Coupled Flow and Geomechanical Modeling of Induced Seismicity in Faulted Reservoirs

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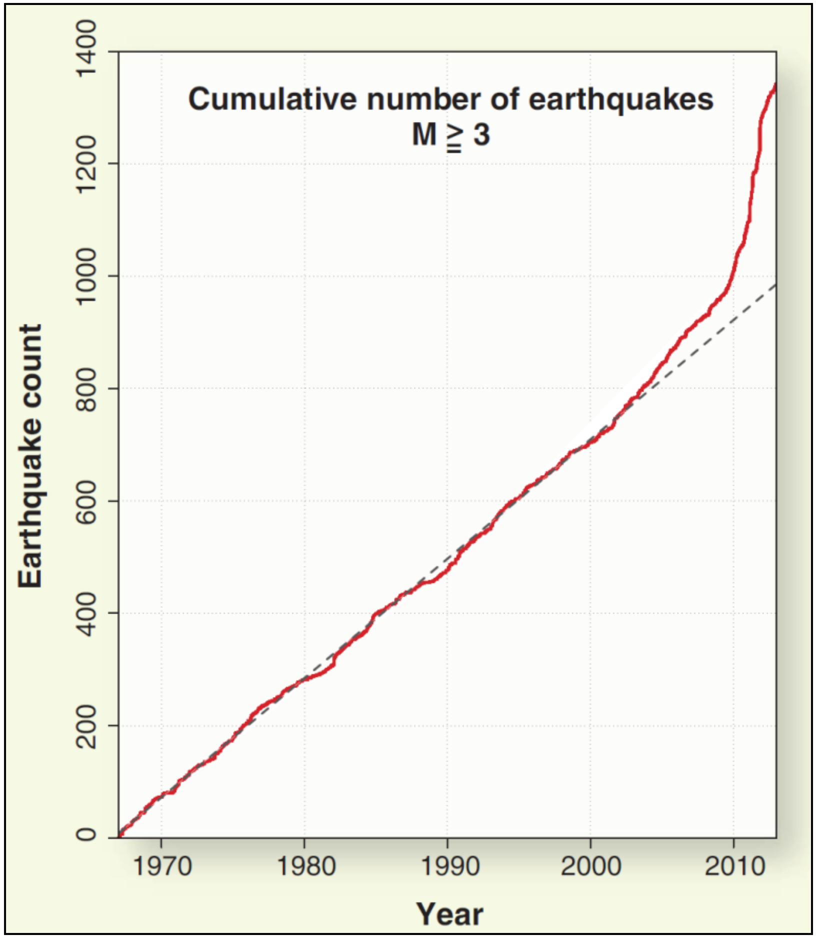
Key questions in the industry

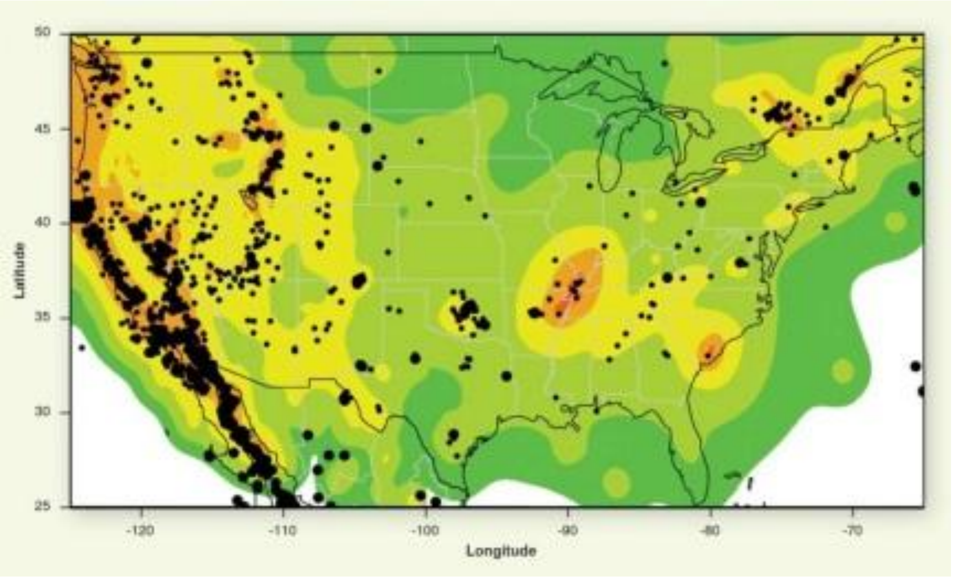
- How much can be extracted/stored, and at what rate?
- What is the risk of triggered/induced seismicity?
- What is the risk of fluid leakage?

Geomechanical modeling of faults is essential

Birkholzer and Zhou, *IJGGC* 2009; Morris et al., *IJGGC* 2011; Szulczewski et al, *PNAS* 2012; Chiaramonte et al., *EG* 2008; Rutqvist et al, *IJGGC* 2010; Cappa and Rutqvist, *GRL* 2011; Zoback and Gorelick, *PNAS* 2012; Juanes et al., *PNAS* 2012

Induced seismicity: a rising concern



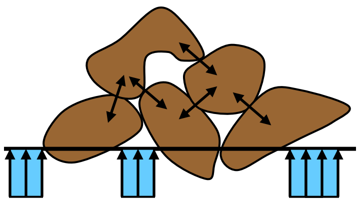


What is the mechanism?

Fluid mass conservation
- Primary unknown: p

Linear momentum balance
- Primary unknown: $\boldsymbol{u}$

Two-way coupling:



$$\boldsymbol{\sigma}' = \boldsymbol{\sigma} - bp\mathbf{1}$$

Effective stress

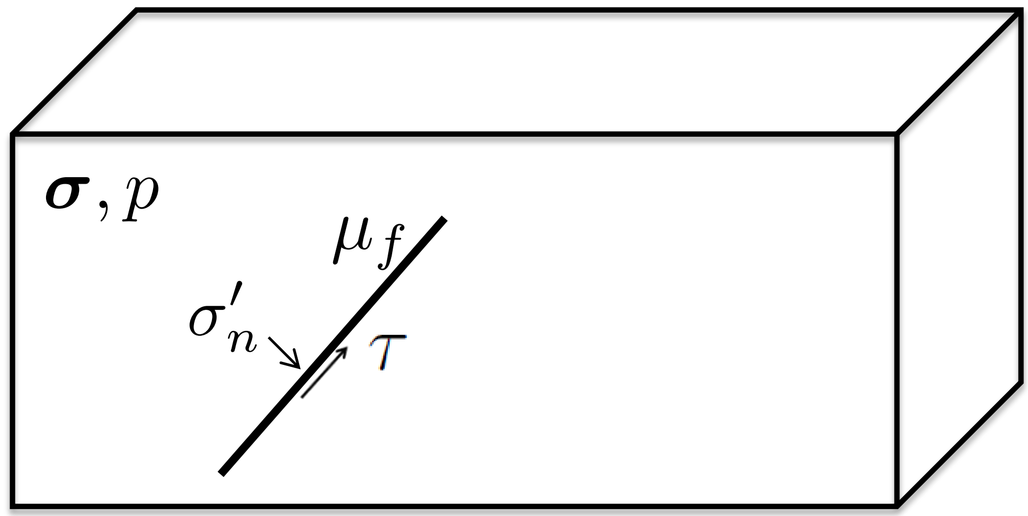
$$\boxed{\text{F}} \rightleftarrows \boxed{\text{M}}$$

Change in volume

Change in reservoir properties: ϕ, $\boldsymbol{k}$

Biot, *JAP* 1941
Geertsma, *AIME* 1957
Rice et al, *RGSP* 1976

What is the mechanism?



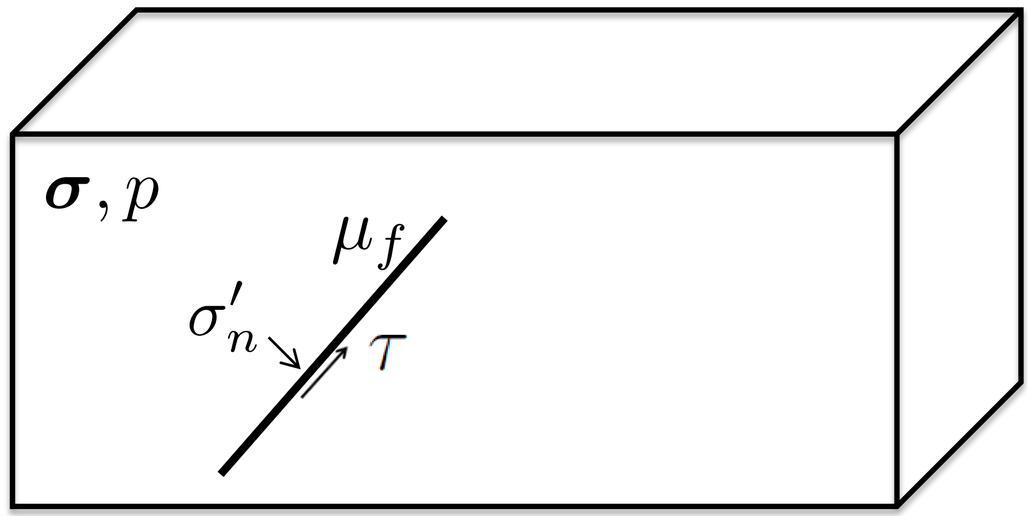
Effective normal stress on fault: $\sigma'_n = \sigma_n - bp$

Fault friction stress: $\mu_f \sigma'_n$

Fault slips (Mohr-Coulomb) if: $\tau - \mu_f \sigma'_n > 0$

Define Coulomb Failure Function: $\Delta\mathrm{CFF} = \Delta\tau - \Delta\left[\mu_f(\sigma_n - bp)\right] > 0$

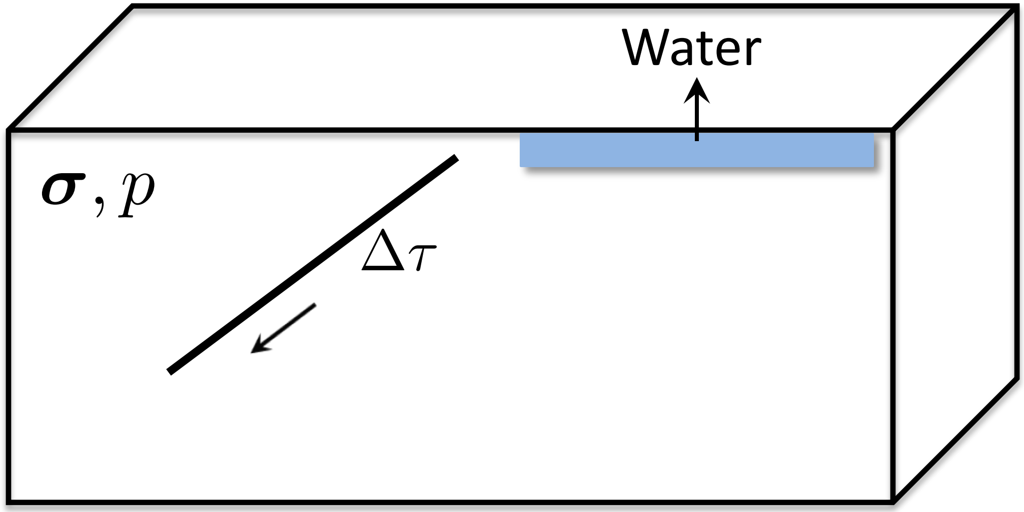
What is the mechanism?



Tendency to slip if: $\Delta\mathrm{CFF} = \Delta\tau - \Delta\left[\mu_f(\sigma_n - bp)\right] > 0$

$$\Rightarrow \begin{cases} \Delta\tau > 0 & \text{(poroelastic loading)} \\ \Delta\sigma_n < 0 & \text{(poroelastic unloading)} \\ \Delta p > 0 & \text{(fluid injection)} \\ \Delta\mu_f < 0 & \text{(fault weakening)} \end{cases}$$

Groundwater extraction can induce fault slip



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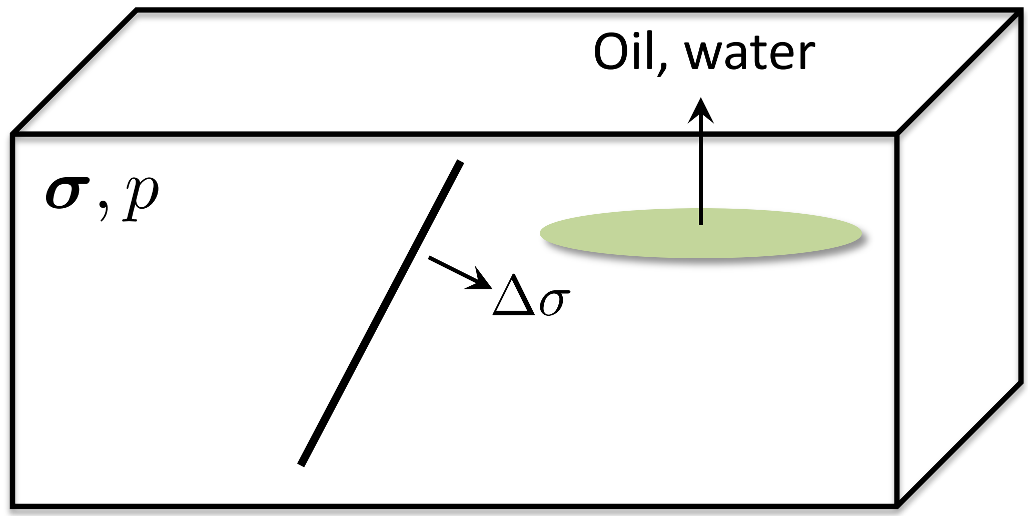
Production can induce fault slip



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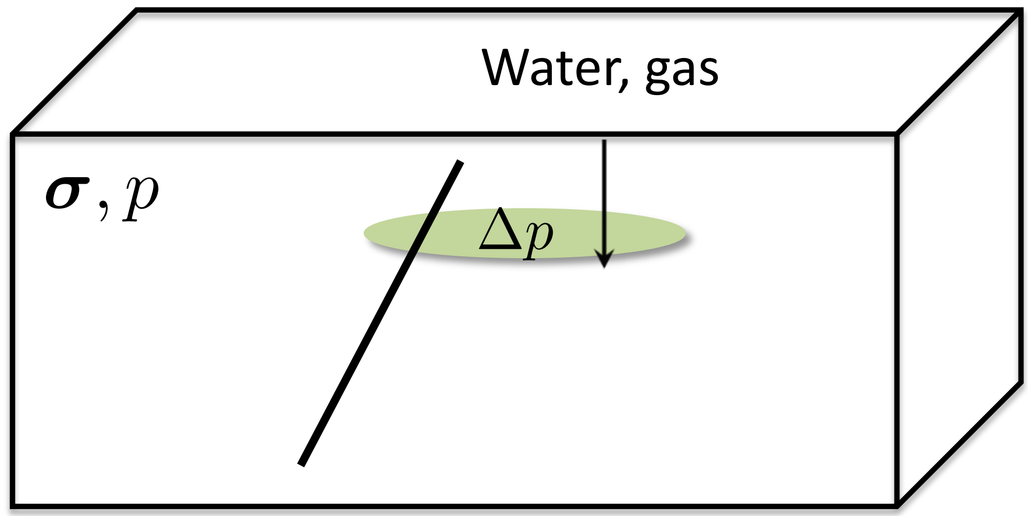
Injection can induce fault slip



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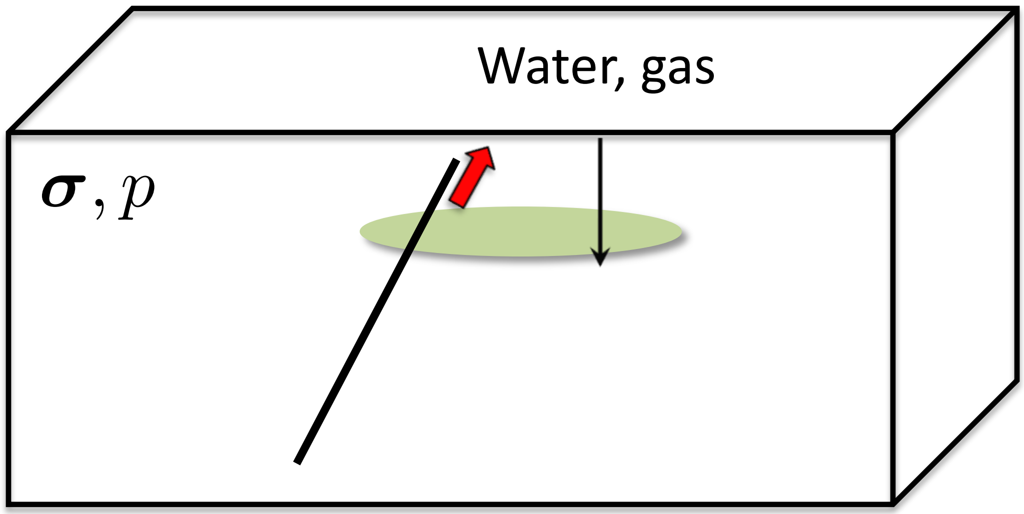
Fault slip can lead to leakage



Δk_f = f (slip, compression)

Fault leaks if: $\Delta k_f > 0$

$$\Rightarrow \begin{cases} \Delta\tau > 0 & \text{(poroelastic loading)} \\ \Delta\sigma_n < 0 & \text{(poroelastic unloading)} \\ \Delta p > 0 & \text{(fluid injection)} \\ \Delta\mu_f < 0 & \text{(fault weakening)} \end{cases}$$

How can we model it?

*What are the **challenges**?*

- **Coupled physics**: multiphase flow, deformation, rock failure
- **Multi-scale** in space and time
- **Fault modeling**: mechanical and hydraulic behavior in presence of multiple fluids is unknown
- **Computational challenges:** discretization of equations, coupling strategy

Multiphase poromechanics

Fluid mass conservation	Linear momentum balance
- Primary unknowns: p, S_w	- Primary unknown: $\boldsymbol{u}$

Multiphase challenges

- Nonlinear because gases are compressible and phases appear/disappear
- Defining effective stress in presence of multiple fluid phases
- Coupling is pervasive.

State variables: pressures, saturations, displacement

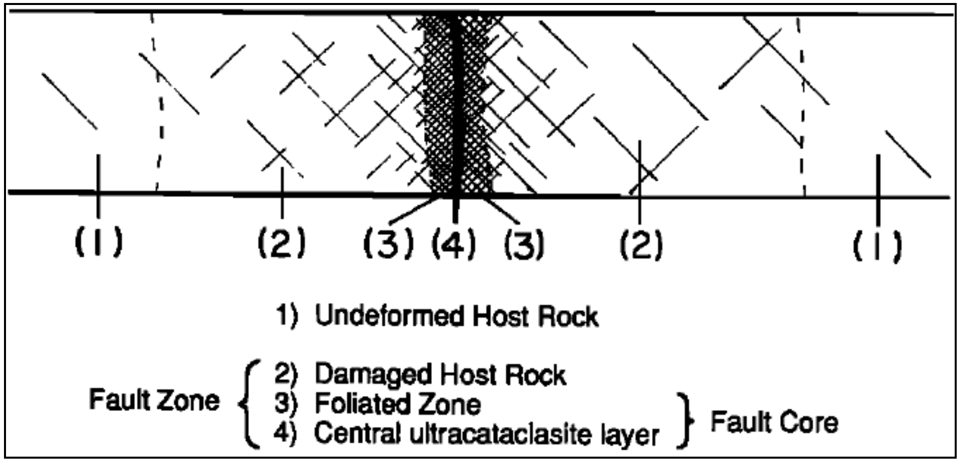
Material coefficients: bulk density, poroelastic coefficients and moduli, pore compressibility, porosity, permeability

Coussy, 1995

Seismicity is induced due to rupture of a fault

Structural interpretation of a fault

surface of discontinuity

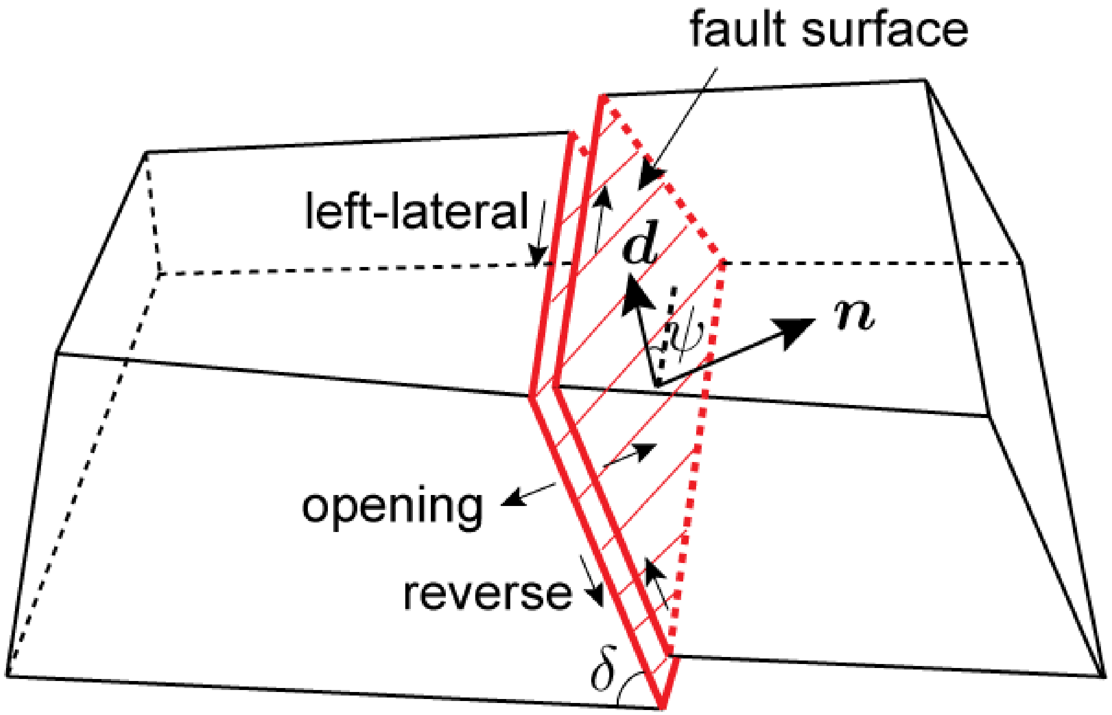


zone of different properties

Chester et al., *J. Geophy. Res.* 1993
Anderson, *Tectonophy* 1983
Marone, *Ann. Rev. EPS*, 1998

Structural interpretation in our framework

surface of discontinuity, with different properties across the surface



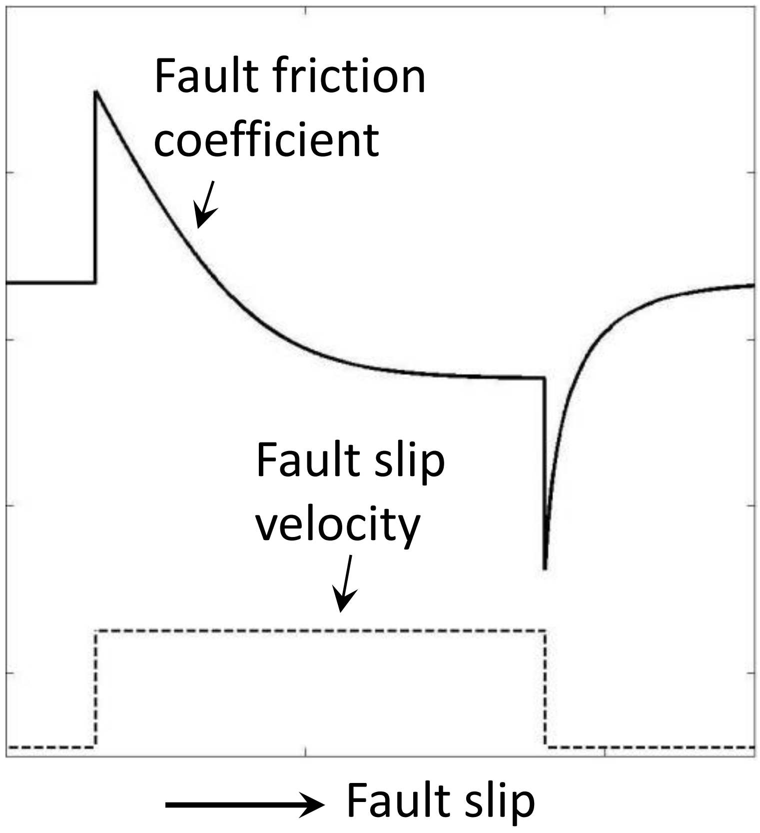
$\boldsymbol{d}$: fault slip vector

$\boldsymbol{n}$: normal vector

δ: dip angle

Functional interpretation of a fault

Fault friction and strength evolve *non-linearly* and *dynamically*

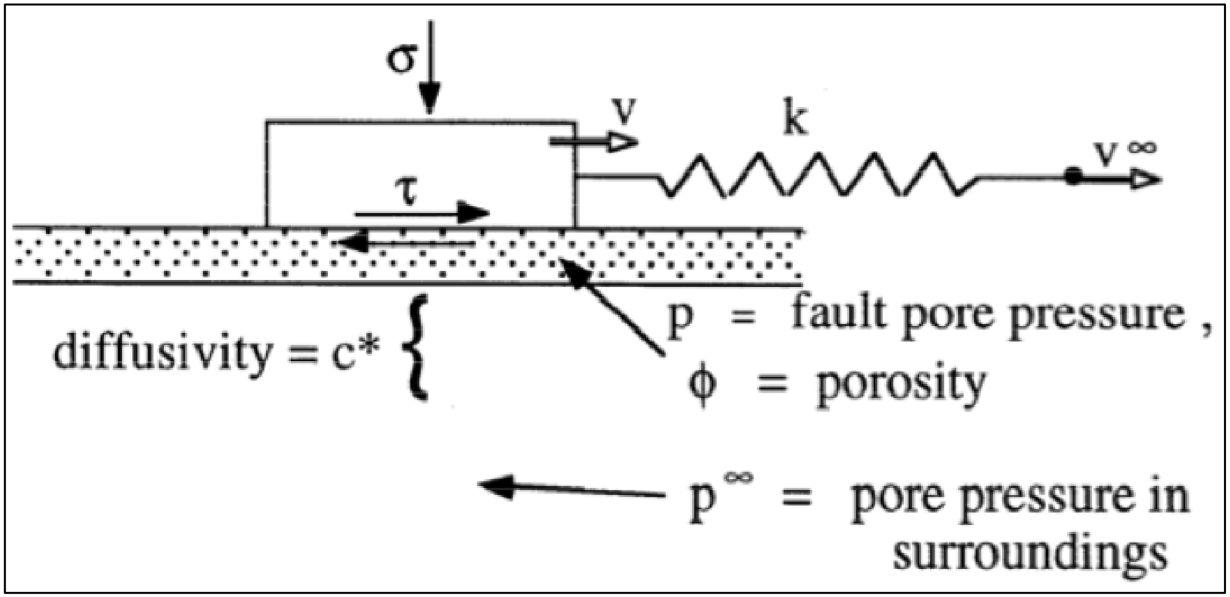


Friction depends on rate of sliding and history of sliding

Marone, *Ann. Rev. EPS* 1998

Functional interpretation in our framework

A block-spring model under quasi-dynamic sliding



Friction model:

$$\mu_f = \mu_0 + A \ln\left(\frac{V}{V_0}\right) + B \ln\left(\frac{V_0 \theta}{d_c}\right),$$

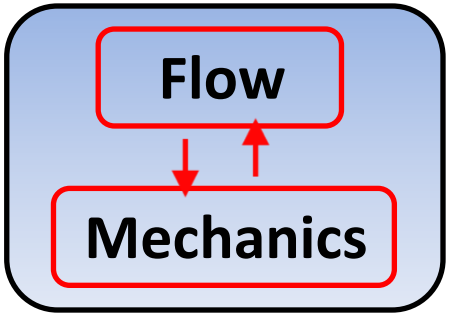
$$\frac{d\theta}{dt} = 1 - \frac{\theta V}{d_c},$$

Slip velocity

Slip history parameter

Coupled multiphase flow and geomechanics simulator

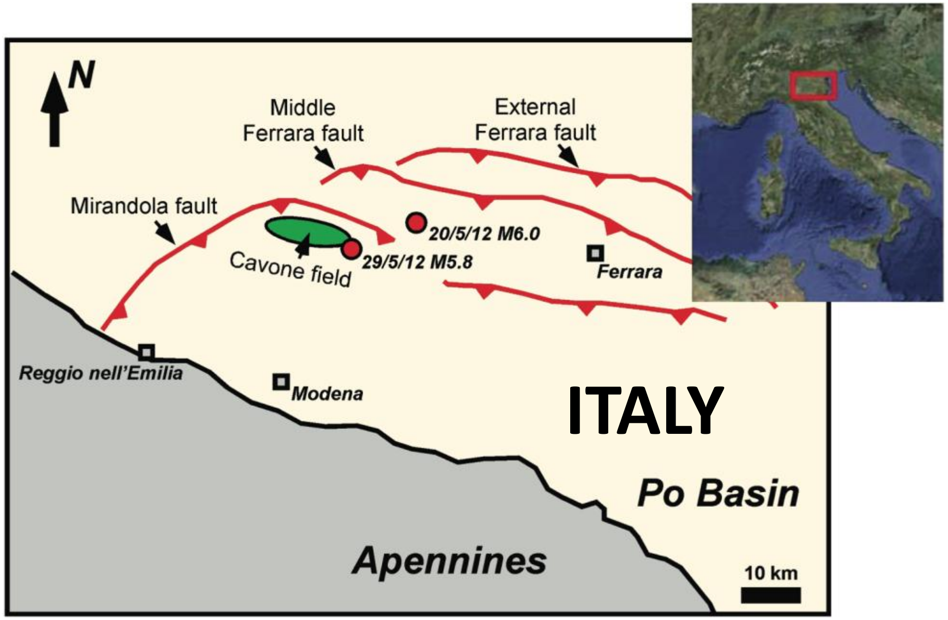
(Jha and Juanes, *Water Resour. Res.* 2014)



- Computationally efficient sequential solution
- Sophisticated formulation for fault slip
- Flow along and across fault, fracture propagation
- Viscoelastic and elastoplastic rheology
- Field-scale (unstructured grid, complex production-injection scenarios, parallel computing)

The 2012 Emilia seismicity

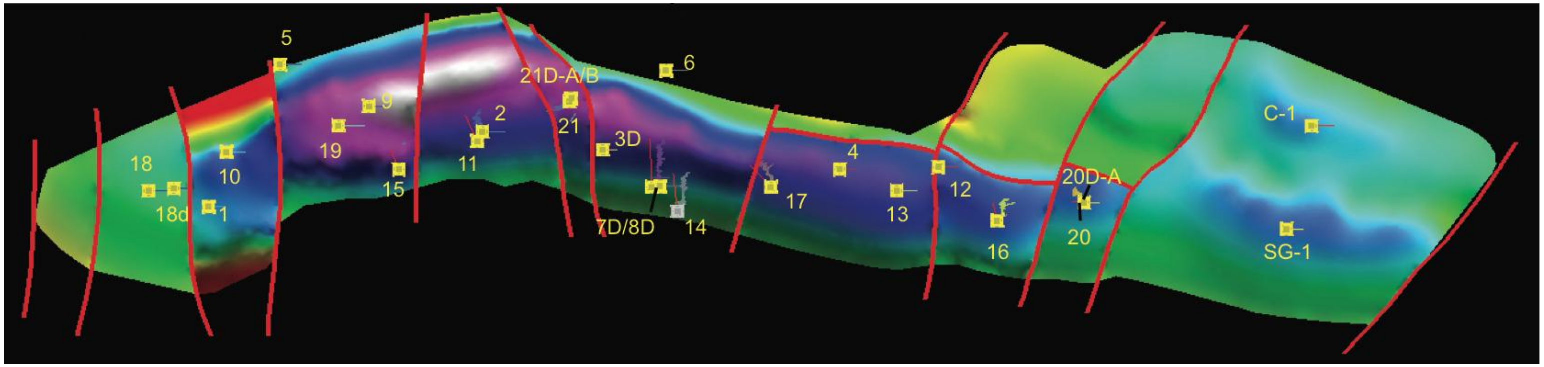
- Sequence of earthquakes (M_w= 6, M_w= 5.8) in May 2012 near the Cavone oil field in Italy



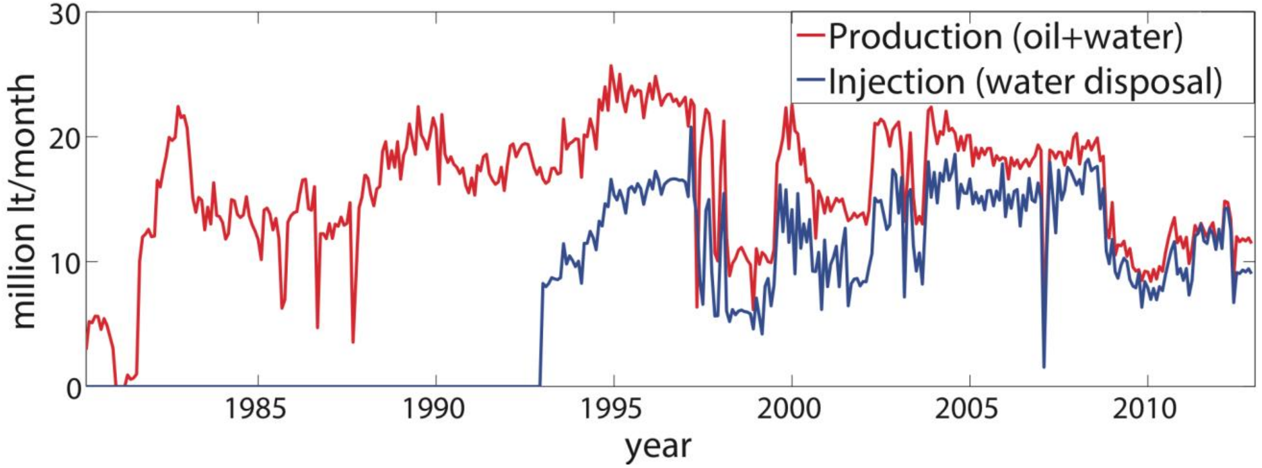
- Raised the question: *Was it induced by production/injection?*
- We address the question by means of coupled flow and geomechanical modeling, integration of geologic constraints, seismic observations, and historical production/injection

Cavone oilfield

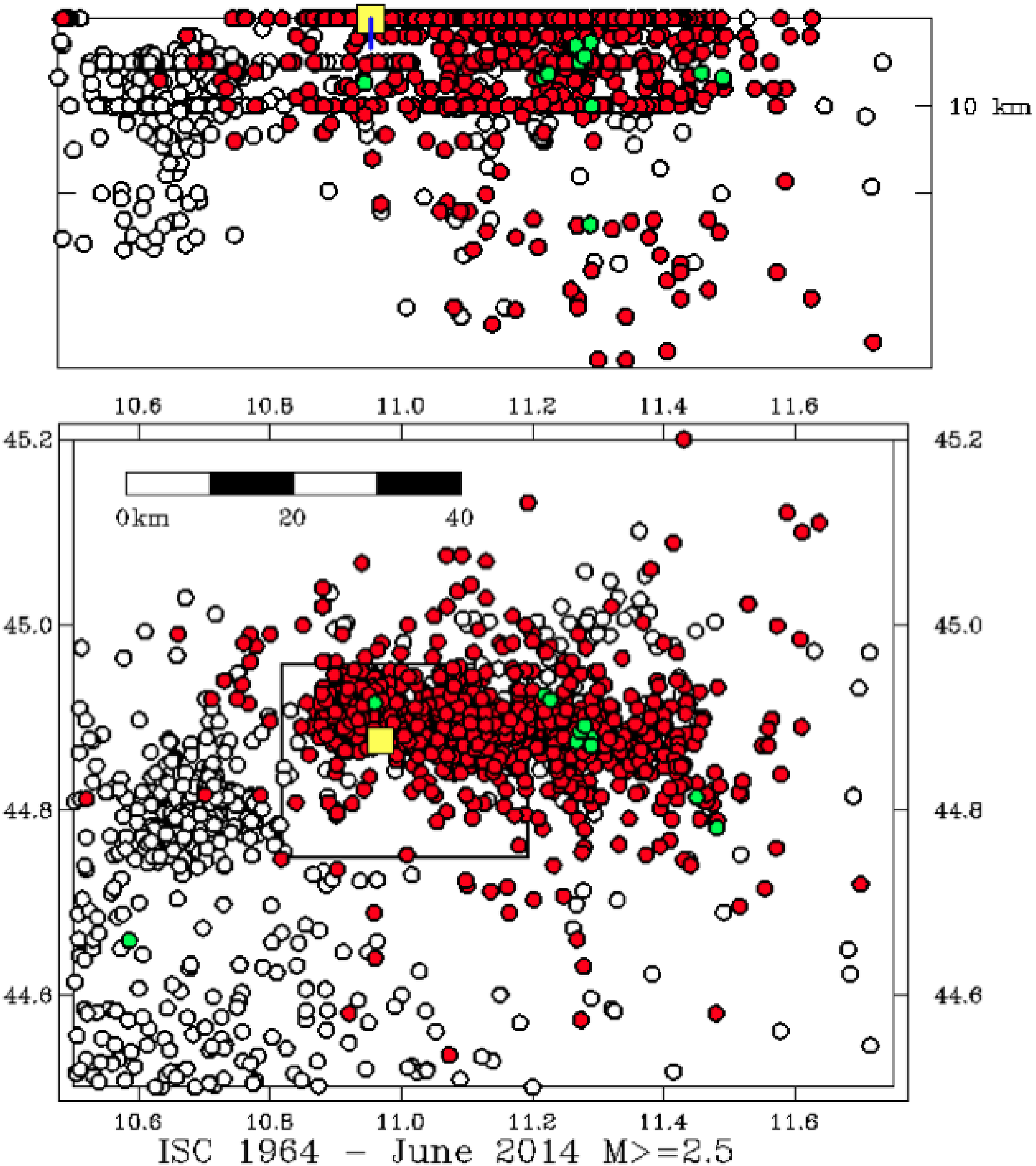
(Top view)



- Oil production started in 1980. Injection of produced water began in 1993. 16 producers, 1 injector. Strong aquifer support. Compartmentalized.



Seismically active even before May 2012



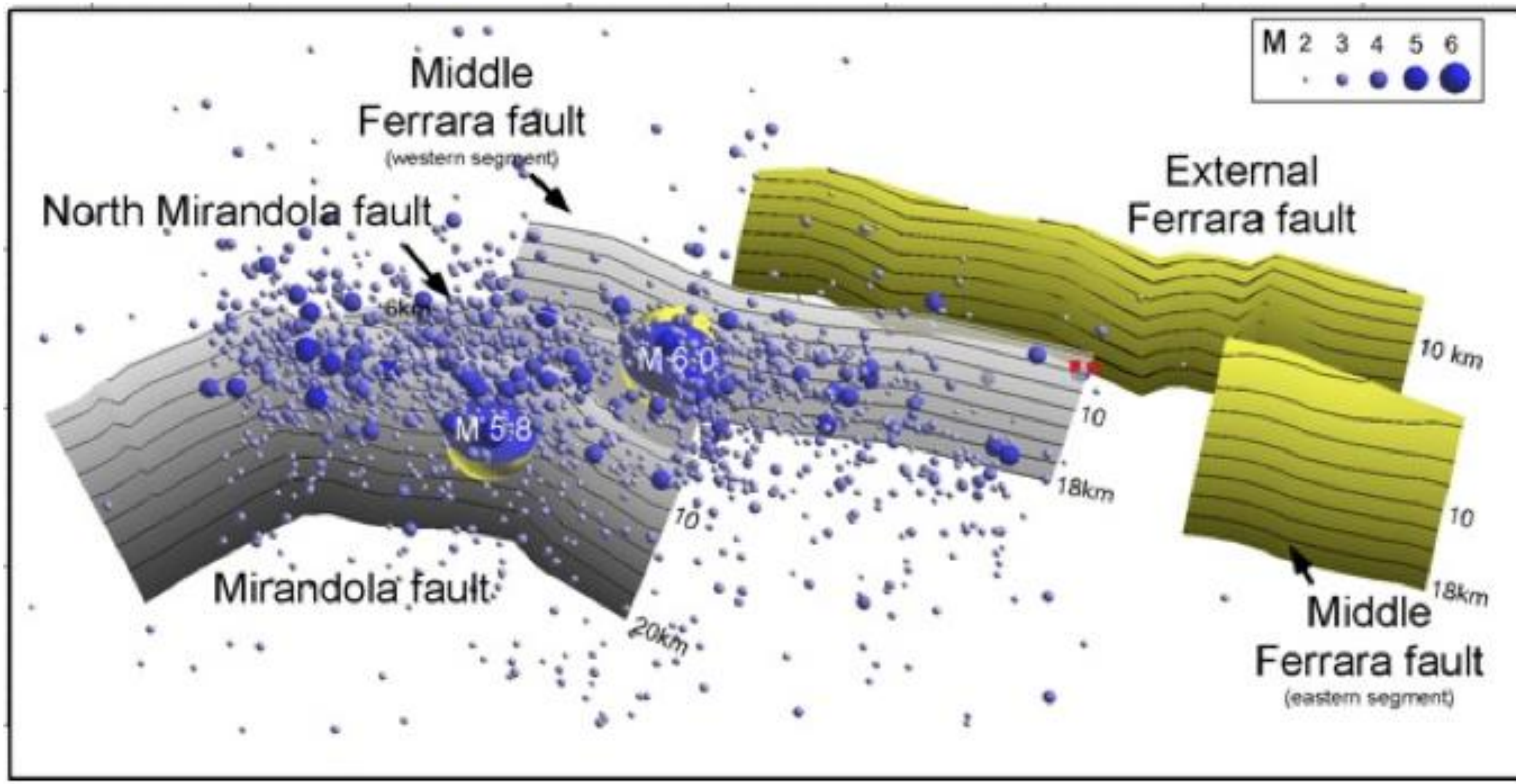
Cross-section view

White circle: 1964 – 04/12
Red circles: 05/12 – 06/12
Green circles: 07/12 - 06/14

Top view

Multiple seismogenic faults

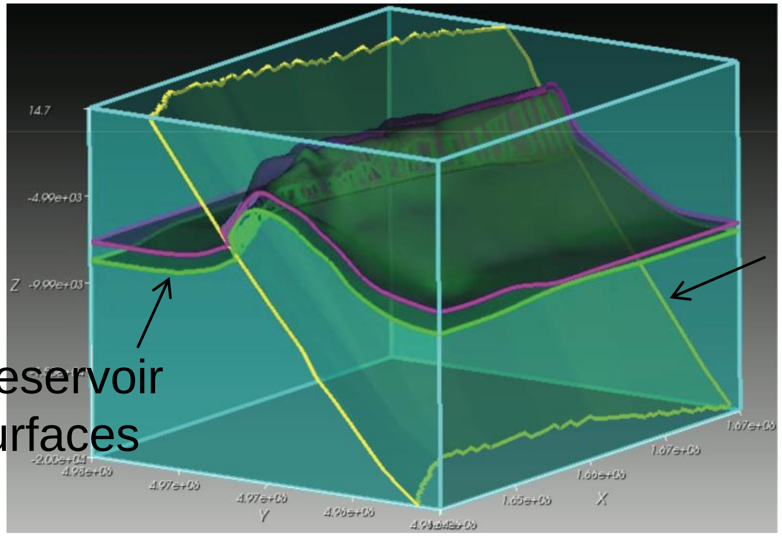
Seismicity recorded during 01/11 - 02/13



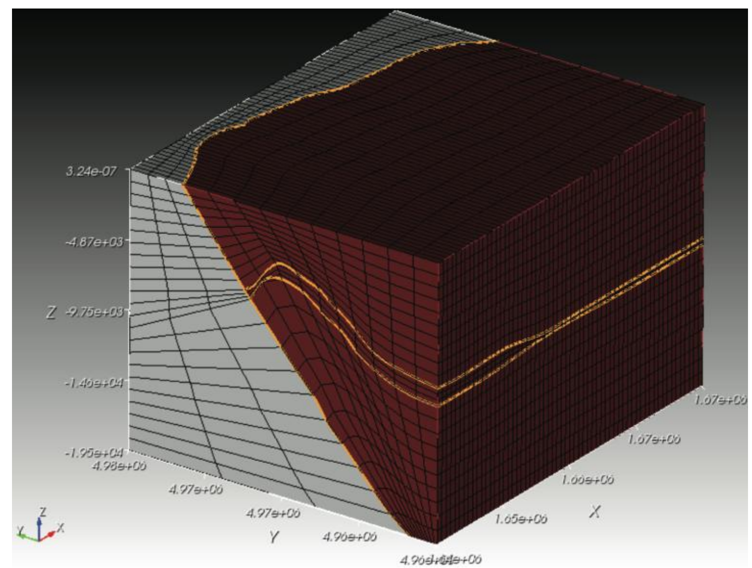
Mw=6 event occurred on Middle Ferrara fault,
9 days later, Mw=5.8 occurred on Mirandola fault

3D model

Structural model (29x24x20 km)

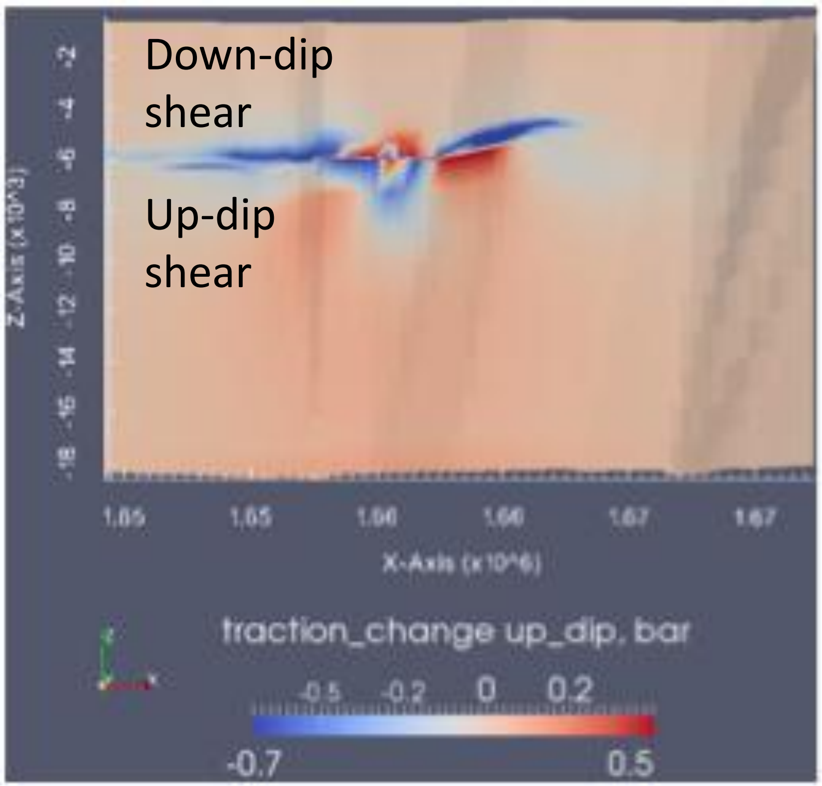


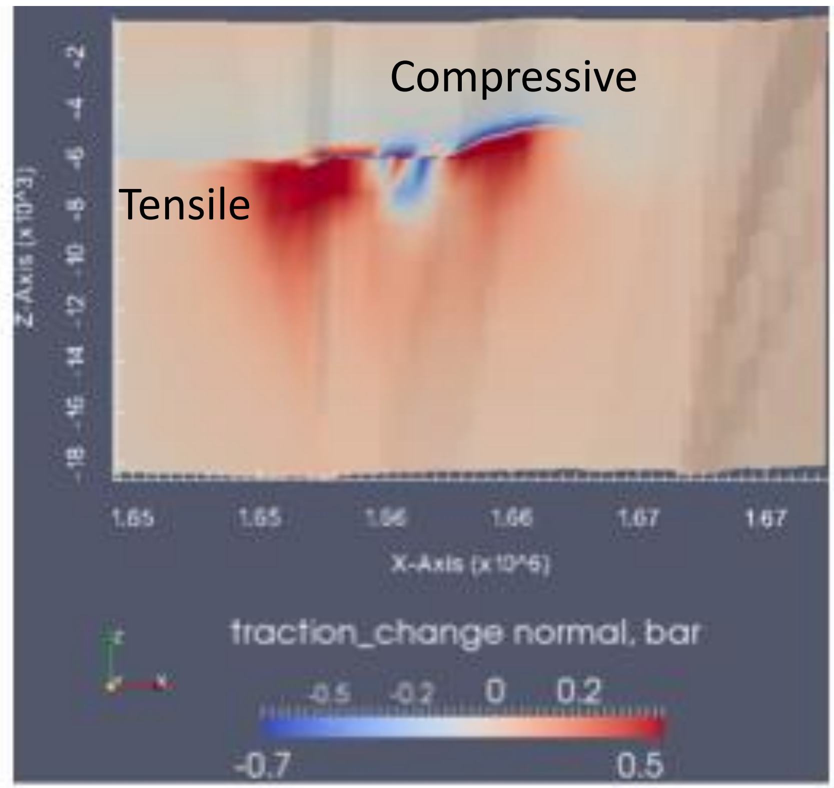
Geomechanical grid

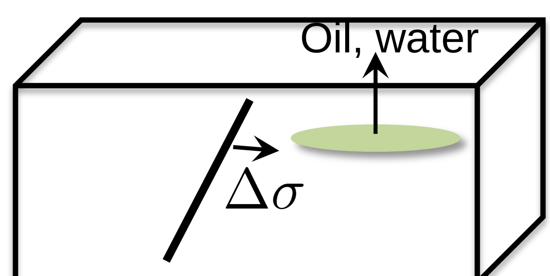


Non-trivial because of steeply dipping reservoir, and pinch-out against fault

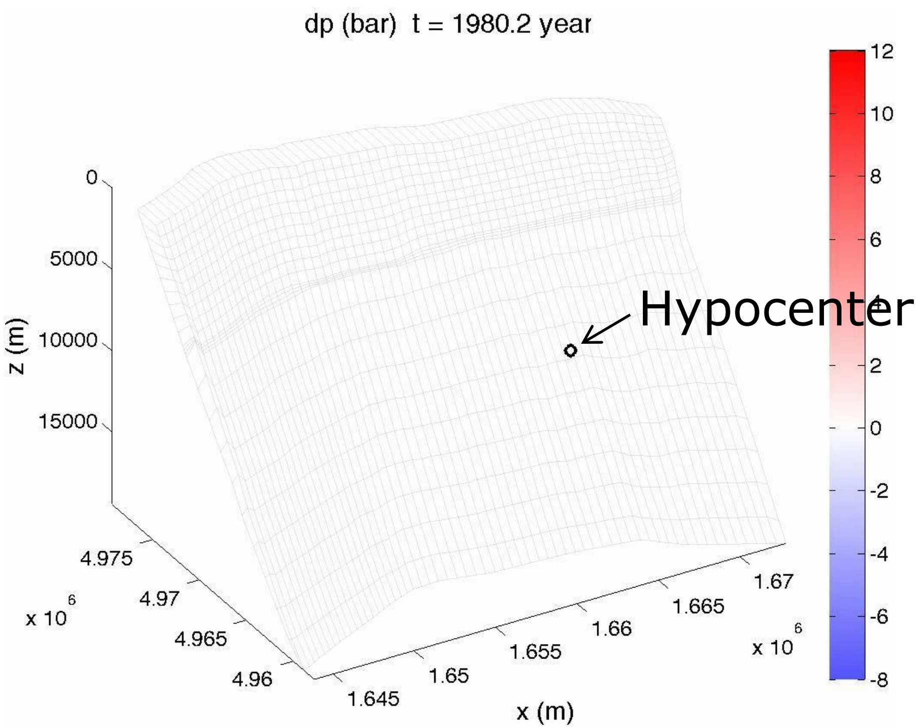
Shear and normal fault tractions due to pressure drop







Fault stability evolves in time with prod and inj



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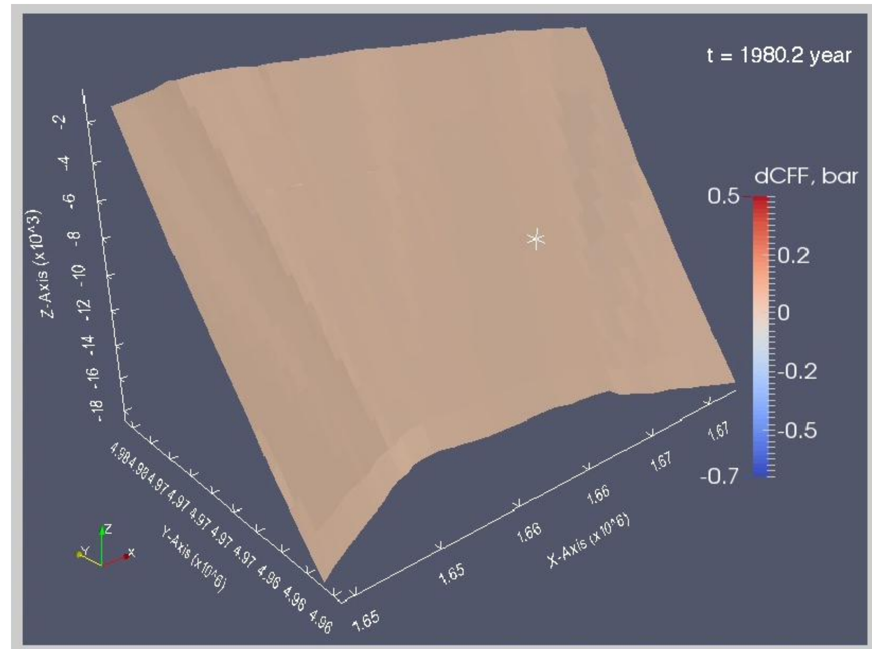

Increase in Coulomb stress is localized, and not enough to trigger seismicity

Conclusions

- A **new computational framework** to model the coupled processes of flow and deformation in faulted, stress-sensitive reservoirs
- A promising approach for **assessment** and **management of risk** due to induced seismicity
- Post-mortem analysis of earthquakes, poroelastic inversion to estimate reservoir properties