Dilatation and shearing in tectono-volcanic systems from poro-elasto-plastic models set in the Southern Andes Volcanic Zone, inferences on geofluid flow

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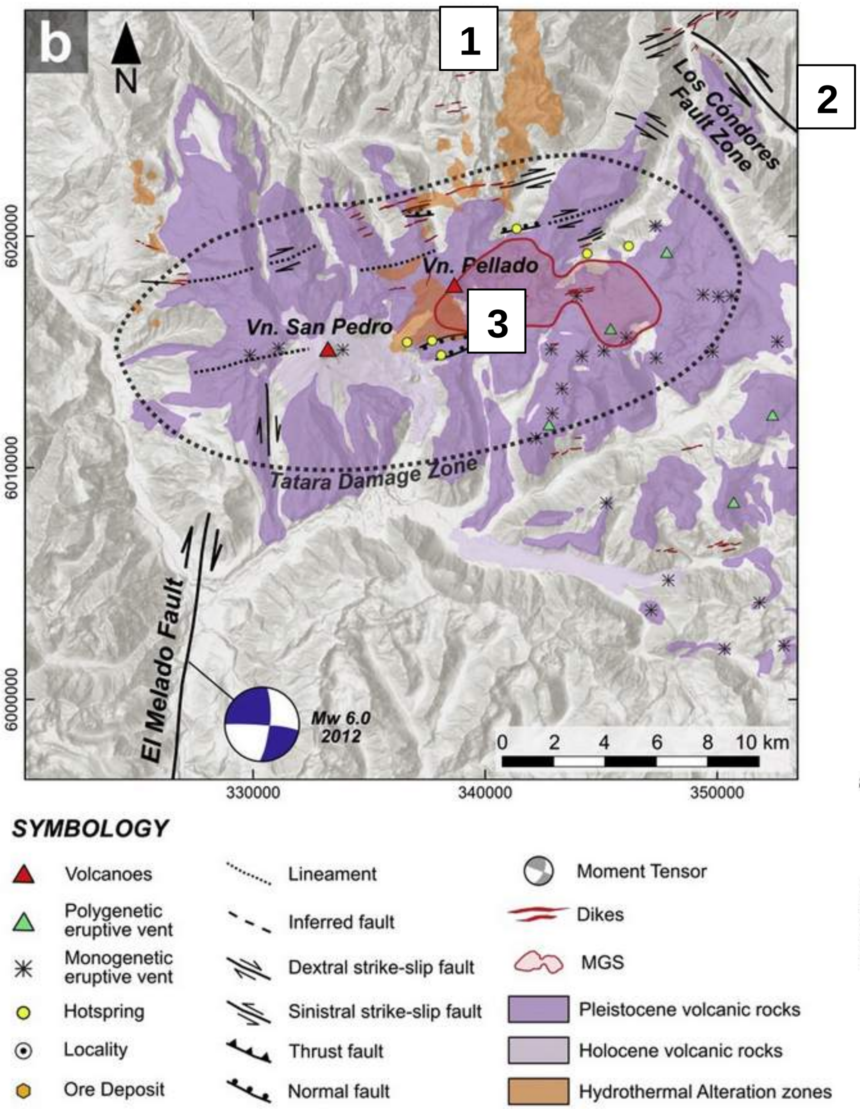
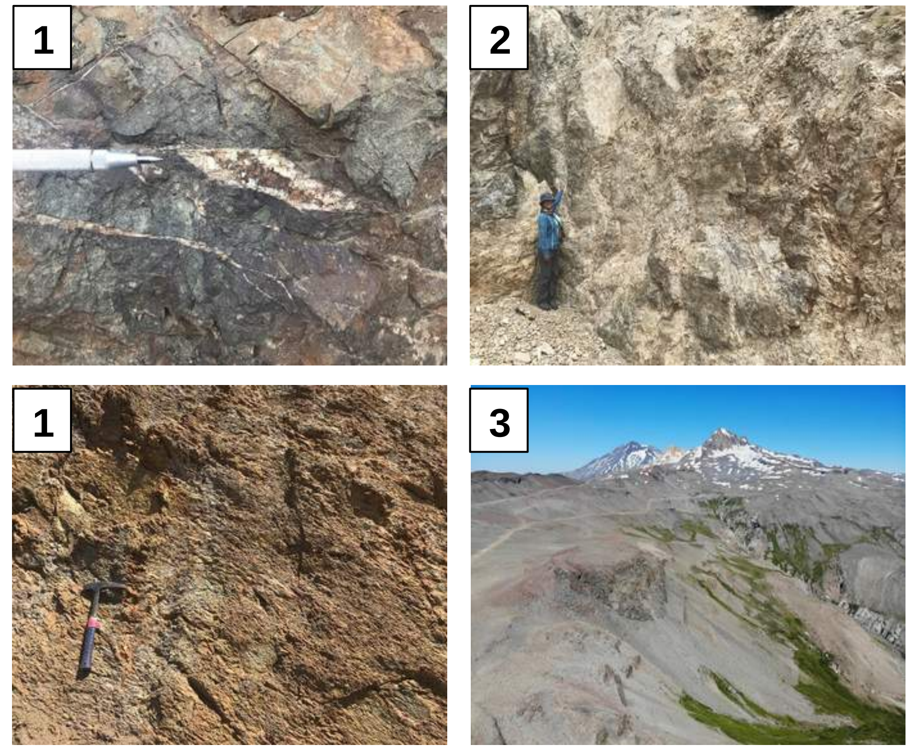
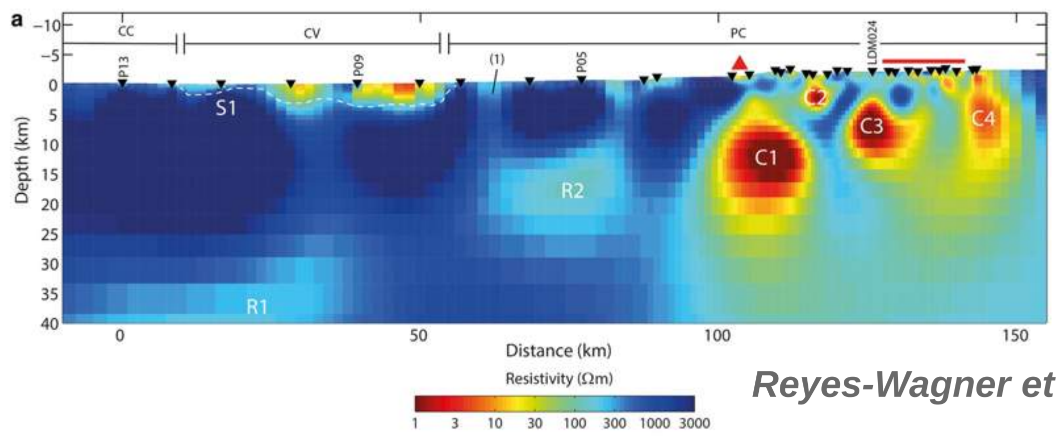
Ruz Ginouves et al., JGVR 2020, 2021

Step 1 - The Tatara-San Pedro complex : a geothermal field, volcano, faults ⟶ How do they play ?



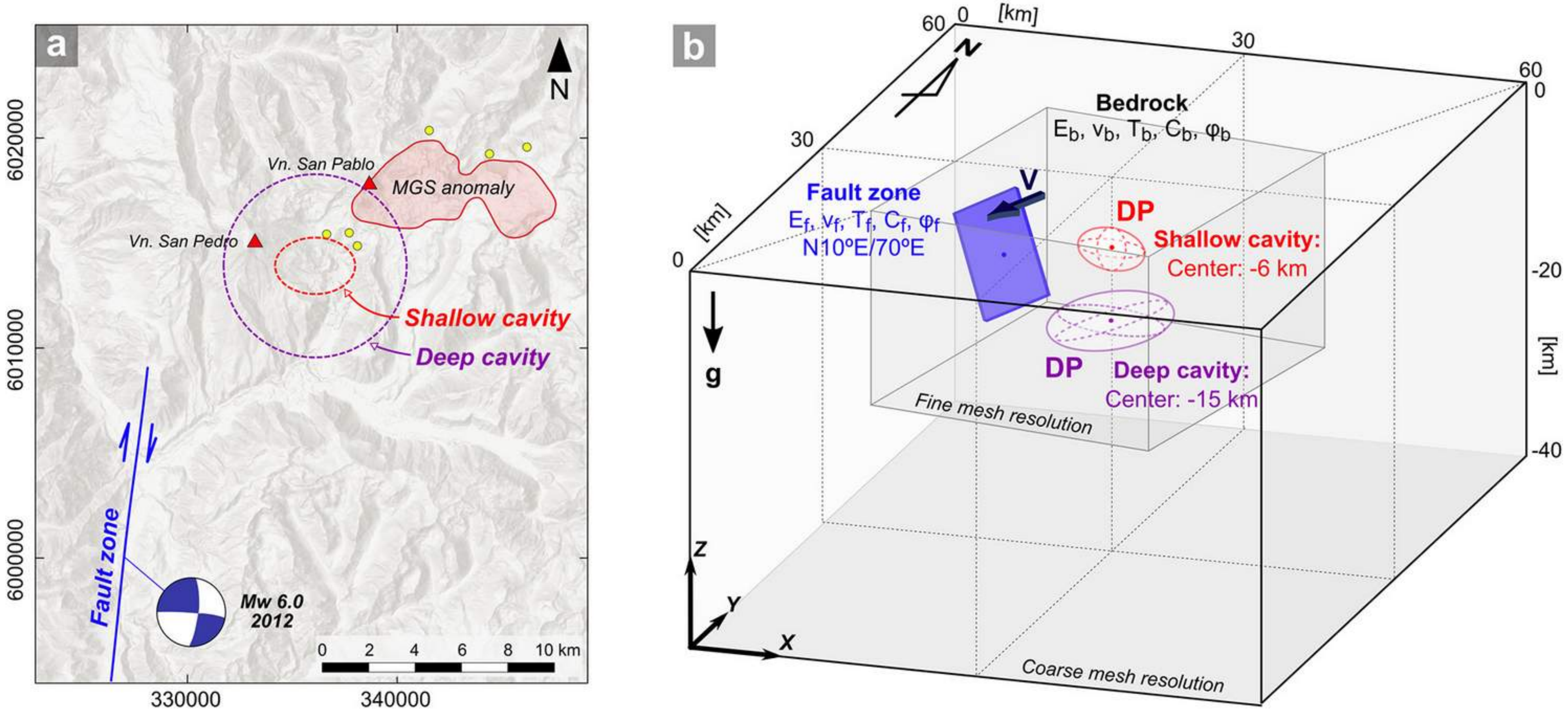




Reyes-Wagner et al., 2017

What drives the interaction between magma reservoirs and fault systems ?

From field to model : conceptual setup



Two cases tested:

1. **Slipping fault's** effect on a reservoir
2. **Chamber inflation's** effect on a fault

We test the influence of **elasto-plastic properties:**

E, T, C, φ of the fault and bedrock

Numerical Method: Adeli

Riad Hassani et al., 1997, 2007, ...
Cerpa et al., 2015, Gerbault et al., 2018, ...

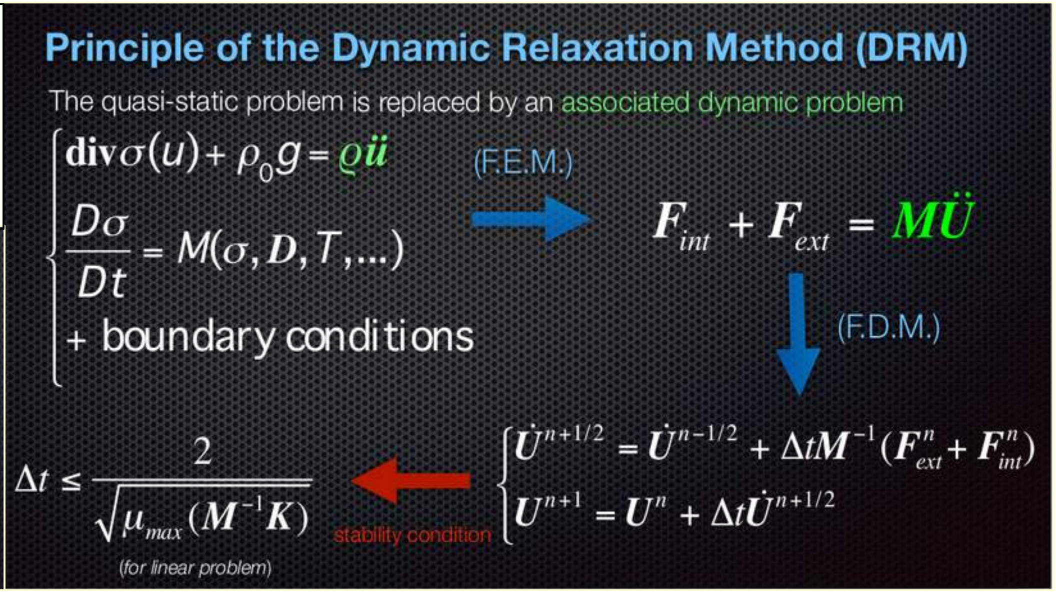
https://code.google.com/archive/p/adeli/

Spatial Discretisation : F.E.M. (P1-interpolation)

3-noded triangles (2D) or 4-noded tetrahedra (3D) elements

Time Discretisation : explicit F.D.M.

Dynamic Relaxation Method (Otter, 1966; Underwood, 1983; Cundall, 1988)



Elasto-plastic rheology accounts for **Drucker-Prager and Tensile yields** :

$$F_{DP}(\sigma) = J_2(\sigma) + \alpha I_1(\sigma) - \alpha P_o \leq 0,$$

$$F_T(\sigma) = I_1(\sigma) - T \leq 0$$

with mean pressure $I_1(\sigma) = \frac{1}{3}\mathrm{tr}(\sigma)$, 2nd stress invariant $J_2(\sigma) = \left(\frac{3}{2} s : s\right)^{\frac{1}{2}}$; $s = \sigma - I_1(\sigma) I$.

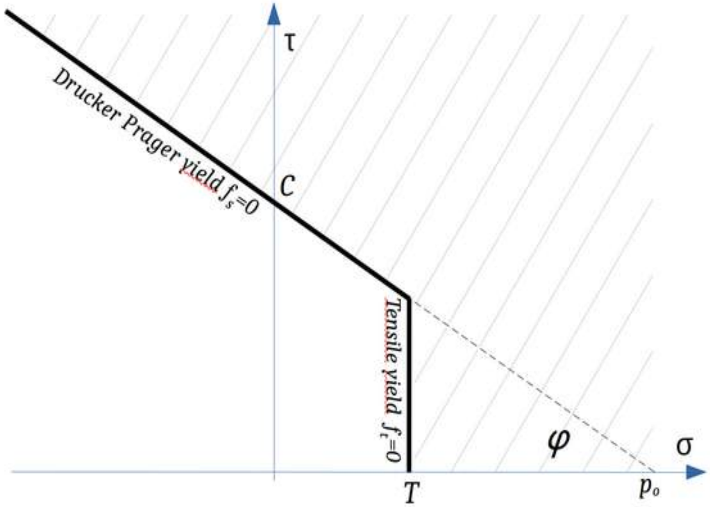
$P_o = \frac{C}{\tan\varphi}$, $\alpha = \frac{6\sin\varphi}{(3-\sin\varphi)}$, tensile strength T, cohesion C and friction angle φ.

Plastic potentials determines the plastic flow :

$$G_{DP}(\sigma) = J_2(\sigma) + \alpha_p I_1(\sigma),$$

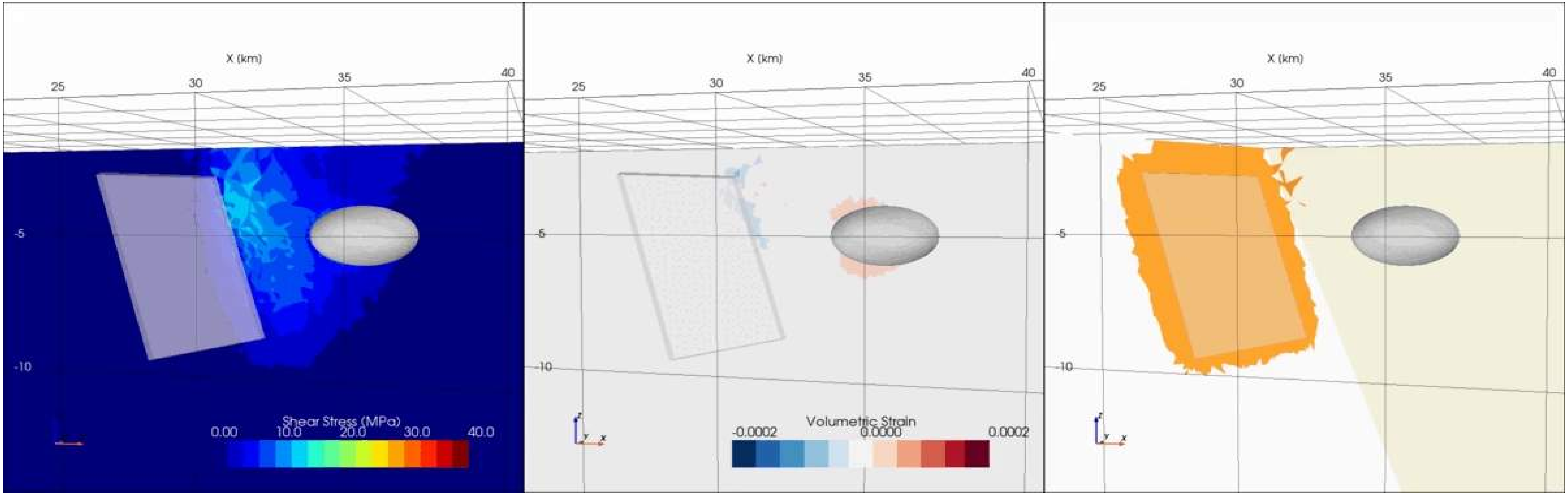
$$G_T(\sigma) = F_T(\sigma)$$

with $\alpha_p = \frac{6\sin\psi}{3-\sin\psi}$, ψ the dilatancy angle, here set to zero.



1. Sliding fault induces reservoir failure ?

How much fault motion is required to trigger cavity walls failure?
What characterizes the bedrock intermediate volume?
For which reasonable rheology?



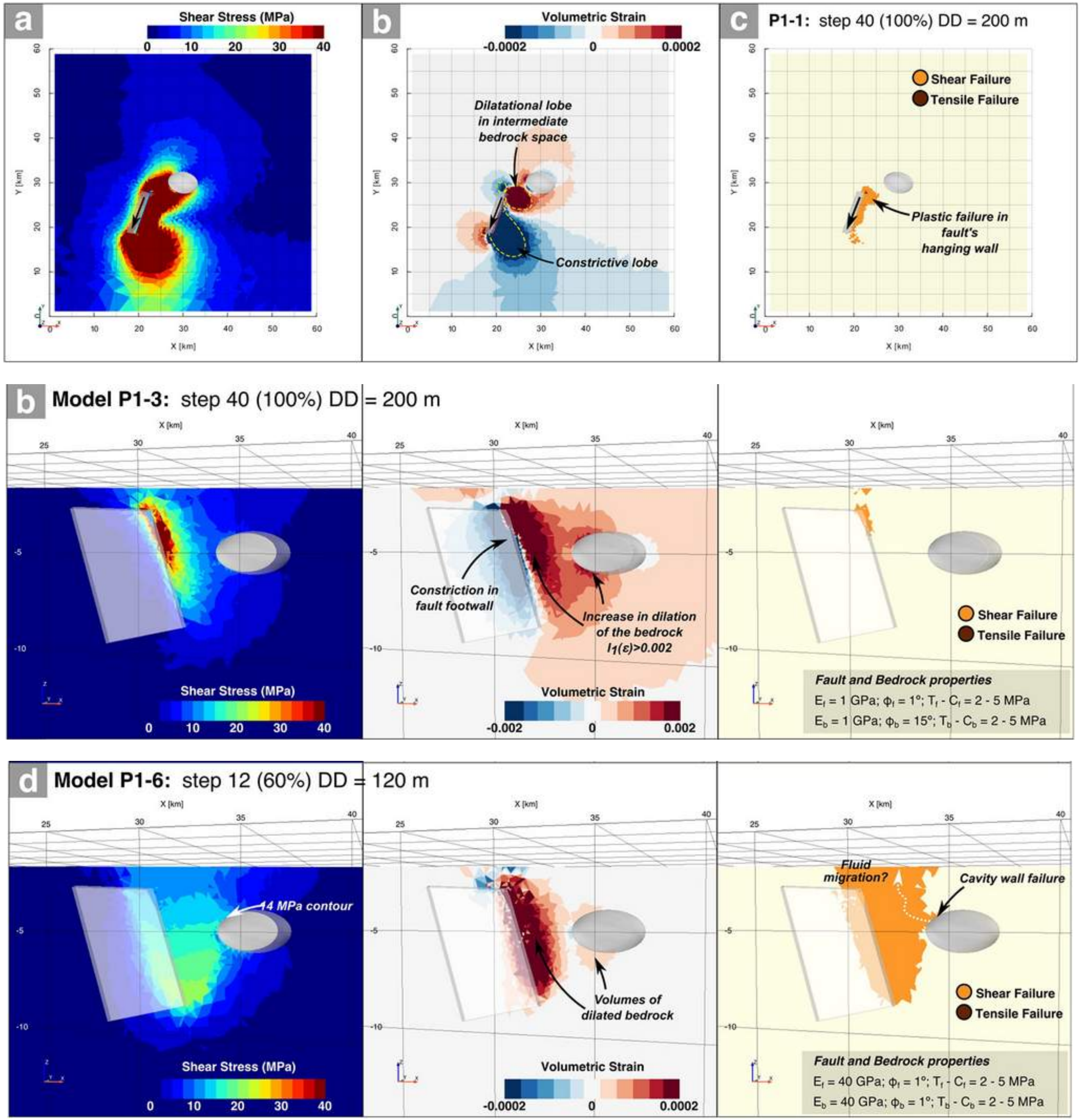
About 60-200 m of accumulated slip is required to fail the reservoir 3 km away !

Sliding fault induces reservoir wall failure ?

Top-plane view: Dextral motion favors dilation close to the chamber

Rheology favors diffuse dilation in the bedrock

Rheology favors shear failure in the bedrock

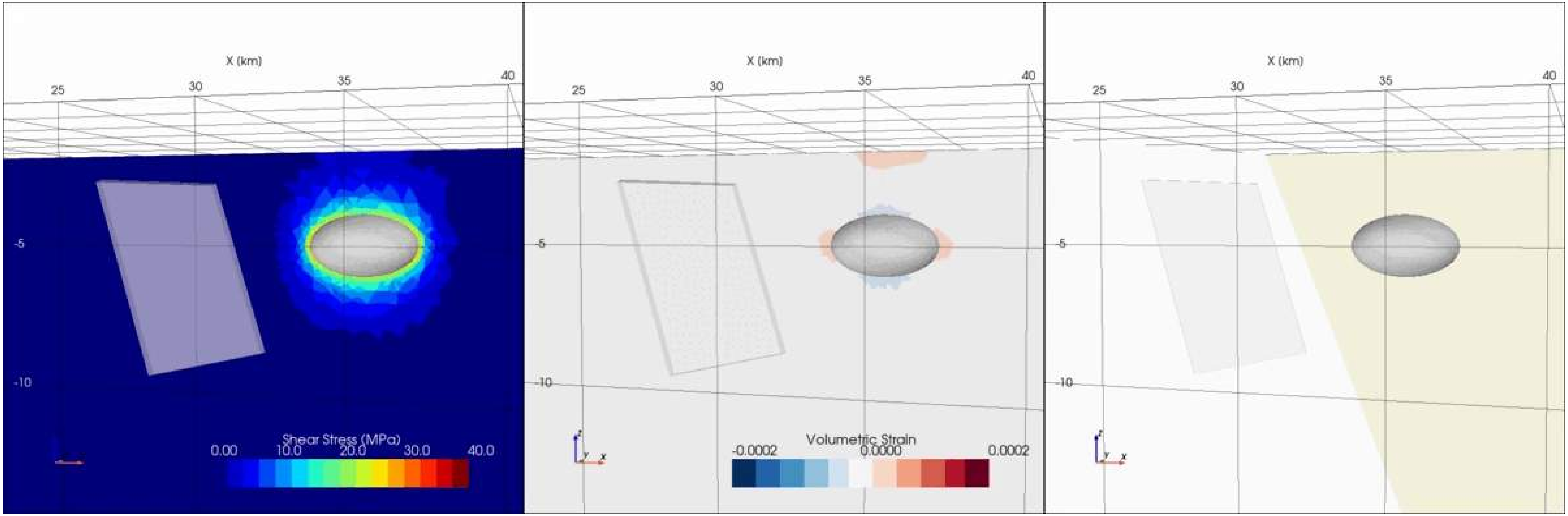


Low E and high bedrock friction

High E and low bedrock friction

2. Inflating chamber induces fault failure ?

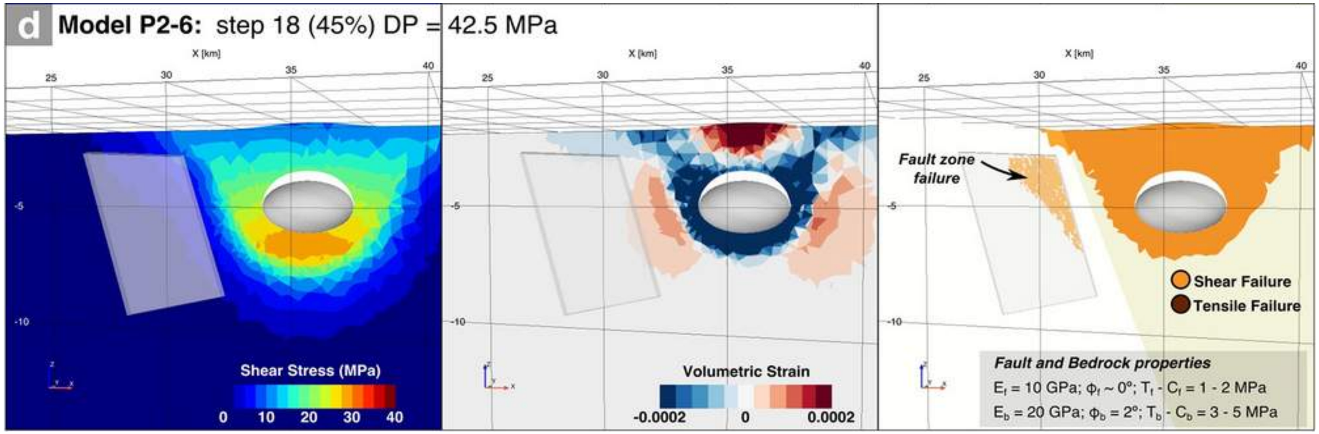
How much magma overpressure triggers fault motion?
Where does dilation occur?



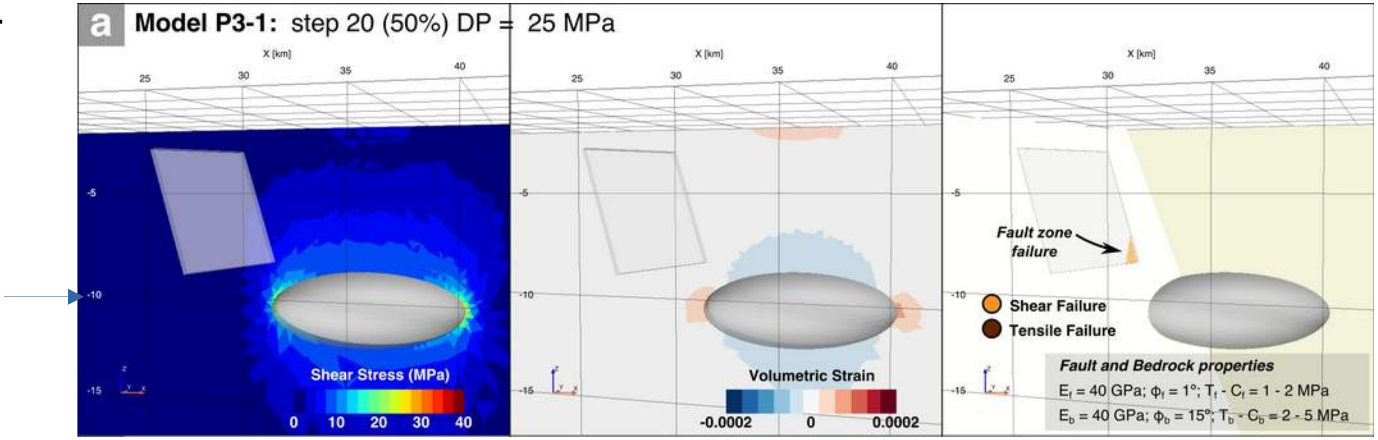
40-100 MPa of overpressure required to induce plastic motion along fault 3 km away !

Inflating chamber induces fault failure?

Shear failure along WEAK faults



A DEEP chamber facilitates fault failure for low DP~25 MPa



Slip and Dilation Tendency Analysis

Adeli model results as **.vtk** files. Results include the full stress and strain tensors, displacement magnitudes, among others.

↓

Extract domain of interest using a sphere filter for a given center and radius.

↓

For each element contained within the sphere, the stress tensor is extracted. The weighted average stress tensor is calculated.

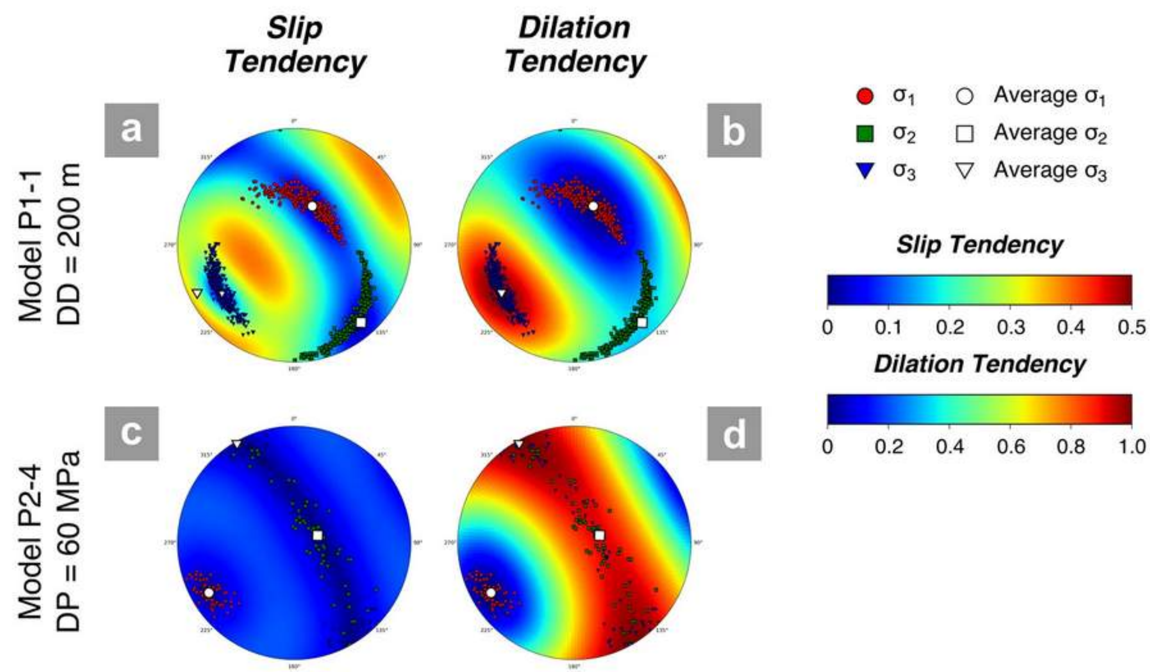
↓

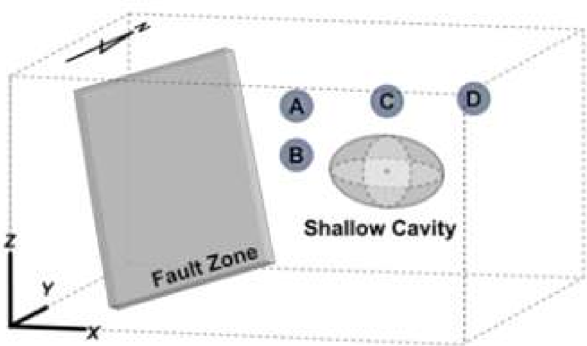
For each n^{th} plane, slip and dilation tendency are plotted as the pole-to-the-plane.

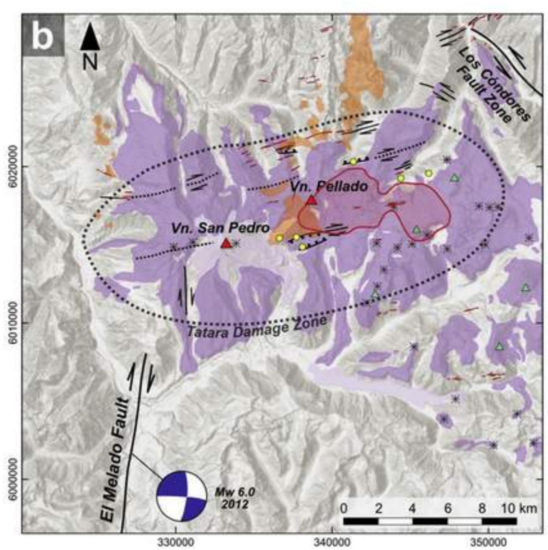
↓

For a finite number of *n* planes in all orientations and considering the weighted average stress tensor, slip and dilation tendency (T_S and T_D) are calculated for each plane:

$$T_S = \frac{\sigma_s}{\sigma_n} \qquad T_D = \frac{\sigma_1 - \sigma_n}{\sigma_1 - \sigma_3}$$







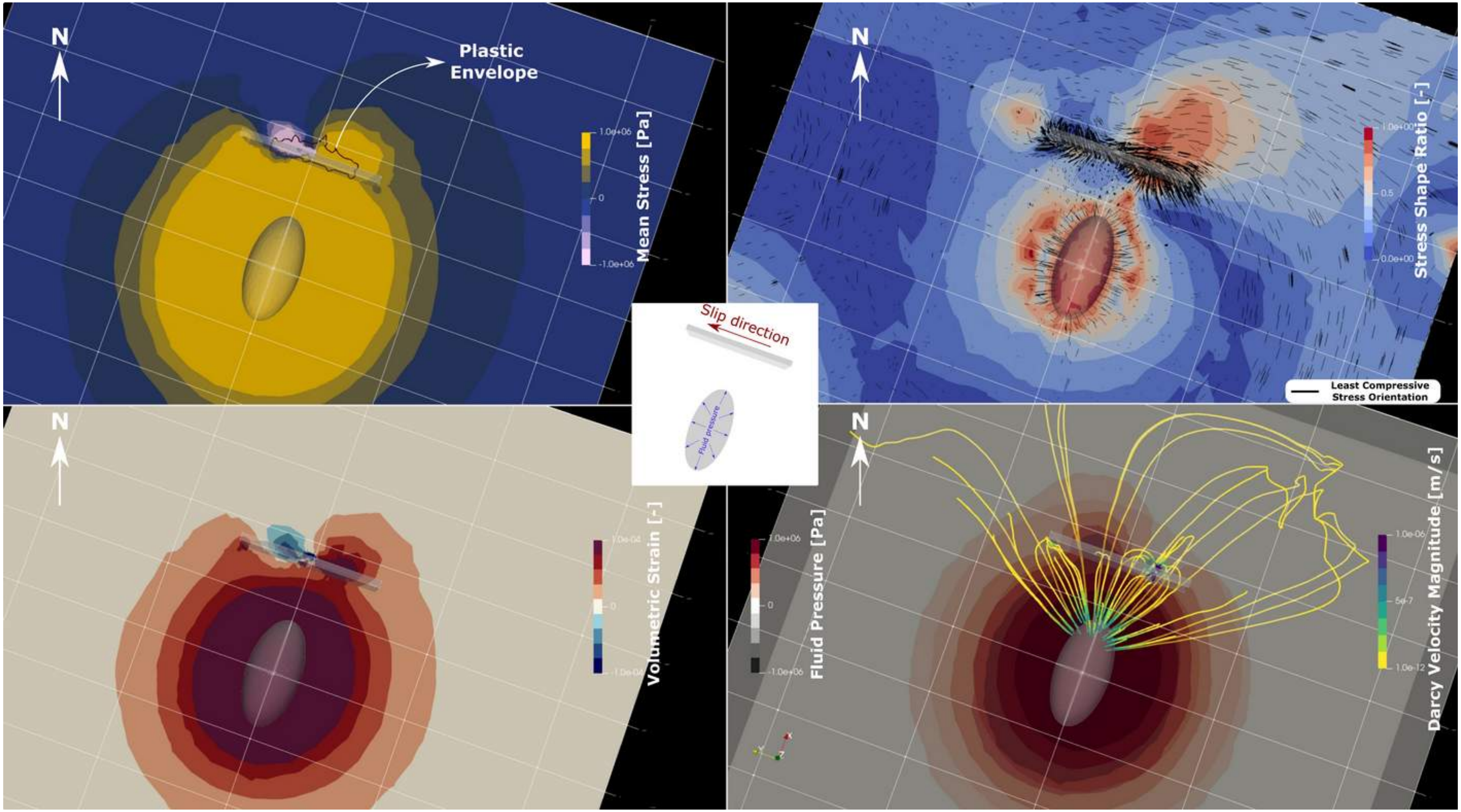
Slip tendency consistent with E-NE oriented fault scars in « Damage zone »

Link other structures to regional stress field which was not accounted for here.

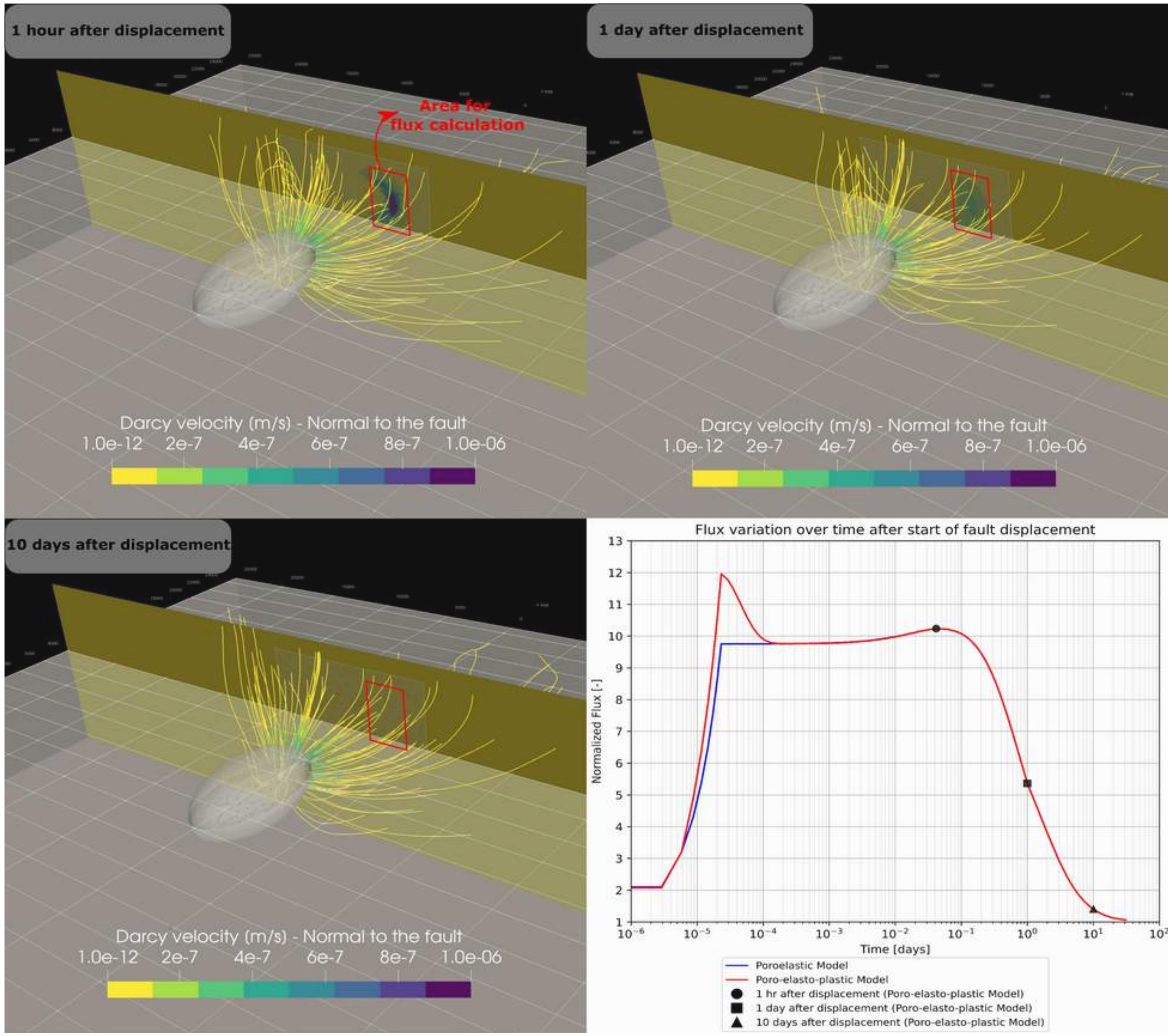
Step 2 - Implementation of a coupled fluid-solid poro-elasto-plastic approach (Sáez et al., in prep)

A numerical scheme is developed to quantify fluid flow in a 3D fully coupled poro-elasto-plastic approach implemented using Python's opensource FEM library FEniCS.

This approach is first validated with benchmarks : Cryer's sphere test, and a cylinder loading test. A synthetic geothermal system with the presence of a crustal fault is then modeled to evaluate suction pumping mechanisms from a geothermal reservoir due to fault motion.



Synthetic model results: Fluid flow and rock deformation over time



1. Fluids flow out of a pressurized source and concentrate in the dilatational domains induced by an imposed sinistral fault motion.

2. Fluid flux variation is a TRANSIENT process: it increases 10 times relative to the stationary flux an hour after slip, but it almost goes back to stationary flux 10 days after fault motion.

3. Fluid flux increases during plastic failure development, in comparison to an elastic rheology.

Main Conclusions

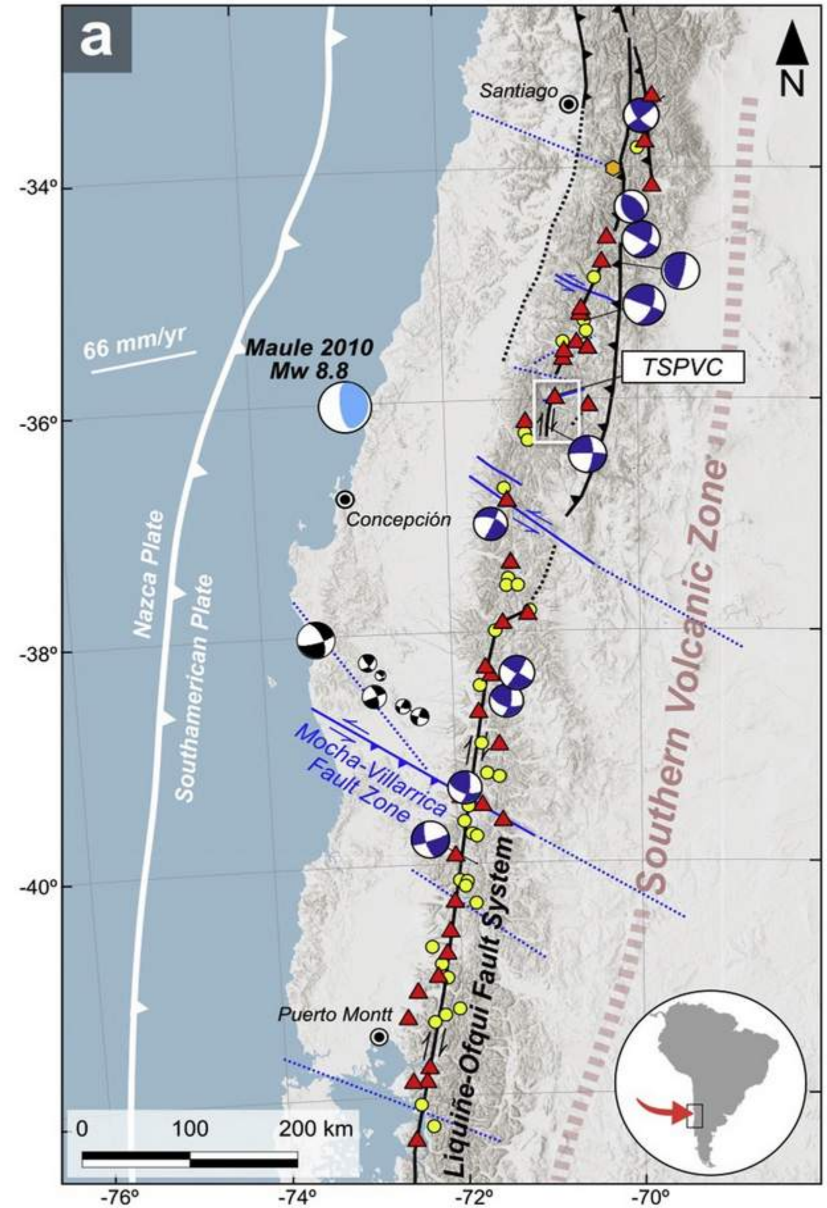
- Both reservoir inflation and dextral fault motion can induce dilatation domains in bedrock, and open fluid pathways.
- Slip tendency consistent with E-NE oriented fault scars in « Damage zone » at TSP
- Need to link quantified parameters at sample and field scales.
- Role of regional stress field remains to be incorporated.
- Coupled Darcy flow and poro-elasto-plastic behavior on its way.

Ruz Ginouves et al., JGVR 2020, 2021

Motivation

- Andean margin hosts >90 active volcanoes & >300 active geothermal systems.
- Dyking and volcanic activity spatially associated with fault zones, crustal earthquakes broadly related to volcanic activity.
- This interplay is widely addressed through structural geology, laboratory and numerical experiments:

  Identification of feedback relationships between deformation and fluid migration.



What drives the interaction between magma reservoirs and fault systems over time-scales?

Influences of φ and E on conditions for brittle failure