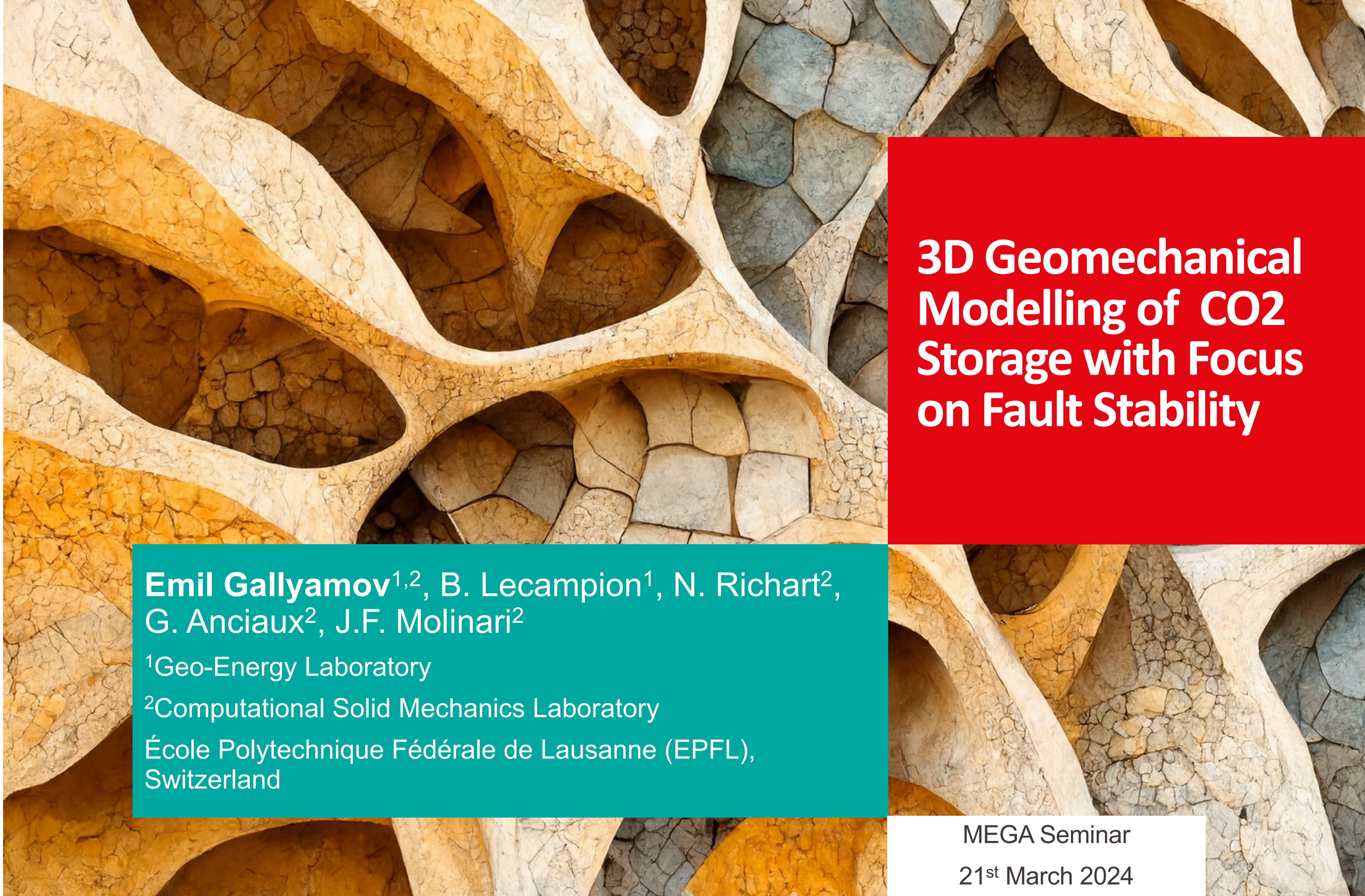
EPFL



3D Geomechanical Modelling of CO2 Storage with Focus on Fault Stability

Emil Gallyamov[1,2], B. Lecampion[1], N. Richart[2], G. Anciaux[2], J.F. Molinari[2]

[1]Geo-Energy Laboratory

[2]Computational Solid Mechanics Laboratory

École Polytechnique Fédérale de Lausanne (EPFL), Switzerland

MEGA Seminar

21st March 2024

École polytechnique fédérale de Lausanne

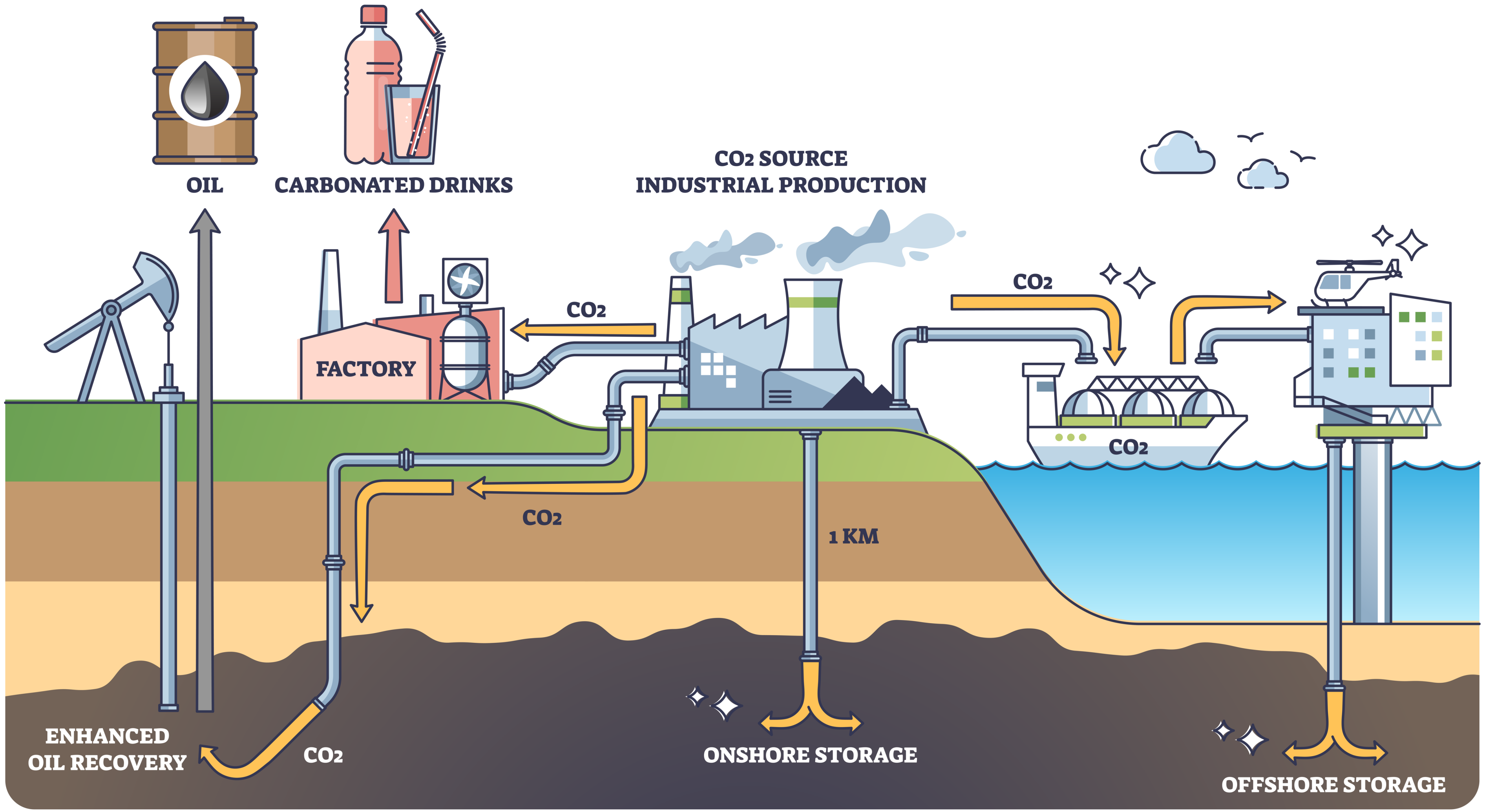
Team

Prof. Brice Lecampion
Geo-Energy Lab,
Gaznat Chair on Geo-energy,
EPFL

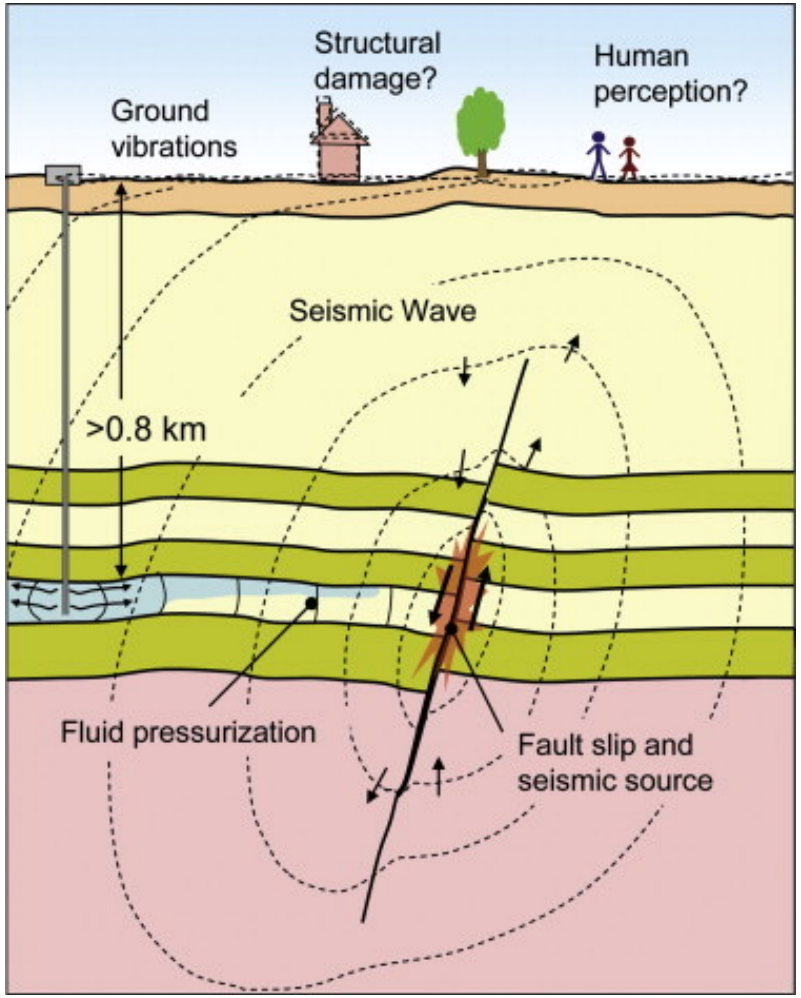
Prof. Jean-François Molinari,
Computational Solid Mechanics Laboratory,
EPFL

Dr. Nicolas Richart
HPC Application Expert / Scientist,
Computational Solid Mechanics Laboratory,
EPFL

Dr. Guillaume Anciaux
Research Associate,
Computational Solid Mechanics Laboratory,
EPFL


OIL
CARBONATED DRINKS
CO2 SOURCE
INDUSTRIAL PRODUCTION
CO2
FACTORY
CO2
CO2
CO2
1 KM
CO2
ENHANCED
OIL RECOVERY
CO2
ONSHORE STORAGE
OFFSHORE STORAGE

Environmental risks: Surface Uplift / Subsidence & Induced Seismicity

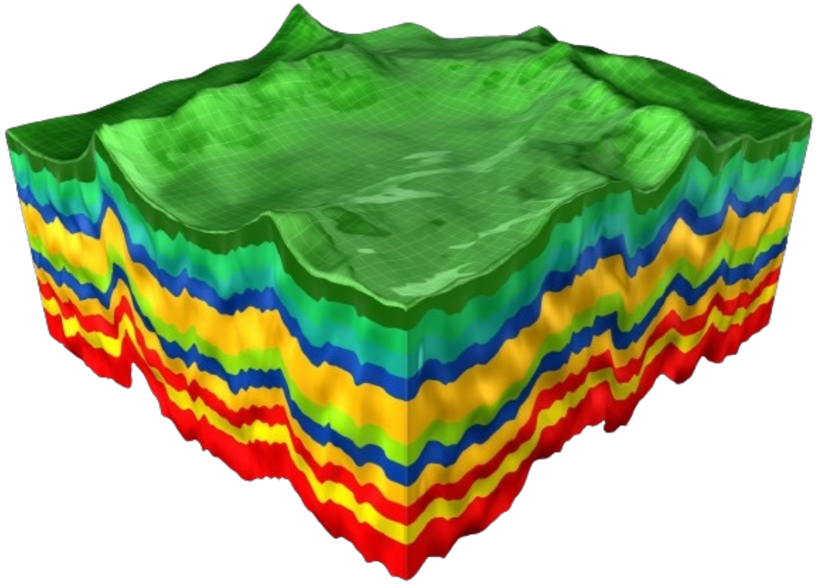


From [Rutqvist et al, 2014]

Emil Gallyamov

Project goals

- Geomechanical evaluation of a potential CO_2 storage sites
- Risks of fault activation and hydraulic fracturing
- Uplift and subsidence



Methodology

- 3D Geomechanical simulator
- Fluid flow in the rock and along faults
- Deformations of the rock
- Opening and shearing of cracks and faults

Parallel open-source FE library Akantu www.akantu.ch, gitlab.com/akantu

Current assumptions:

- Single phase fluid flow
- Constant bulk and fault permeabilities
- Constant friction coefficient along faults

Governing equations for the rock (3D)

- Balance of momentum $$\nabla \cdot \boldsymbol{\sigma}(u,p) + \mathbf{f} = 0$$
- Fluid mass conservation $$\frac{\partial \zeta(u,p)}{\partial t} + \nabla \cdot \mathbf{q}(u,p) = \gamma$$
- Constitutive equations (w.r.t. initial state)
  - Stress state $$\boldsymbol{\sigma} = \mathbb{C}\boldsymbol{\varepsilon}(u) + \boldsymbol{\alpha} p$$
  - Variation in fluid content $$\zeta = \boldsymbol{\alpha} : \boldsymbol{\varepsilon}(u) + \frac{1}{M} p$$
  - Darcy flow $$\boldsymbol{q} = -\boldsymbol{\kappa}(u,p)\nabla p$$
- System to solve after implicit time integration

$$\begin{bmatrix} \mathbb{K} & \mathbb{A}_{p\to u} \\ \mathbb{A}_{u\to p}/\Delta t & \mathbb{S}/\Delta t + \mathbb{C} \end{bmatrix} \begin{bmatrix} \partial u \\ \partial p \end{bmatrix} = \begin{bmatrix} f_{n+1} - \mathbb{K}u_n - \mathbb{A}_{p\to u} p_n \\ \gamma_{n+1} - \mathbb{C} p_n \end{bmatrix}$$

Emil Gallyamov

Governing equations for faults and cracks (2D)

- Continuity of tractions $$\boldsymbol{\sigma}'(u,p)\boldsymbol{n} = -\boldsymbol{t}$$
- Lubrication flow $$\frac{\partial w}{\partial t} + wS_f\frac{\partial p_f}{\partial t} + \boldsymbol{\nabla}_{\parallel}\cdot(w\boldsymbol{q}_{\parallel}) + q_-^{\perp} + q_+^{\perp} = \gamma_f$$
- Constitutive equations
  - Traction $$\boldsymbol{t} = \begin{cases} 0 & \text{if } \delta_n > 0 \\ \mathcal{N}(\boldsymbol{\delta}) & \text{if } \delta_n \leq 0 \end{cases}$$
  - Coulomb friction $$||\boldsymbol{\tau}|| \leq f\boldsymbol{\sigma}_n'$$
  - Darcy flow $$\boldsymbol{q}_{\parallel} = -\frac{\boldsymbol{k}_f}{\mu}\nabla_{\parallel}p_f$$

EPFL

Discretisations

- 1st order FEs for flow and deformations
- Cohesive elements for cracks & faults [Camacho & Ortiz, 1996]
- Flow in a crack is averaged along width
- 2-node interface flow formulation after [Segura & Carol, 2004]
- Longitudinal flow

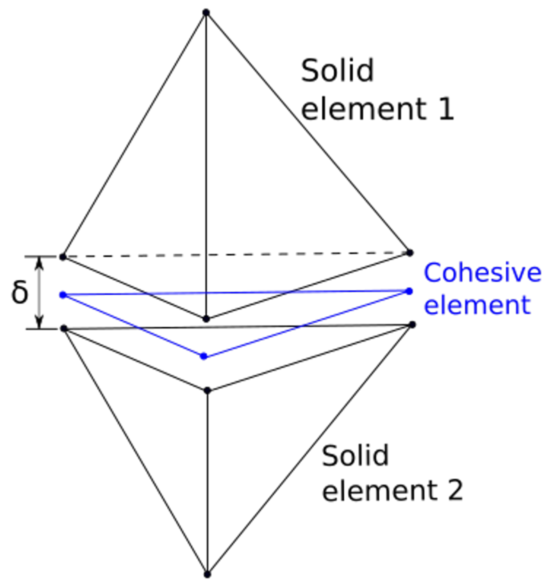
$$\boldsymbol{Q}_{Lmp} = \frac{1}{2}\boldsymbol{K}_{Lmp} \cdot [\mathbb{I}; \mathbb{I}] \cdot \boldsymbol{p}$$

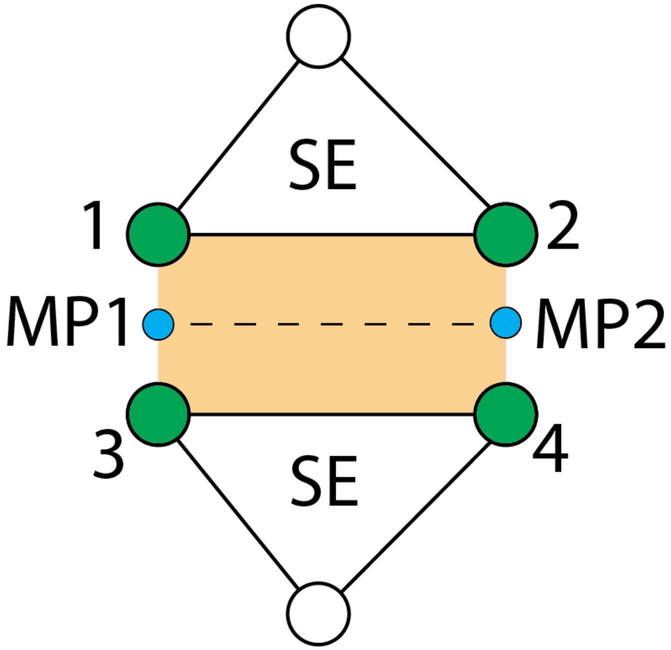
$$\boldsymbol{K}_{Lmp} = \iint_S \hat{k}_l \boldsymbol{B} \cdot \boldsymbol{B}^T dsdt$$

- Transversal flow

$$\boldsymbol{Q}_{Tmp} = \boldsymbol{K}_{Tmp} \cdot [\mathbb{I}; -\mathbb{I}] \cdot \boldsymbol{p}$$

$$\boldsymbol{K}_{Tmp} = \iint_S k_t \boldsymbol{N} \cdot \boldsymbol{N}^T dsdt$$



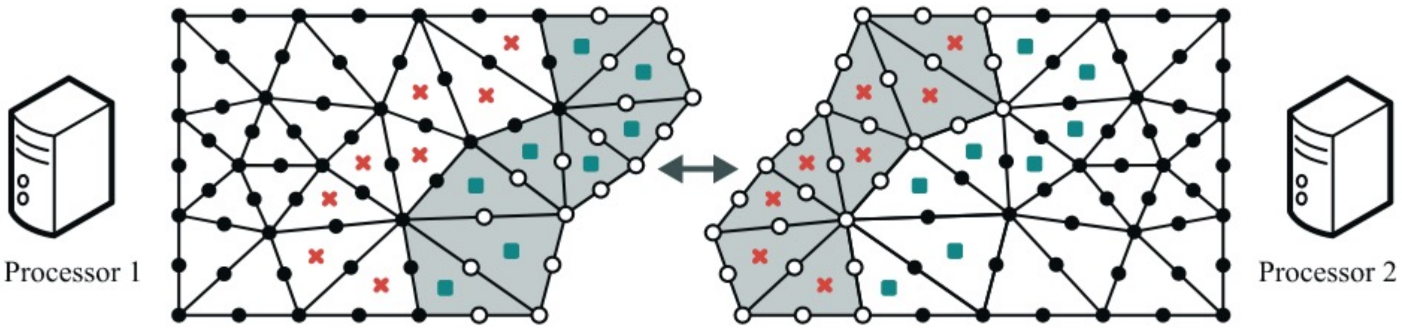


Emil Gallyamov

Solution scheme and numerical details

$$\begin{bmatrix} \mathbb{K} & \mathbb{A}_{p\to u} \\ \mathbb{A}_{u\to p}/\Delta t & \mathbb{S}/\Delta t + \mathbb{C} \end{bmatrix} \begin{bmatrix} \partial u \\ \partial p \end{bmatrix} = \begin{bmatrix} \boldsymbol{f}_{n+1} - \mathbb{K}\mathbf{u}_n - \mathbb{A}_{p\to u} p_n \\ \gamma_{n+1} - \mathbb{C} p_n \end{bmatrix}$$

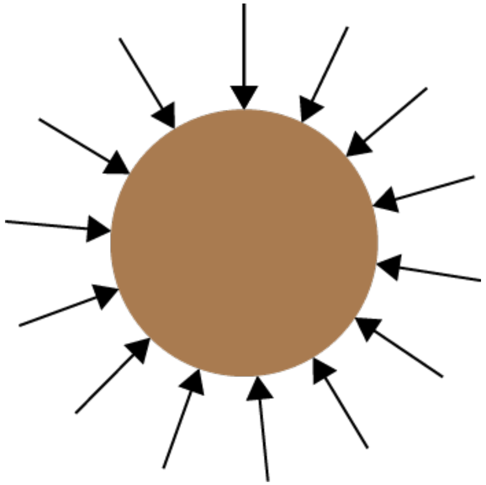
- Solution of nonlinear system by Newton Raphson
- Monolithic solve of Jacobian system by iterative partitioned conjugate gradient [Prevost, 1997]
- Parallel direct solver of linear subsystem (MUMPS)
- MPI parallelization & synchronization at the quadrature points

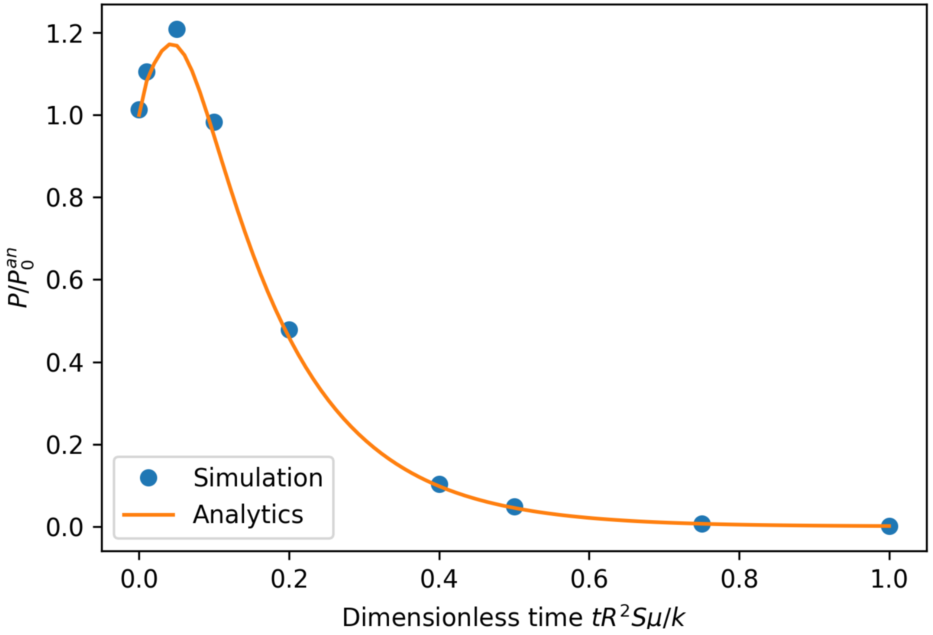


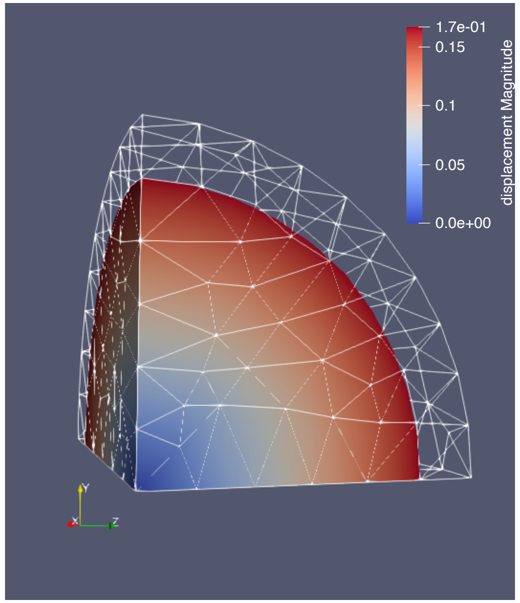
From [Vocialta & Molinari, IJNME 2017]

Benchmark
Poroelasticity

- Compression of saturated porous sphere [Cryer, 1963]
- Initial uniform pressure rise p^0
- Non-monotonic pressure diffusion – Mandel-Cryer effect
- Caused by stresses redistribution upon drainage

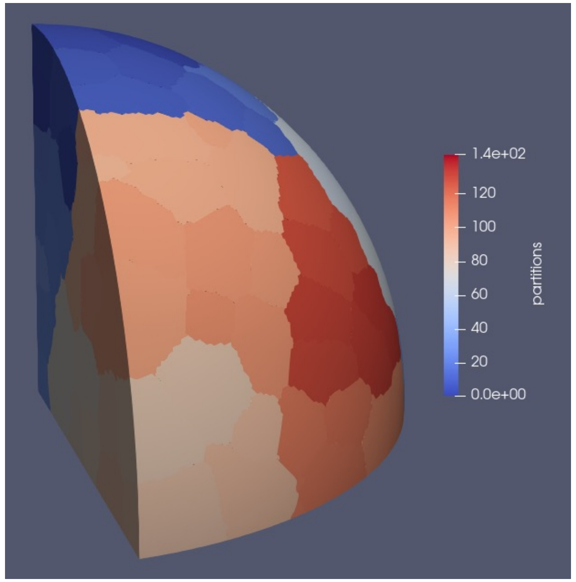


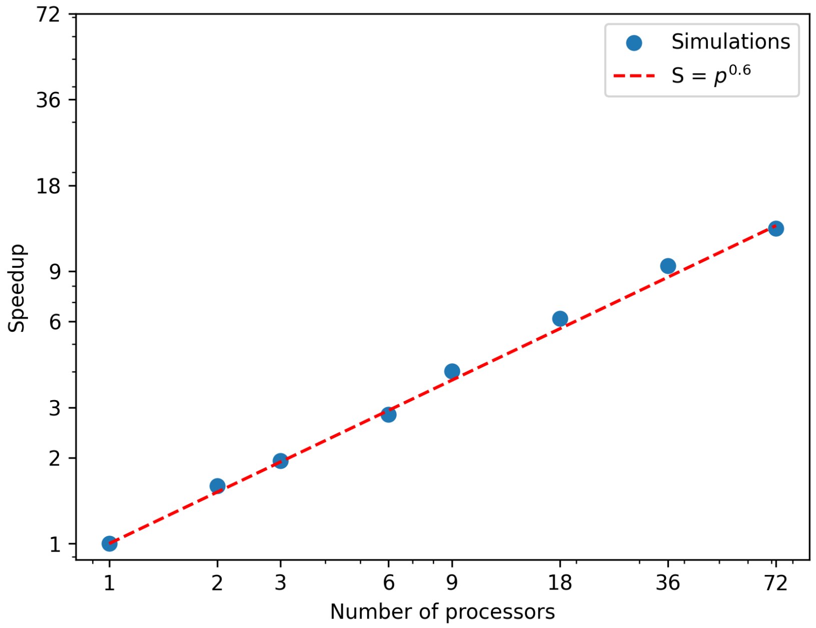




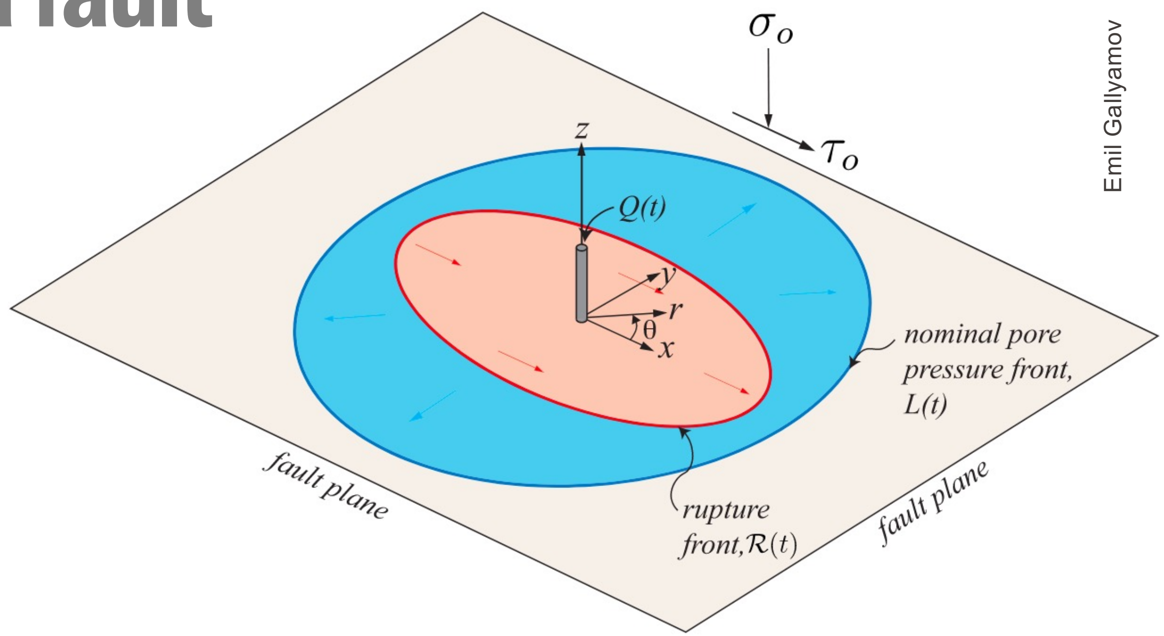
Strong scaling

- Scaling testing on a Cryer sphere with 1,200,000 DOFs
- From 1 up to 72 cores
- Intel Xeon nodes with 2 sockets of 36 cores, 512 Gb RAM and dual 25 Gb Ethernet links
- Speedup $S = T_1/T_p$
- Code scales with exponent of 0.6 (1 for perfect scaling)





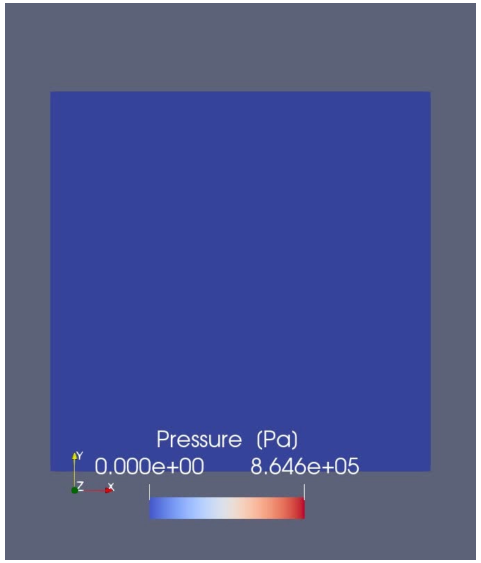
Benchmark | Injection into a fault

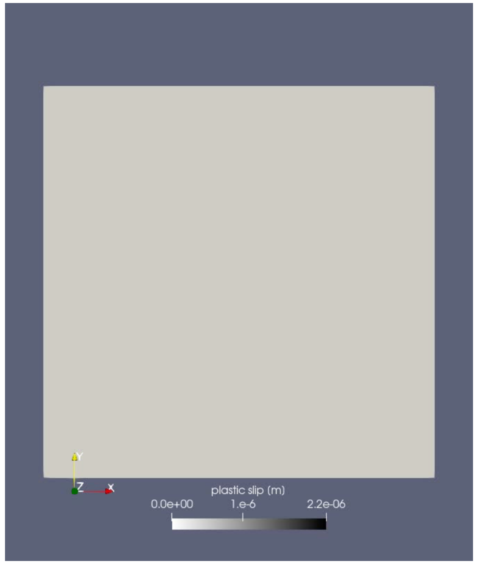


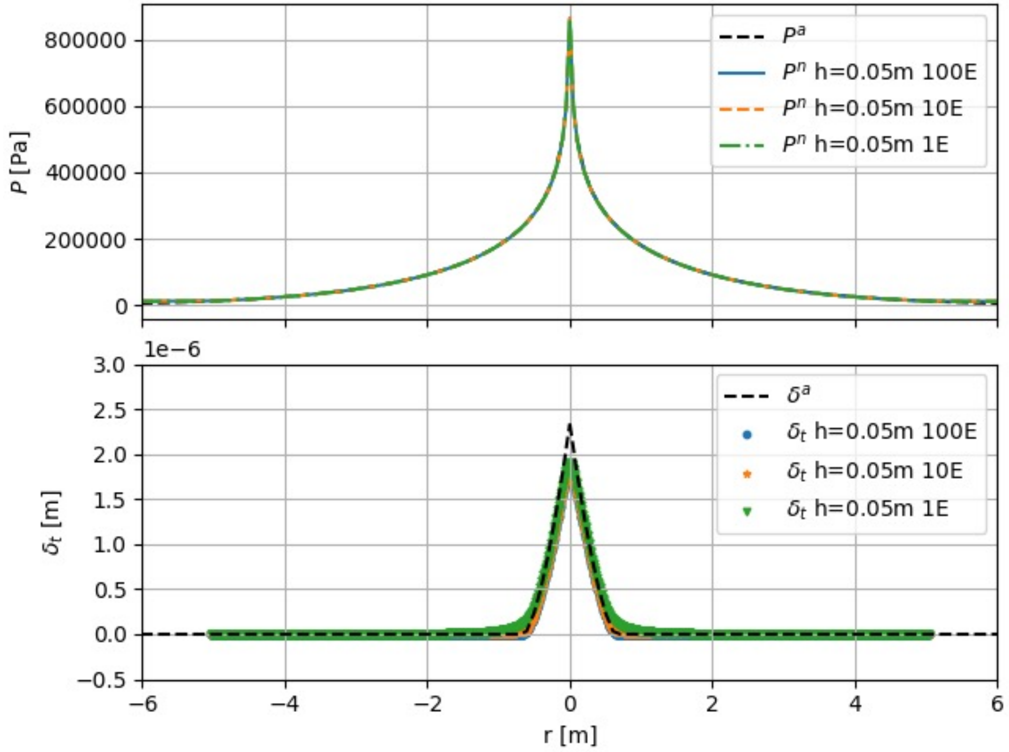
From [Saez et al., JMPS 2022]

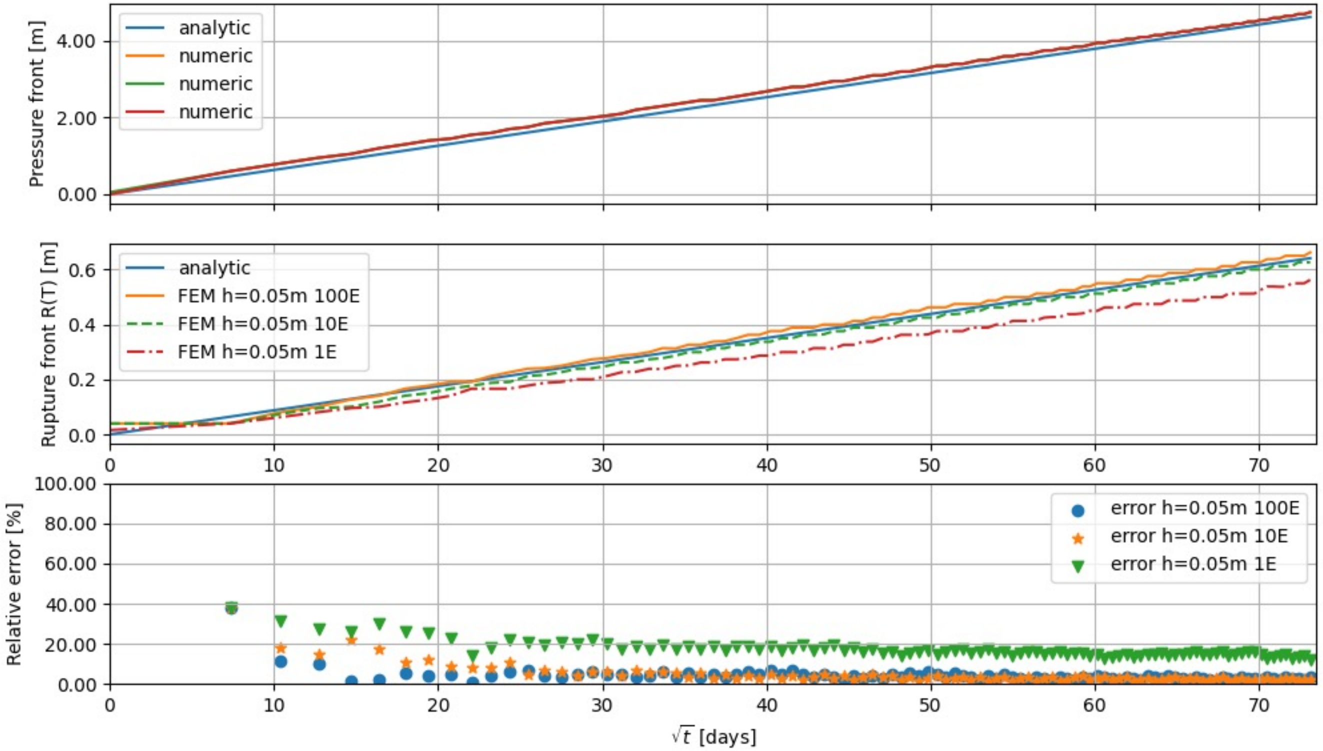
- Friction along a fault
- Point injection into a planar fault
- Fault is under normal and shear stress
- Coulomb friction along the fault
- Pressure diffusion causes evolution of the rupture front
- Stable (aseismic) rupture propagation
- Analytical solution in [Saez et al., JMPS 2022]

Injection into a fault



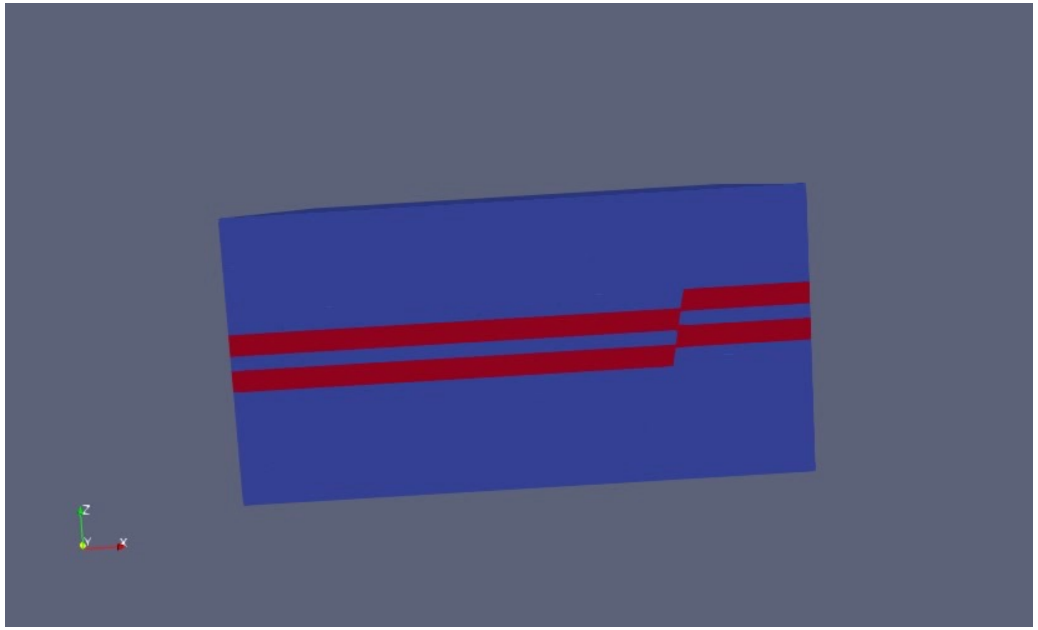


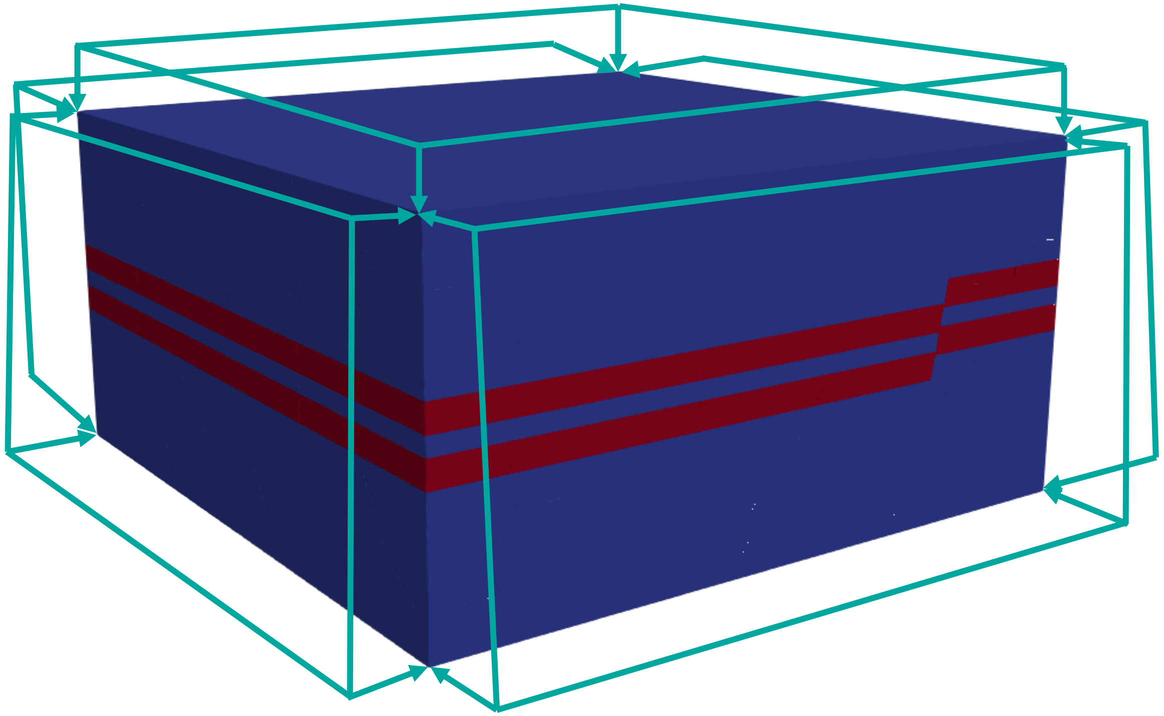




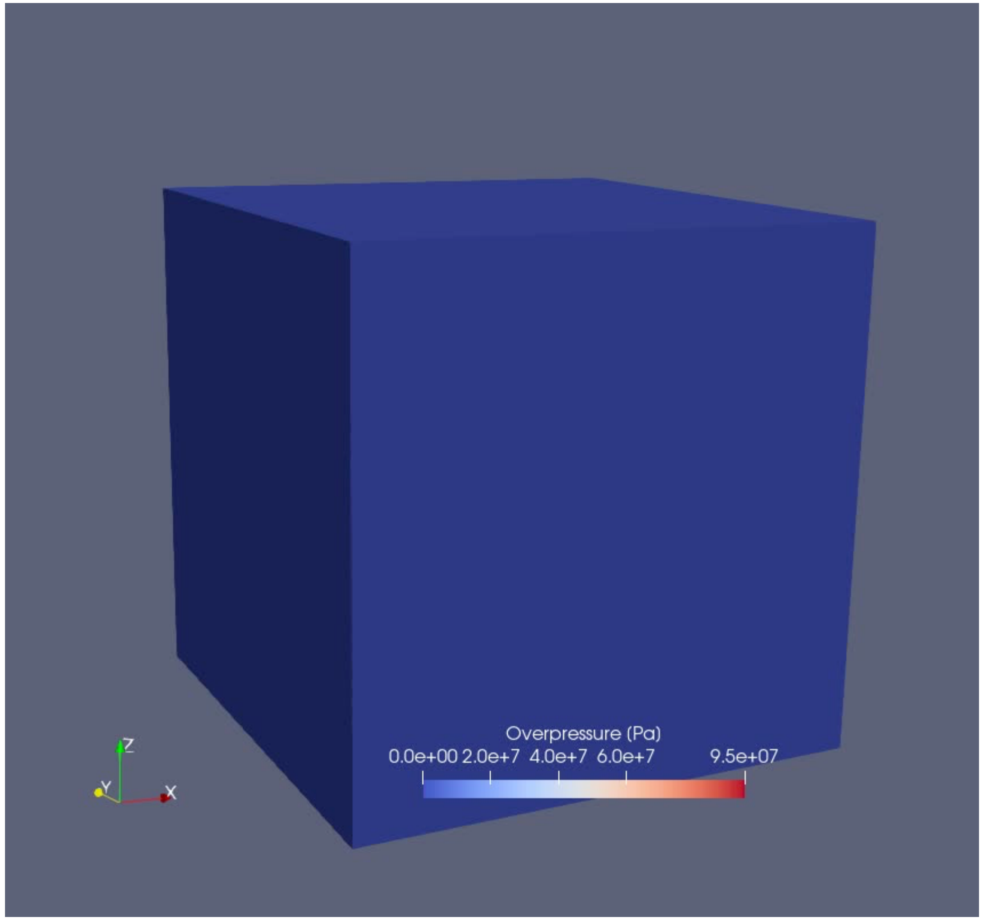
Emil Gallyamov

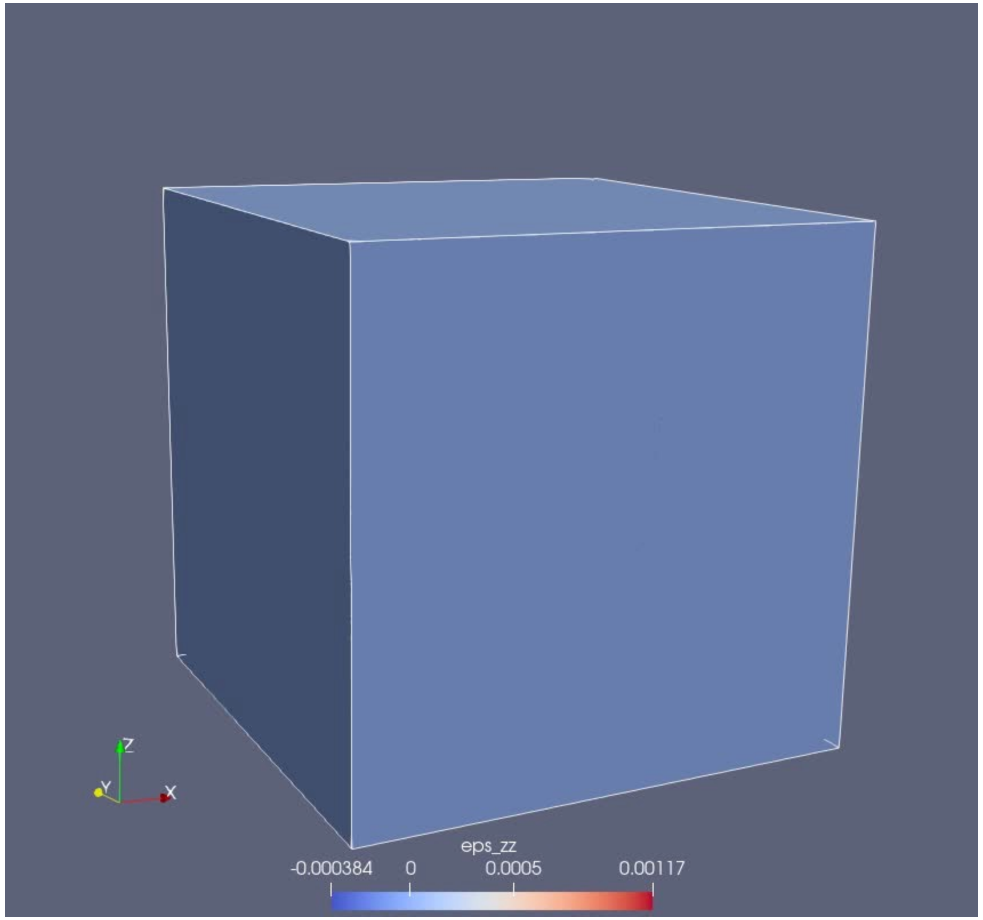
Application | Injection into a faulted aquifer





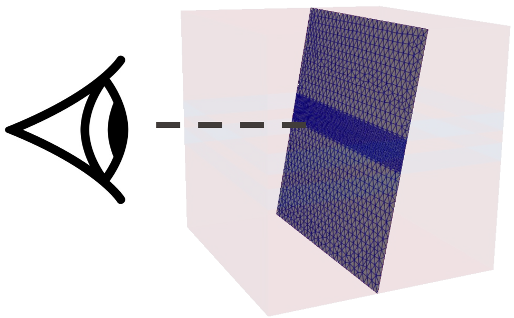
Overpressure and deformations

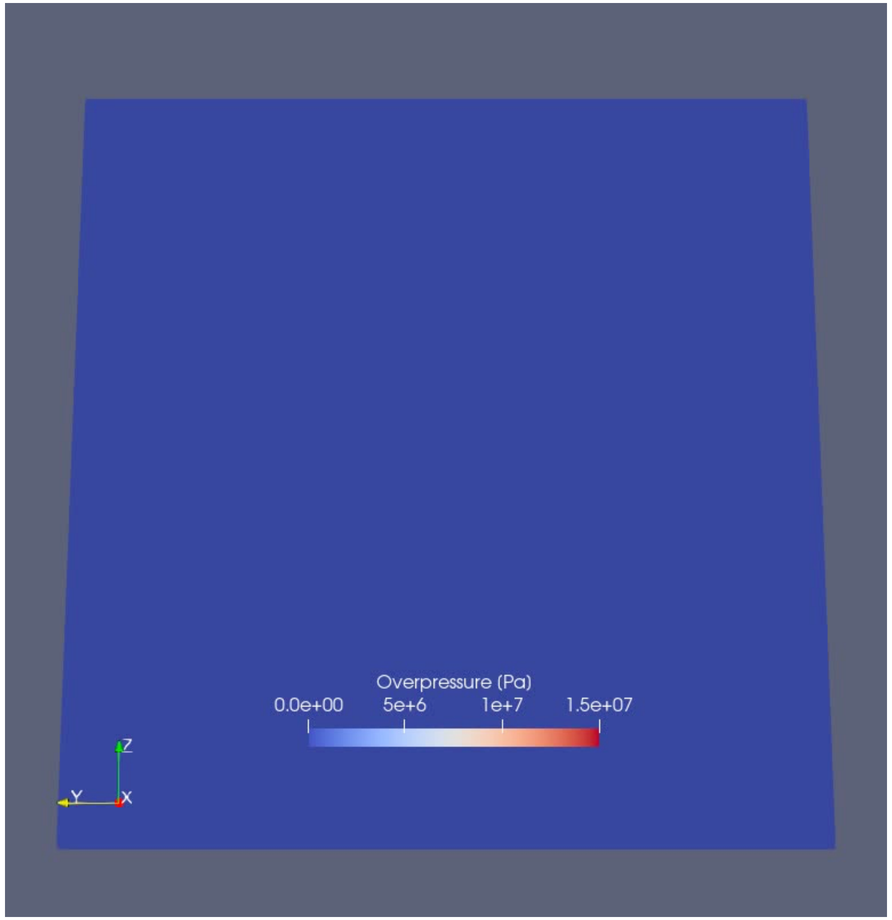


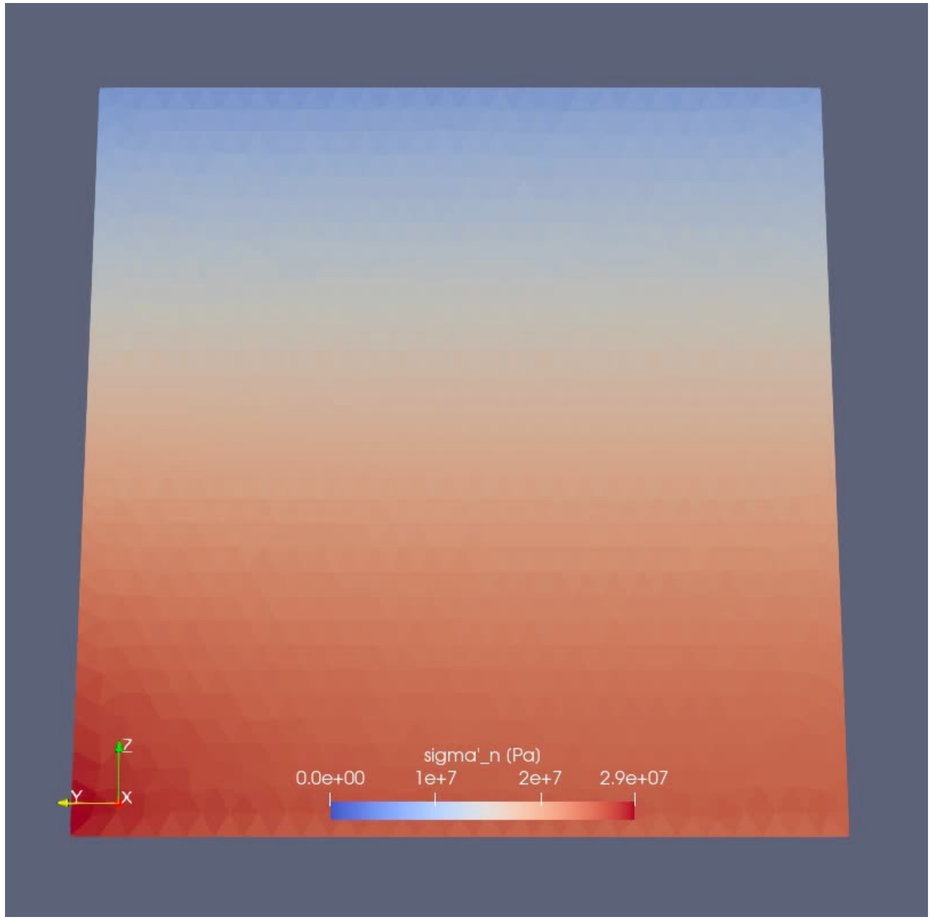


Fault overpressure and stresses

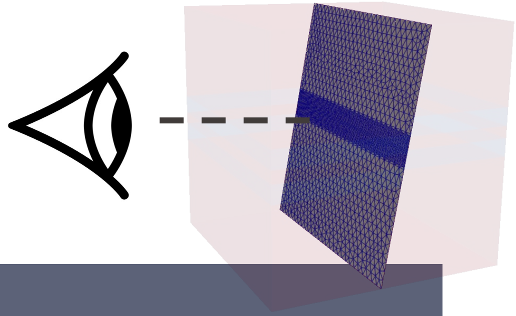
Emil Gallyamov

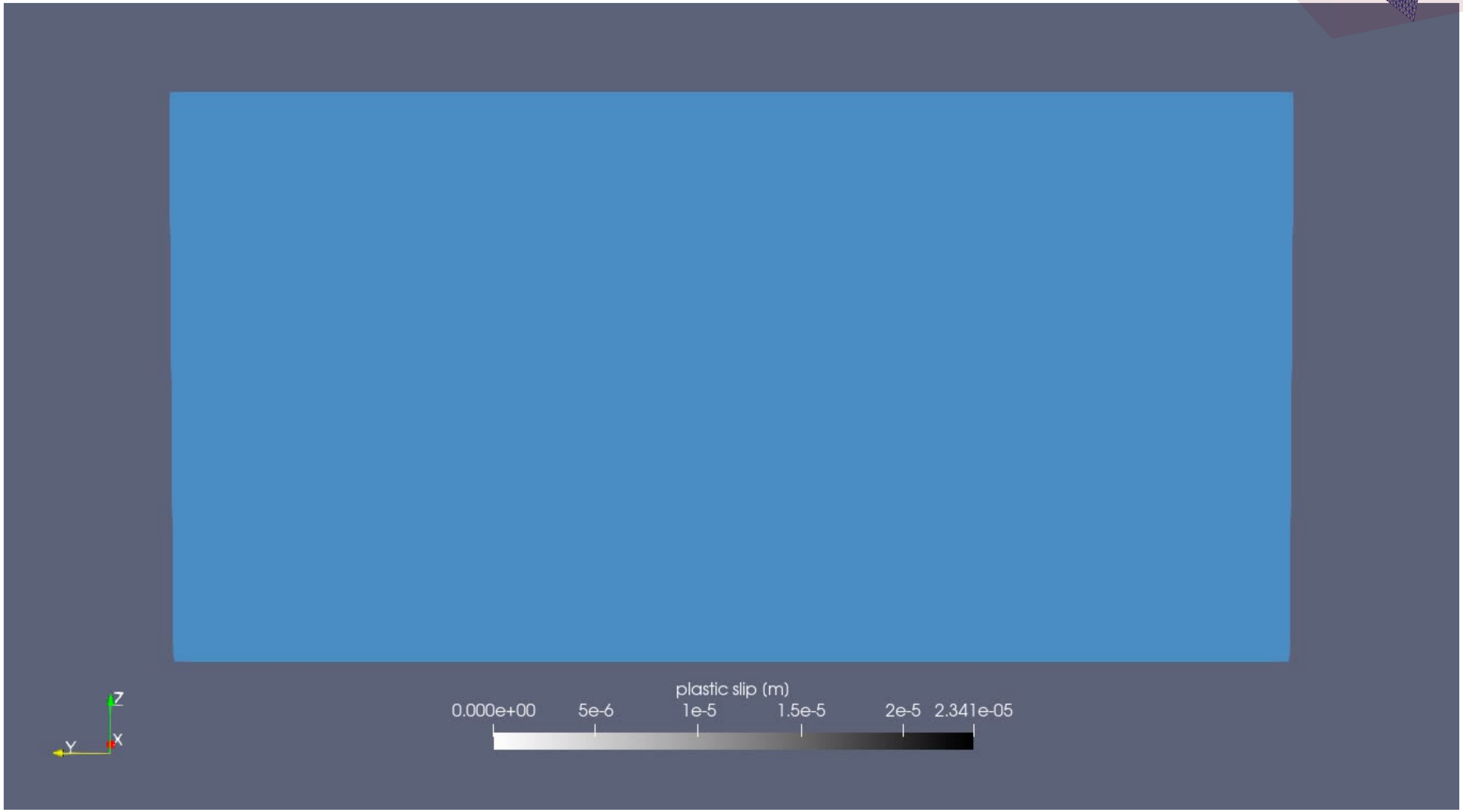




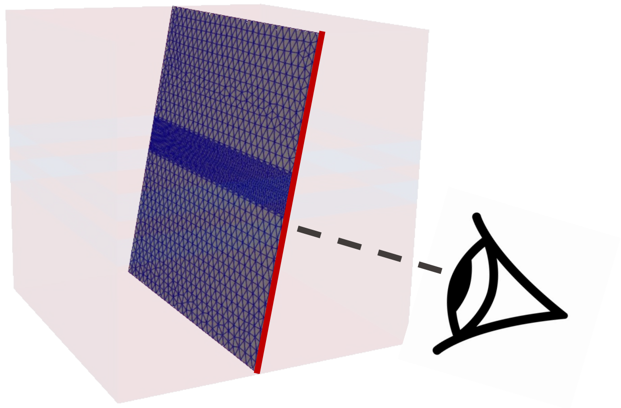


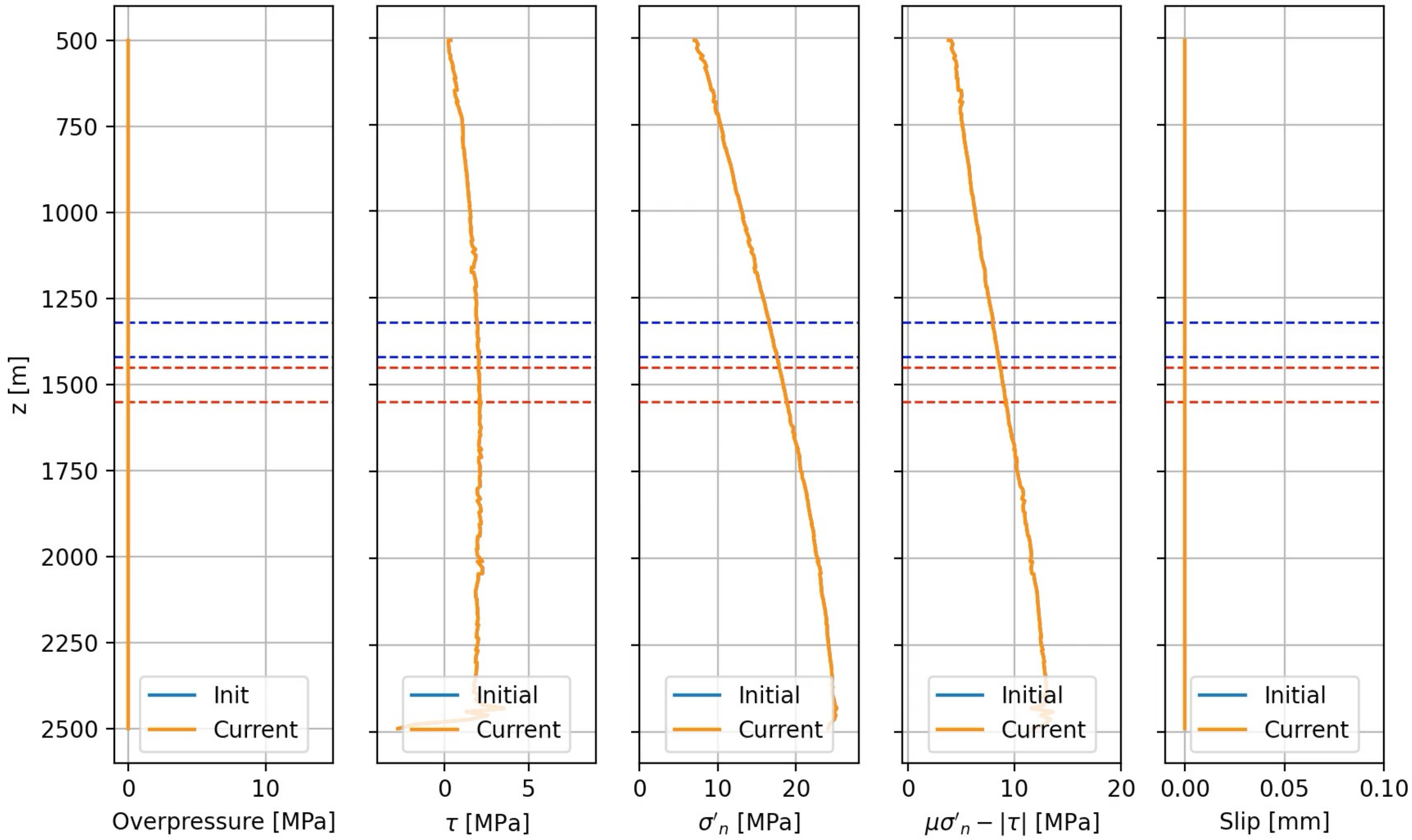
Slip



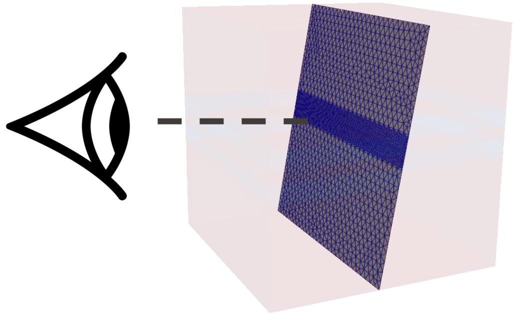


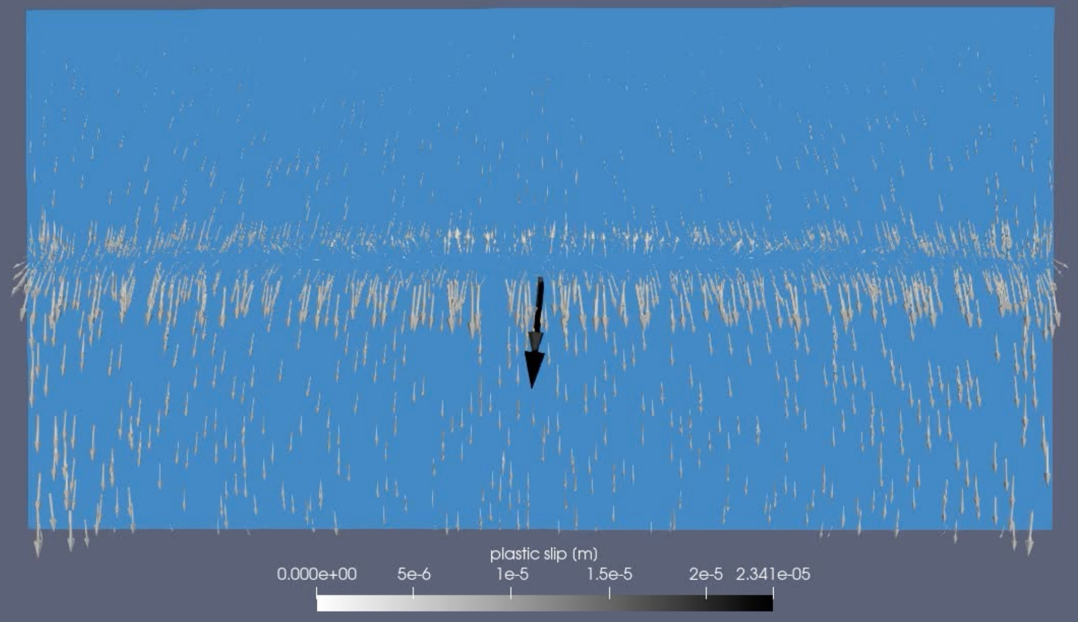
Quantitative evaluation

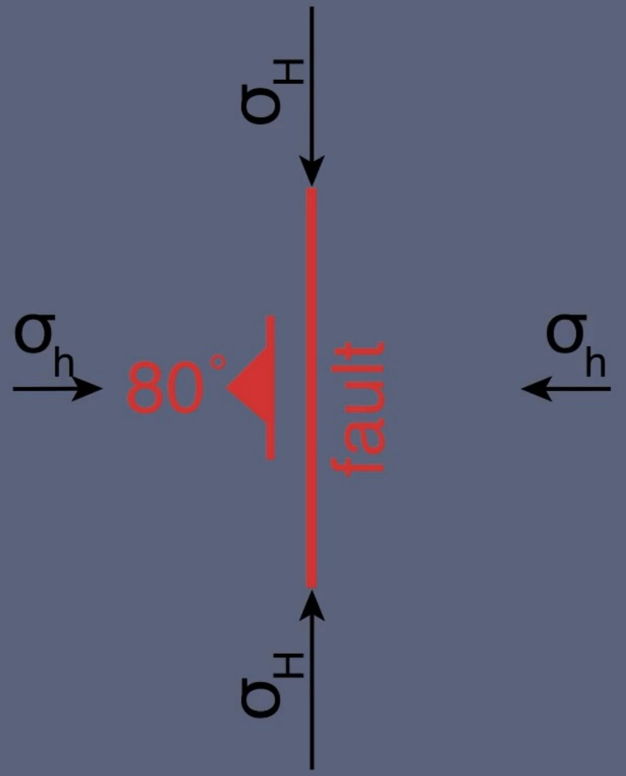




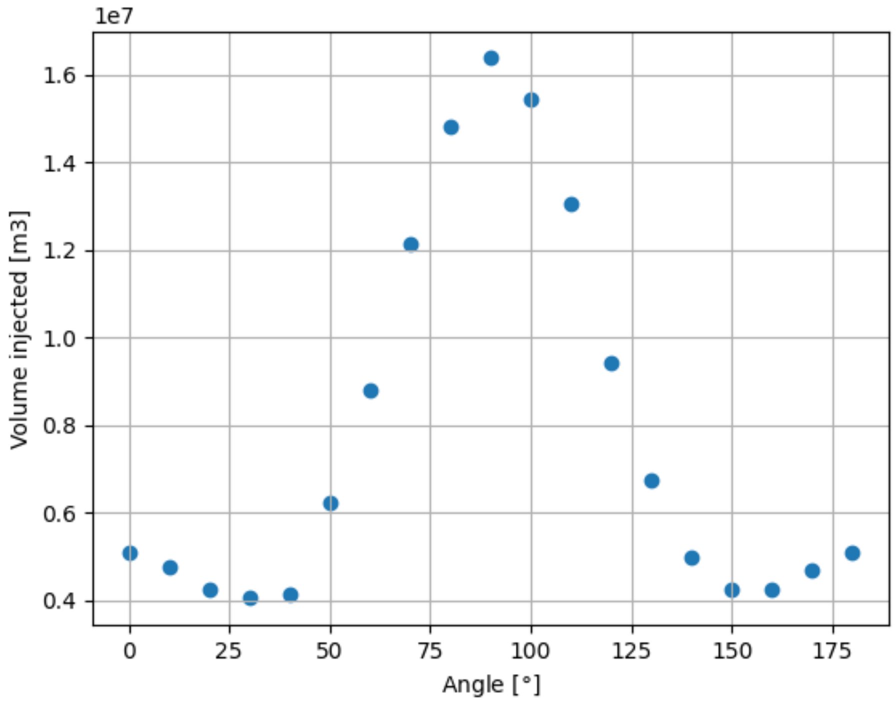
Slip vs stress orientation

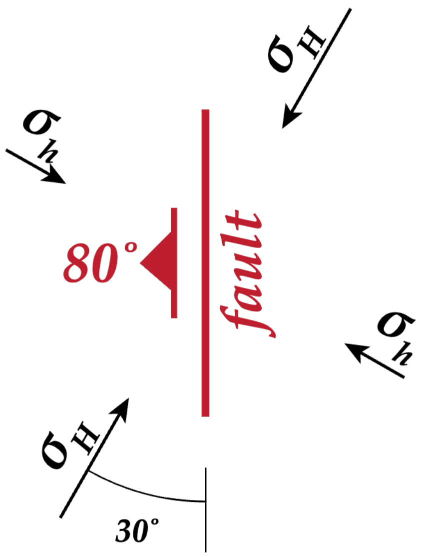


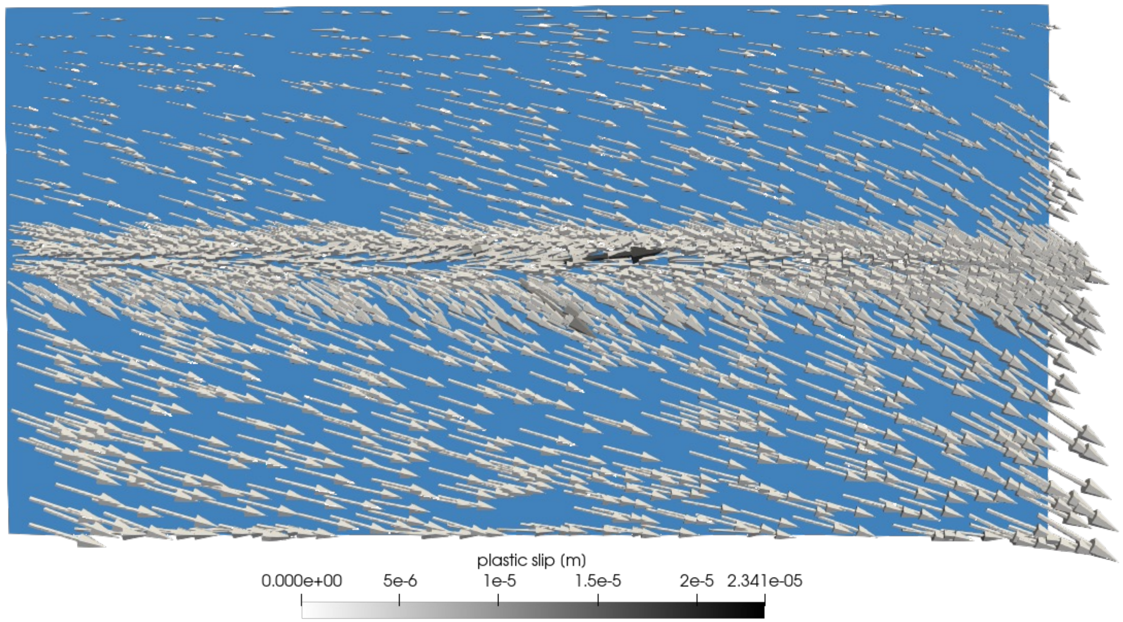




Critical stress orientations







Summary

- Fully-coupled geomechanical simulator was developed
- MPI parallelization allows to solve large geological models
- Helps to evaluate fault slip initiation, aseismic slip, poroelastic effects
- Benchmarked against multiple analytical solutions for flow, solid mechanics, friction and hydro-shearing
- Capacities were demonstrated in the injection into a faulted aquifer scenario

Outlook:

- Investigating the effect of poroelasticity on aseismic slip
- Adding opening-dependent fault permeability
- Coupling with a multi-phase reservoir simulator
- Adding thermal effects into the model

EPFL

Reference works

- Richart, N., & Molinari, J. F. (2015). Implementation of a parallel finite-element library: Test case on a non-local continuum damage model. *Finite Elements in Analysis and Design*, *100*, 41–46.
- Camacho, G. T., & Ortiz, M. (1996). Computational modelling of impact damage in brittle materials. *International Journal of Solids and Structures*, *33*(20–22), 2899–2938.
- Segura, J. M., & Carol, I. (2004). On zero-thickness interface elements for diffusion problems. *International Journal for Numerical and Analytical Methods in Geomechanics*, *28*(9), 947–962.
- Prevost, J. H. (1997). Partitioned solution procedure for simultaneous integration of coupled-field problems. *Communications in Numerical Methods in Engineering*, *13*(4), 239–247.
- Vocialta, M., & Molinari, J.-F. (2015). Influence of internal impacts between fragments in dynamic brittle tensile fragmentation. *International Journal of Solids and Structures*, *58*, 247–256.
- Sáez, A., Lecampion, B., Bhattacharya, P., & Viesca, R. C. (2022). Three-dimensional fluid-driven stable frictional ruptures. *Journal of the Mechanics and Physics of Solids*, *160*, 104754.
- Jha, B., & Juanes, R. (2014). Coupled multiphase flow and poromechanics: A computational model of pore pressure effects on fault slip and earthquake triggering. *Water Resources Research*, *50*(5), 3776–3808.
- Rutqvist, J., Cappa, F., Rinaldi, A., Godano, M. (2014). Modeling of induced seismicity and ground vibrations associated with geologic CO2 storage, and assessing their effects on surface structures and human perception. *International Journal of Greenhouse Gas Control, 24, 64-77.*