Computational Optimization to Minimize Fault Activation

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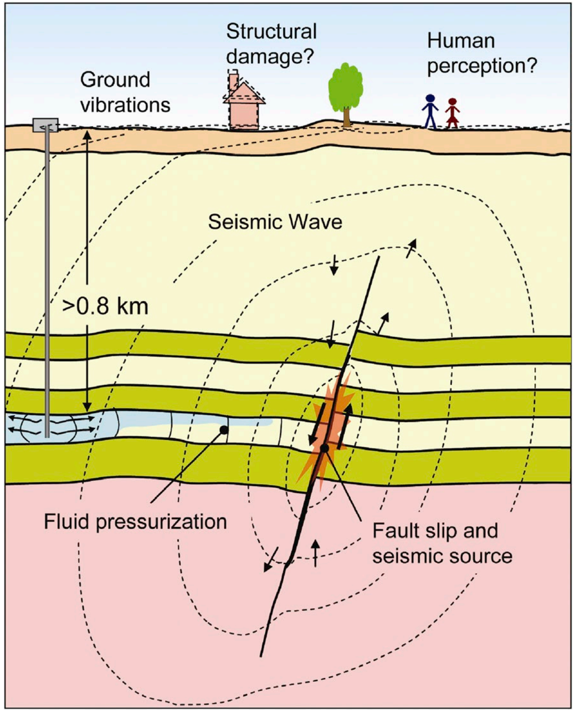
Motivation

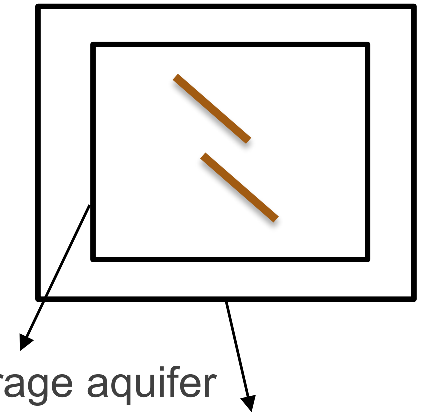


Rutqvist et al., 2014

- Challenge:
  - Pressure build-up due to CO_2 injection can lead to fault slip and induced seismicity
- Goal of this work:
  - Apply Stanford Unified Optimization Framework to determine injection well locations that minimize fault activation risk

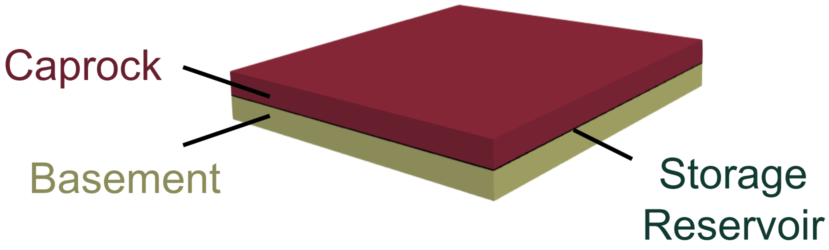
Fault Slip Tendency (FST) Minimization

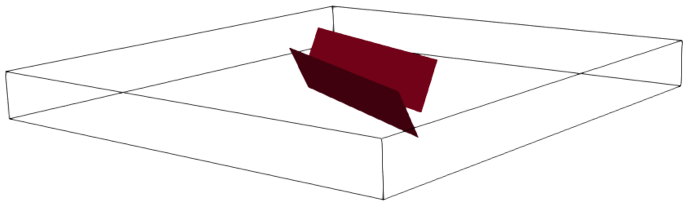
- Fault slip tendency $T_s = \left|\frac{\tau}{\sigma_n'}\right|$, τ: shear stress, σ_n': effective normal stress
- Fault may slip when $T_s \geq \mu$, μ: fault friction coefficient (~0.6)
- Objective
  - Minimize the maximum value of FST on both faults during the CO_2 injection period by optimizing the locations of 3 injection wells
- Constraint
  - All injected CO_2 must stay inside storage aquifer



Geomodel Setup: 3D Faulted System*

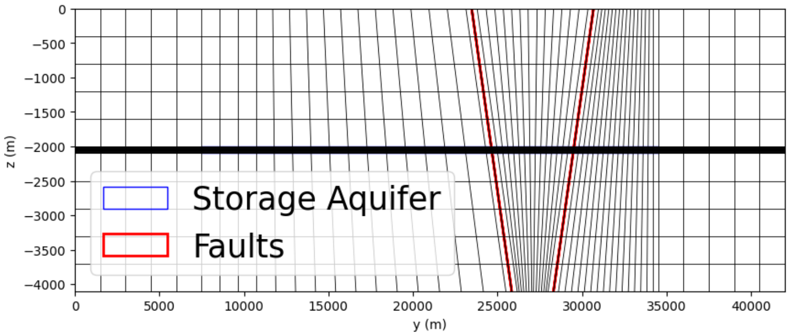
- Setup partly based on Silva et al. (IJGGC 2023) Gulf of Mexico model
- Entire domain: 41 km × 42 km × 4100 m, 60 × 60 × 30 cells (108,000 total)
- Storage aquifer: 25 km × 27 km × 100 m, 50 × 50 × 20 cells (50,000 total)

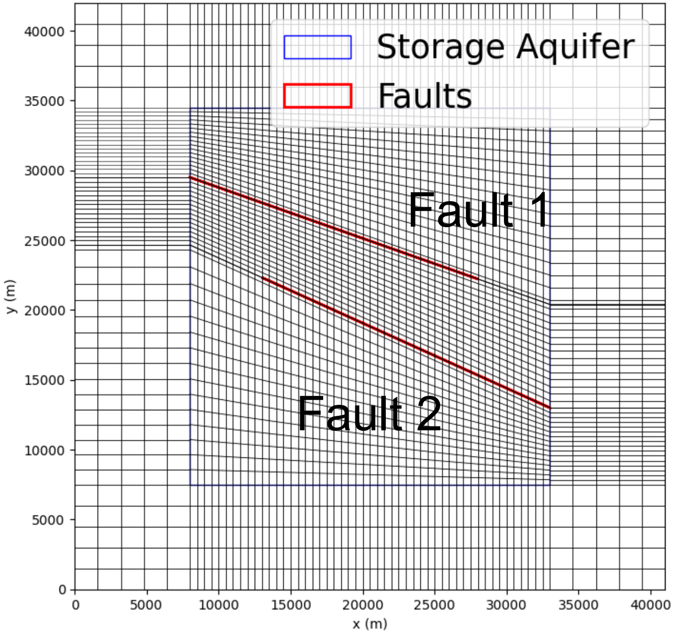




*Model developed by Xiaowen He

Geomodel Setup: 3D Faulted System*

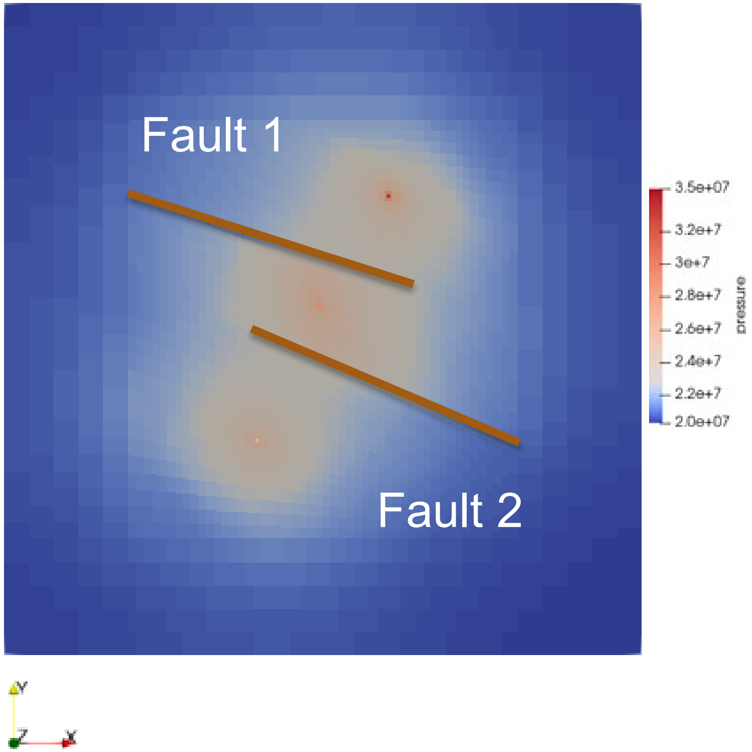




- Fault 1: Azimuth = 25º, Dip = 60º
- Fault 2: Azimuth = 20º, Dip = 60º

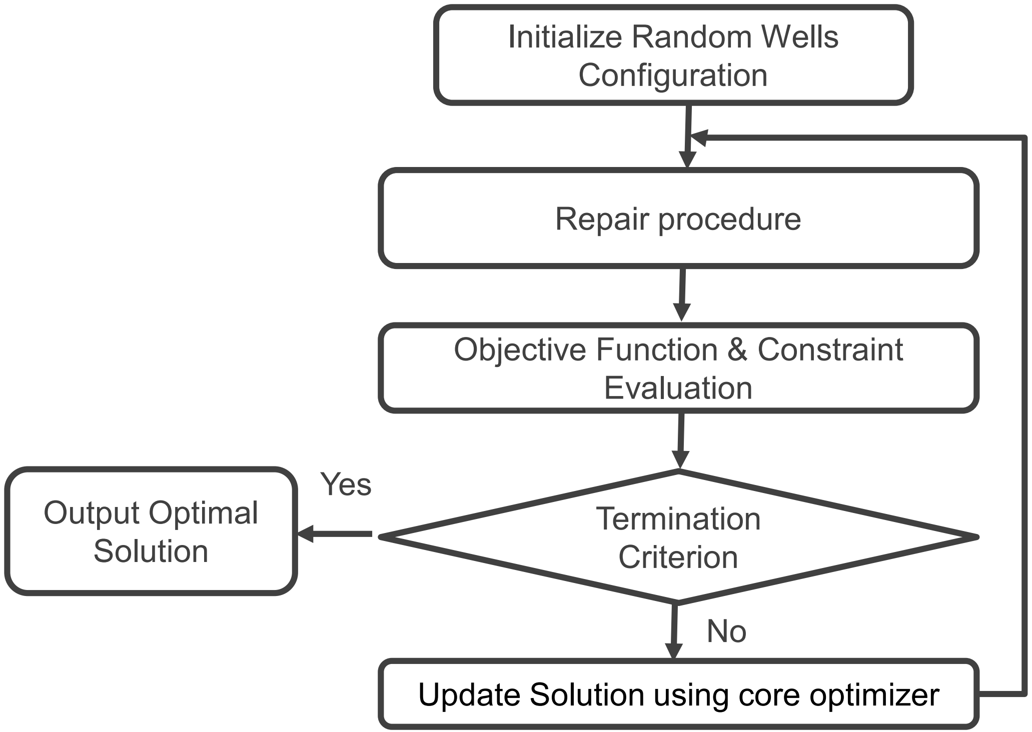
*Model developed by Xiaowen He

Model Description (Single Realization)



- 3 vertical fully perforated wells
- 1.5 Mt/year CO_2 in each well for 50 years
- Stress regime
  - Vertical Stress = 0.24 MPa/km
  - Max. Horizontal Stress = 0.18 MPa/km
  - Min. Horizontal Stress = 0.15 MPa/km
- Poisson's ratio, ν = 0.315
- Young's modulus, E = 15 GPa
- Biot's coefficient, $\alpha = 0.9$
- Fault Permeability = 0.1 mD

Optimization Workflow using UOF

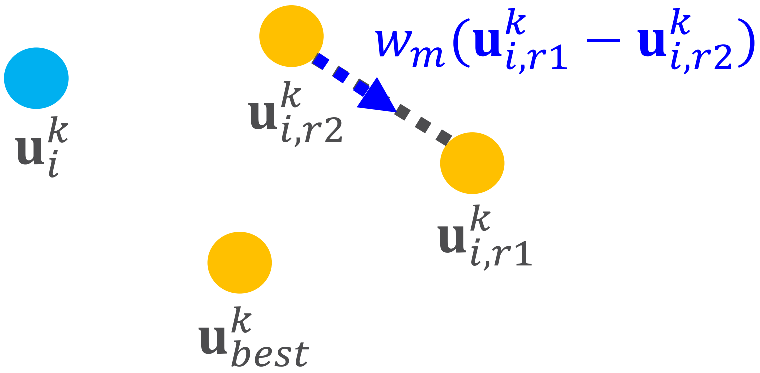


- Repair procedure ensures a minimum well spacing of 1 km
- Objective function is maximum FST over the injection period
- Constraint ensures all injected CO_2 remains in storage aquifer
- Core optimizer for this work is **Differential Evolution**

Zou et al. (2022, 2023)

Differential Evolution (DE) – Particle *i*, Iteration *k*

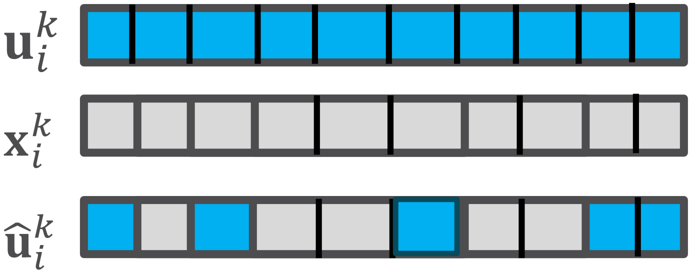
Mutation



$$\mathbf{x}_i^k = \mathbf{u}_{best}^k + w_m(\mathbf{u}_{i,r1}^k - \mathbf{u}_{i,r2}^k)$$

- Population (N) = 8
- Mutation factor (w_m) = 0.5
- Crossover factor (c_f) = 0.7
- DE strategy (mutation & crossover methods) = DE/best/1/bin

Crossover

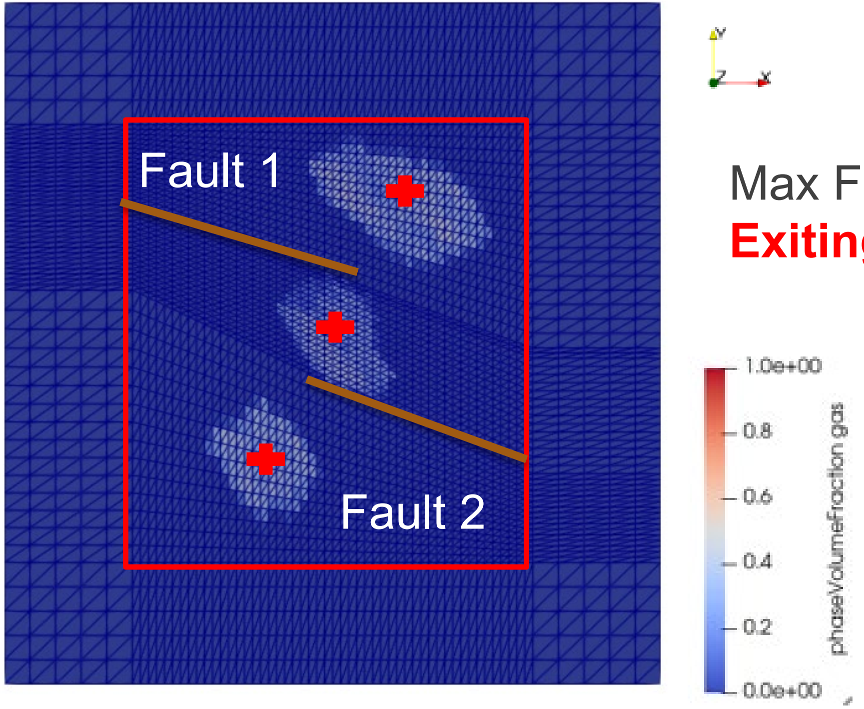


Selection

$$\mathbf{u}_i^{k+1} = \begin{cases} \mathbf{u}_i^k & \text{if } f(\mathbf{u}_i^k) < f(\hat{\mathbf{u}}_i^k) \\ \hat{\mathbf{u}}_i^k & \text{if } f(\hat{\mathbf{u}}_i^k) < f(\mathbf{u}_i^k) \end{cases}$$

Price et al., 2005

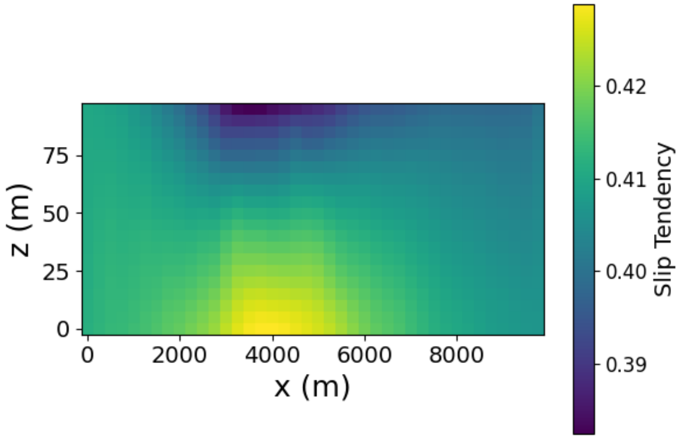
Heuristic Well Placement



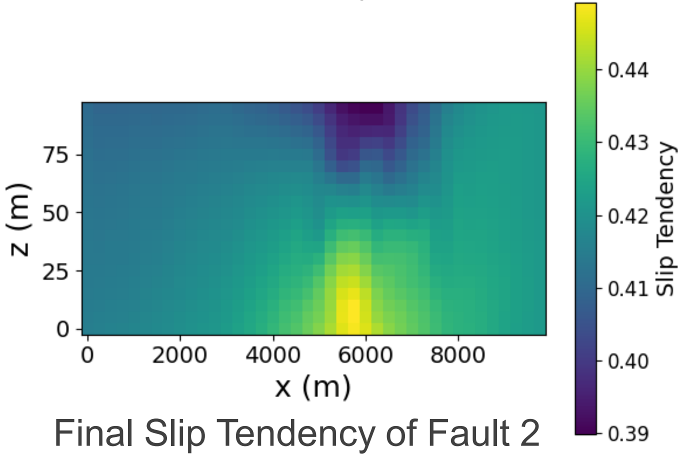
Top Layer Saturation

Max FST = 0.45

Exiting CO_2 = 0.10



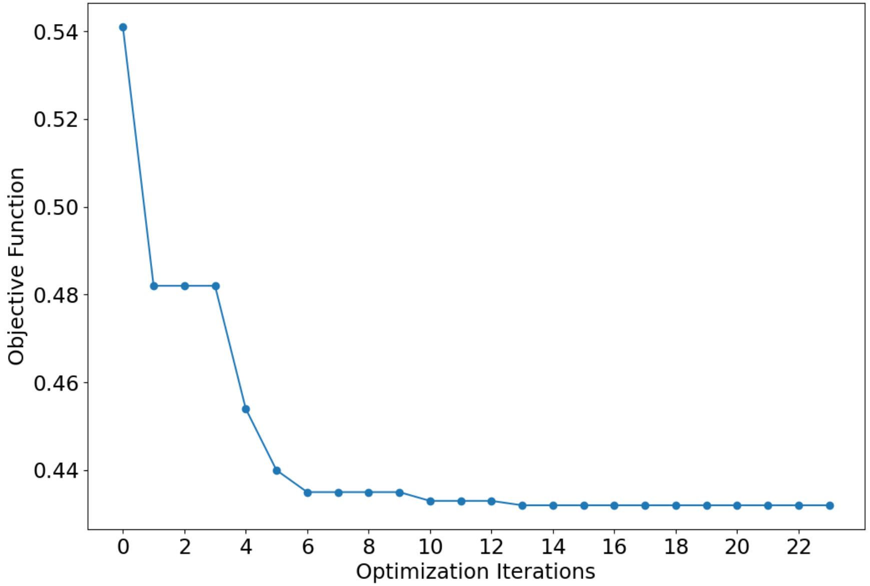
Final Slip Tendency of Fault 1



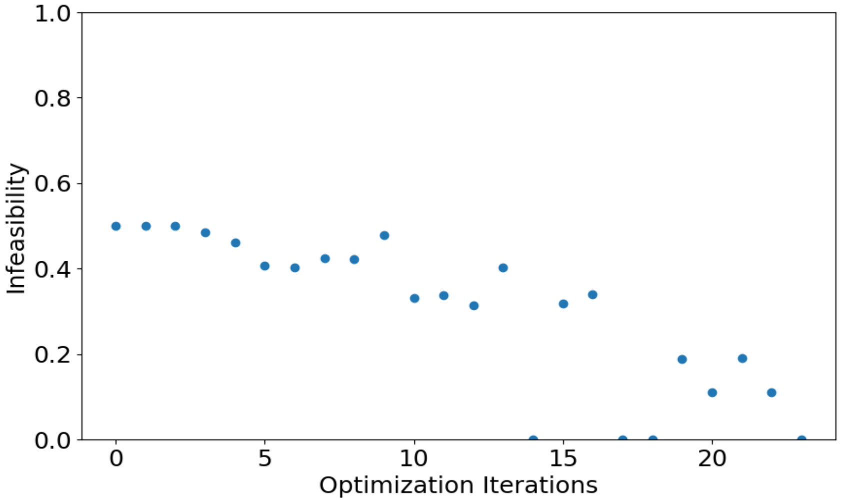
Final Slip Tendency of Fault 2

Differential Evolution Optimizer Performance

Parameter	DE Value	Heuristic Value
Maximum FST	0.431	0.45
Exiting CO2	0.00	0.10

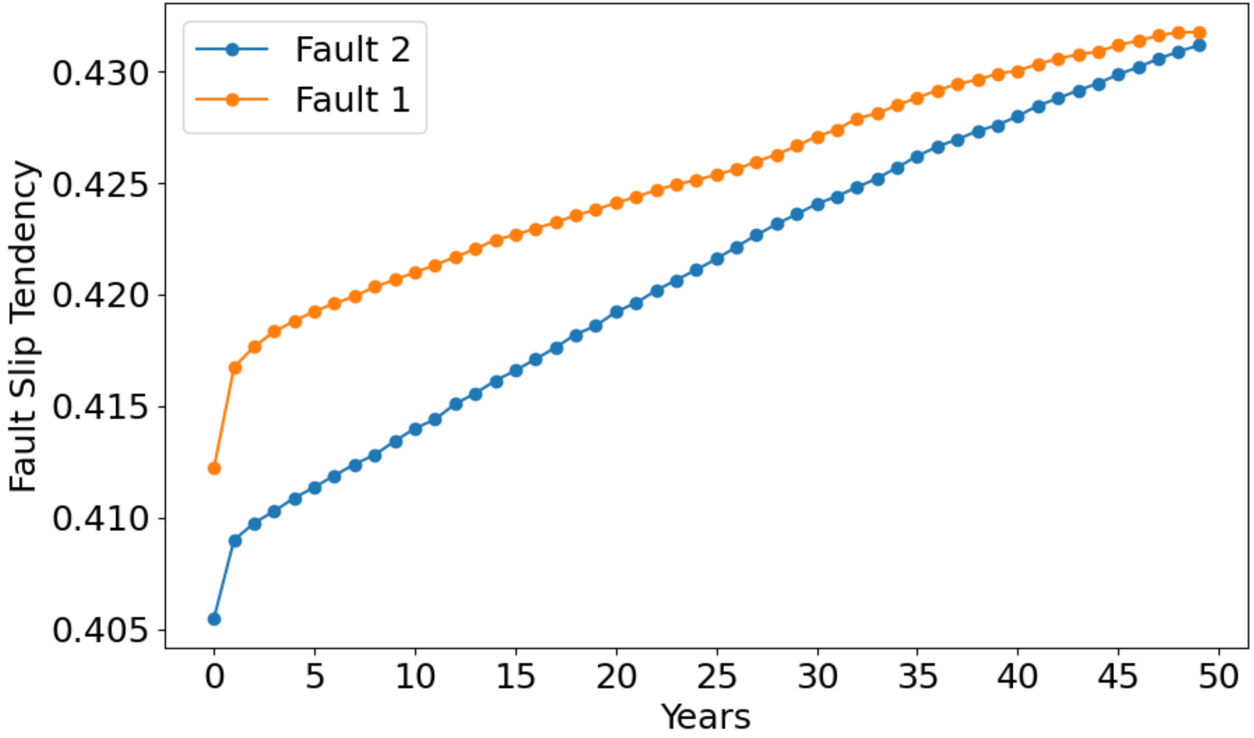


Objective Function (max FST) vs Optimization Iterations

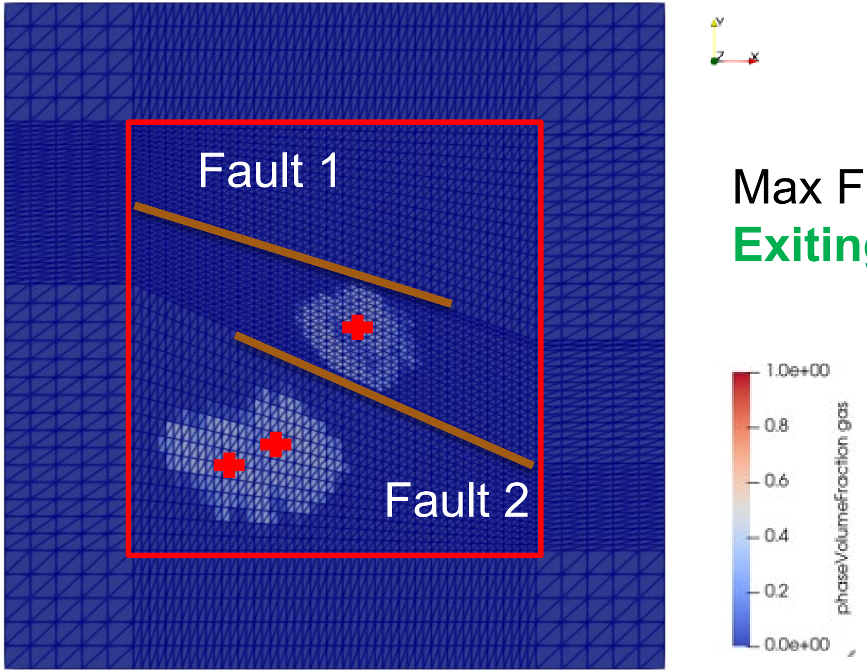


Infeasibility vs Optimization Iterations

Optimization Results



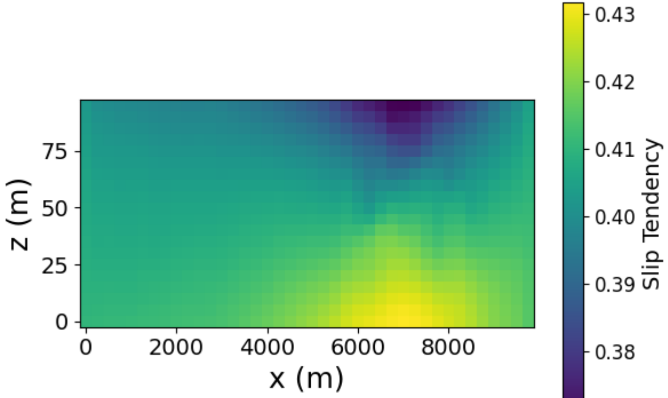
Optimization Results



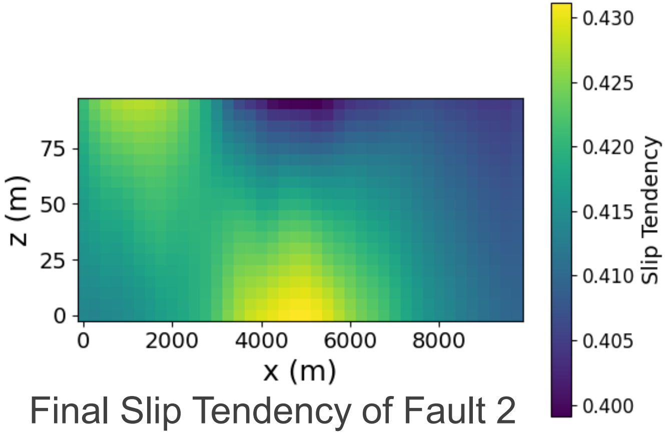
Top Layer Saturation (Largest Plume Spread)

Max FST = 0.431

Exiting CO_2 = 0.00



Final Slip Tendency of Fault 1



Final Slip Tendency of Fault 2

Conclusions

- Optimization framework found a configuration that minimized fault activation risk while ensuring all CO_2 stayed in the storage aquifer
- Optimal well placement is affected by fault geometry, reservoir heterogeneity and initial conditions
- FST experiences slow (approximately linear) growth over the injection period and remains below the risk threshold for the full operation
- Slip tendency at the base of the fault is higher than in other regions, suggesting that monitoring should be performed in that region

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Thank you!