Earth Beat

A Multi-Scale Approach to Fault-Valve Systems and Their Evolution

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Full abstract

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EGU26 GENERAL ASSEMBLY

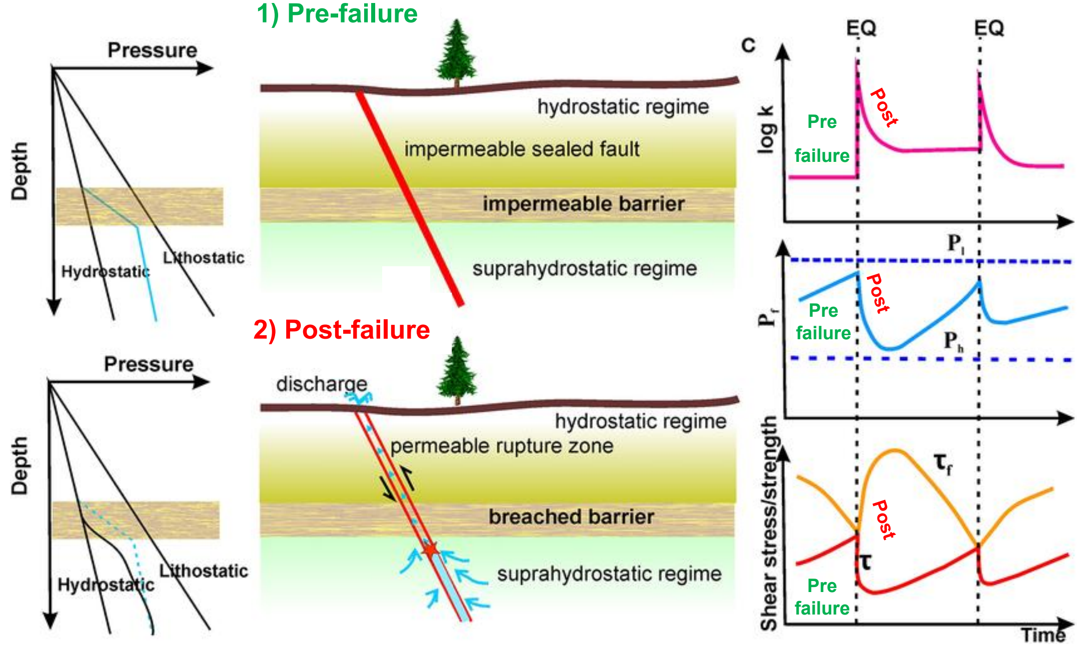
Sharing not permitted

Introduction

Faults act alternately as hydraulic barriers or conduits, reflecting the **Fault-Valve Behavior**

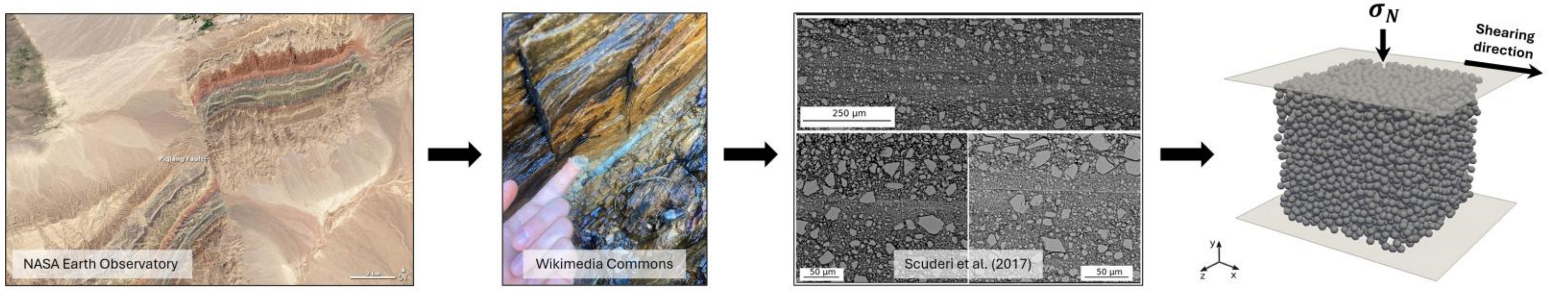
A key process in hydrothermal systems and industrial activities

Challenge : Fault reactivation involves complex permeability – strength coupling not fully captured by continuum models (Marguin & Simpson 2024, Zhu et al 2020)



Fault Valve Schematics, **Sibson (2020)**

Proposed approach : Grain scale modeling using the **Discrete Element Method (DEM)**, to bridge micro and macro-scale behaviors

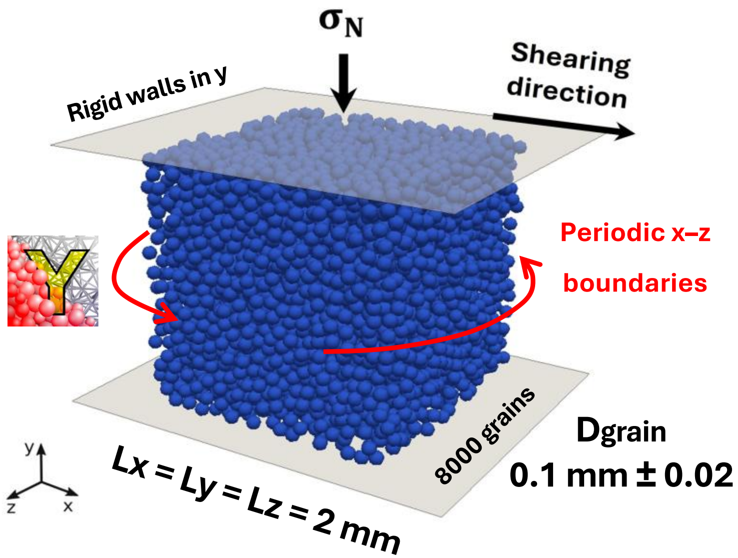


Macroscale · Mesoscale · Microscale · DEM Model

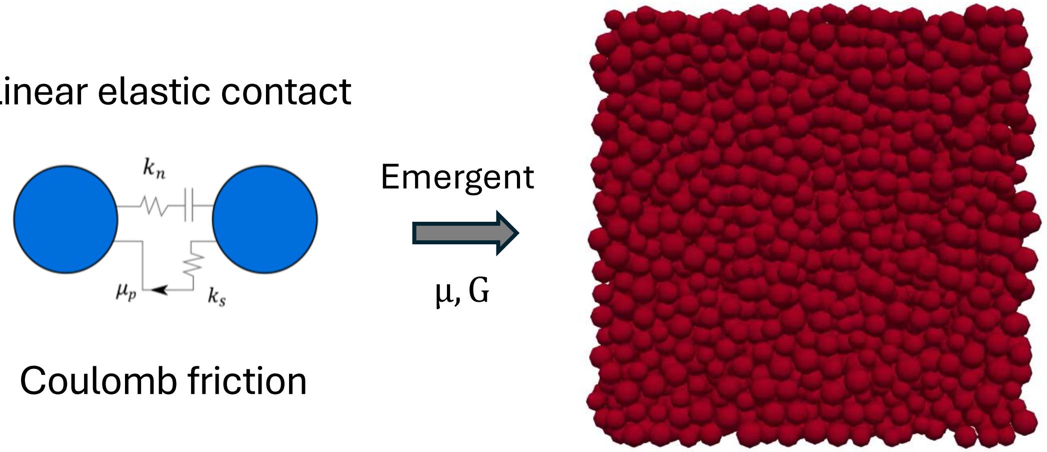
Methods – DEM Model

Numerical gouge set-up

We use 3D DEM formulation implemented in **Yade DEM** (https://yade-dem.org/)

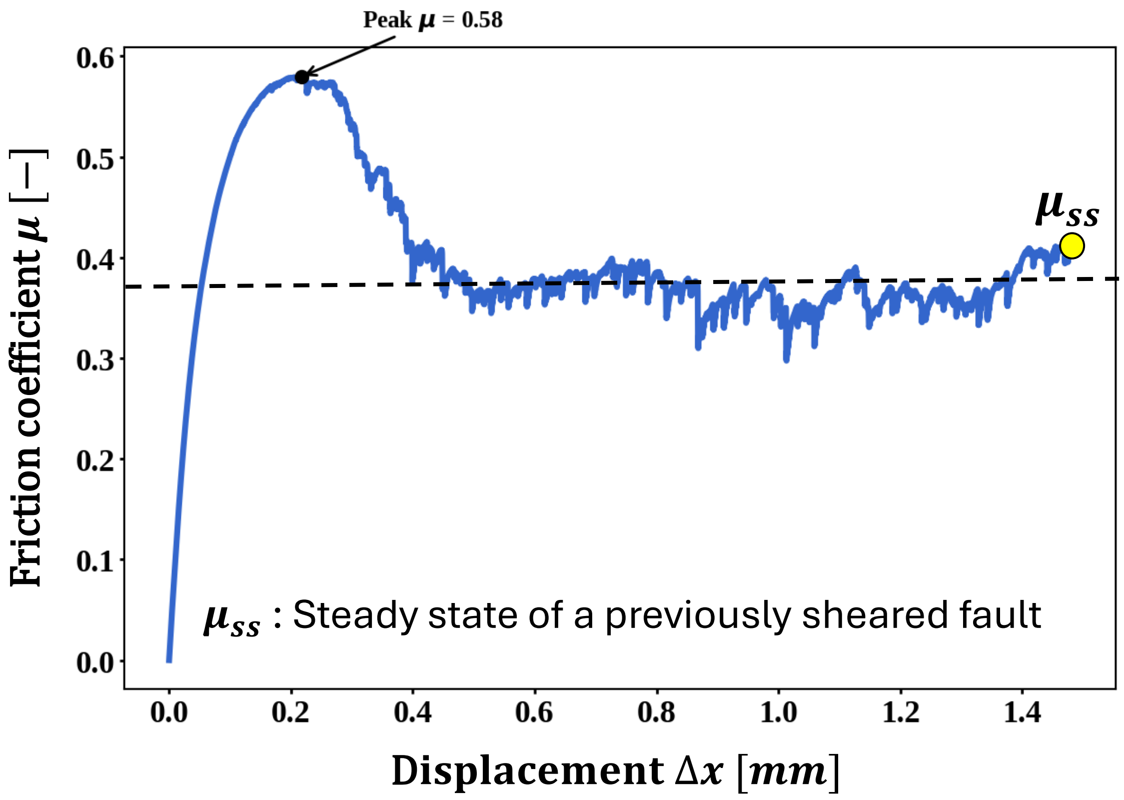


From grain-scale contacts to macroscopic friction



For example :

Vx = 0.2 mm/s , σn = 5 MPa



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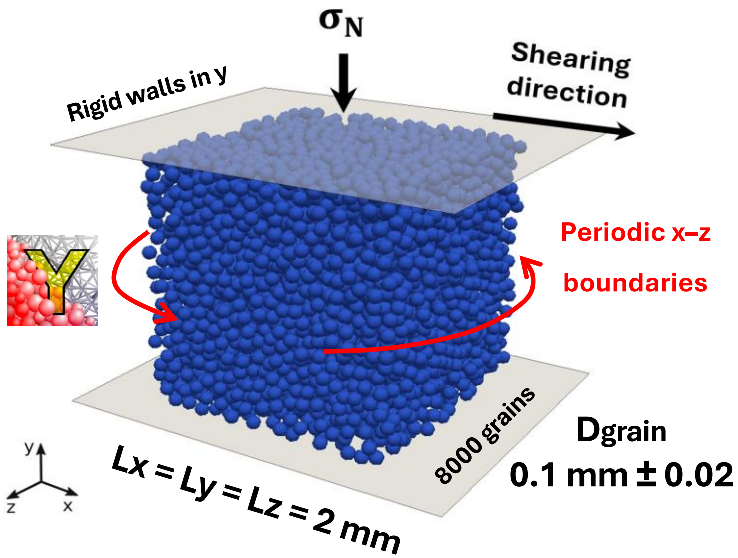
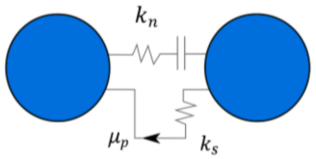


From grain-scale contacts to macroscopic friction

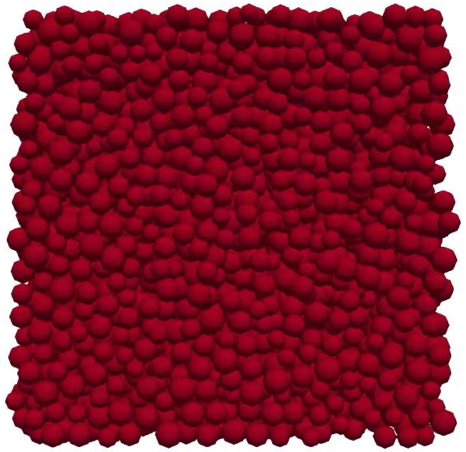
Linear elastic contact



Coulomb friction

Emergent

μ, G



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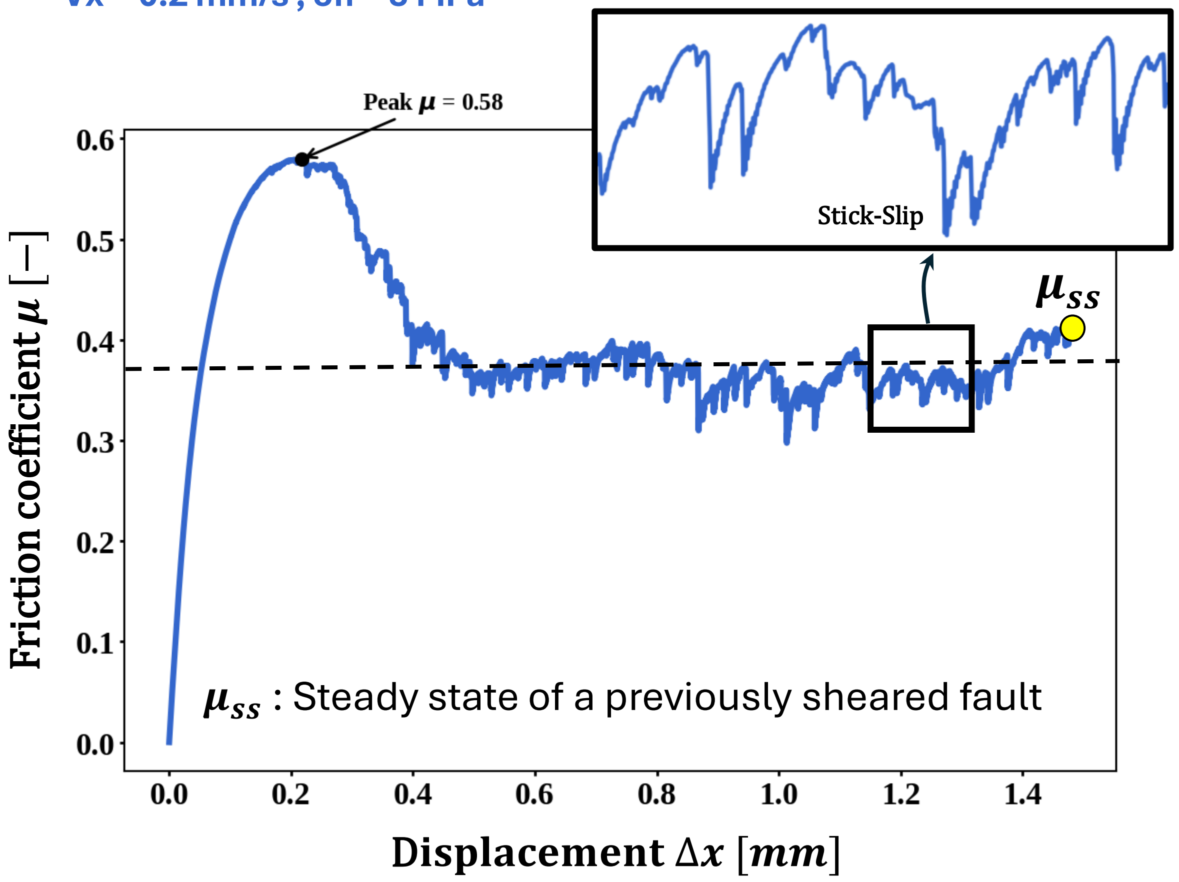
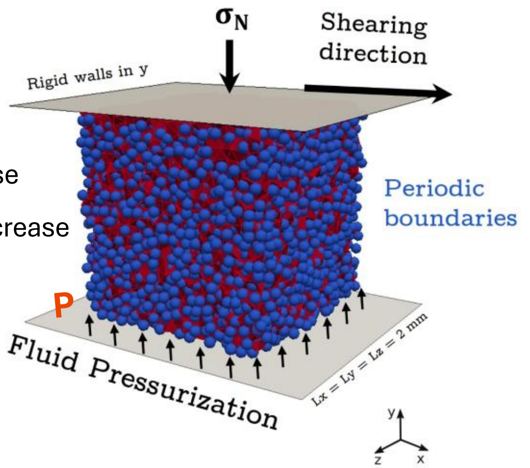


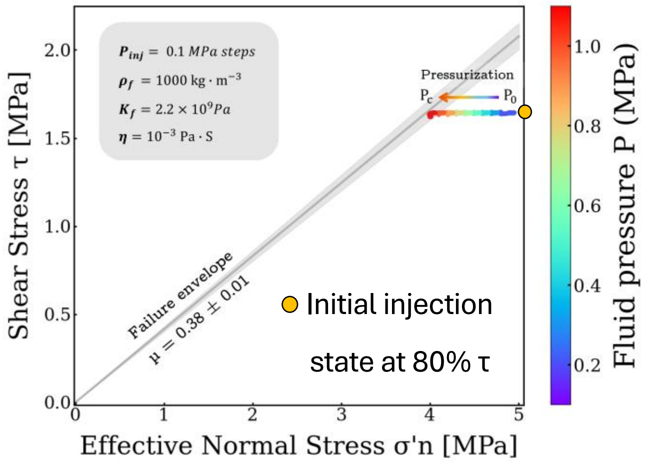
Our model shows classic fault behaviors such as **Stick-Slip** motion

Pore scale Finite Volume (PFV) method in Yade to apply fluid forces to grains

Stepwise pressure increase

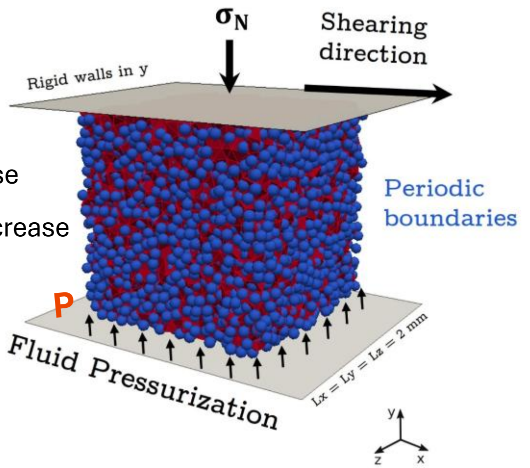


Loading Protocol :



Methods - Hydro-Mechanical Loading

Pore scale Finite Volume (PFV) method in Yade to apply fluid forces to grains



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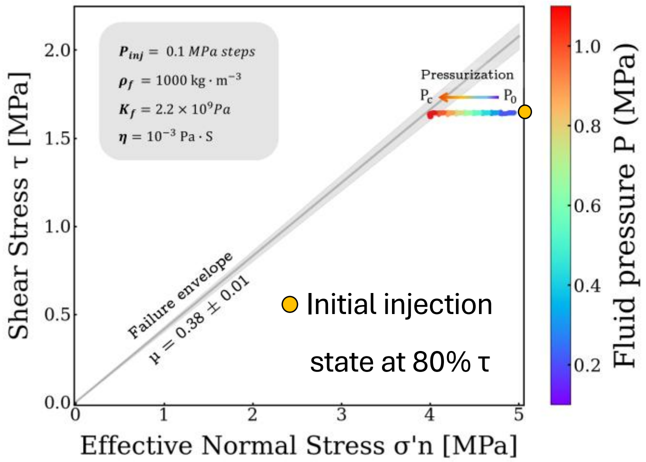
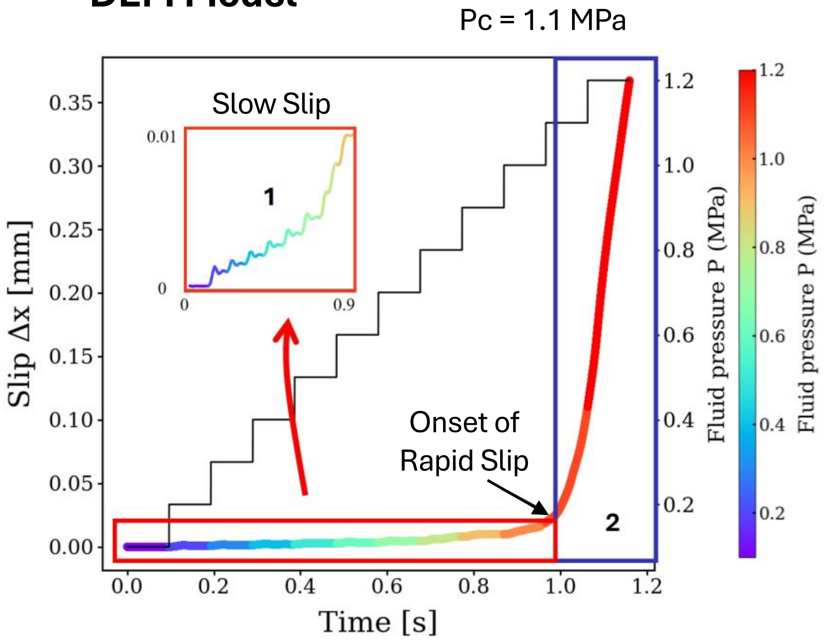


1) **Monotonic Injection :** to identify the onset of recativation

DEM Model

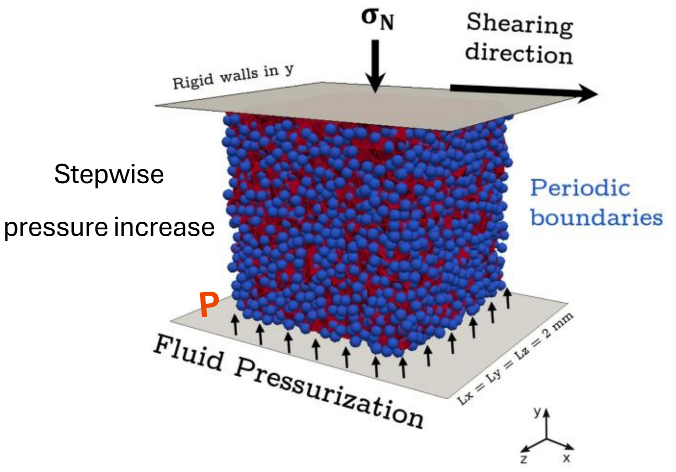


Two distinct stages are observed :

1) Initial Pressurization (Slow Slip)
2) Failure and Dynamic Slip

Methods - Hydro-Mechanical Loading

Pore scale Finite Volume (PFV) method in Yade to apply fluid forces to grains



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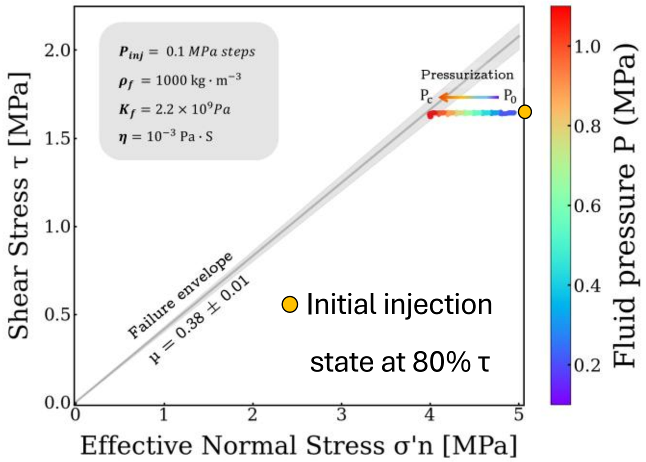

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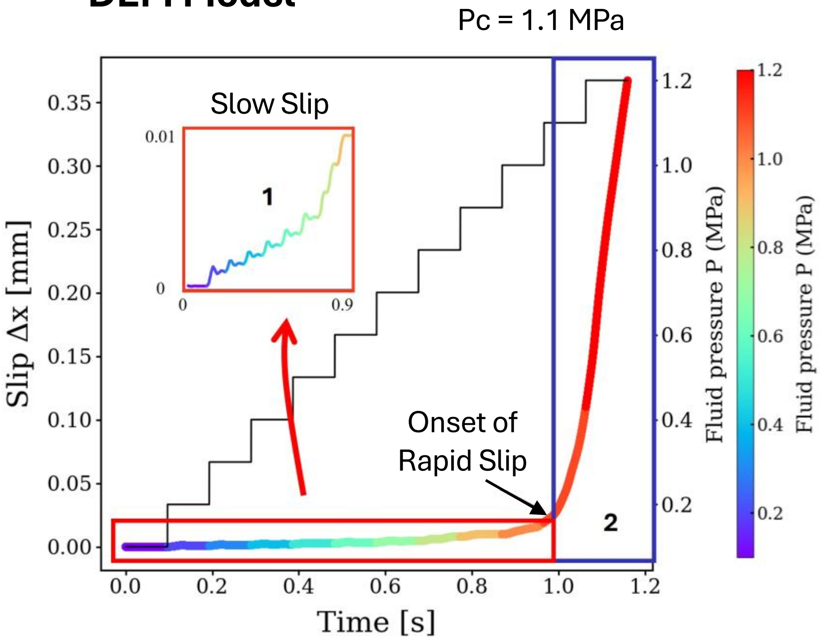
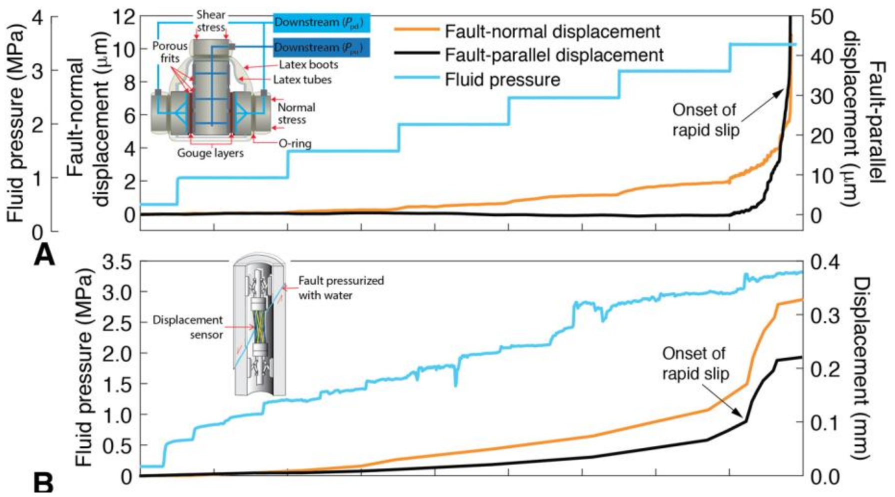


Laboratory (A) and in situ (B) experiments

Cappa et al 2019



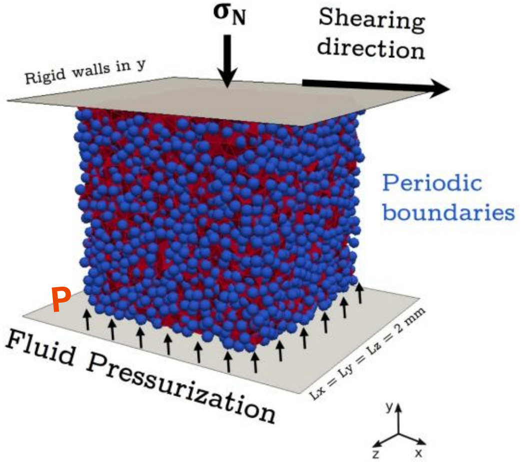
Two distinct stages are observed :

1) Initial Pressurization (Slow Slip)
2) Failure and Dynamic Slip

The DEM emergent behavior shows **great similarities with those observed in laboratory and in situ studies**

Methods - Hydro-Mechanical Loading

Pore scale Finite Volume (PFV) method in Yade to apply fluid forces to grains



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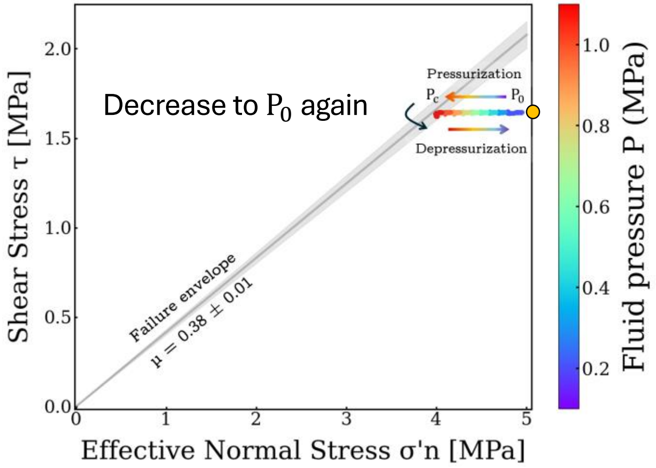
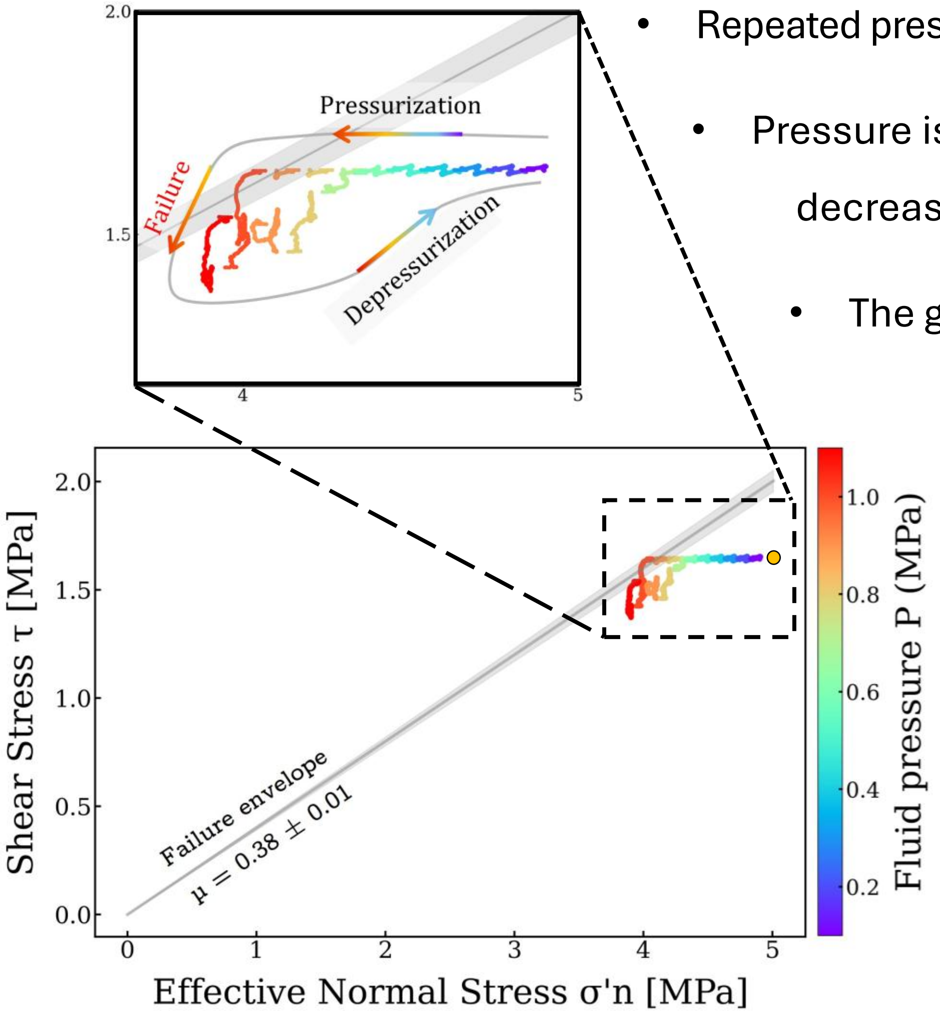
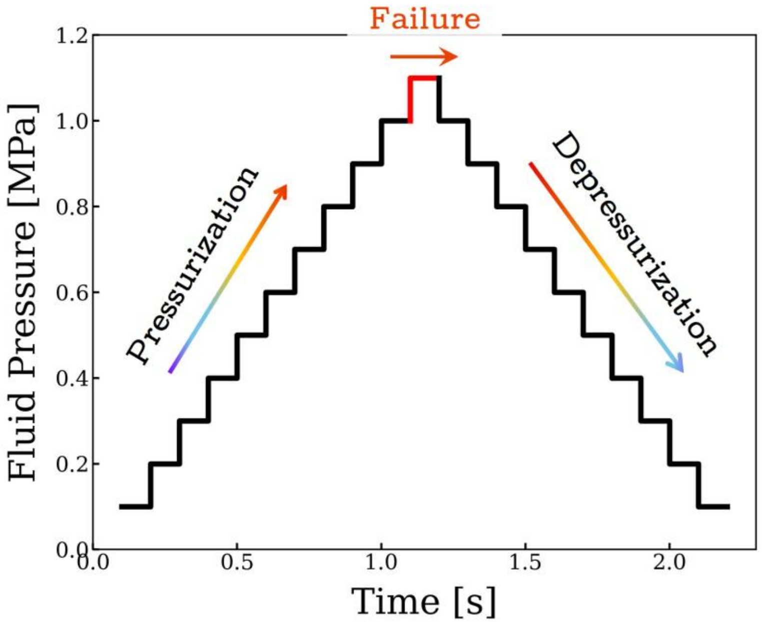


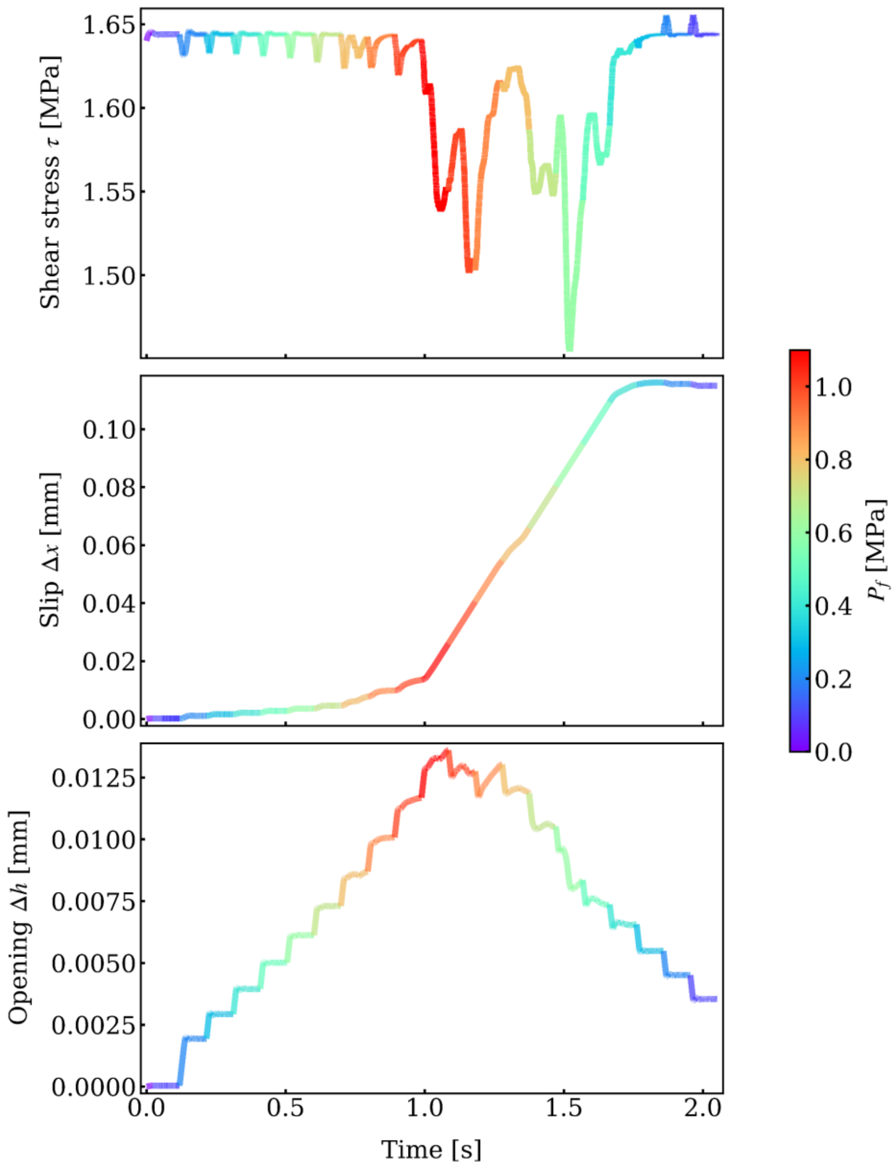
2) Cyclic Injection (Fault Valve Behavior)



- Repeated pressurization–depressurization sequence
  - Pressure is increased from P_0 until failure P_c and decreased again to P_0
    - The goal is to reproduce fault-valve-like cycles



Results - Cyclic Reactivation



One Cycle

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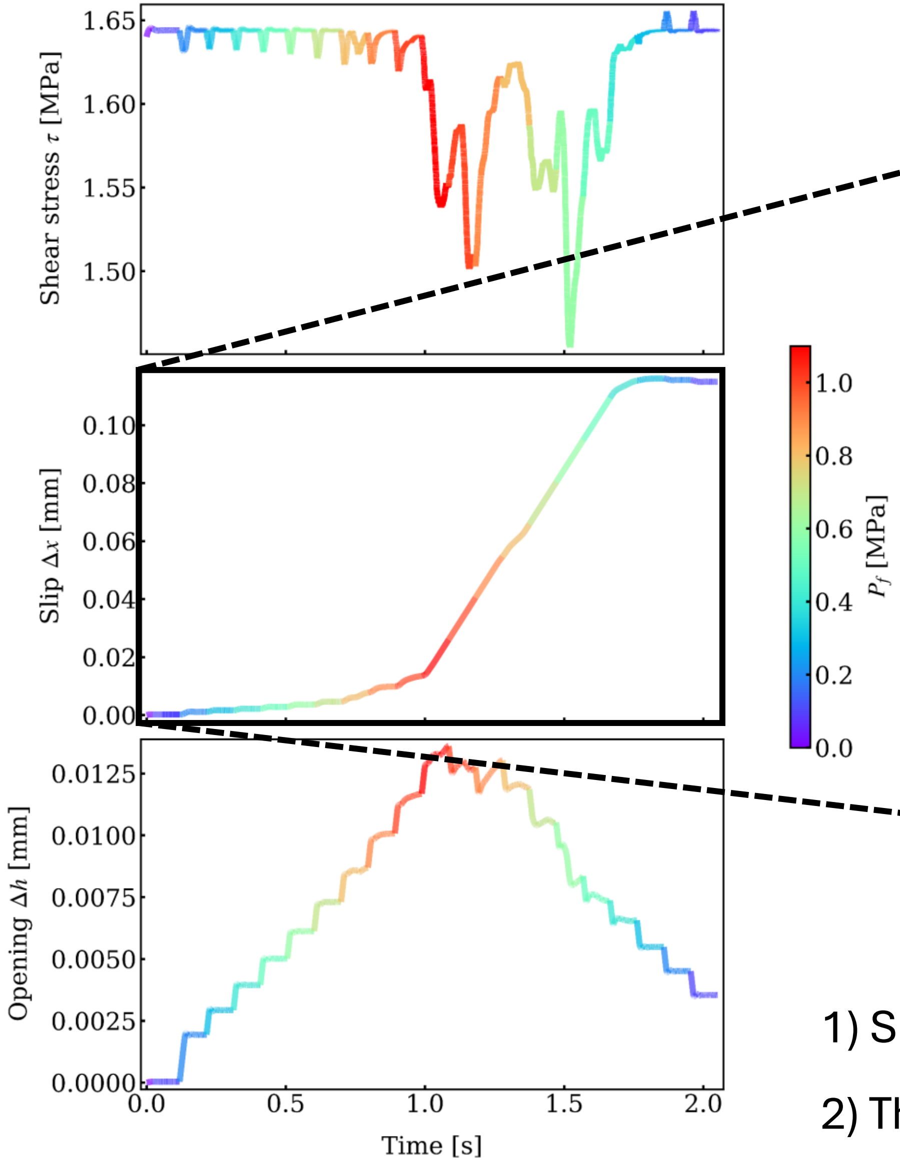
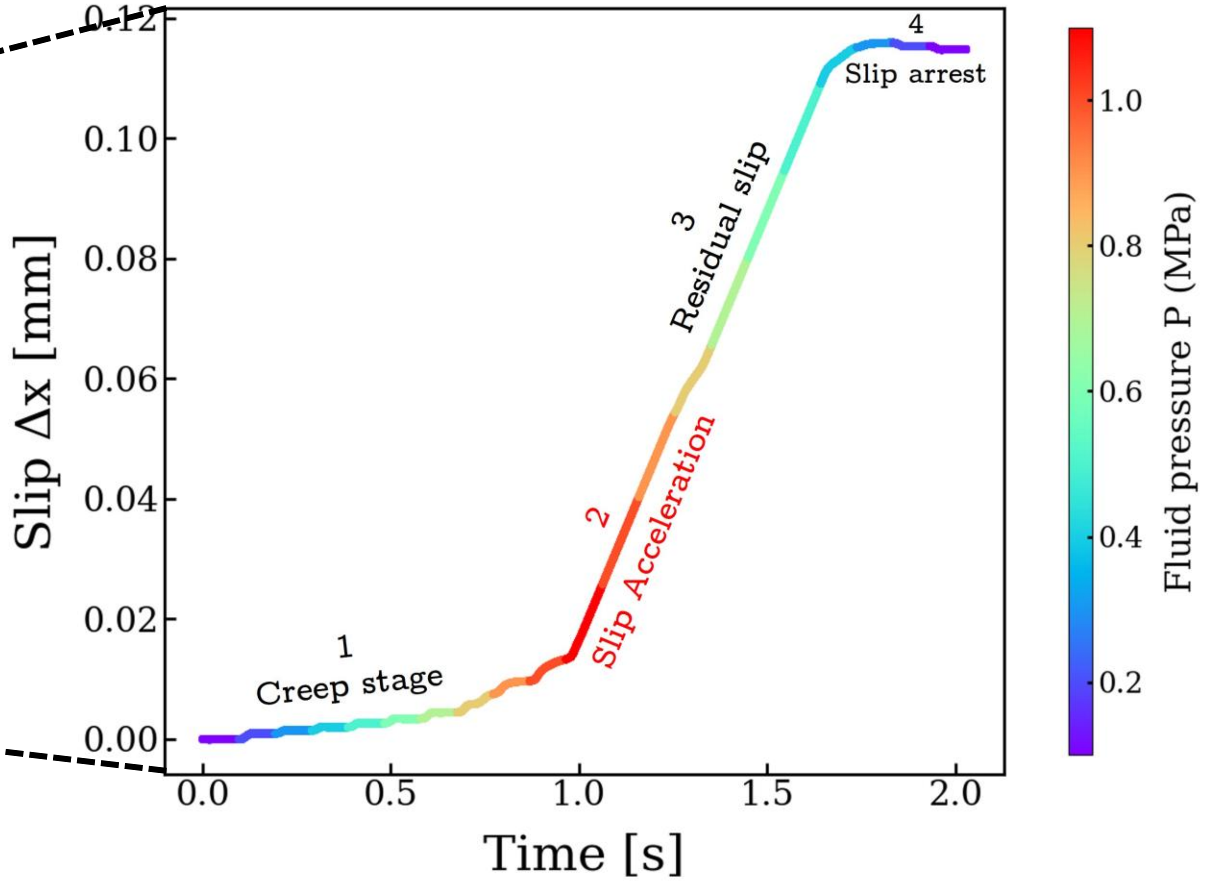


One Cycle



1) Slip continues at the start of pressure reduction

2) The gouge stops once pressure is reduced to a low enough level

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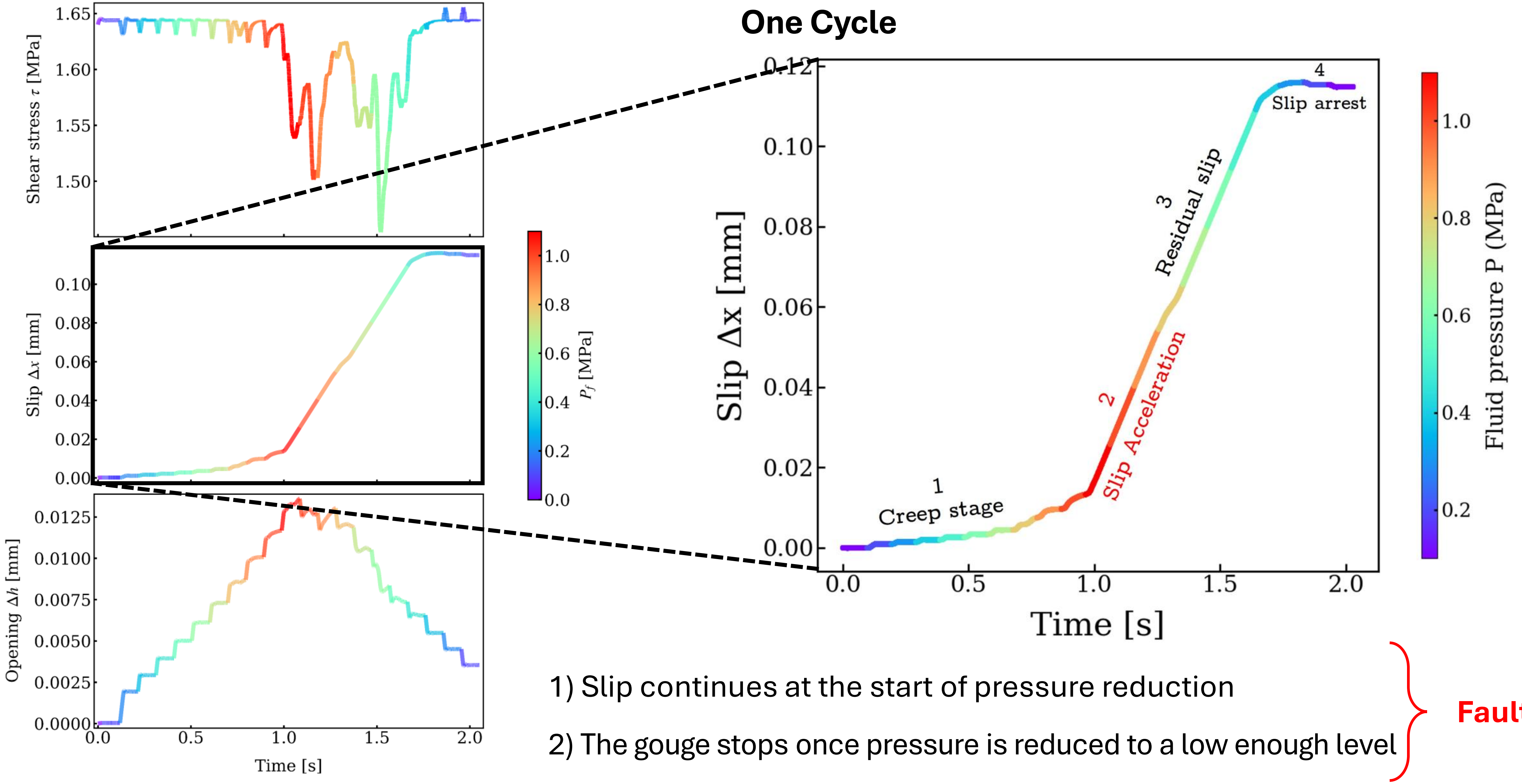

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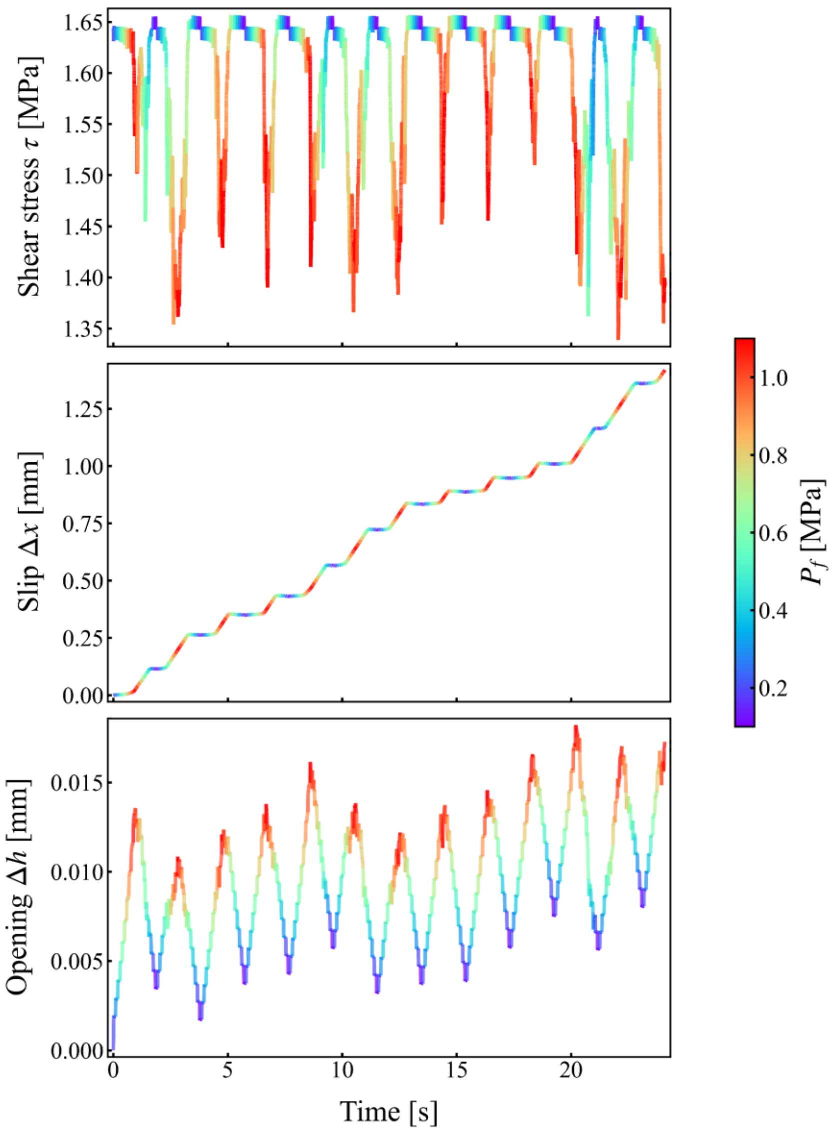
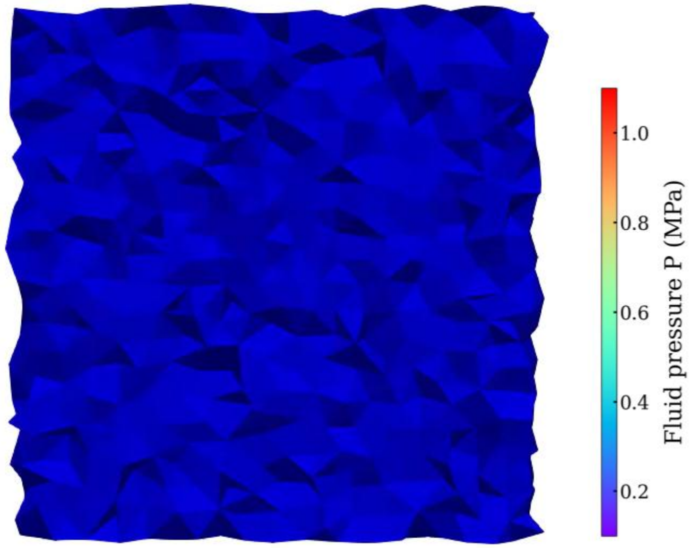
Fault Valve !

Multiple Cycles





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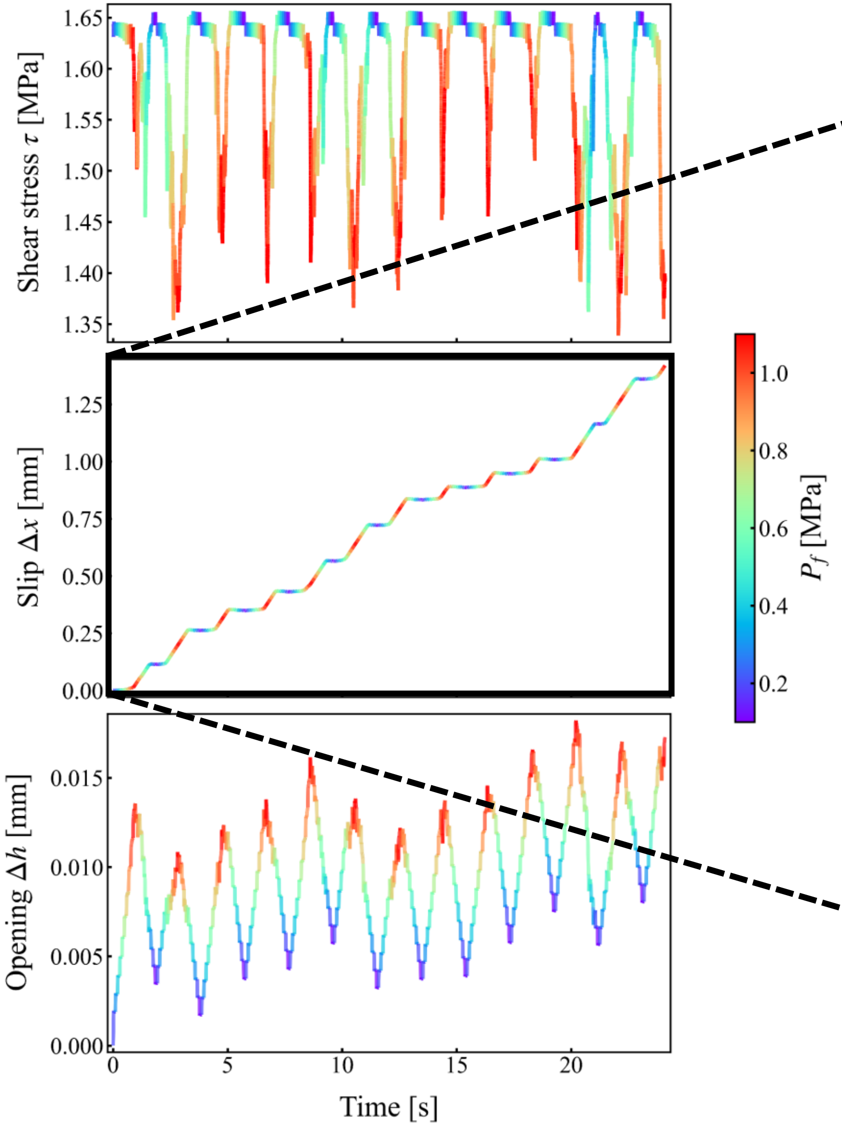

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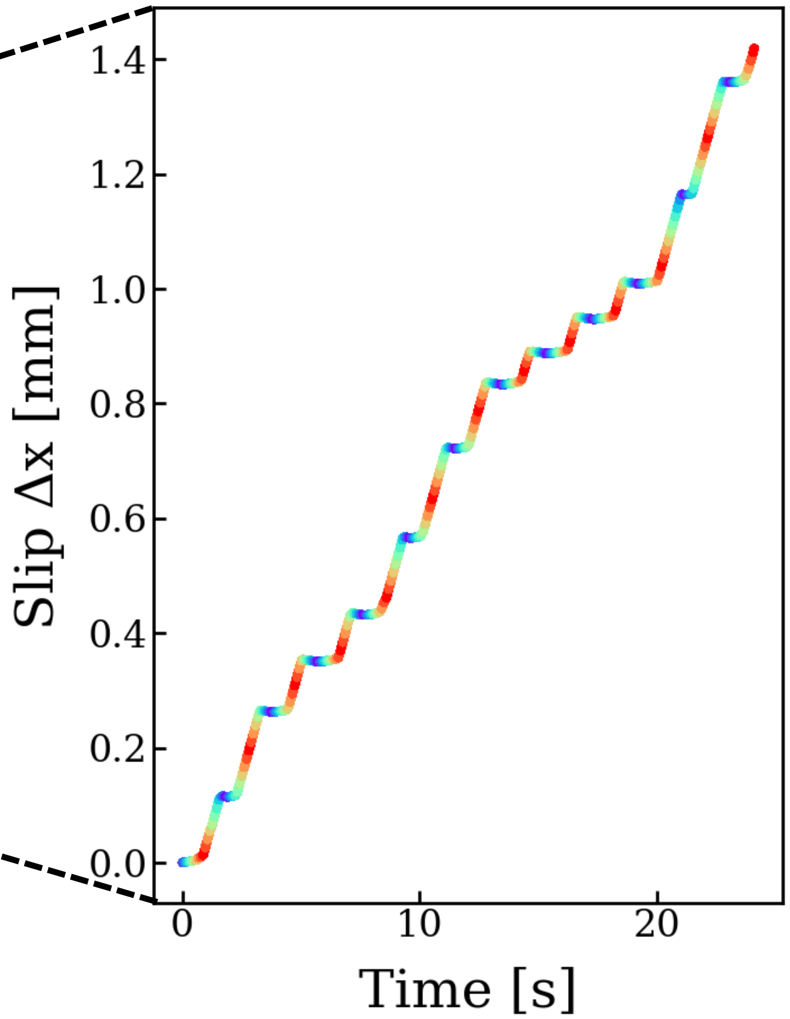

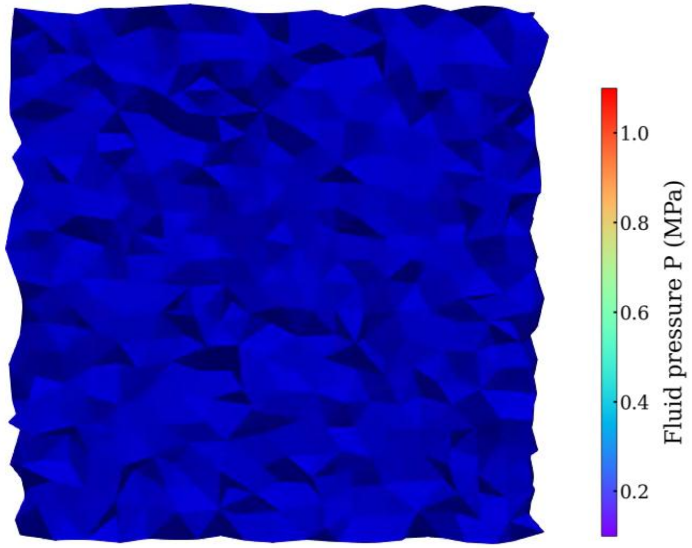

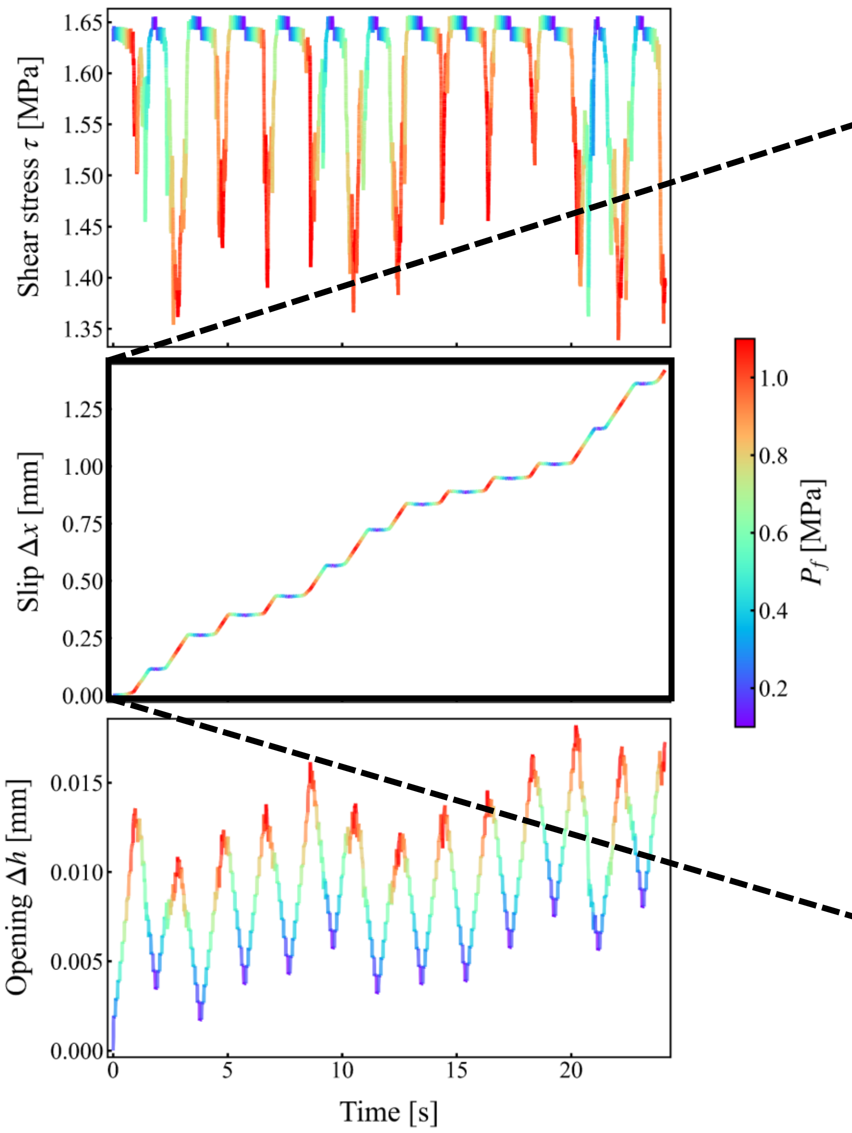

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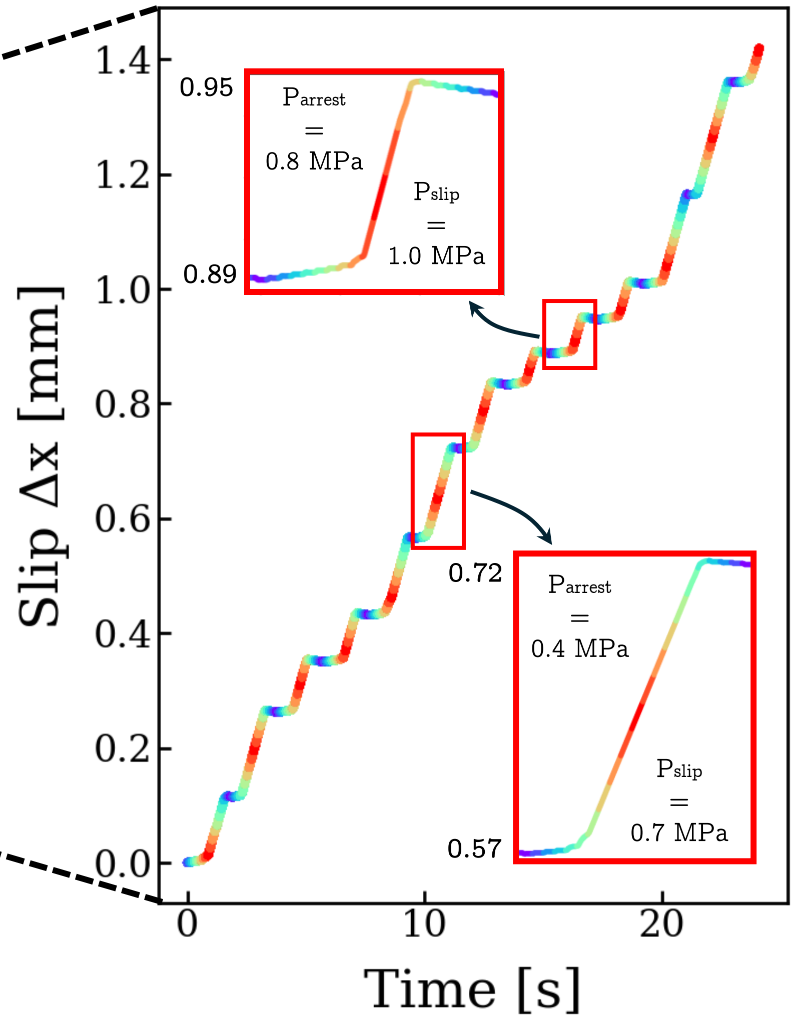
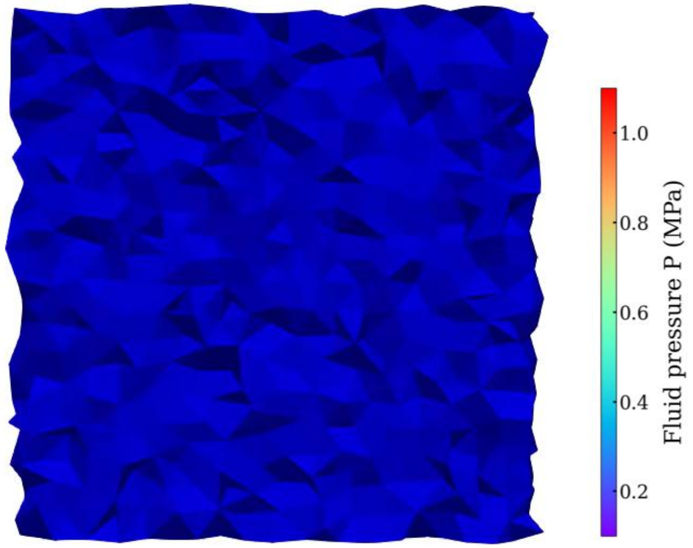
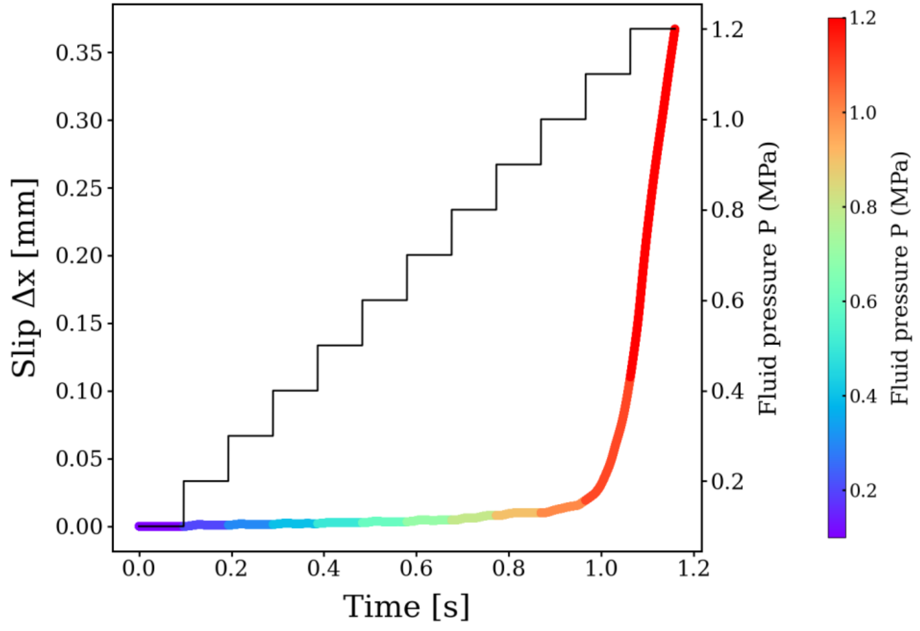




Strong variability in both onset and slip magnitude

Results – Seismicity



- The maximum seismic moment is recovered from the measured slip associated with each pressure step increase
- Previous studies suggest a direct scaling :

$$M_{0,\max} = G\Delta V \quad (McGarr2014)$$

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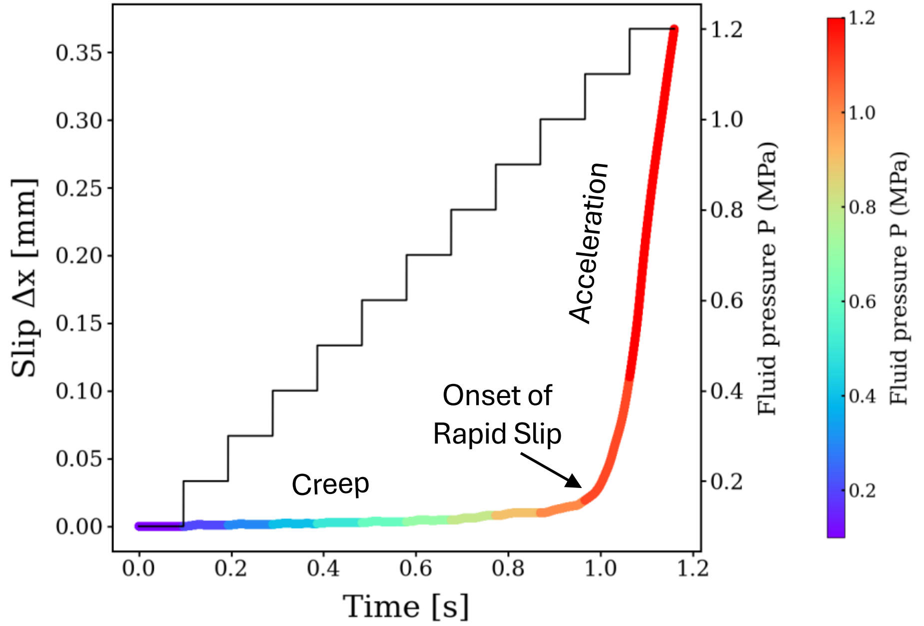


Maximum seismic moment :

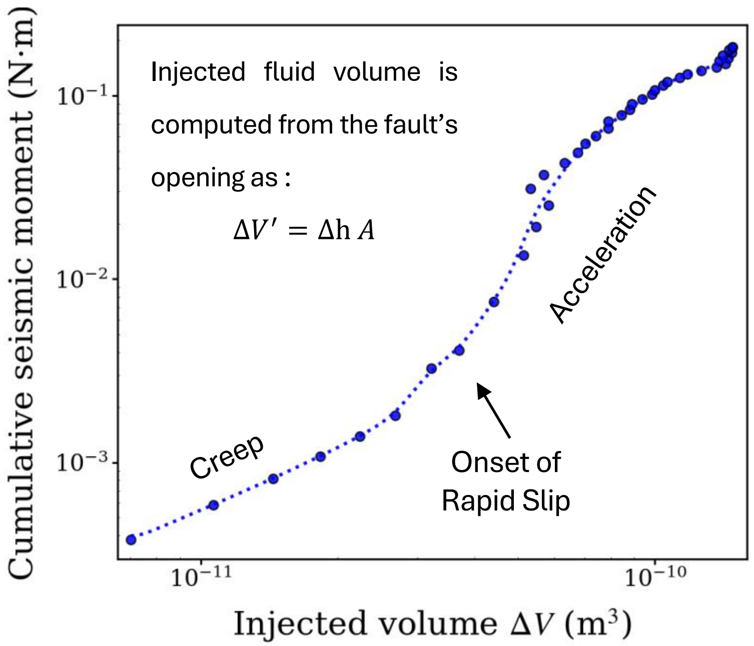
$$M_{0,max} = A\, G\, \Delta x$$

G = Shear modulus

A = Area of the rupture

Δx = Slip per Pstep

ΣM0,max vs ΔV



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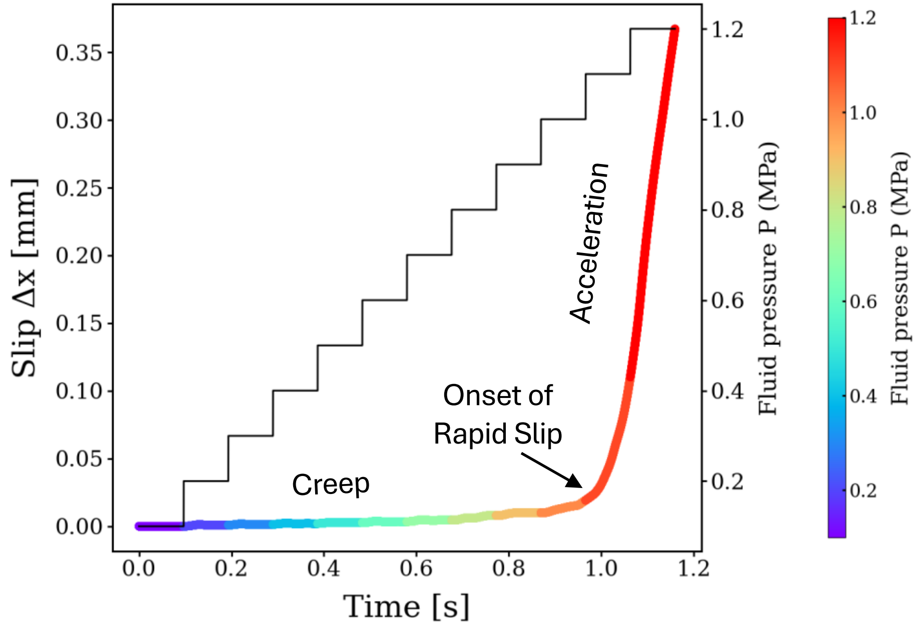

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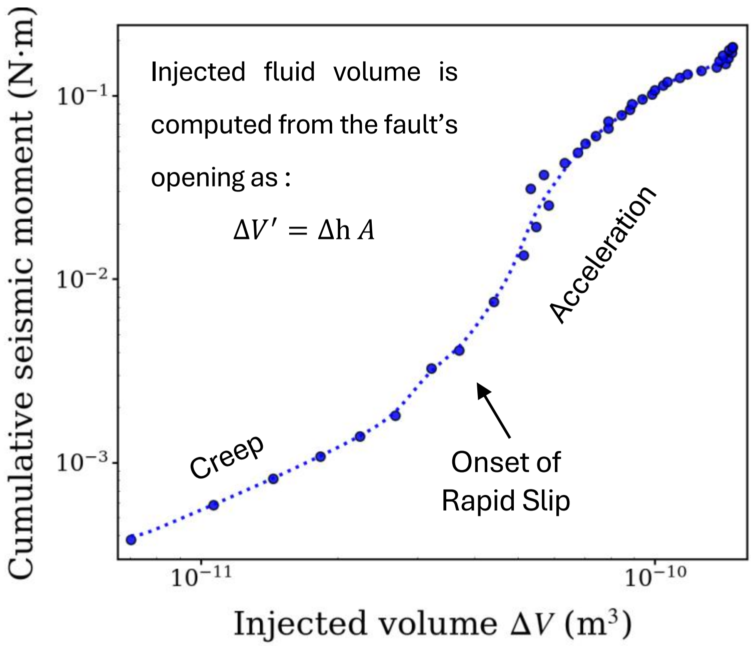
$\Sigma M_{0,\max}$ vs ΔV



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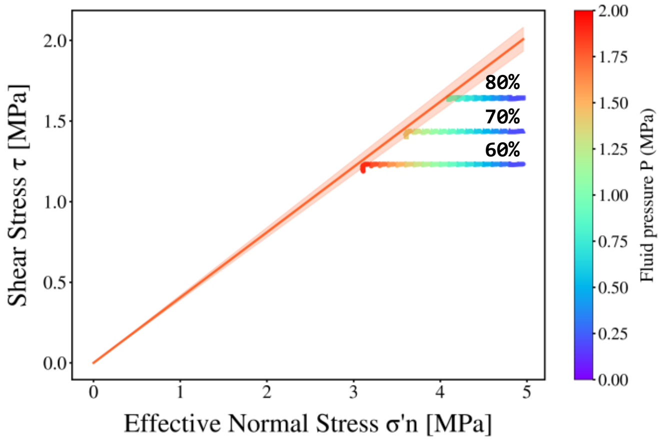
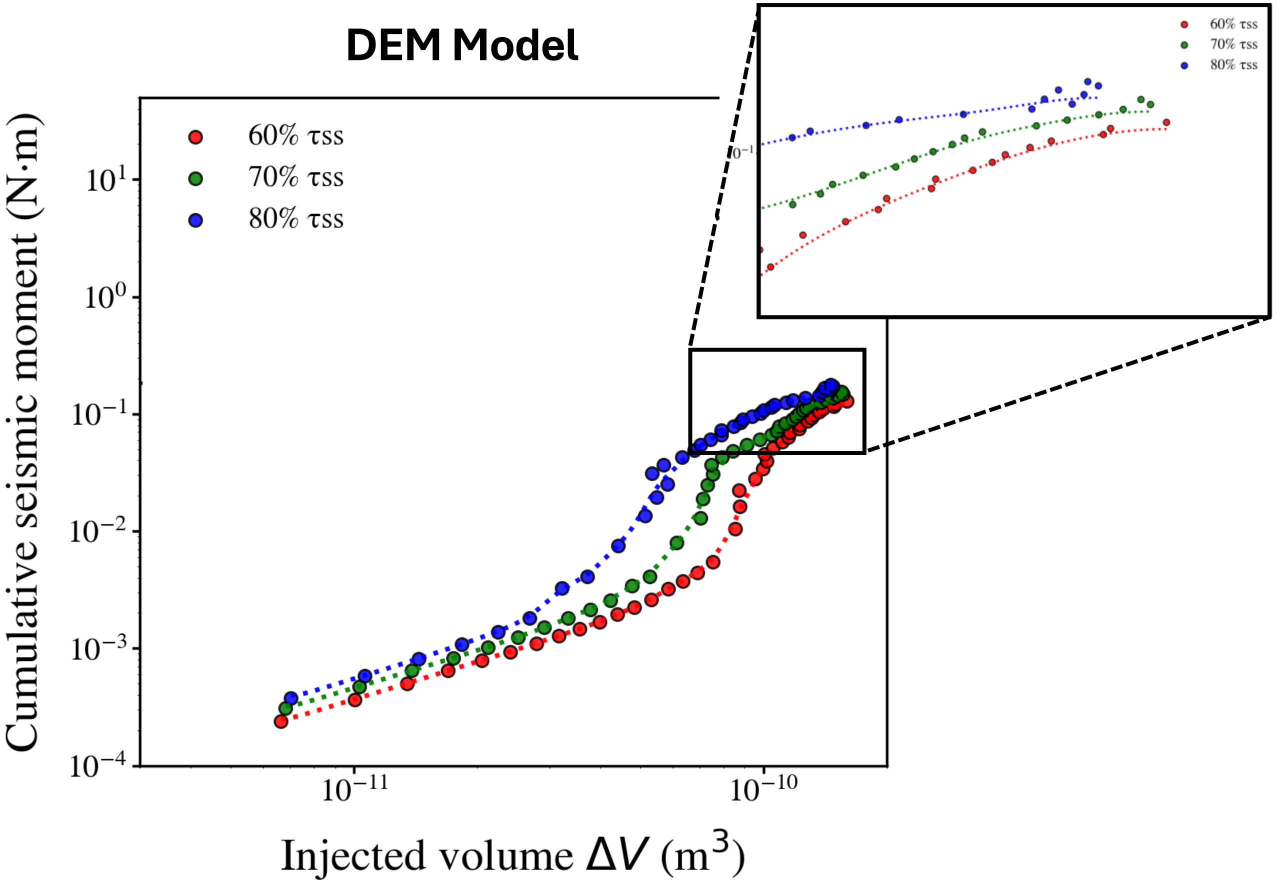


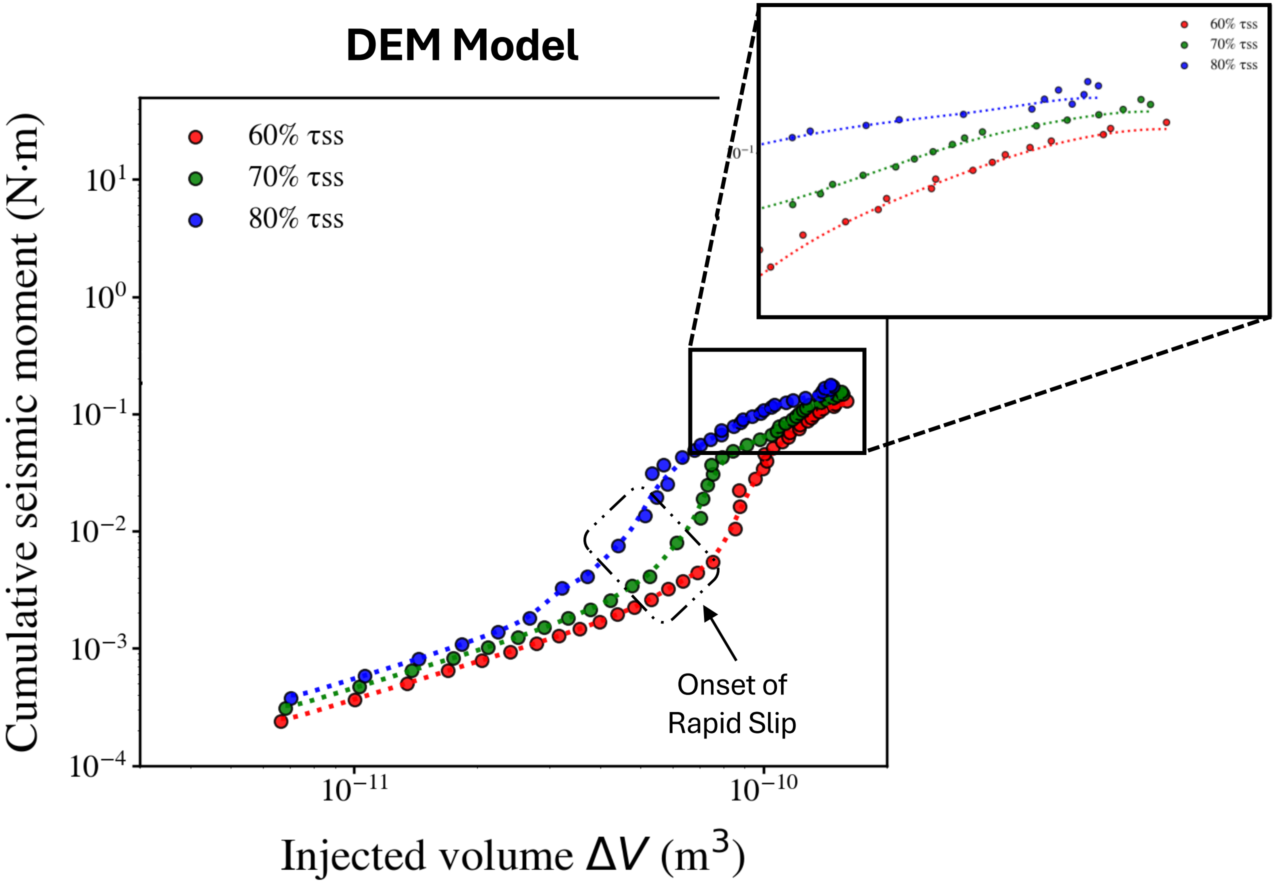
Compare seismic potential under different initial shear stress levels before injection

Results – Seismicity

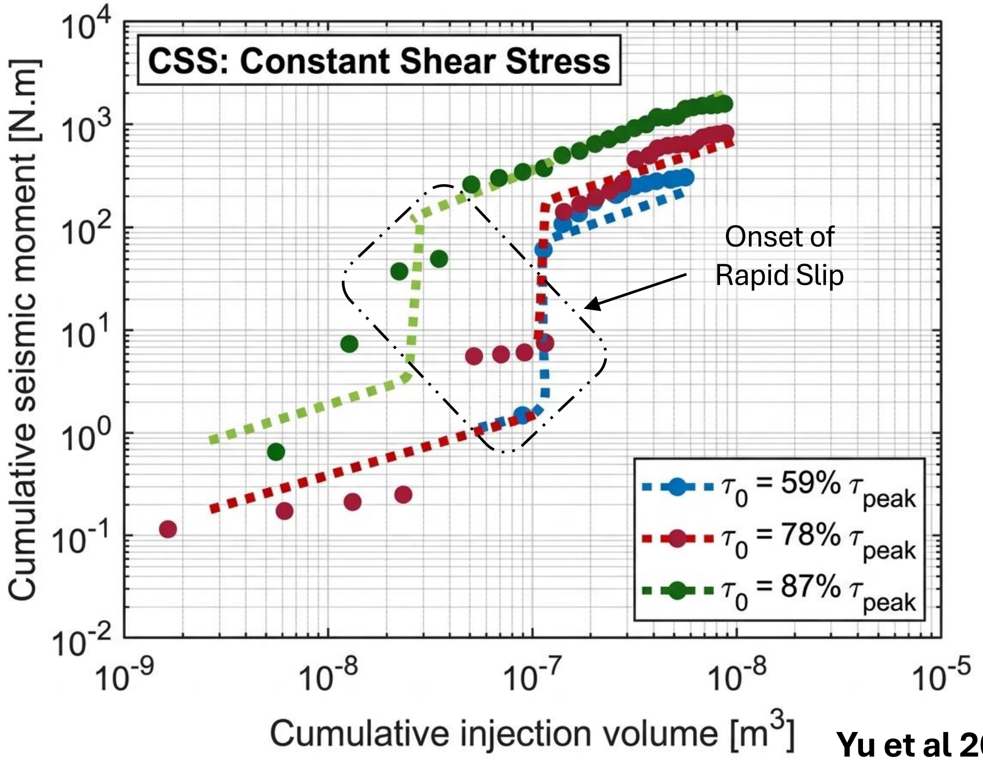


- Higher pre-stress increases seismic potential by reducing the critical volume required for fault reactivation.

DEM Model



Laboratory experiments



Yu et al 2024

- Higher pre-stress increases seismic potential by reducing the critical volume required for fault reactivation.
- Our model confirms laboratory observations from previous studies.

Conclusion

1. DEM–PFV reproduces key fault HM behaviors

Stick-slip during direct shear and fluid-induced reactivation during pressurization.

2. Cyclic injection produces fault-valve-like cycles

- Repeated reactivation – arrest sequences with residual slip
- Reactivation pressure and slip magnitude vary strongly from cycle to cycle.

3. DEM-based seismic moment scaling

The model reproduces observed seismic moment trends, with initial shear stress as the key control on seismic potential.

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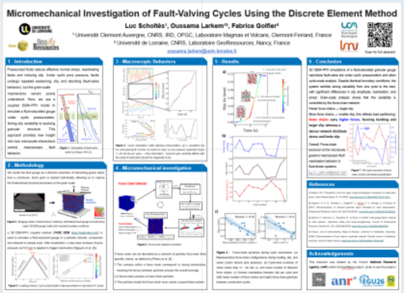
Want to know more ?



Everything is related to the **evolving microstructure of the gouge !**

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Laboratoire Magmas et Volcans

anr

Thank you !

Full abstract

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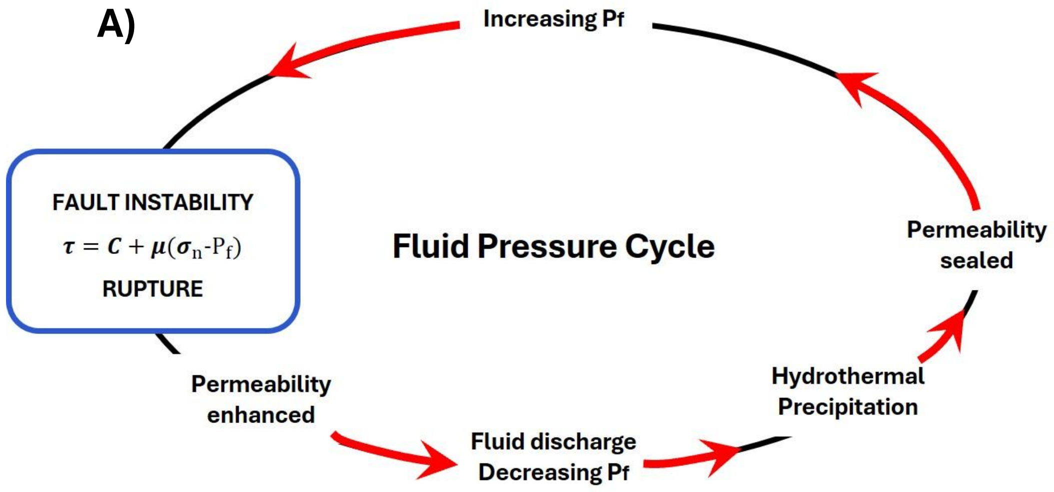
Results : Cyclic Injection

Using **the DEM×PFV** formulation we aim to **: Simulate the Fault Valve Behavior**

A)

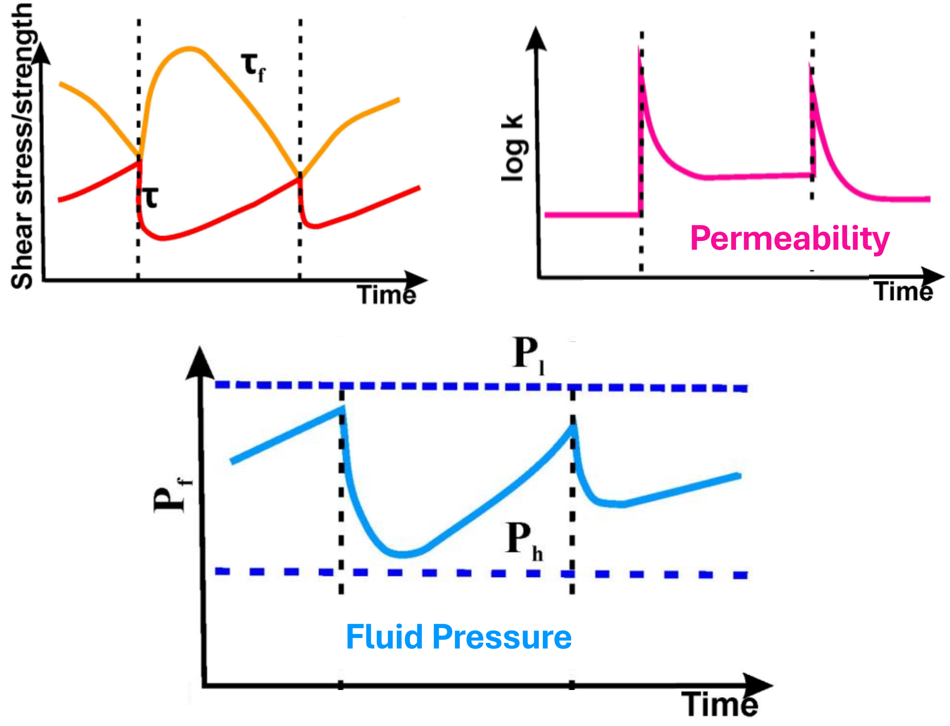


After ***Sibson 2020***

Fault Valve Behavior

Fluid Pressure, Shear Stress, and Permeability, all go through cycles of build-up and release

B) Fluid pressure, frictional strength and permeability cycles resulting from valving action



Therefore, we simulate **Cyclic Injection** tests to reproduce and analyze these recurring fault valve processes (pressurization and release cycles)

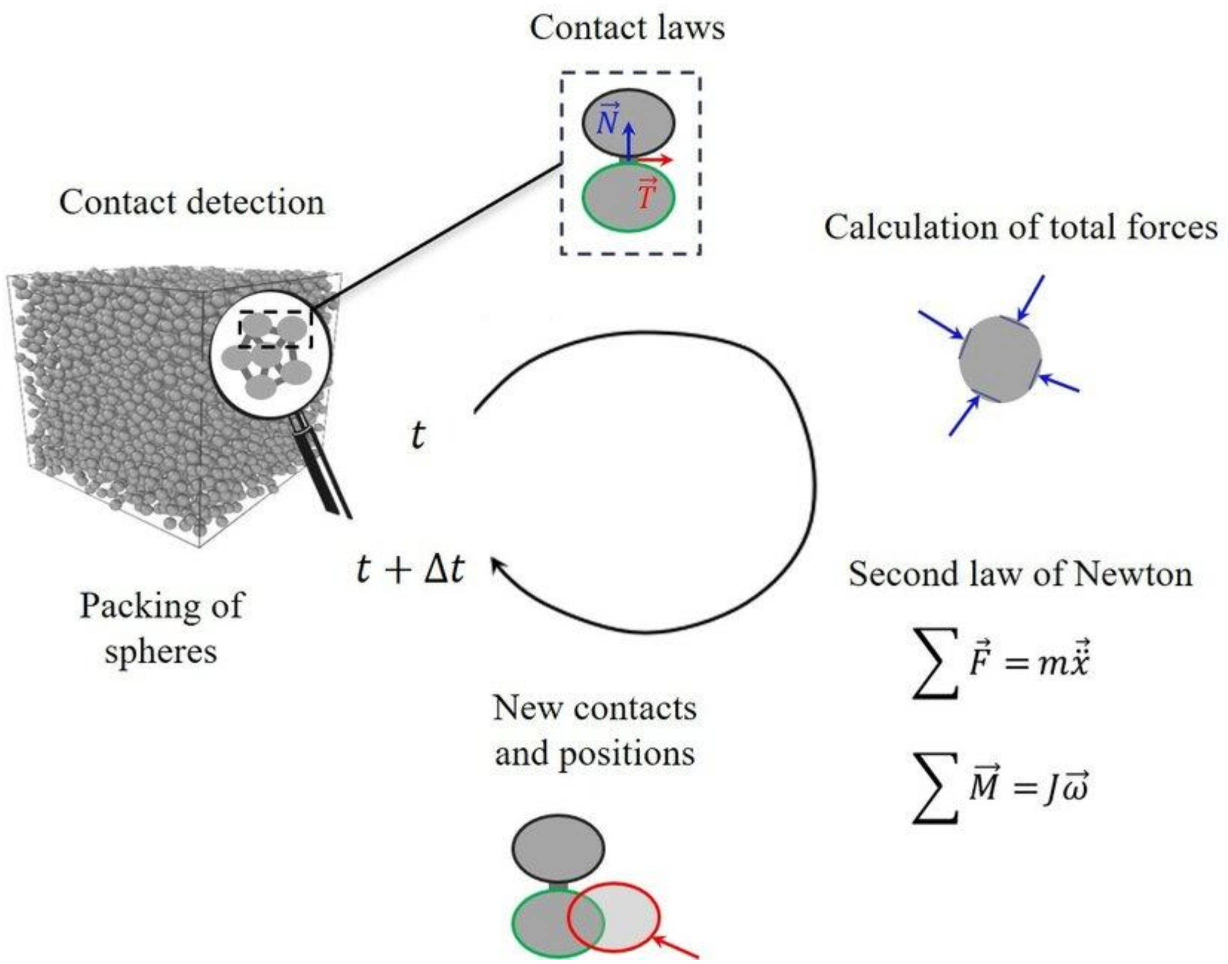
Appendix A: How DEM works

1) DEM represents materials as individual ***particles*** that interact at contact points.

2) Detect contacts between particles and apply ***contact laws*** (normal and tangential forces).

3) Calculate total forces on each particle and apply ***Newton's laws*** of motion.

4) Update particle ***positions and velocities***, then repeat for the next time step.



Radi, Kaoutar. (2019). Bioinspired materials : Optimization of the mechanical behavior using Discrete Element Method.

Appendix A: DEM – Contact law

We use a 3D DEM formulation implemented in **Yade DEM**

Interactions are governed by **linear elastic contact** laws and **Coulomb friction**.

- **Normal Contact Force F_n:**

$$F_n = \min(k_n(u_n - u_n^p), a_n)$$

k_n : normal stiffness

a_n : normal adhesive strength

- **Tangential (Shear) Force F_s :**

$$F_s = k_s \, . \, u_s$$

k_s : shear stiffness

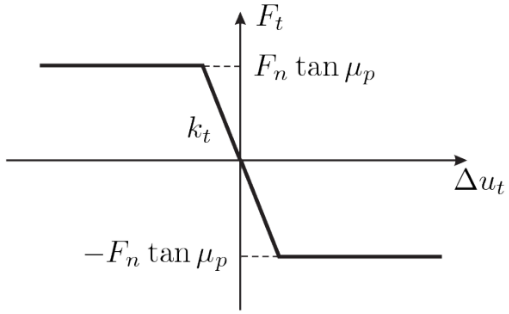
u_s : relative tangential displacement

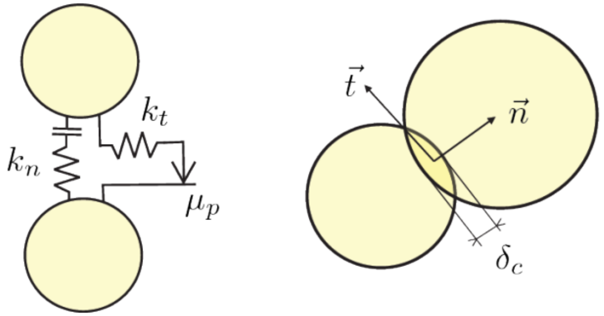
- **Maximum Shear Force (F_s^{max} - Mohr-Coulomb type):**

$$F_s^{max} = F_n \, . \tan(\varphi) + a_s$$

φ : friction angle

a_s: shear adhesion

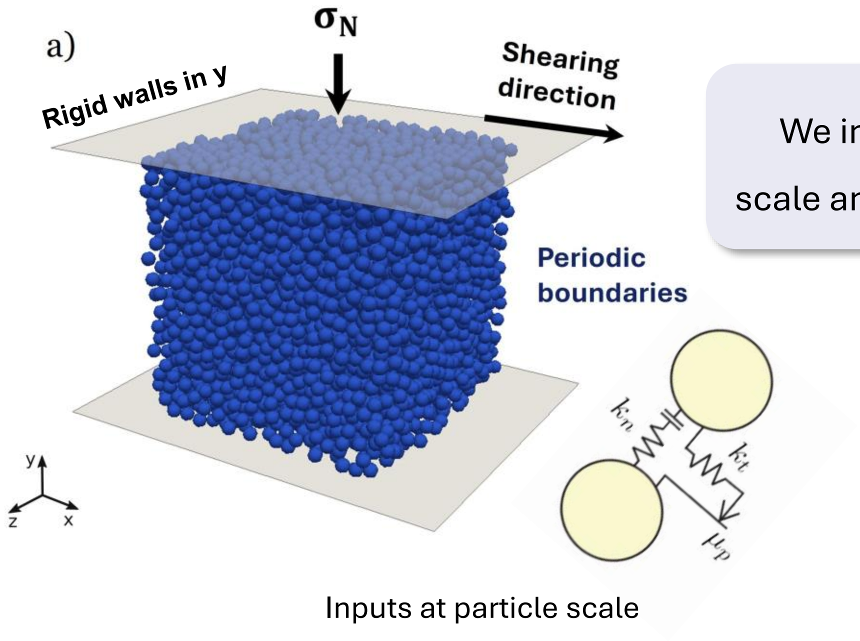




Contact Interaction

Scholtès (2008)

Appendix A: Emergent Properties



Inputs at particle scale

We impose properties at the grain scale and look for emergent properties.

Outputs →

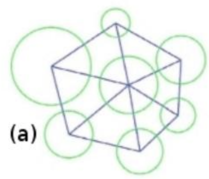
Parameter	Value
Particle density ρ	2600 $\mathrm{kg/m^3}$
Particle Young's modulus E	1 GPa
Particle Poisson's ratio ν	0.25
Particle Friction angle	30°
Mean diameter D_p	0.1 mm
Normal load σ_N	5 MPa
Shear velocity V	2×10^{-5} m/s
Initial porosity n_0	0.428

Mechanical Properties

Imposed	Tracked
Particle Properties: E, ν, friction angle . . .	**Boundary Forces:** total and tangential forces
	Particle States: positions, velocities
Boundary Conditions: Applied σ_n , Shear Velocity	**Inter-particle Forces:** normal (F_n), shear (F_s)

Stresses	Method
Wall Stresses	From recorded forces on boundary walls: $\sigma_{ij}^{\text{wall}} = \frac{F_{\text{boundary}}}{A_{\text{boundary}}}$
Contact Stresses	Summation over all inter-particle contacts, averaged over volume: $\sigma_{ij}^{\text{contact}} = \frac{1}{V} \sum_c F_i^c L_j^c$

Hydraulic Properties

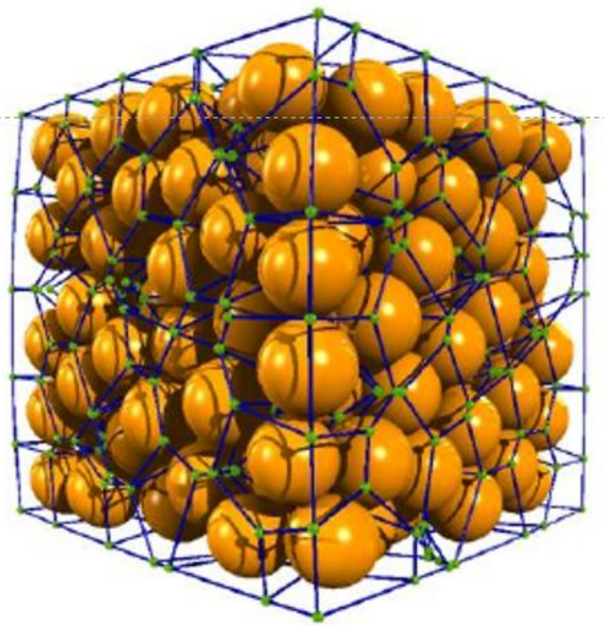


Imposed	Tracked / Computed
Fluid Properties: Viscosity (μ), Fluid Bulk Modulus. . . etc	**Pore Pressures:** P_k solved from mass conservation equations.
Boundary Conditions: Imposed pressure P_f or fluid flux.	**Fluxes:** q_{ij} calculated using local Poiseuille flow between neighboring pores.
Pore Network: Defined by particle configuration (geometry of pores via trangulation).	**Pore-scale average velocities:** $\mathbf{v}_{avg}^k = \frac{1}{V_k} \sum_{j \in N(k)} (q_{kj} \cdot \mathbf{r}_{kj})$
	Global flow average velocity: Volume-averaged over all pores.
	Fluid forces on particles: F_p, F_v.
	Permeability: via Darcy's Law: $\mathbf{v}_{avg} = -\frac{k}{\mu} \nabla P$

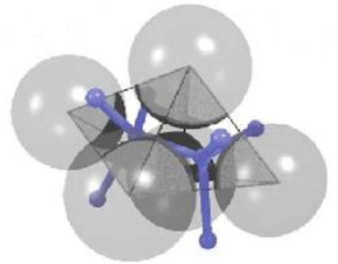
Appendix A: PFV Method

[Chareyre et al, TIPM 2011; Scholtès et al, CMT 2015]

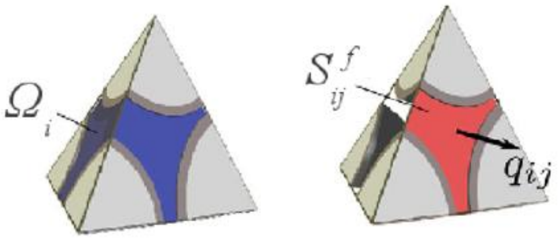
Pore space partition through a regular **Delaunay triangulation** (Laguerre Voronoï tesselation) + a **Finite Volume** scheme



Pore/Pipe network (interporal Darcy flow)



Fluid flow in a deformable medium



$$\dot{P}_i = \frac{-K_f}{V_{f,i}}\left[\dot{V_{p,i}} + \sum_{j=1}^{4} k_{ij}\left(P_i - P_j\right)\right]$$