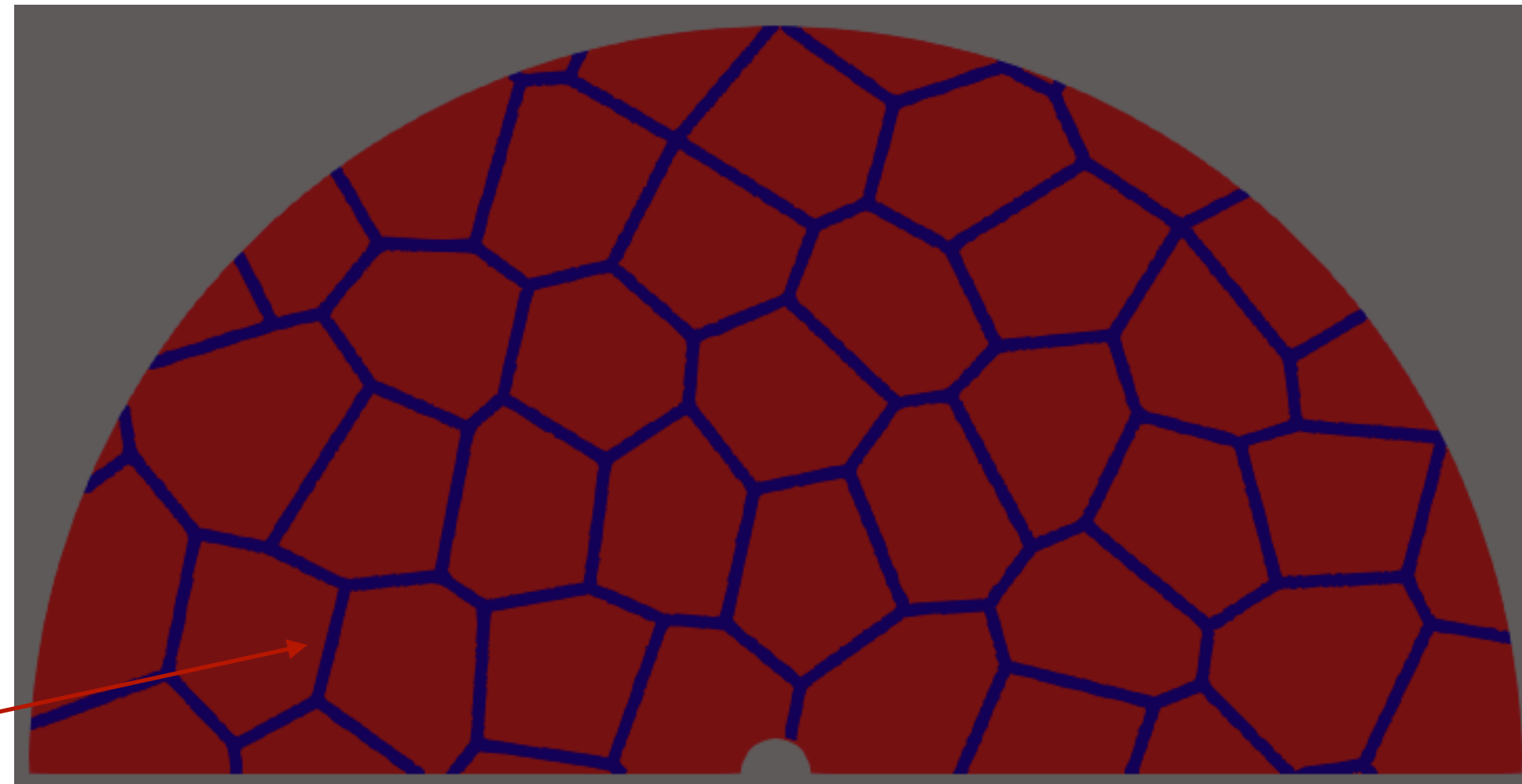
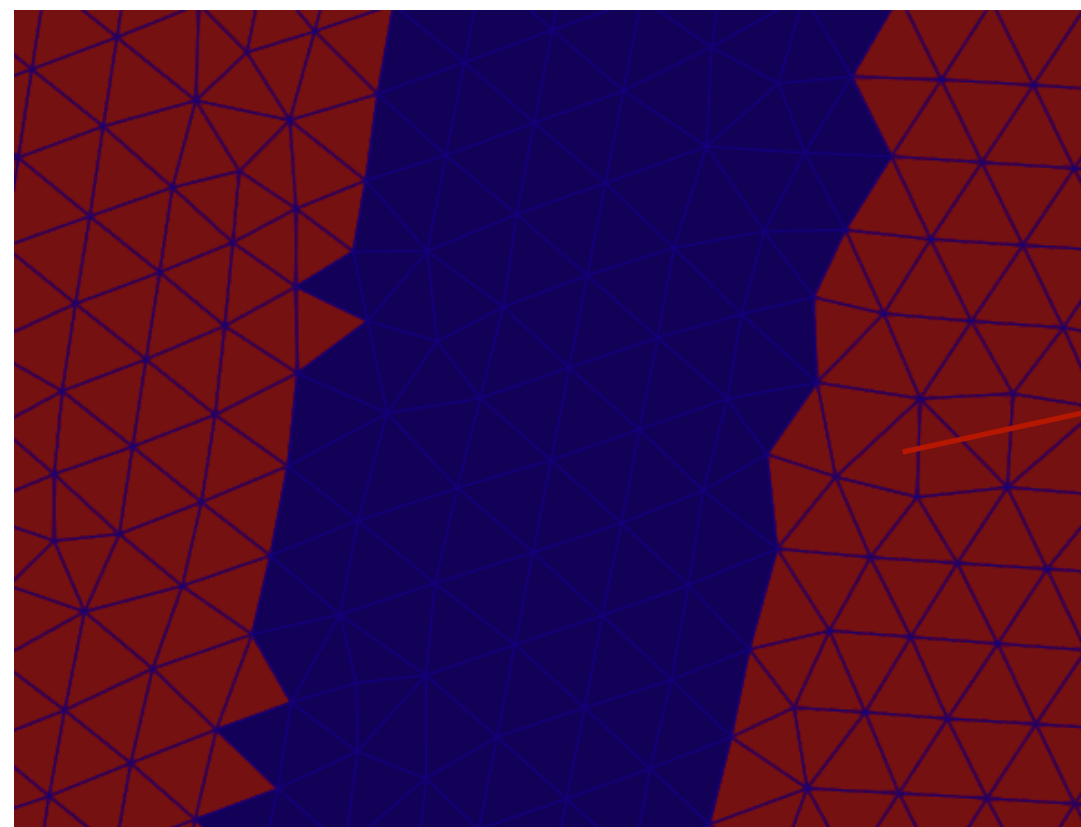
Polycrystalline topology



Half ring

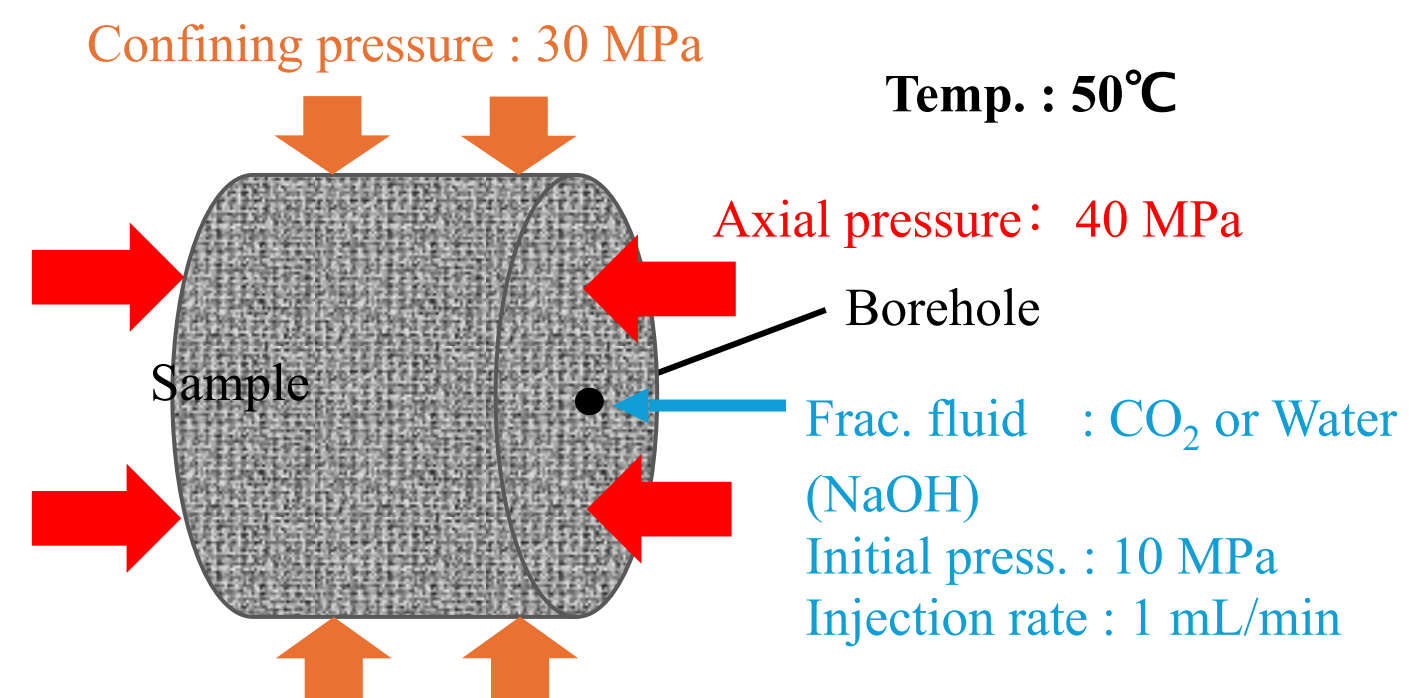
Interface

- The interface width is 6-8 element

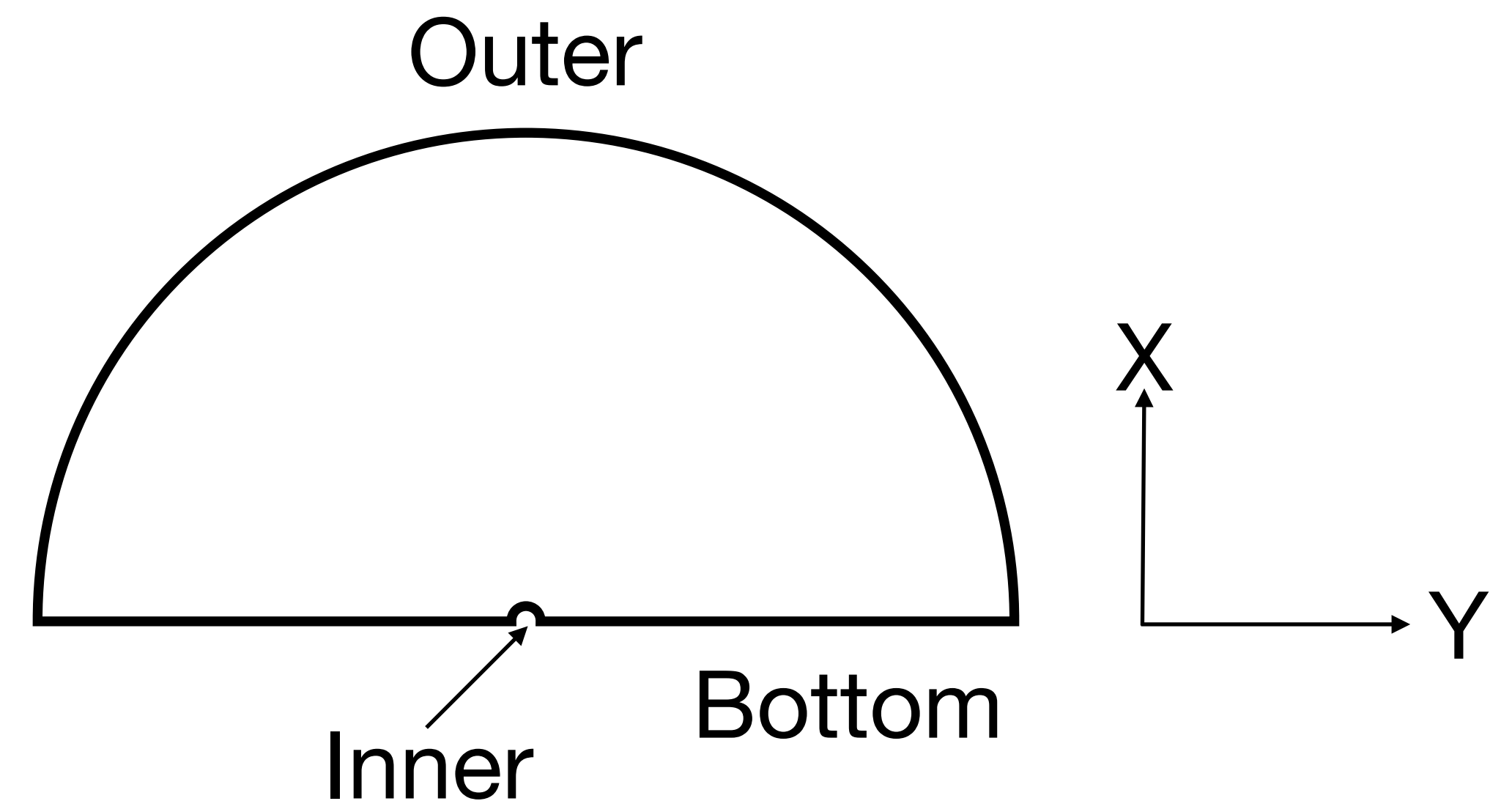


Boundary conditions

- Outer: confined pressure 30 MPa; no-flow
- Inner: initial pressure =10 MPa, then fluid inject; u_x and $u_y=0$
- Bottom: $u_y=0$



Kanemaru et al.



Material parameters

- Akigawa coarse-grained marble

	Grain	Interface
Porosity	0.2%	
Permeability (m²)	1E-19	2.8E-16
Biot coefficient	0.2	0.8
Tensile strength (MPa)	3.6	
Young's modulus (GPa)	46	
Poisson's ratio	0.11	
Critical energy release rate (N/m)	30	6

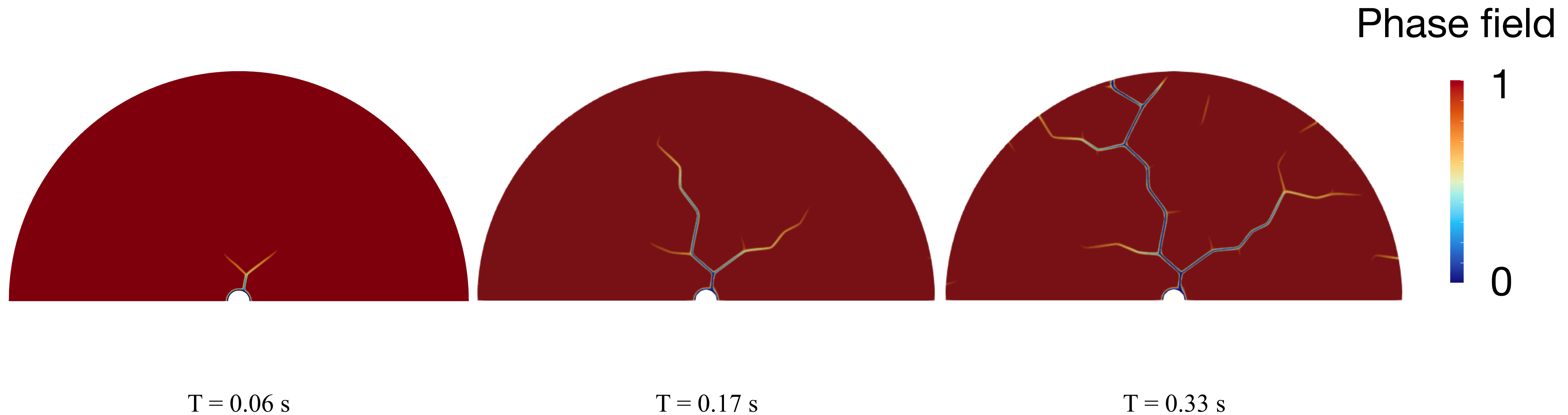
Material parameters

- Condition: 50°C, 10MPa

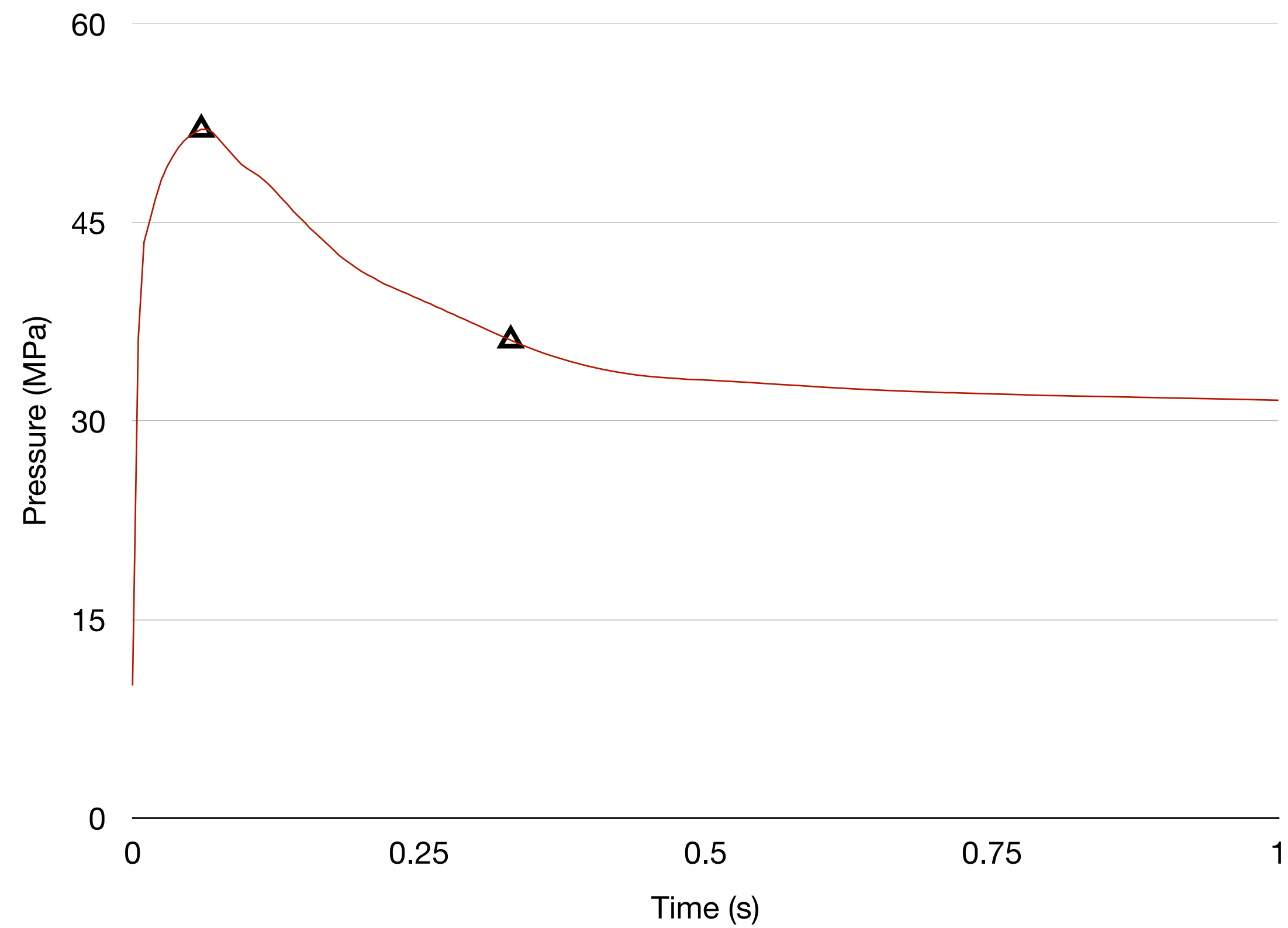
	Water	sCO2
Compressibility (Pa⁻¹)	4.4E-10	3.1E-04
Viscosity (Pa·s)	1.0E-3	2.8E-05
Density (kg/m³)	1.0E3	3.8E2

Water injection

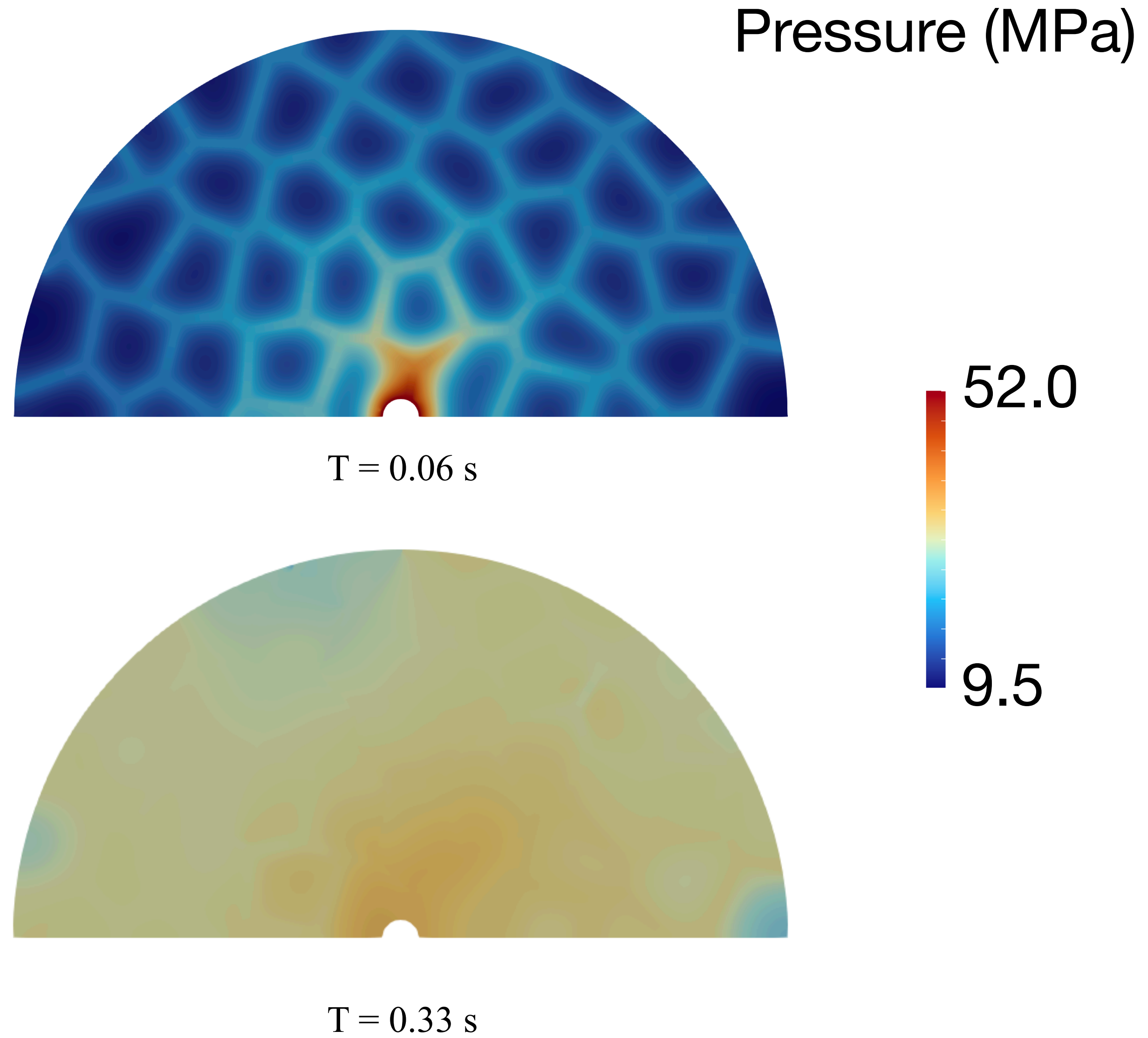
- Fractures initiate at the borehole and propagate along the interface.



Water injection

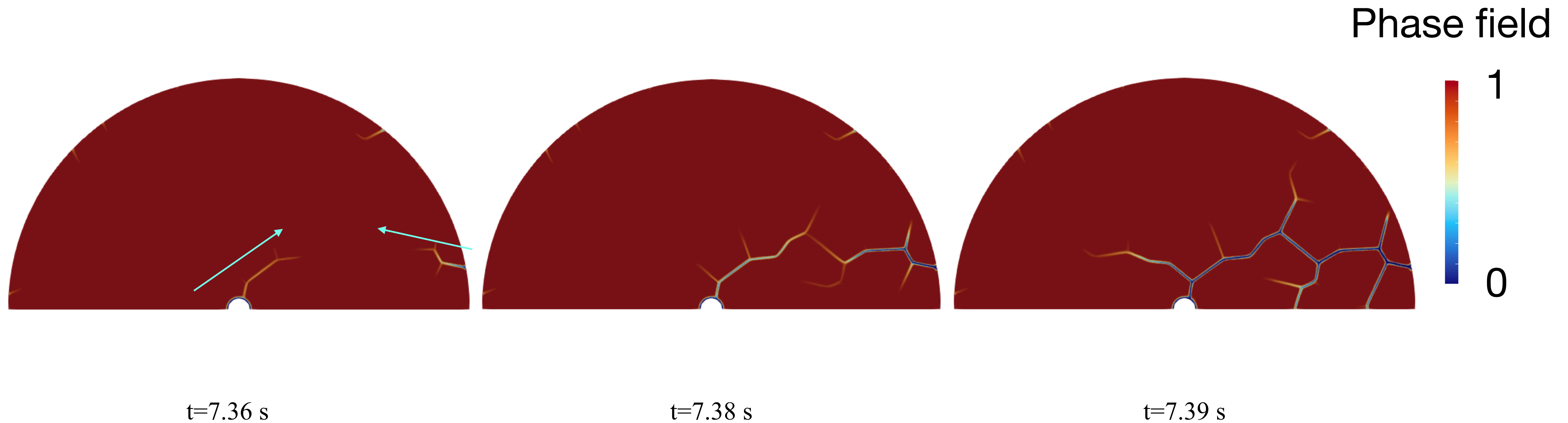


Injection pressure over time

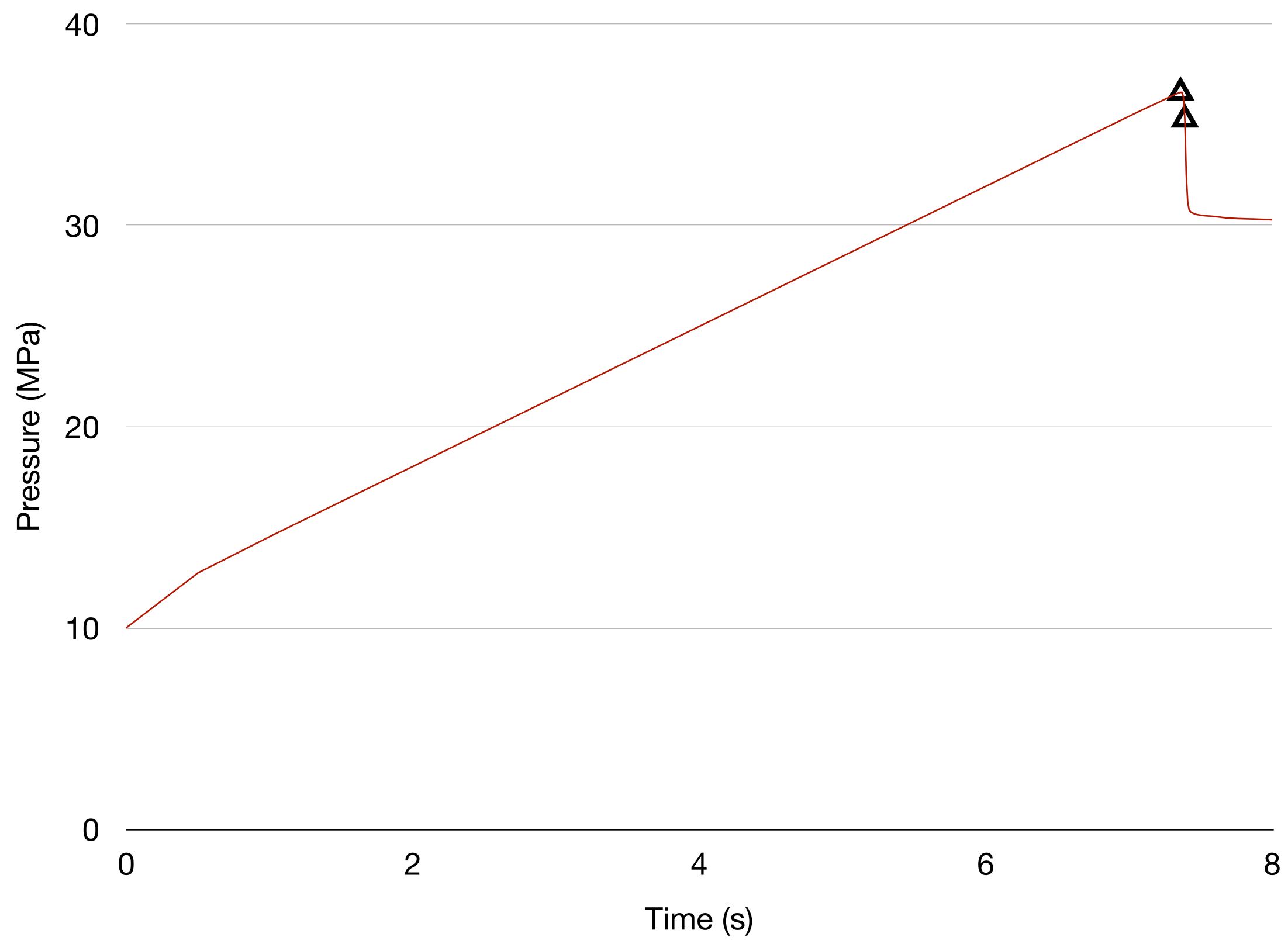


sCO₂ injection

- Initiate at the borehole and remote
- Propagate along the interface

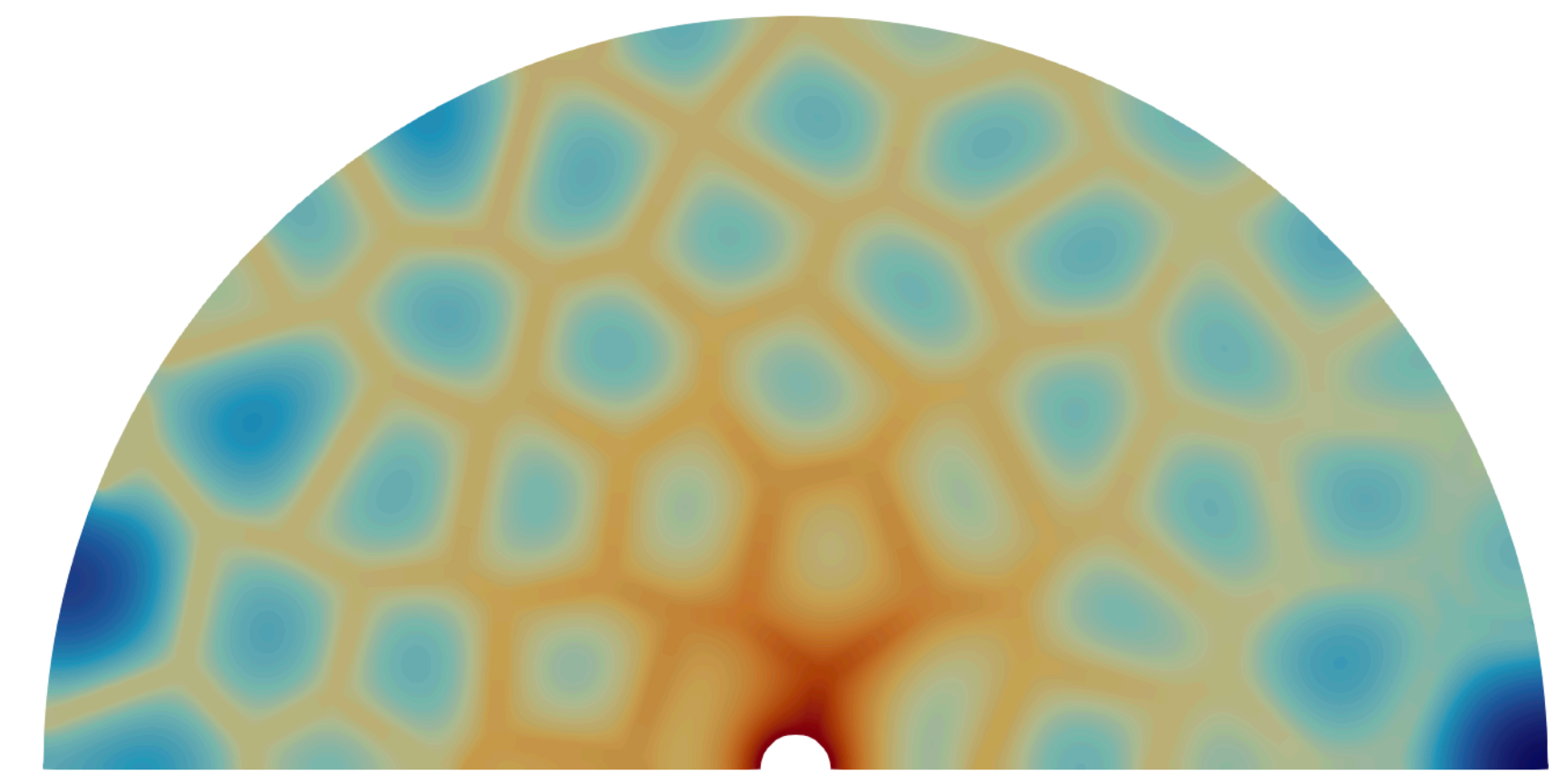


sCO₂ injection

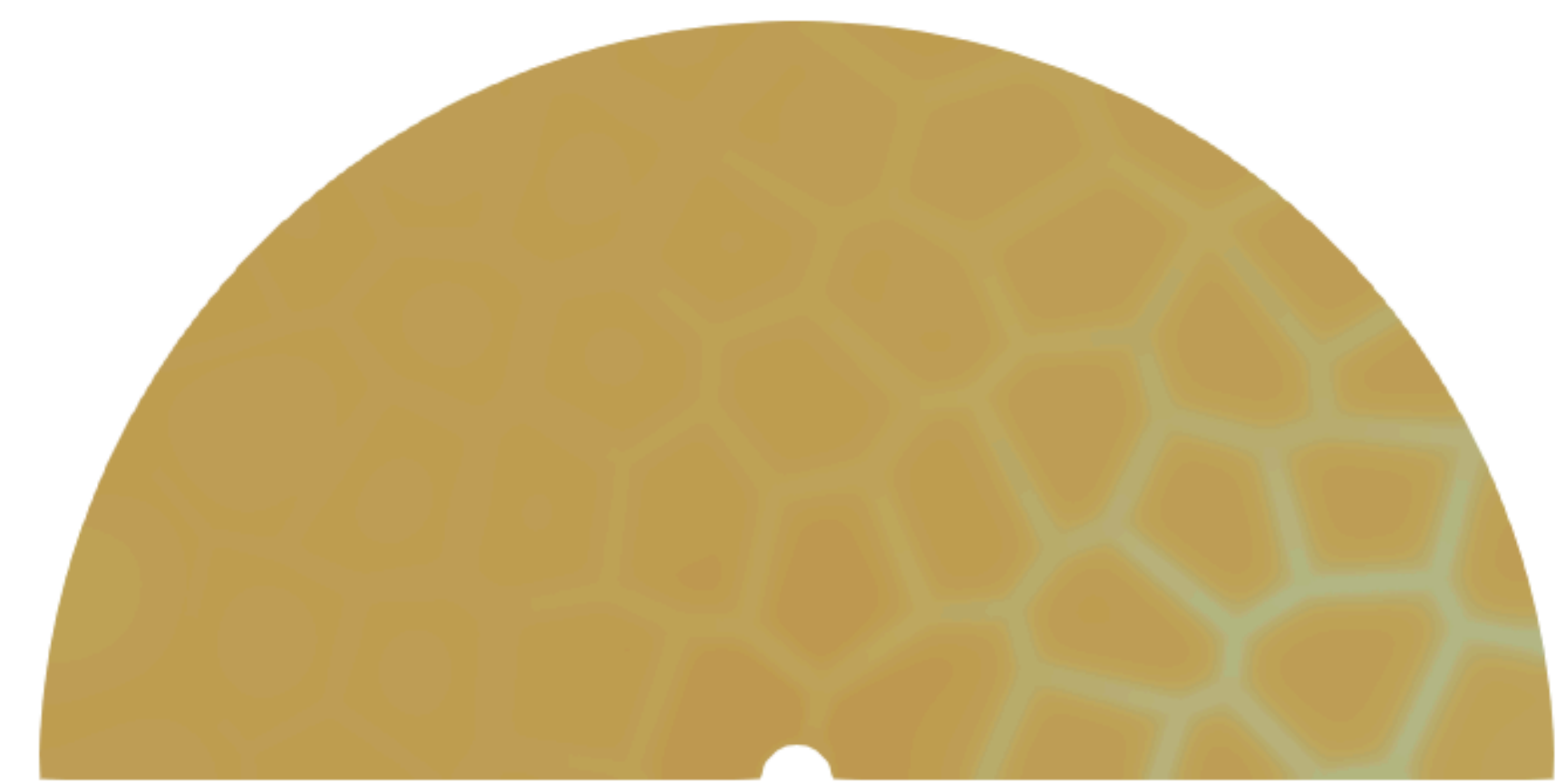


Injection pressure over time

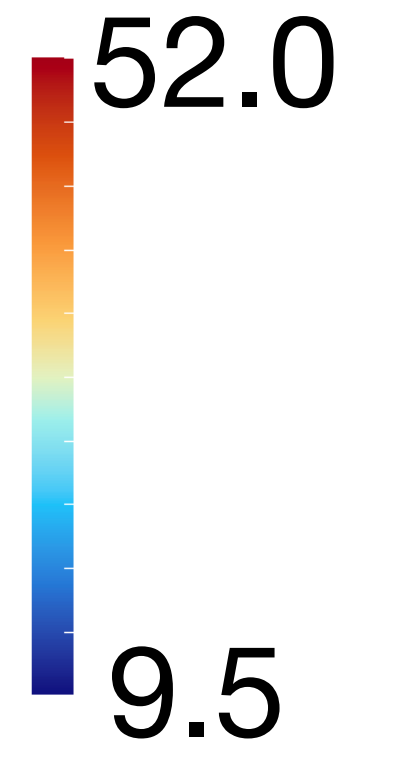
Pressure (MPa)



T = 7.36 s



T = 7.39 s



Future work

- Change the crystalline topology. No interface intersects with the borehole.
- Consider the random distribution of interface property.
- Adopt more proper parameters.