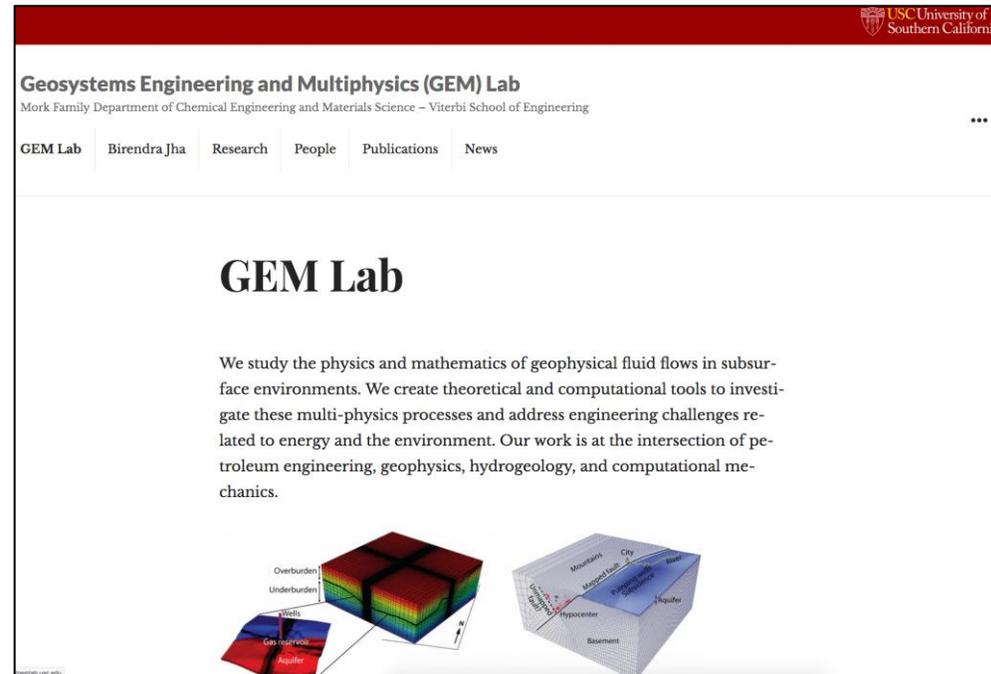# Computational Geomechanics for Induced Seismicity and Leakage Modeling

gemlab.usc.edu

Birendra Jha

Assistant Professor

Department of Chemical engineering and Materials Science

University of Southern California

Geosystems Engineering & Multiphysics (GEM) Lab

==Coupled flow and geomechanics of==

- Induced seismicity and leakage
- Hydraulic fracturing
- Enhanced oil recovery
- Underground gas storage

==Students and postdocs==

==Funding sources==

Induced seismicity

Injection-Induced Earthquakes

William L. Ellsworth · *Science* · JULY 2013

Human Activity May Have Triggered Fatal Italian Earthquakes, Panel Sa...

ROME—A pair of d...kes that ...the north of Italy in 2012 could have been triggered by the extraction of petroleum ... *Science* APRIL 2014 ...ter Styles of Keele U... in the United Kingdom—as well ... Terlizzese, an engineer at Italy's M...

INDUCED EARTHQUAKES · *Science* · July 3, 2014

Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection

K. M. Keranen,[1]* M. Weingarten,[2] G. A. Abers,[3]† B. A. Bekins,[4] S. Ge[2]

Gas injection may have triggered earth... Cogdell oil field, Texas

Wei Gan[a,b] and Cliff Frohlich[b,1]

[a]School of Earth Sciences and Resources, China University of Geosciences, Beijing 10083, China; and [b]Institute for ... University of Texas at Austin, Austin, TX 78758-4445

Edited by Donald W. Forsyth, Brown University, Providence, RI, and approved October 4, 2013 (received for revie...

Between 1957 and 1982, water flooding was conducted to improve petroleum production in the Cogdell oil field north of ... the Late Paleozoic and is on... reef mounds in the world (1...

PNAS

Cumulative number of earthquakes M ≥ 3

Disposal of Hydrofracking Waste Fluid by Injection into Subsurface Aquifers Triggers Earthquake Swarm in Central Arkansas with Potential for Damaging Earthquake

S. Horton[1] · Seismological Research Letter · March/April 2012

Geophysical Research Letters

RESEARCH LETTER
10.1002/2016GL069284

Were the May 2012 Emilia-Ro... A coupled flow-geomechanics...

Key Points:
· Coupled flow-geomechanics

R. Juanes[1,2], B. Jha[1,3], B. H. Hager[2], J. H. Shaw[4], A...

Earthquake triggering and large carbon dioxide

Mark D. Zoback[a,1] and Steven M. Gorelick[b]
Departments of [a]Geophysics and [b]Environmental Earth System Science, Stan...

PNAS

The Dallas–Fort Worth Earthquake Sequence: October 2008 through May 2009 · February 2011

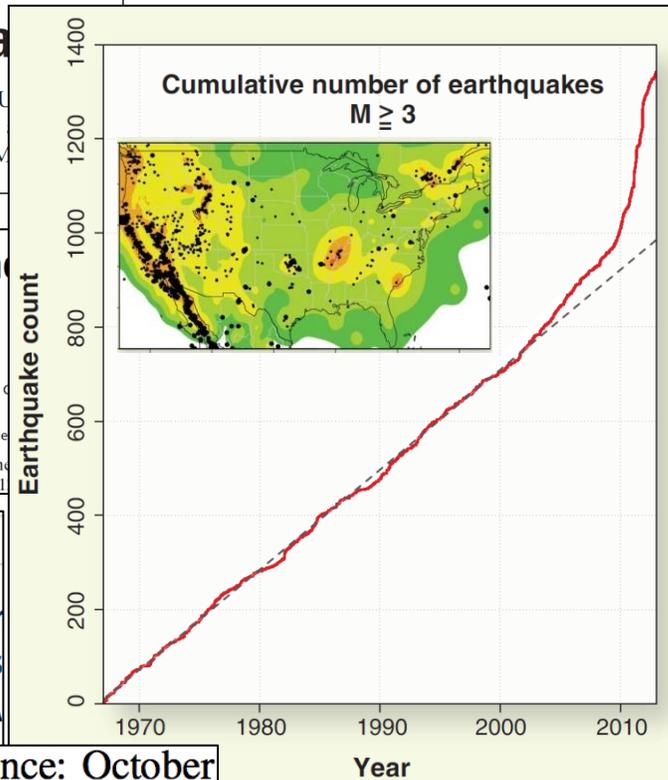by Cliff Frohlich, Chris Hayward, Brian Stump, and Eric Potter

INDUCED SEISMICITY · *Science* · JUNE 2015

**High-rate injection is associated with the increase in U.S. mid-continent seismicity**

M. Weingarten,[1]* S. Ge,[1] J. W. Godt,[2] B. A. Bekins,[3] J. L. Rubinstein[3]

Geomechanical Analysis to Evaluate Production-Induced Fault Reactivation at Groningen Gas Field · Society of Petroleum Engineers

Pablo F. Sanz, ExxonMobil Upstream Research Co. (EMURC), Suvrat P. Lele, EMURC, Kevin H. Sea... EMURC, Sheng-Yuan Hsu, EMURC, Jorge L. Garzon, EMURC, Jason A. Burdette, ExxonMobil Deve... Co., William E. Kline, EMURC, Bruce A. Dale, ExxonMobil Production Co., Paul D. Hector, ExxonMob...

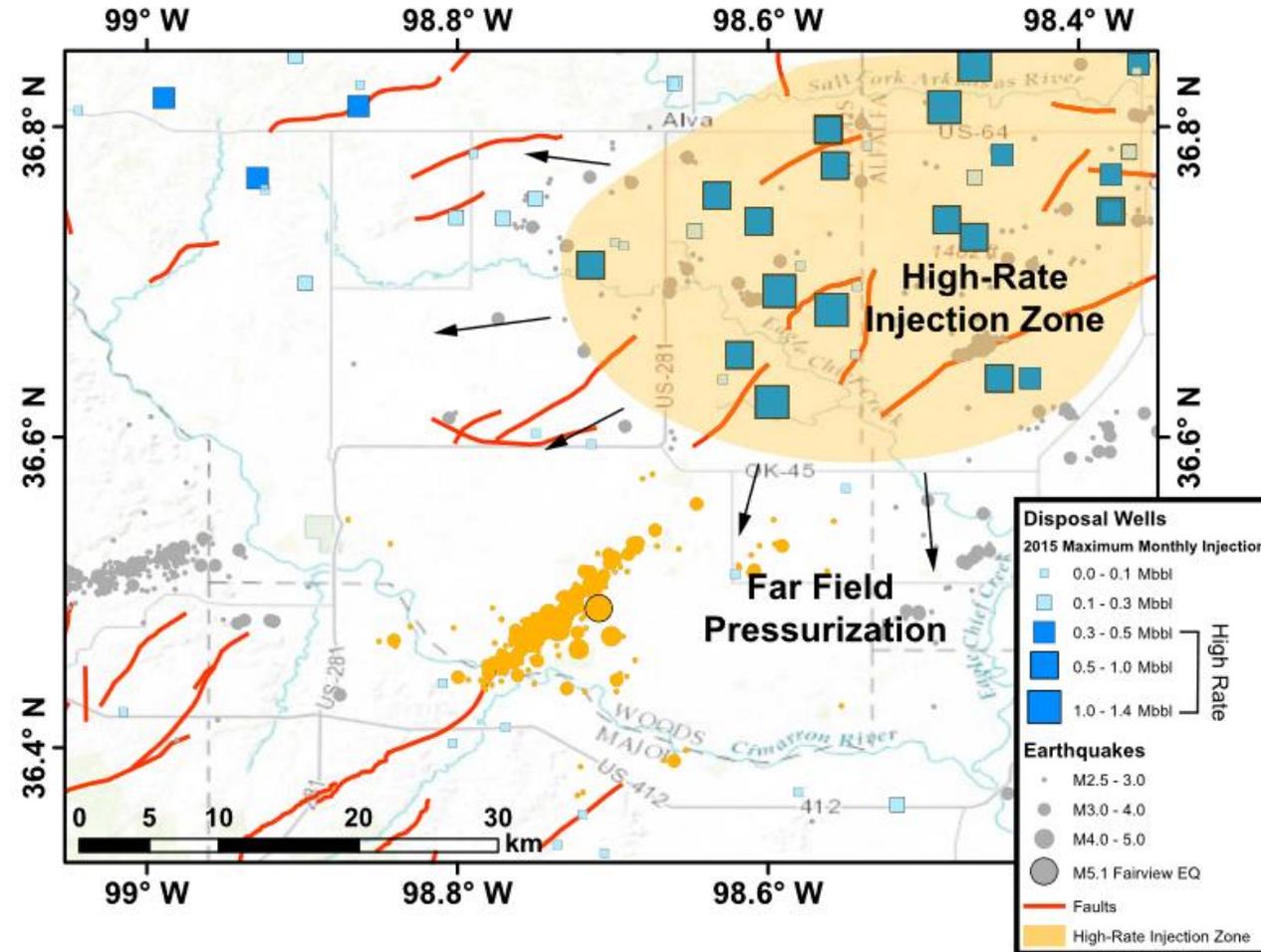Causal factors for seismicity near Azle, Texas · nature · Apr 2015

Matthew J. Hornbach[1], Heather R. DeShon[1], William L. Ellsworth[2], Brian W. Stump', Chris Hayward[1], Cliff Frohlich[3], Harrison R. Oldham[1], Jon E. Olson[4], M. Beatrice Magnani[1], Casey Brokaw[1] & James H. Luetg...

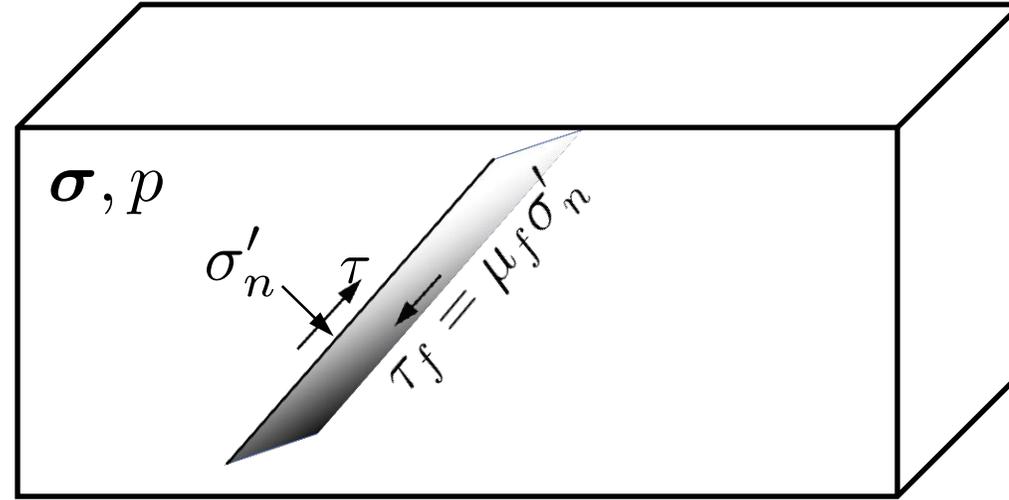# Production and injection close to faults is inevitable
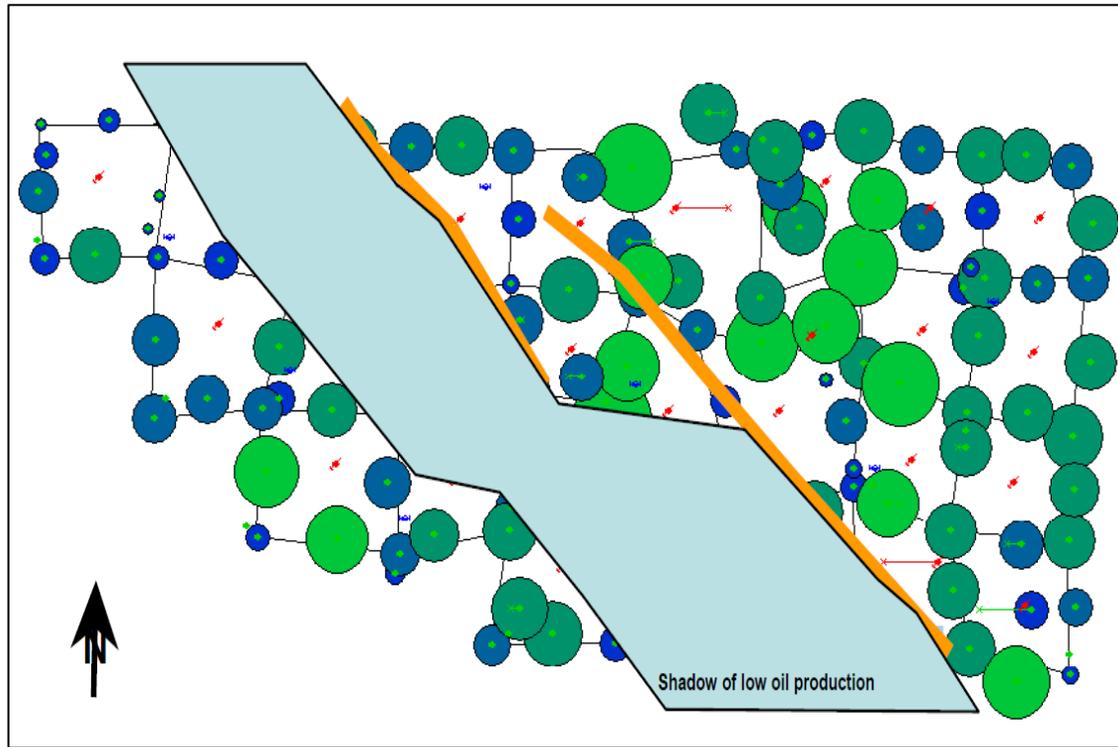
Producers in Kern River Oilfield

Injectors in Fairview, OK (Yeck et al., GRL 2016)

Induced seismicity mechanism: Coulomb theory of failure

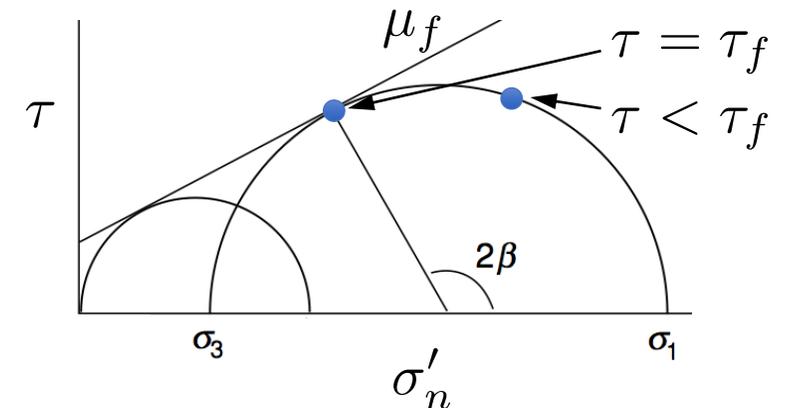Effective normal stress: $\sigma'_n = \sigma_n - bp$

Friction stress: $\tau_f = \mu_f \sigma'_n$

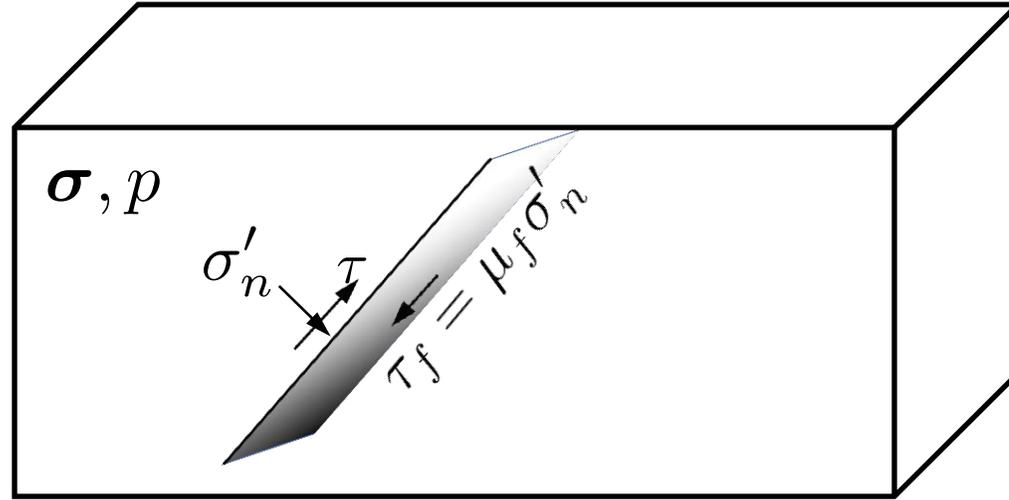Shear failure criterion: $\tau \geq \tau_f$

Coulomb Failure Function:

$$\text{CFF} = \tau - \mu_f \sigma'_n$$

Coulomb theory

Induced seismicity mechanisms

Tendency to slip if:

$$\Delta\text{CFF} = \Delta\tau - \Delta\left[\mu_f(\sigma_n - bp)\right] > 0$$

$\Delta\tau > 0 \quad$ (poroelastic loading)

$\Delta\sigma_n < 0 \quad$ (poroelastic unloading)

$\Delta p > 0 \quad$ (fluid injection)

$\Delta\mu_f < 0 \quad$ (fault weakening)

Water extraction from unconfined aquifer
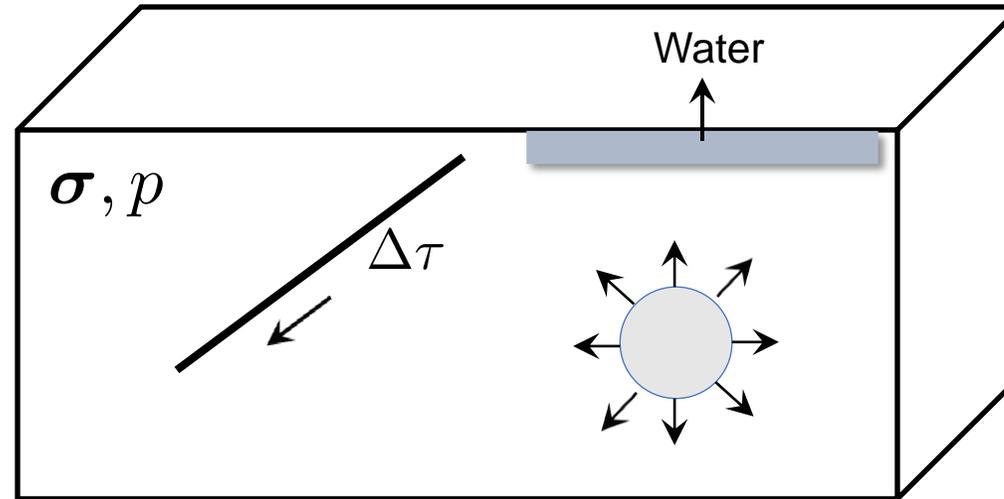
$$\Delta\text{CFF} = \Delta\tau - \Delta\left[\mu_f(\sigma_n - bp)\right] > 0$$

$\Delta\tau > 0$ (poroelastic loading)

$\Delta\sigma_n < 0$ (poroelastic unloading)

$\Delta p > 0$ (fluid injection)

$\Delta\mu_f < 0$ (fault weakening)

Hydrocarbon production from confined reservoir

$$\Delta\text{CFF} = \Delta\tau - \Delta\left[\mu_f(\sigma_n - bp)\right] > 0$$

$\Delta\tau > 0$ (poroelastic loading)

$\Delta\sigma_n < 0$ (poroelastic unloading)

$\Delta p > 0$ (fluid injection)

$\Delta\mu_f < 0$ (fault weakening)

Fluid injection into a confined reservoir

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

$\Delta\tau > 0$ (poroelastic loading)

$\Delta\sigma_n < 0$ (poroelastic unloading)

$\Delta p > 0$ (fluid injection)

$\Delta\mu_f < 0$ (fault weakening)

Fault slip can lead to leakage

Water, gas

$\boldsymbol{\sigma}, p$

Fluid leakage if: $\Delta k_f > 0$

$\Delta k_f = f$ (fault slip, fault compression)

$\Delta \tau > 0$ (poroelastic loading)

$\Delta \sigma_n < 0$ (poroelastic unloading)

$\Delta p > 0$ (fluid injection)

$\Delta \mu_f < 0$ (fault weakening)

Seismicity triggered by fluid injection–induced aseismic slip

Yves Guglielmi,[1]* Frédéric Cappa,[2,3] Jean-Philippe Avouac,[3]† Pierre Henry,[1] Derek Elsworth[4]

Science

Anthropogenic fluid injections are known to induce earthquakes. The mechanisms involved are poorly understood, and our ability to assess the seismic hazard associated with geothermal energy or unconventional hydrocarbon production remains limited. We directly measure fault slip and seismicity induced by fluid injection into a natural fault. We observe highly dilatant and slow [~4 micrometers per second (μm/s)] aseismic slip associated with a 20-fold increase of permeability, which transitions to faster slip (~10 μm/s) associated with reduced dilatancy

Can we develop an induced seismicity/leakage simulator based on the coupled physics of fluid flow and fault poromechanics?

(Jha and Juanes, *WRR* 2014; Asaithambi and Jha, *SPE* 190032, 2018)

Multiphase flow and geomechanics

Load
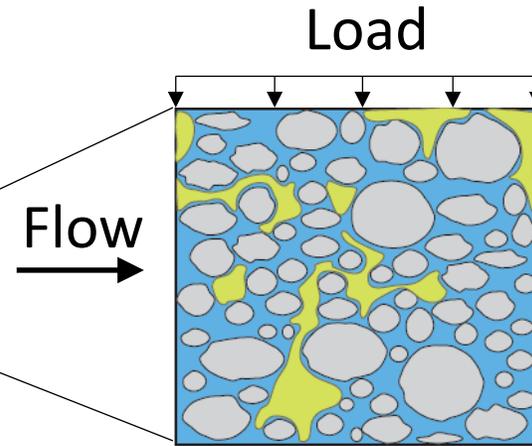
Flow

Oil, water, gas have different pressures and densities.
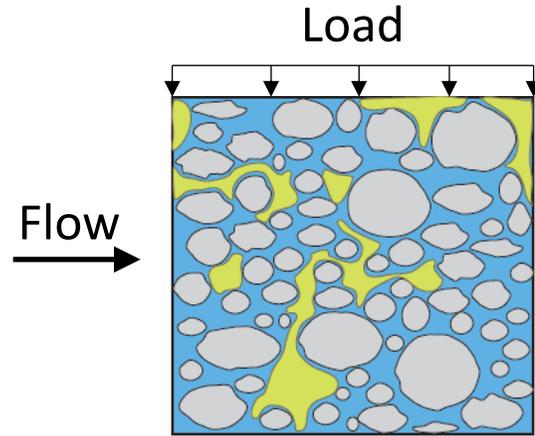
Governing equations

Force balance (quasi-static):

$$\nabla \cdot \boldsymbol{\sigma} + \rho_b \boldsymbol{g} = 0 \qquad \rho_b = (1 - \phi)\rho_s + \phi \sum_\alpha \rho_\alpha$$
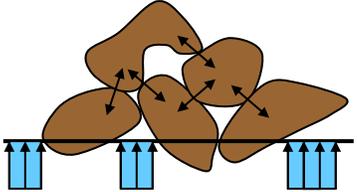
Fluid mass balance:

$$\frac{\partial m_\alpha}{\partial t} + \frac{1}{K_{dr}} \frac{\partial}{\partial t} (\rho_\alpha b_\alpha \sigma_v) + \nabla \cdot \boldsymbol{w}_\alpha = \rho_\alpha f_\alpha \qquad \alpha, \beta = \text{Oil, water, gas}$$

Multiphase flow and geomechanics

Constitutive equations

Poroelasticity:

$$\left(\frac{dm}{\rho}\right)_\alpha = b_\alpha d\varepsilon_v + \sum_\beta N_{\alpha\beta} dp_\beta$$

Effective stress:

$$\delta\boldsymbol{\sigma} = \delta\boldsymbol{\sigma}' - b\delta p_E \mathbf{1}$$

$$\delta\boldsymbol{\sigma}' = \boldsymbol{C}_{dr} : \boldsymbol{\varepsilon}$$

Darcy flux:

$$\boldsymbol{w}_\alpha = -\frac{\boldsymbol{k}k_\alpha^r \rho_\alpha}{\mu_\alpha}(\nabla p_\alpha - \rho_\alpha \boldsymbol{g})$$

Flow and mechanics are coupled processes

Coupling through parameters (PDE coefficients)

- Mechanical properties (Biot modulus, Biot coefficient, bulk density) are functions of fluid saturation/type

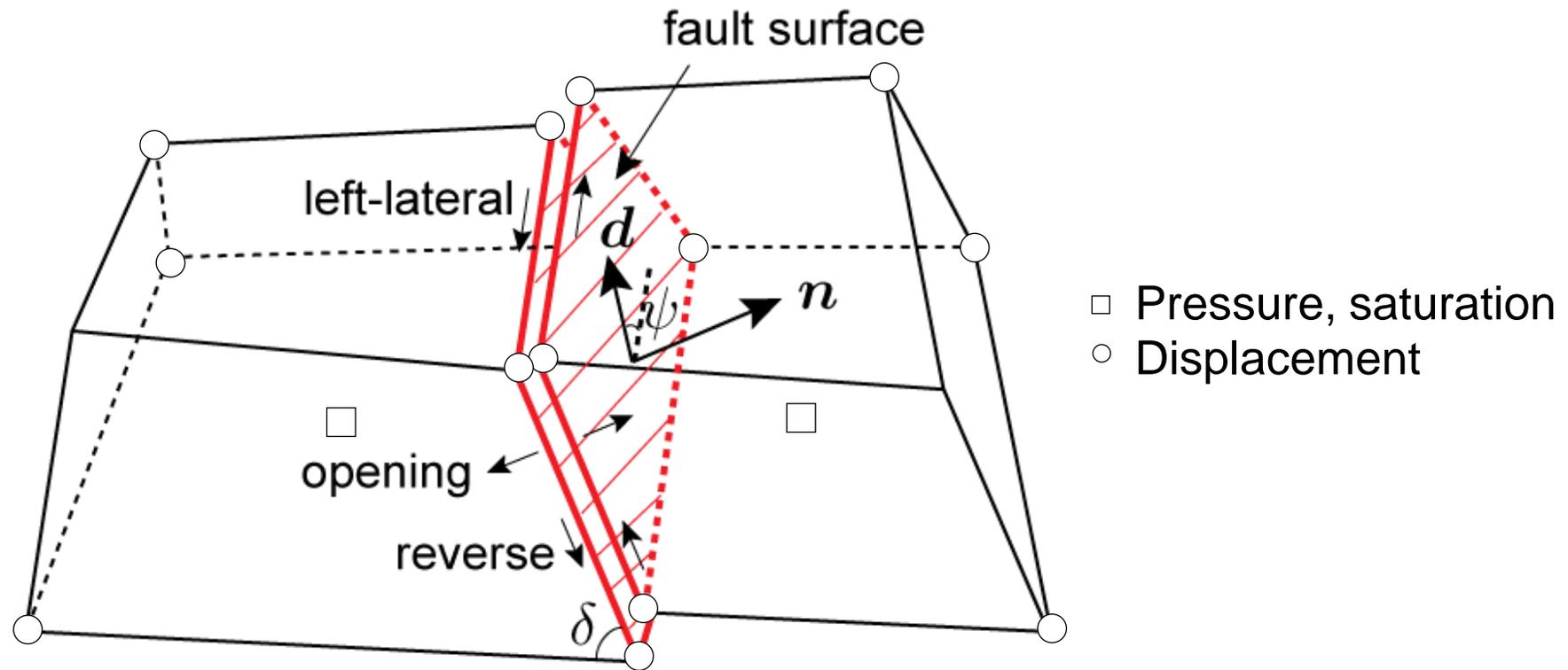- Flow properties (porosity, permeability) are functions of stress

Coupling through processes (PDE terms)

$$\nabla \cdot \boldsymbol{\sigma}' = -b\nabla p - \rho_b \boldsymbol{g}$$

$$\frac{\partial m_\alpha}{\partial t} + \frac{1}{K_{dr}}\frac{\partial}{\partial t}\left(\rho_\alpha b_\alpha \sigma_v\right) + \nabla \cdot \boldsymbol{w}_\alpha = \rho_\alpha f_\alpha$$
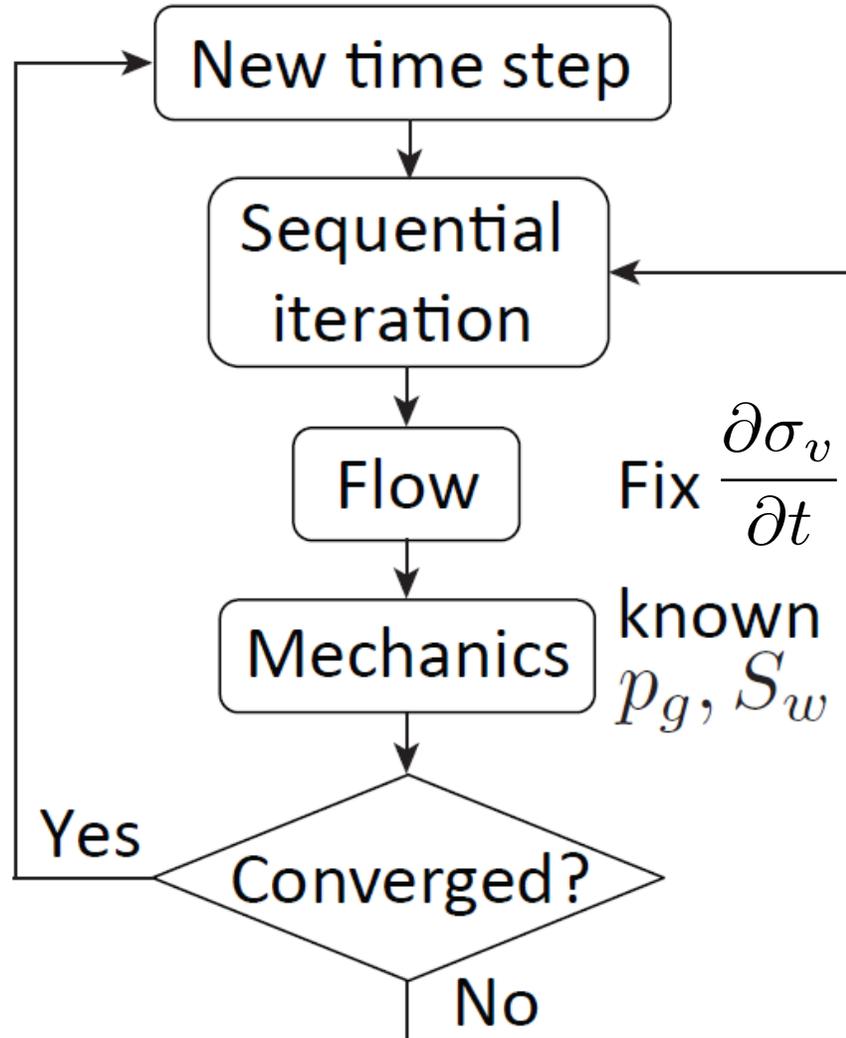
Computational model - Discretization

- Stable, local mass conservation (FEM-FVM)
- Single, unstructured computational grid

□ Pressure, saturation
○ Displacement

Jha and Juanes, *Acta Geotech.* 2007
Kim, Tchelepi and Juanes, *CMAME* 2011
Jha and Juanes, *WRR* 2014

Numerical scheme to couple flow and mechanics

- Fixed stress scheme: Efficient, unconditionally stable sequential solution scheme

$$\left(\frac{b^2}{K_{dr}} + \frac{1}{M} \right) \frac{\partial p}{\partial t} + \frac{b}{K_{dr}} \frac{\partial \sigma_v}{\partial t} + \nabla \cdot \boldsymbol{v} = f$$

$$\nabla \cdot \boldsymbol{\sigma} + \rho_b \boldsymbol{g} = \boldsymbol{0}$$

Fix $\dfrac{\partial \sigma_v}{\partial t}$

known p_g, S_w

Physical model of a fault

surface of discontinuity

1) Undeformed Host Rock

Fault Zone { 2) Damaged Host Rock
              3) Foliated Zone   } Fault Core
              4) Central ultracataclasite layer
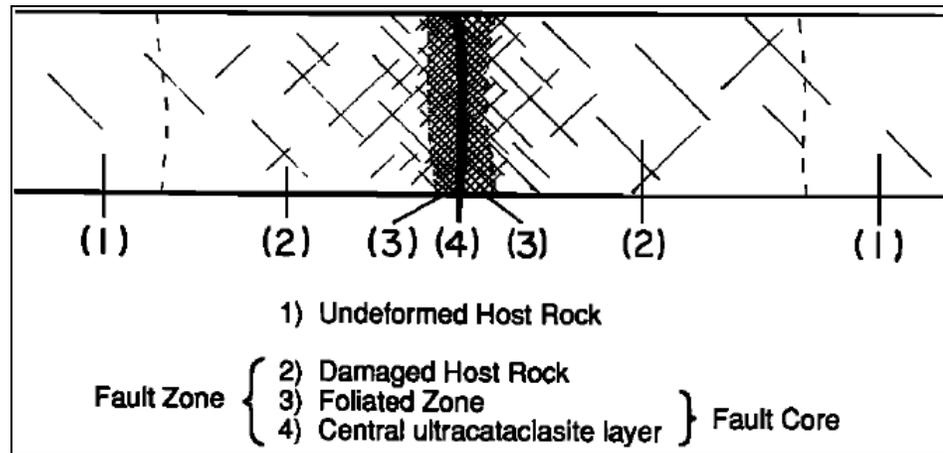
zone of different properties

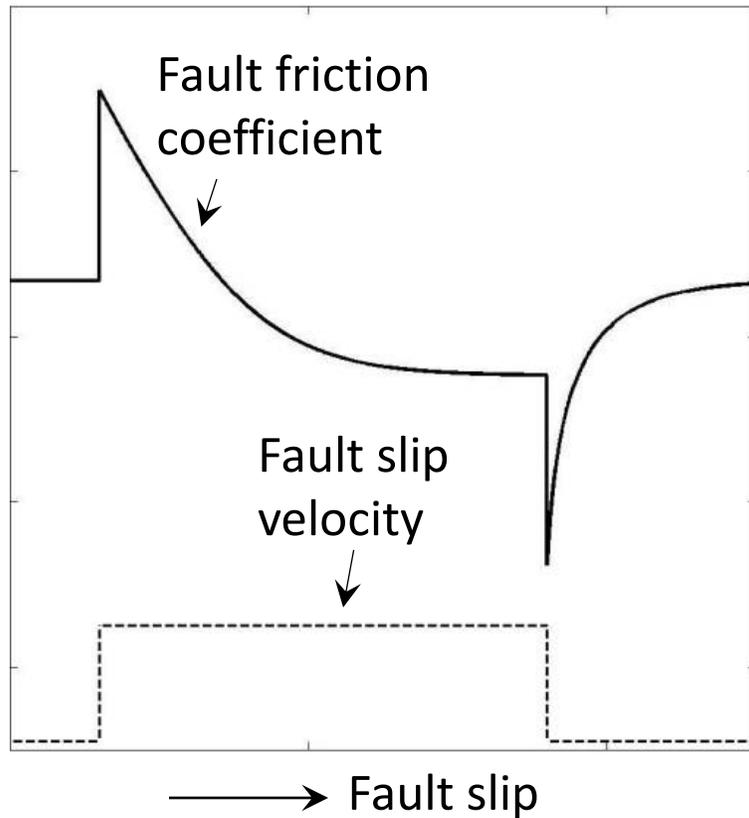Chester et al, *JGR* 1993
Anderson, *Tectonophy* 1983
Marone, *Ann. Rev. EPS*, 1998

Functional model of a fault

- Coulomb stability criterion: $\tau < \tau_f(\sigma'_n, \mu_f)$

$$\sigma'_n = \sigma_n - bp$$

- Slip weakening: fault friction decreases linearly with amount of fault slip
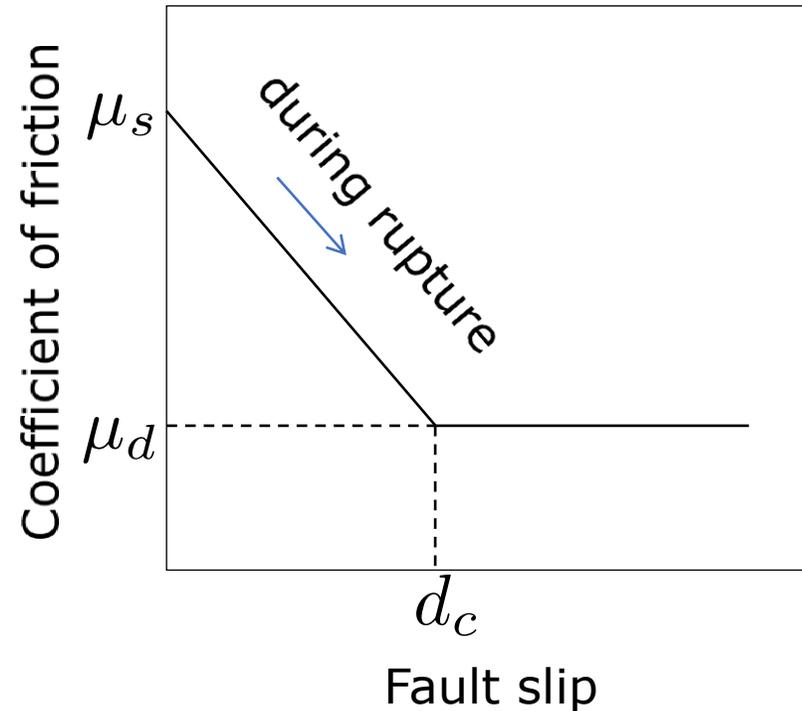
Functional model of a fault

Rate and state friction model

Fault friction coefficient

Fault slip velocity

Fault slip

Friction evolves *non-linearly* with slip leading to seismic and aseismic slip

(Marone, *Ann. Rev. EPS* 1998)

Computational model of fault

Fault is discretized with interface finite elements.

negative side, Γ_{f-} positive side, Γ_{f+}

zero-thickness fault element

□ p_i, S_i ● L_a

○ U_b ◐ U_{b+}

◑ U_{b-}
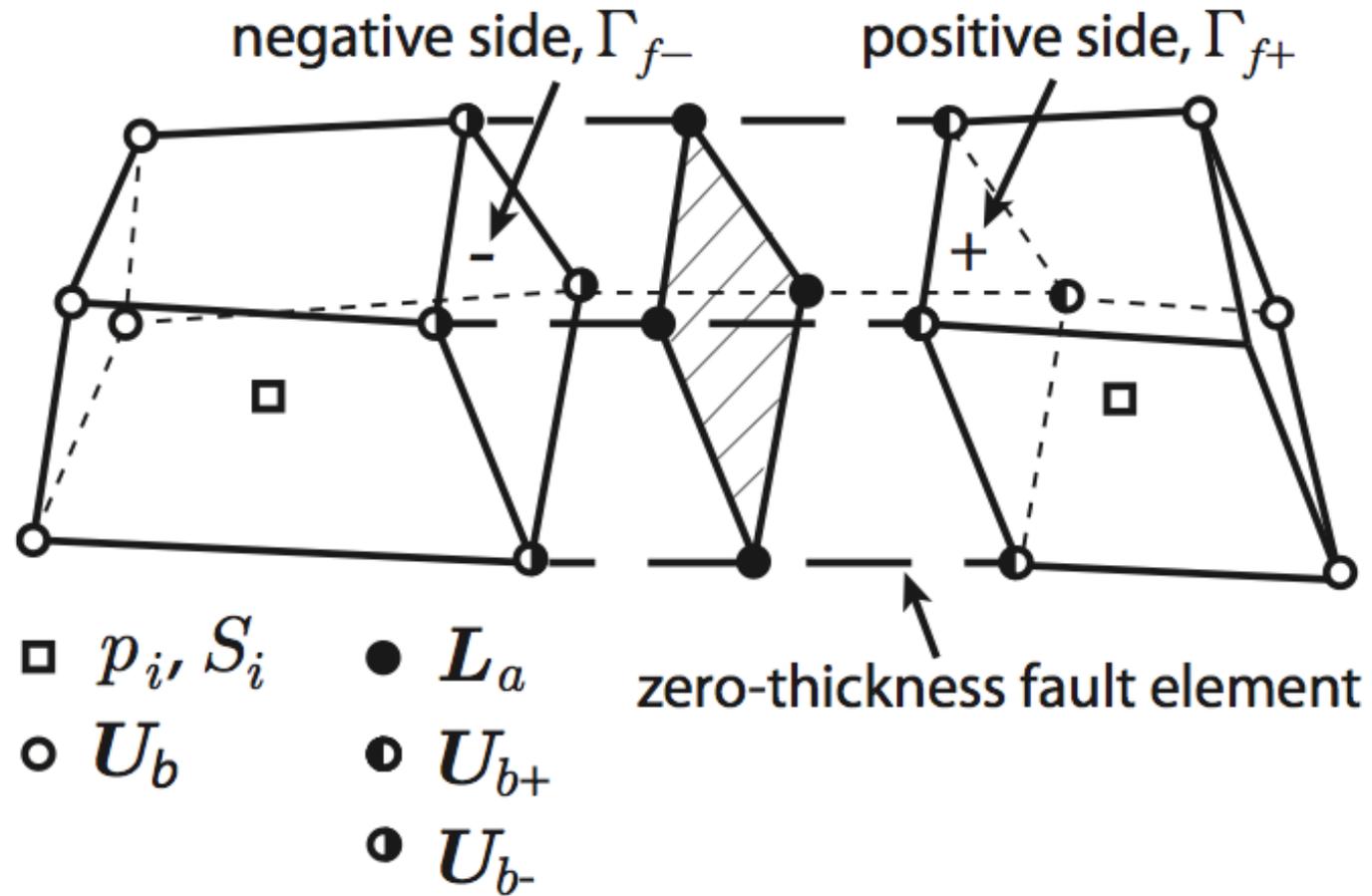
Coupled flow-deformation-faulting problem

Lagrange multiplier approach to solve the contact problem

$$\begin{bmatrix} K & C^T \\ C & 0 \end{bmatrix}^{(k)} \begin{bmatrix} \delta U \\ \delta L \end{bmatrix}^{(k)} = - \begin{bmatrix} R_u \\ R_l \end{bmatrix}^{(k)}$$

Coupled multiphase flow and geomechanics simulator
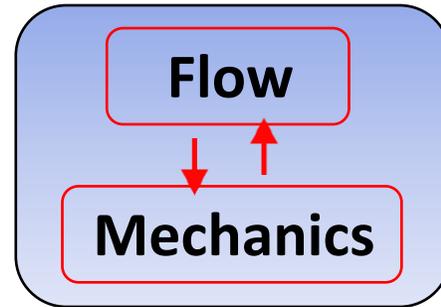
- Computationally efficient sequential solution
- Sophisticated formulation for fault slip (Rate and State Friction)
- Flow along and across fault
- Viscoelastic, elastoplastic, and viscoplastic rheology. Rate and State fault friction
- Field-scale (unstructured grid, complex production-injection scenarios, parallel computing)

Can we predict the maximum magnitude induced event?

(Jha and Juanes, *WRR* 2014; Asaithambi and Jha, *SPE* 190032, 2018)

Physical model of injection-induced seismicity
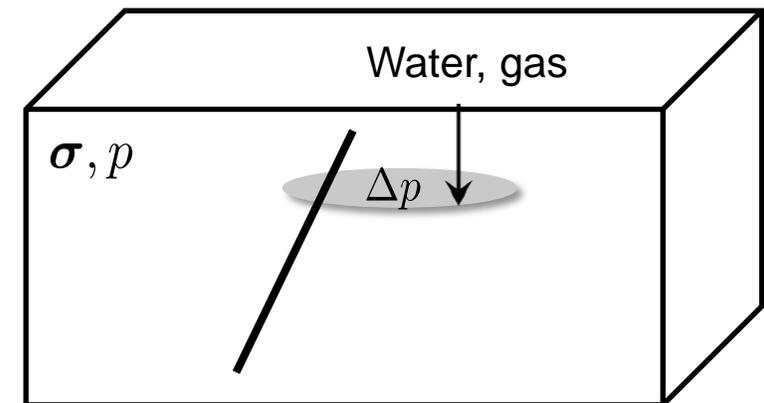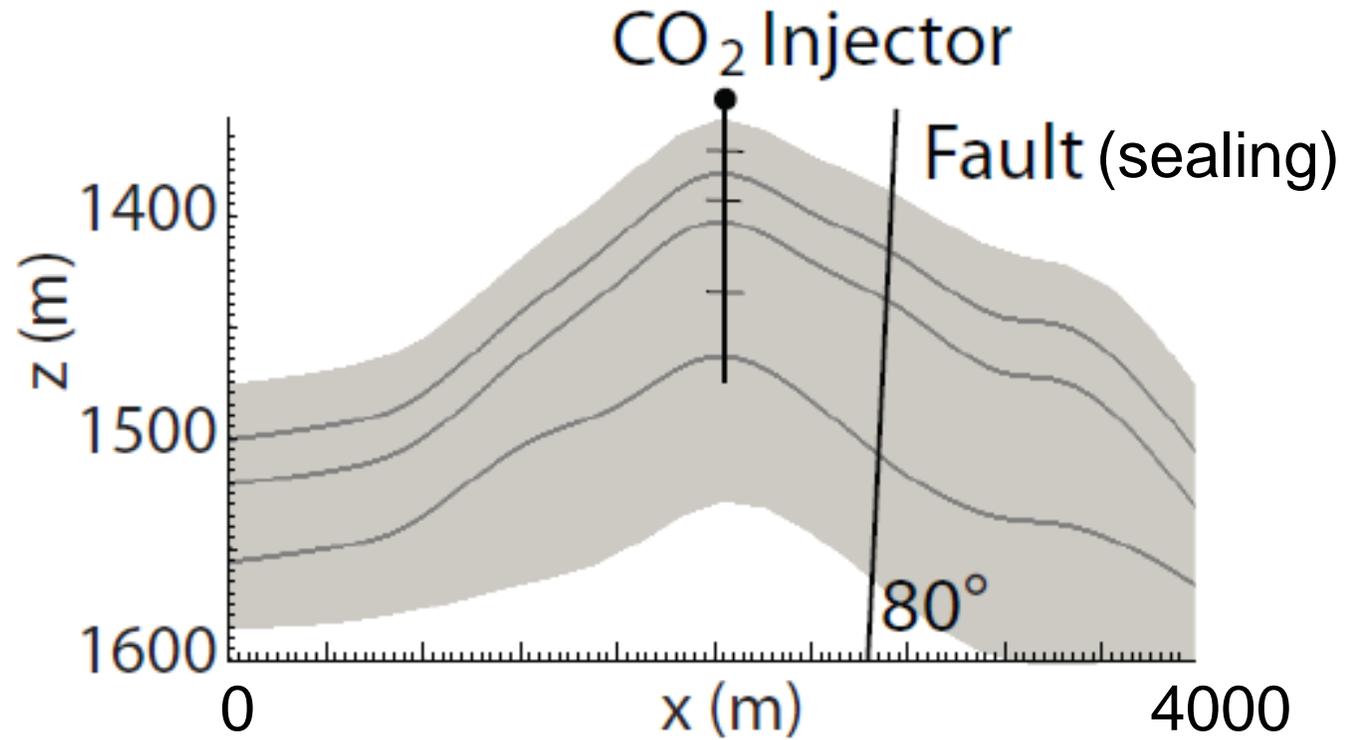
Computational model

Aquifer domain
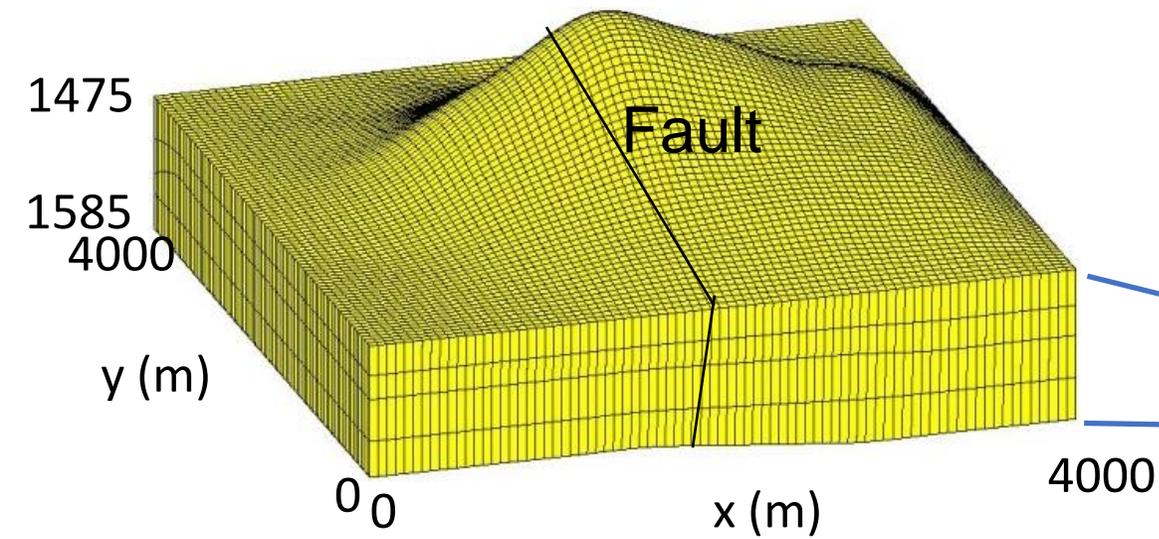
Geomechanical domain

(Jha and Juanes, *WRR* 2014)
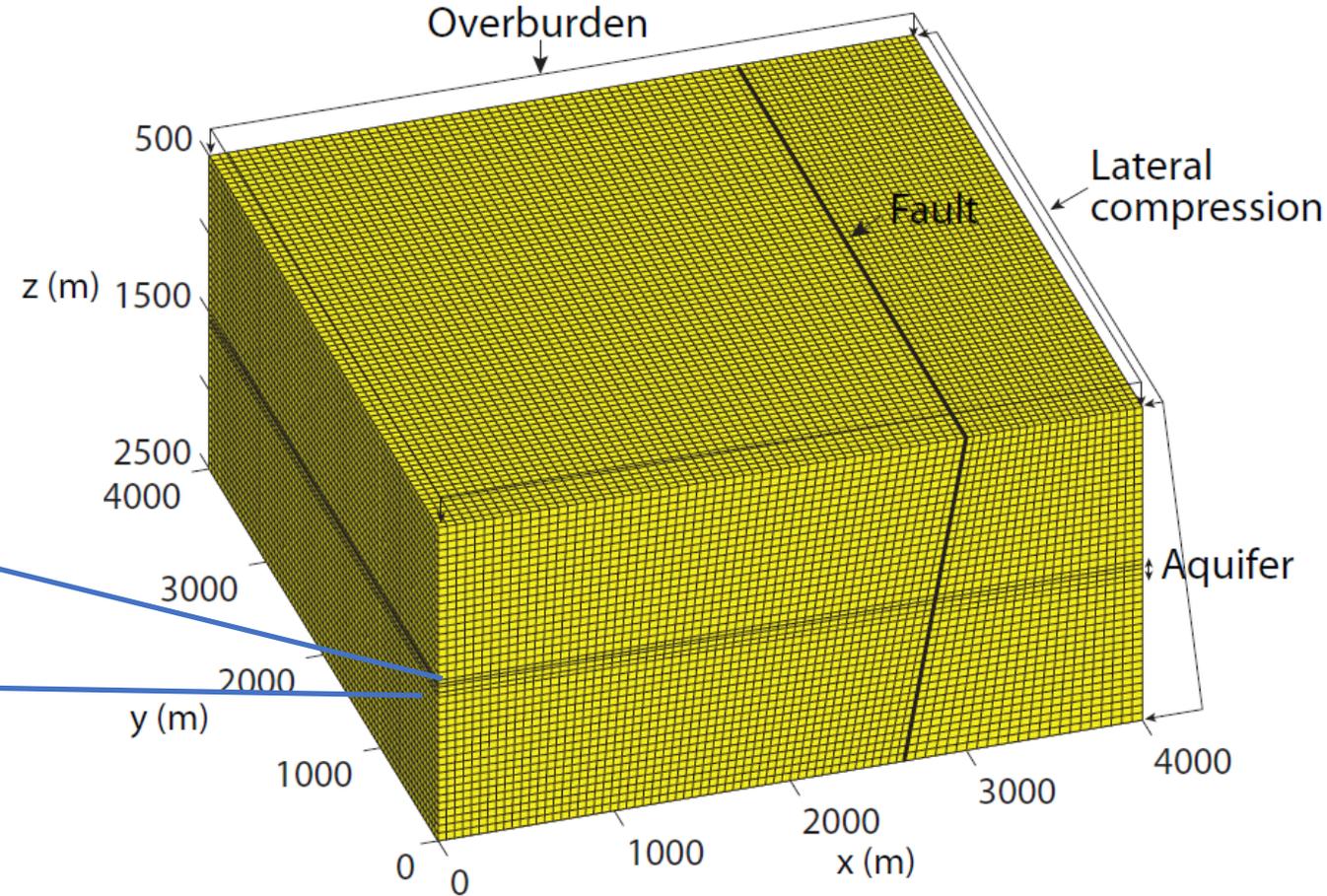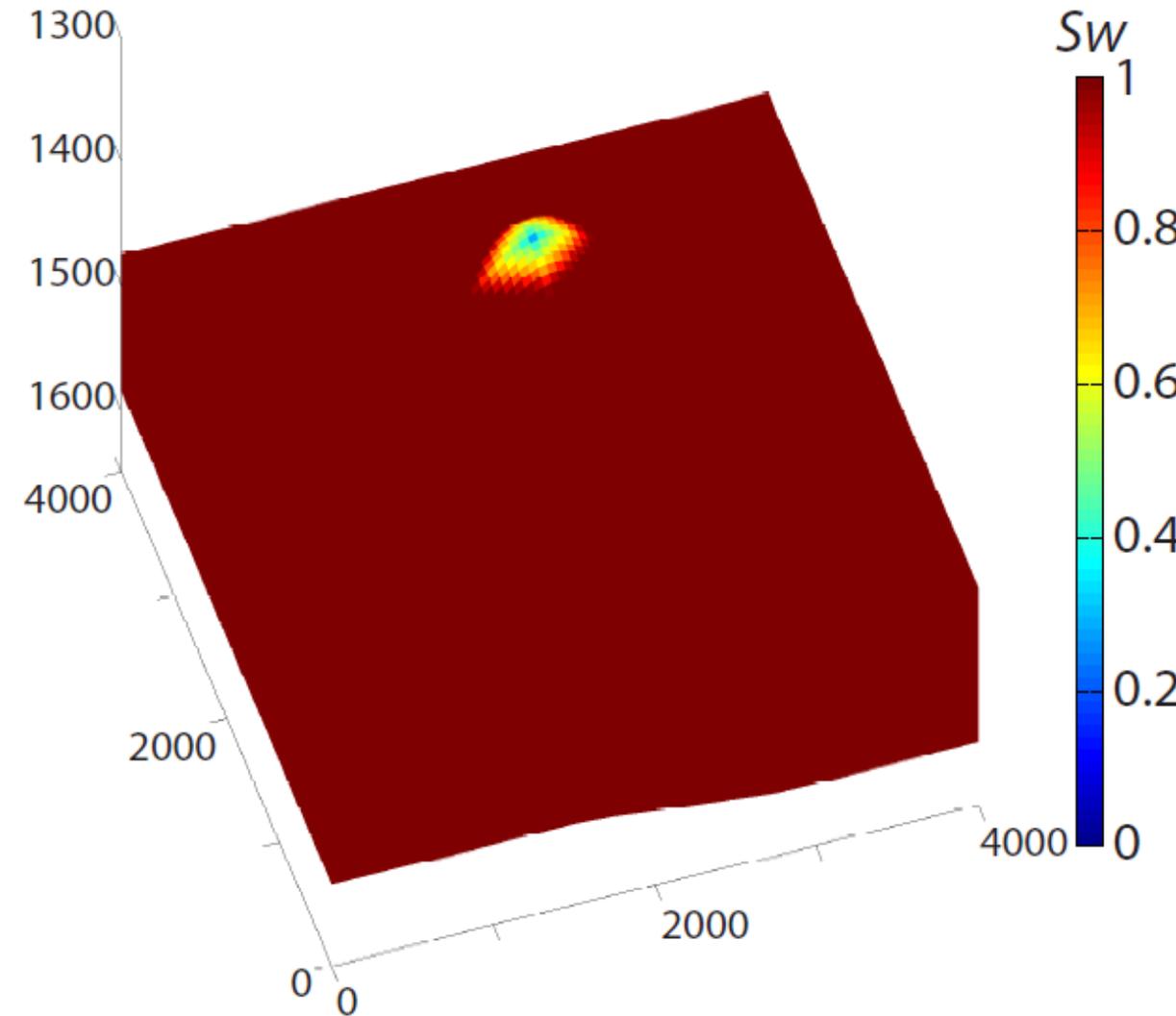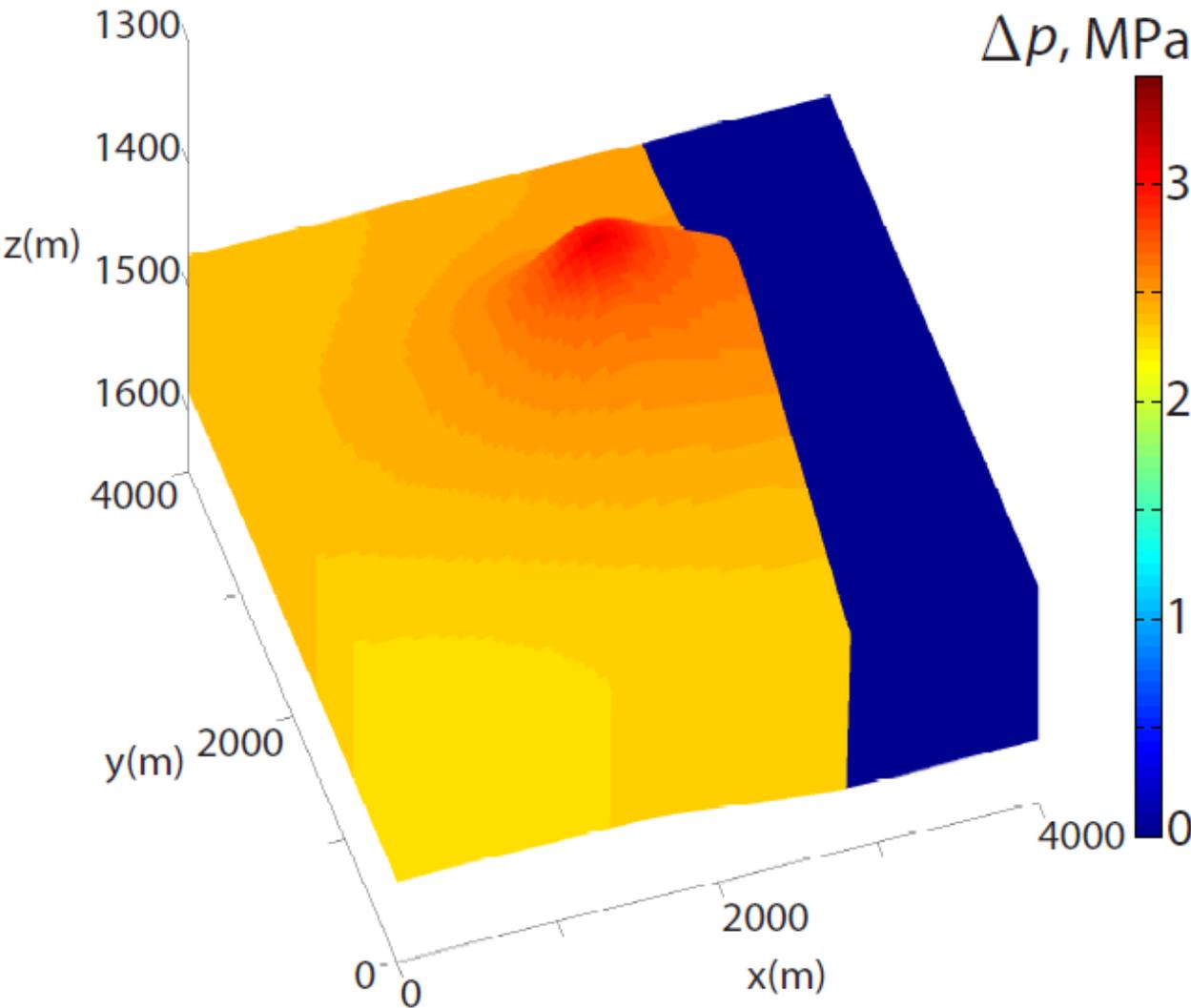
Over-pressurization due to injection
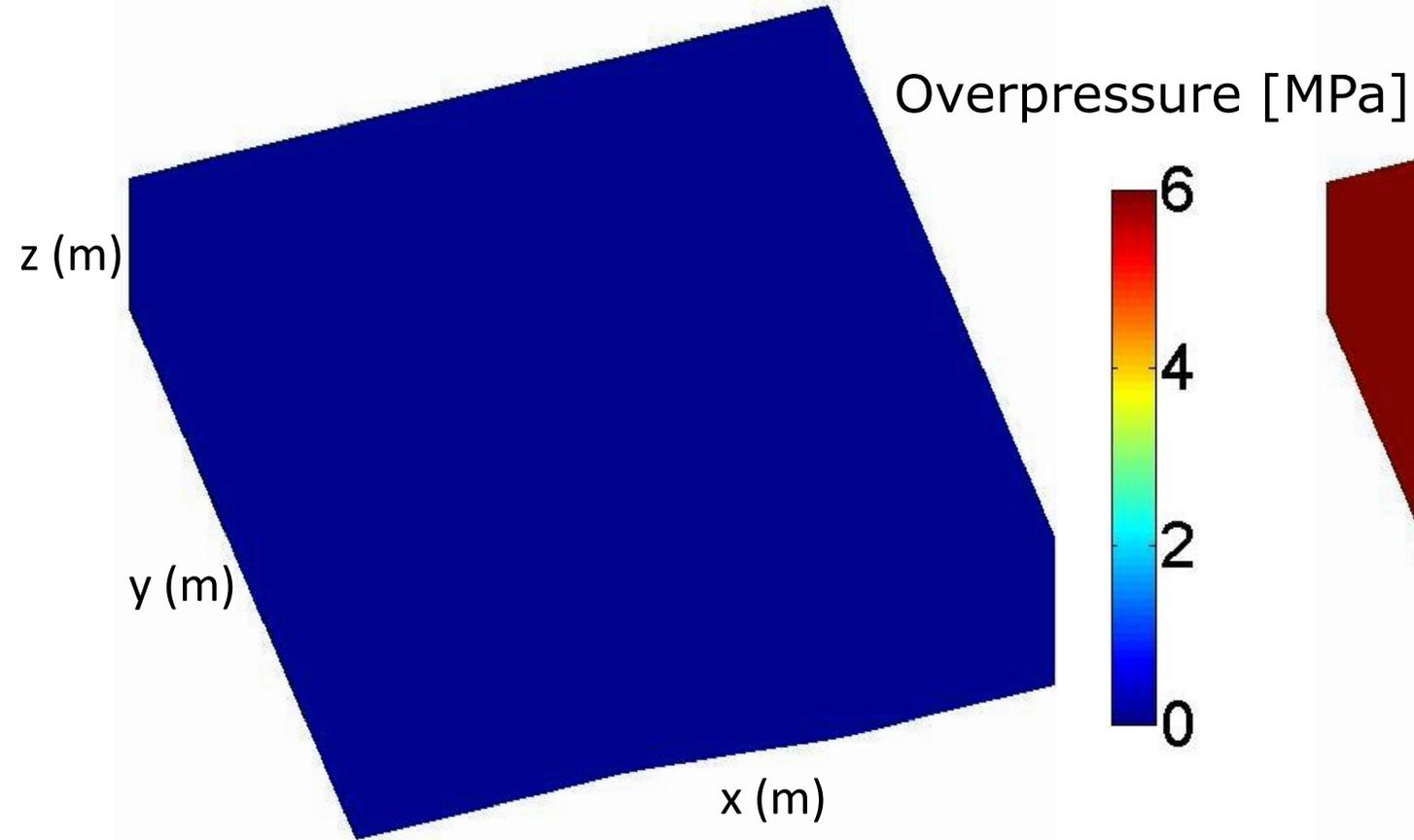
Pressure rises in the fault block where the injector is located.
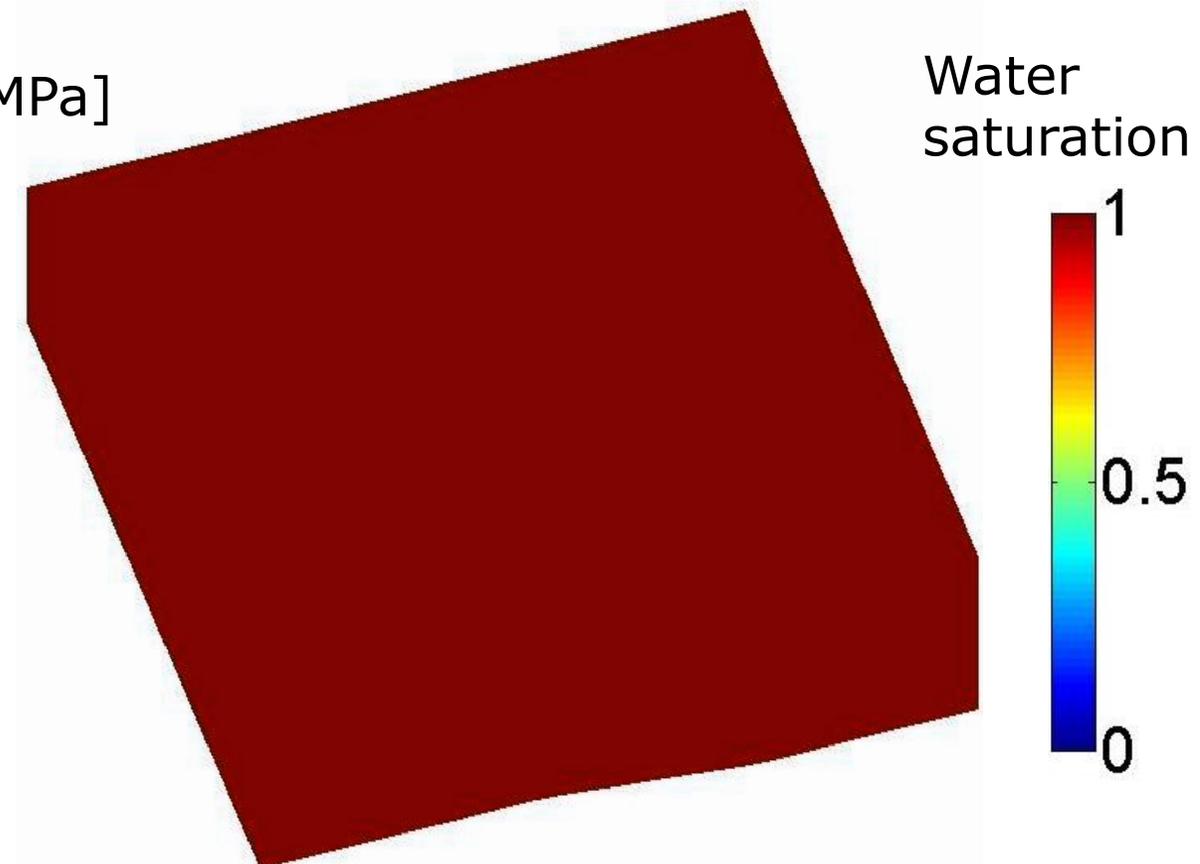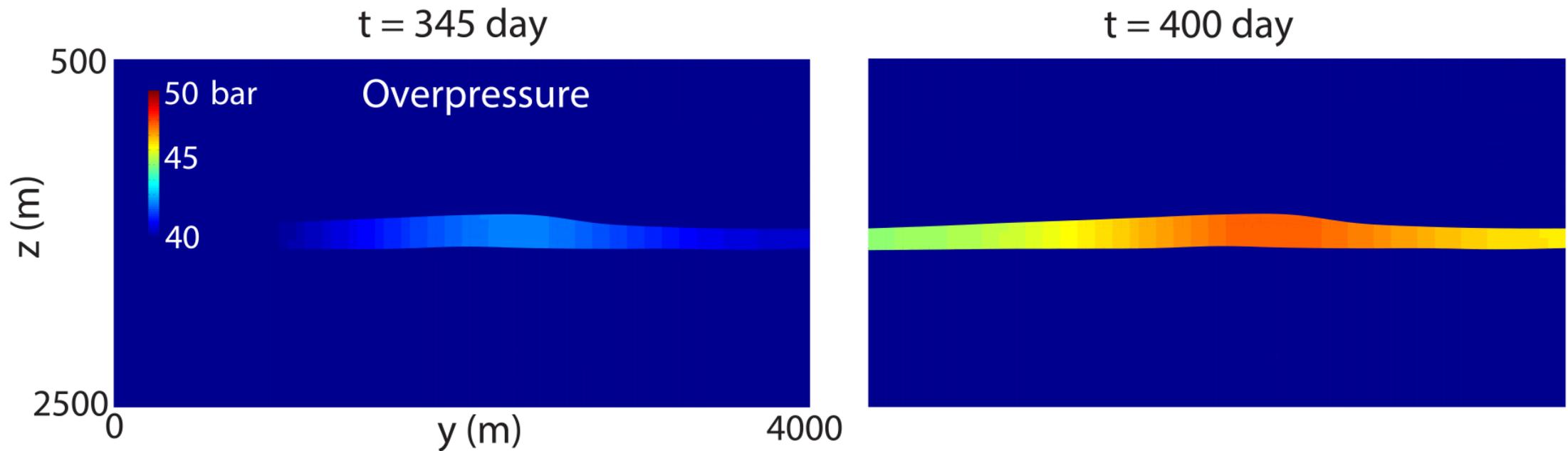
CO_2 accumulates near the top because of buoyancy.
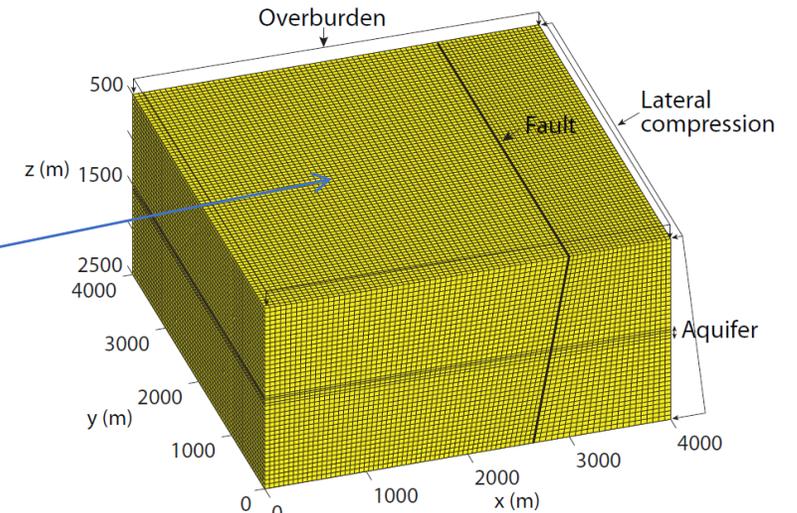
Over-pressurization due to injection

Fault pressure

t = 345 day

t = 400 day

Overpressure
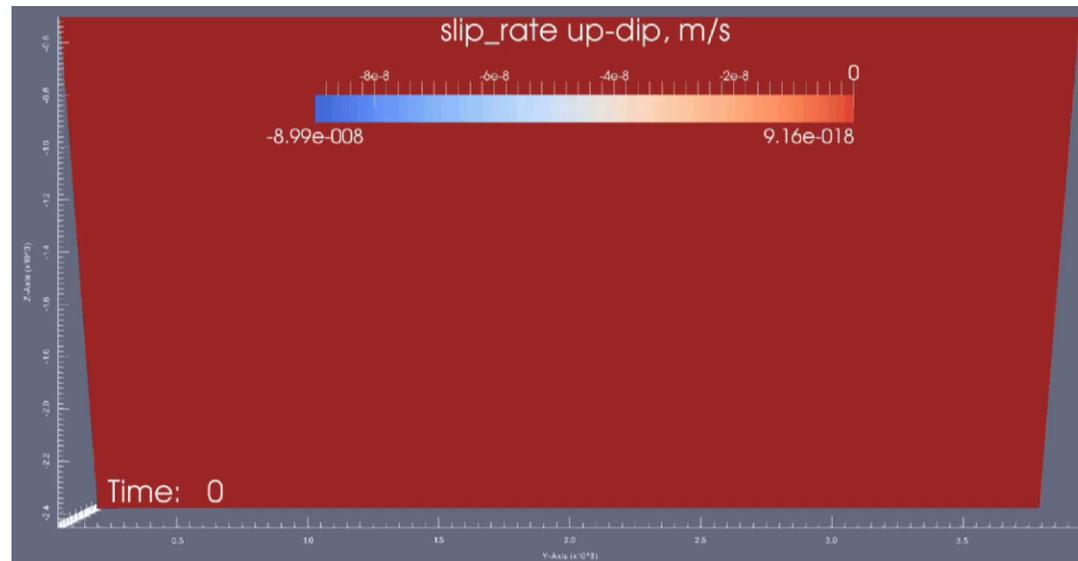
50 bar
45
40

z (m)

y (m)

500
2500
0
4000

Pressure on the fault also increases in the reservoir depth interval.

View angle for images above
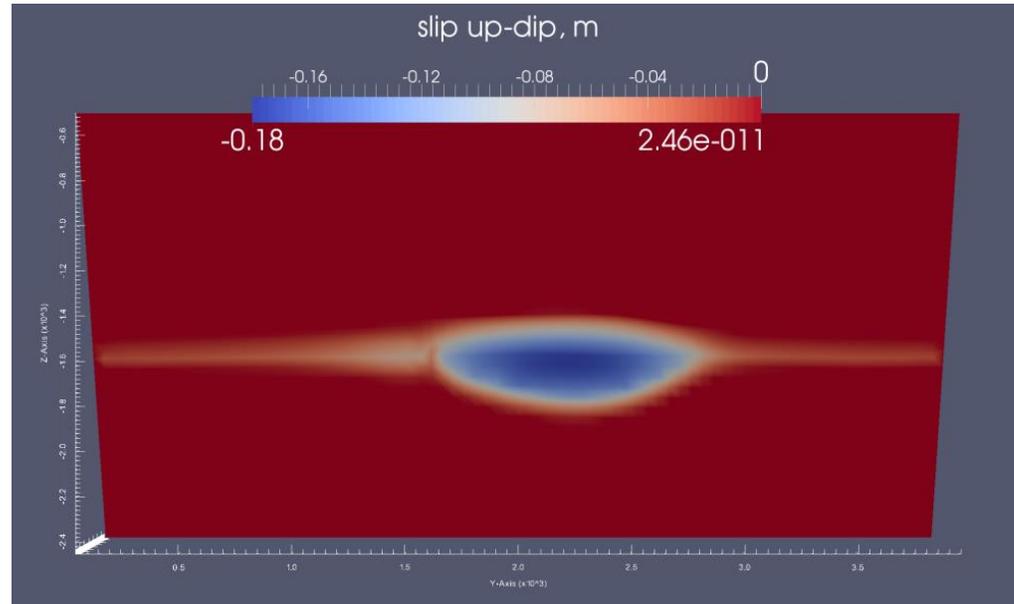
Overburden

Lateral compression
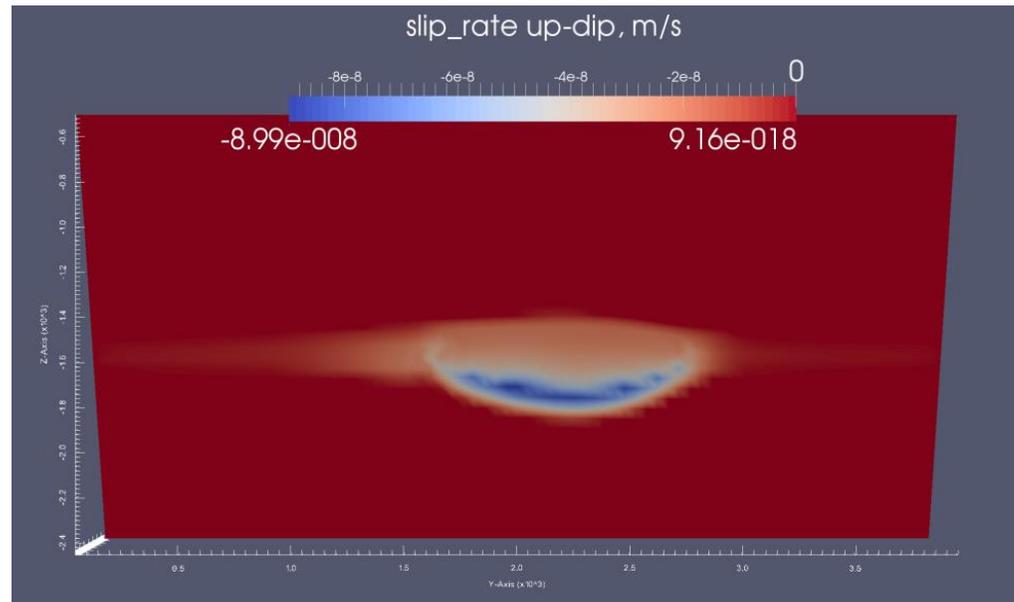
Fault

Aquifer

z (m)

y (m)

x (m)

Fault slips due to over-pressurization
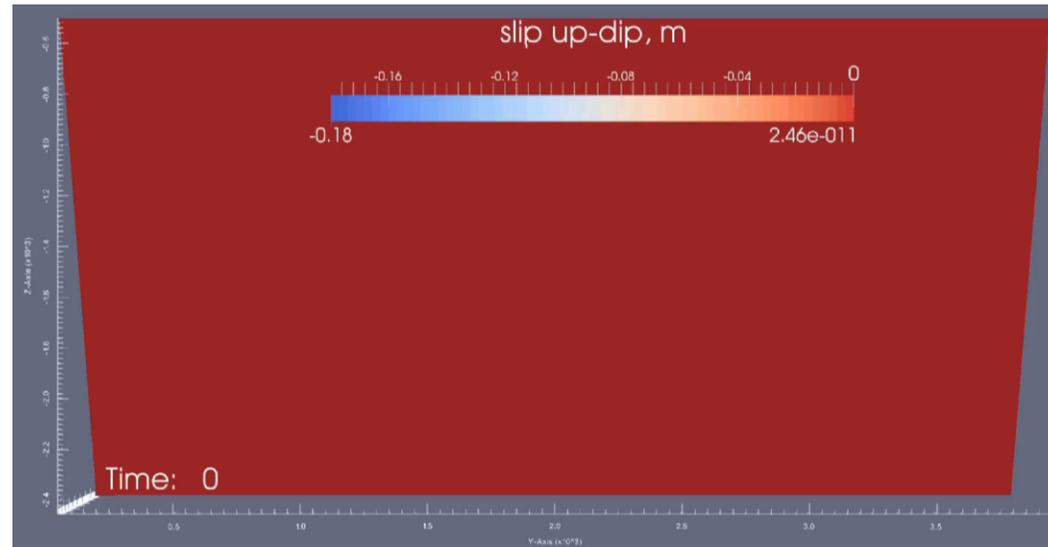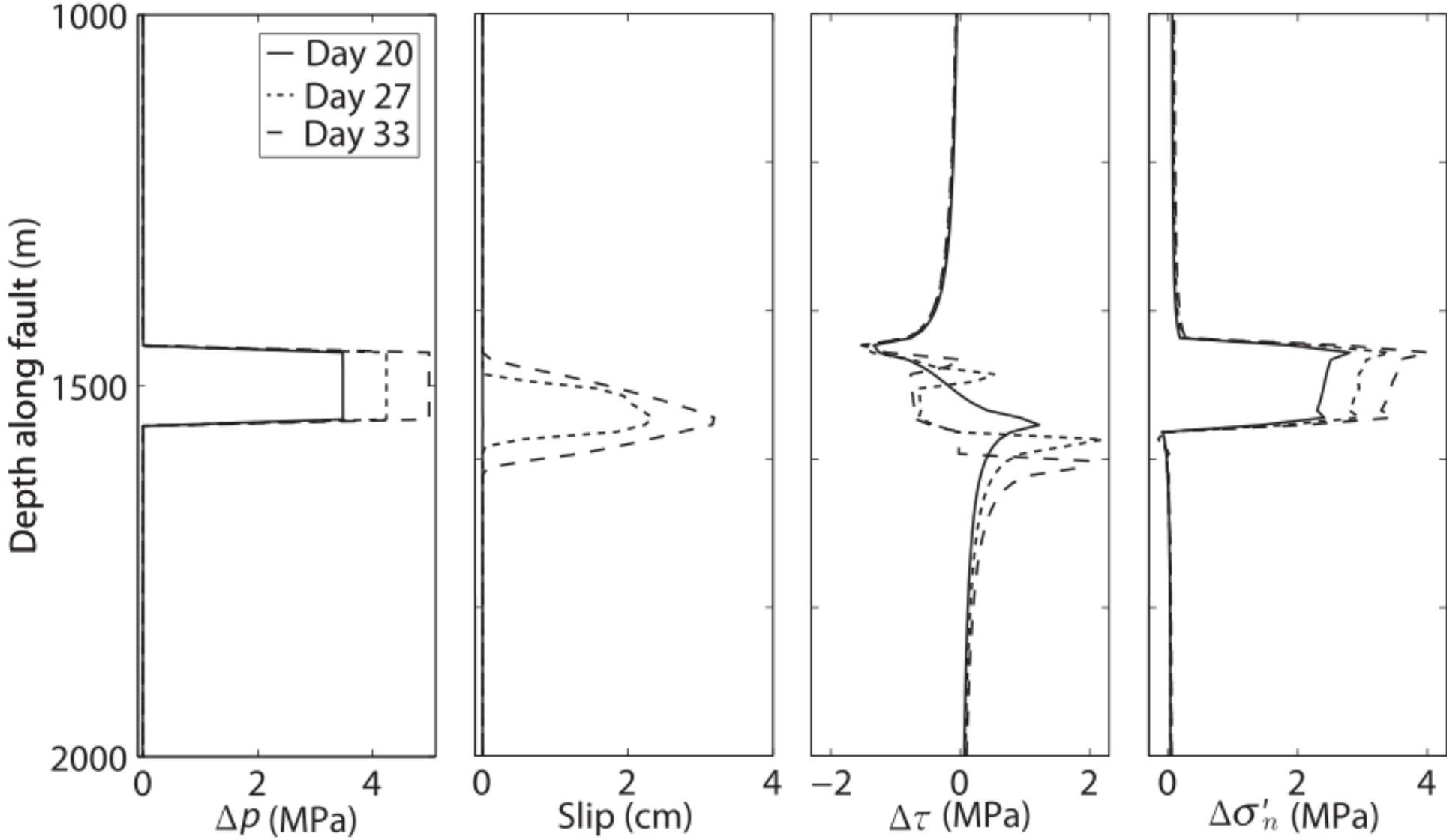
Fault slips due to over-pressurization

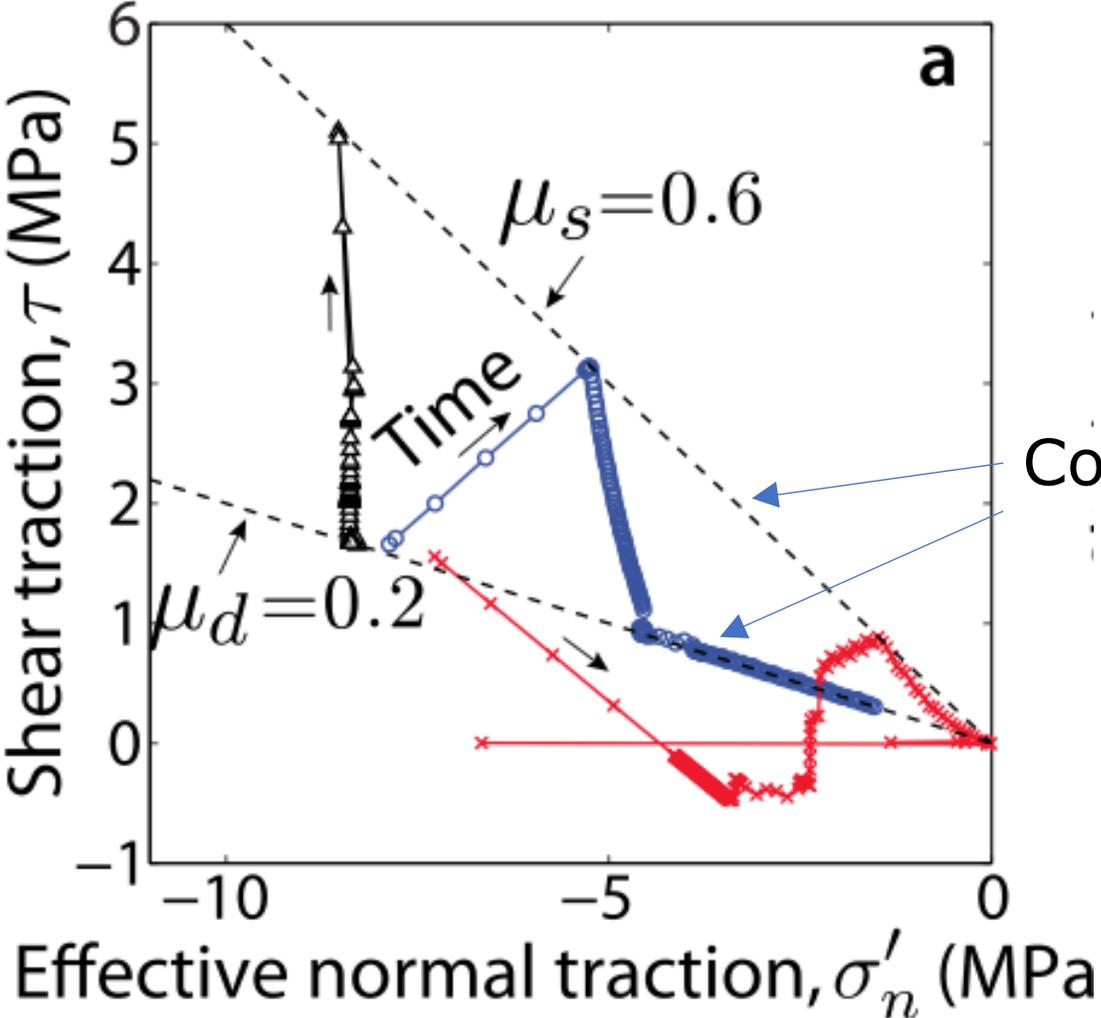Slip area gives magnitude of seismicity

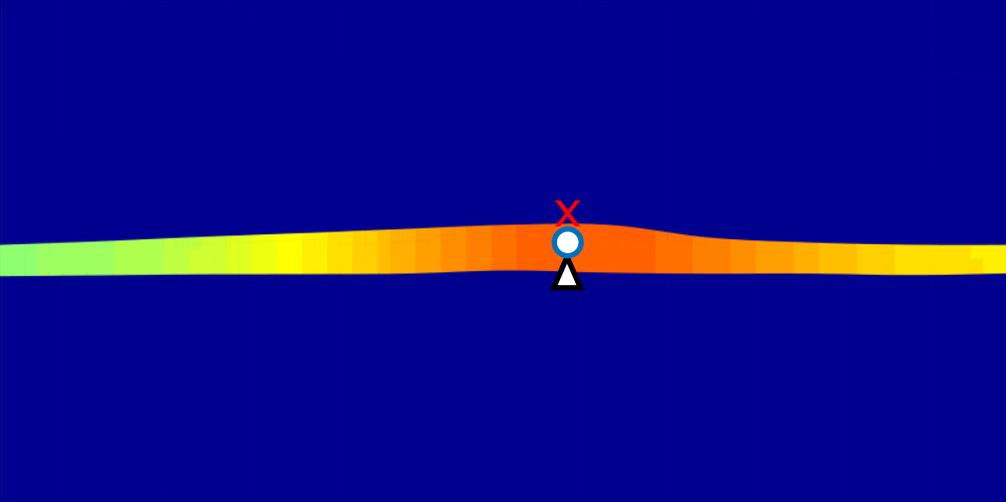Slip direction gives directivity of seismic energy released

Depth profiles of pressure and stresses along the fault

Different points on the fault approach failure differently


Coulomb Failure Lines

Conclusions

Computational modeling of coupled flow and fault poromechanics is a powerful tool. It

- Identifies storage strategies that can mitigate seismicity/leakage risks and increase storage capacity
- Provides mechanistic explanation of our observations (seismicity, ground deformation, hydrocarbon recovery, storage capacity)

Can we develop simpler models of induced seismicity that can account for multiple (10+) faults?
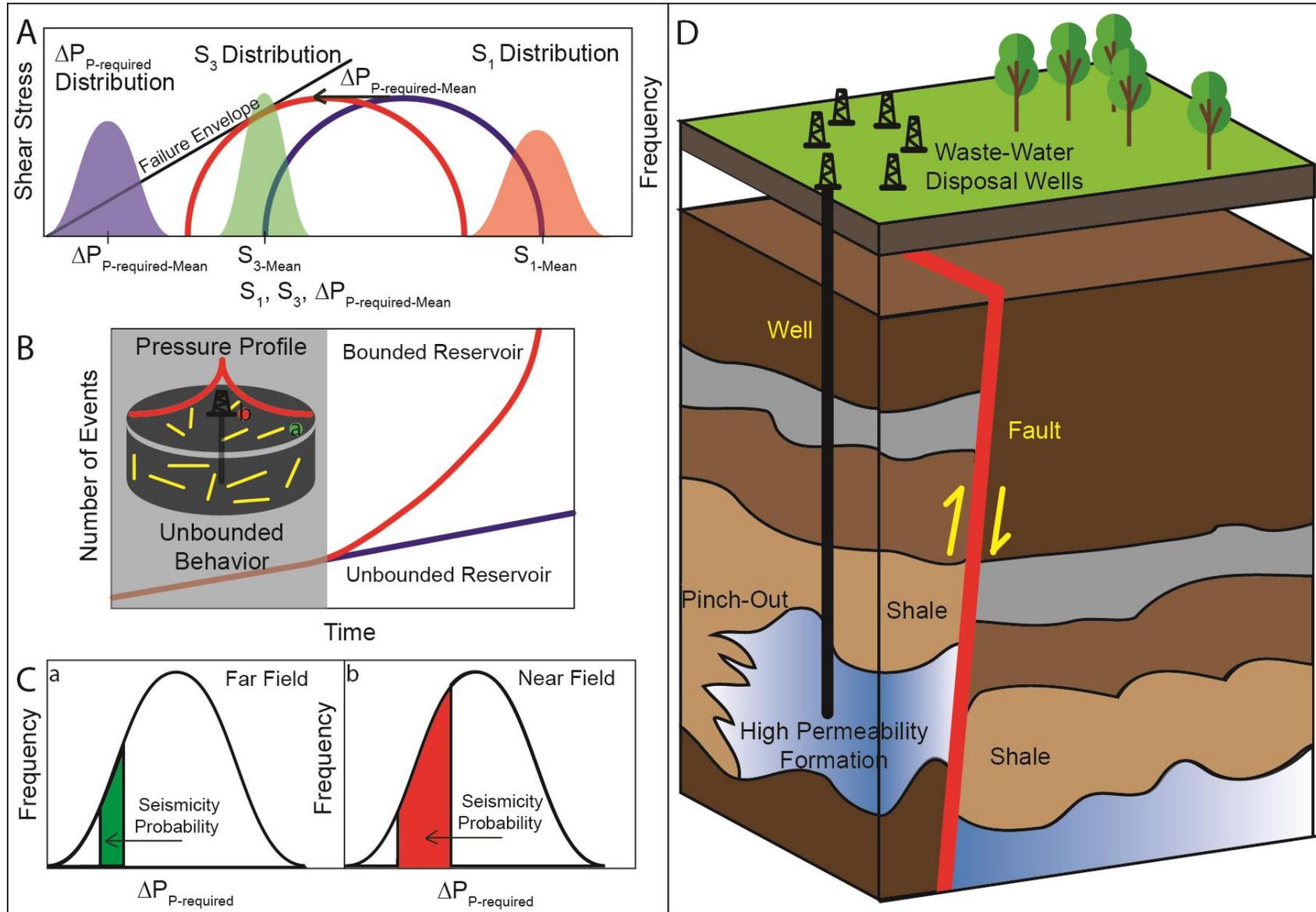
(Hosseini et al., *GRL* 2018)

Number of induced events not linear with the injected volume
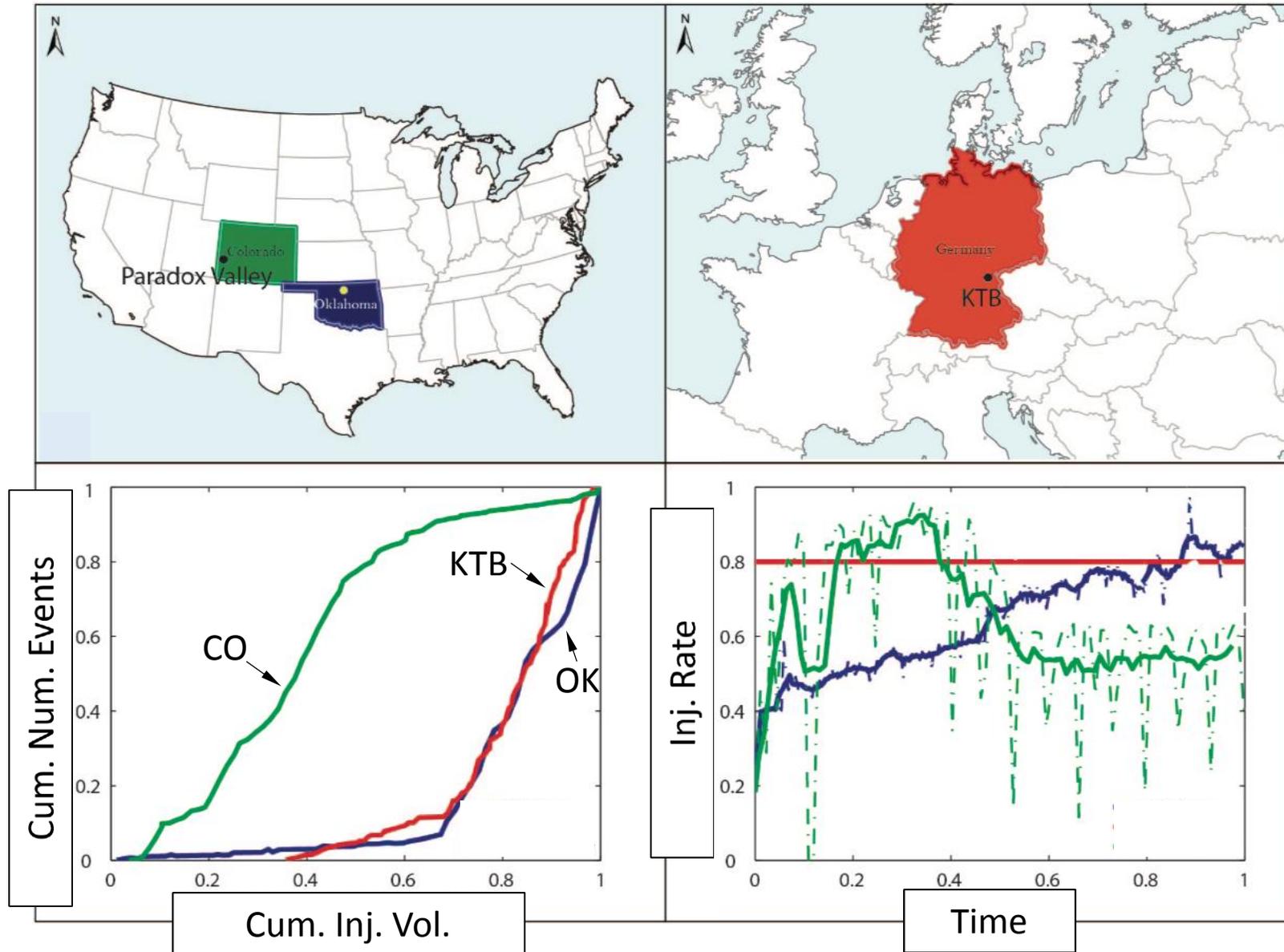
Maximum magnitude estimations of induced earthquakes at Paradox Valley, Colorado, from cumulative injection volume and geometry of seismicity clusters, Yeck et al., GJI, 2015

(Hosseini et al., *GRL* 2018)

Flow boundaries must be accounted

A probabilistic model of induced seismicity

Min and Max principal stress

Pressure required
for slip

$$\Delta P_{p-req} = \frac{nS_3 - S_1}{n-1} - P_{p0}$$ (Zoback, 2010)

Probability of
injection-induced
seismicity

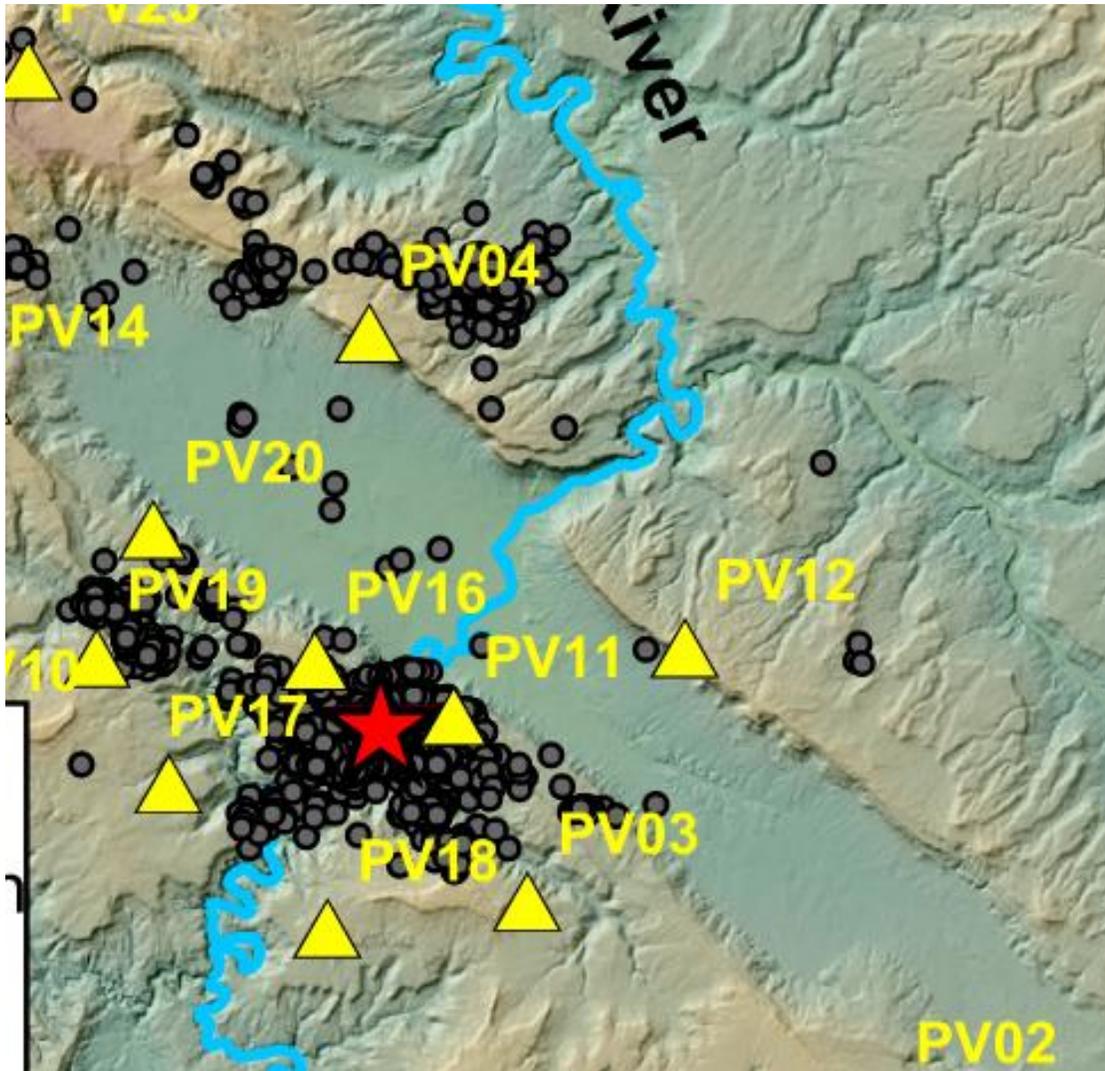$$G(\Delta P_p) = \int_0^{\Delta P_p} f(\Delta P_{p-req}) d\Delta P_p = F(\Delta P_p) - F(0)$$

Number of events

$$N_{M>M_0}(t) = \left[\int_V G(\Delta P_{p(x,y,z)}) \rho_{(x,y,z)} \, dv \right] R(M_0)$$

Frequency of events

$$R(M_0) = \frac{N_{M>M0}}{N_{total}} = 10^{-bM0}$$ (Gutenberg-Richter)

An unbounded reservoir model of Paradox Valley

(Yeck et al., *GJI*, 2015)

Pressure in an Infinite-acting reservoir

$$\Delta P_p(r, t) = \frac{qB\eta}{4\pi kh} Ei\left(-\frac{r^2 \phi \eta c_t}{4kt}\right)$$

(Lee et al., 2003)

Model predicts seismicity rate for the Paradox Valley data