Project number DE-FE0009738

Area 4 — Enhanced Simulation Tools to Improve Predictions and Performance of Geologic Storage: Coupled Modeling of Fault Poromechanics, and High-Resolution Simulation of CO_2 Migration and Trapping

Ruben Juanes
Bradford H. Hager
Massachusetts Institute of Technology

Carbon Storage and Oil and Natural Gas Technologies Review Meeting
Pittsburgh, August 18, 2016

Project objectives

- **Overall objective:** develop tools for better understanding, modeling and risk assessment of CO2 permanence in geologic formations

- Specific technical objectives:
  1. Develop efficient mathematical and computational models of the coupling between CO2 injection and fault mechanics, which will enable assessing the potential for fault slip, leakage, and induced seismicity
  2. Develop high-resolution computational methods of CO2 migration during injection and post-injection, for better predictions of capillary and solubility trapping at large scales and in the presence of aquifer heterogeneity
  3. Apply the models of fault poromechanics and CO2 migration and trapping to synthetic reservoirs as well as actual deep saline aquifers in the continental United States

Organization chart

- Key personnel:

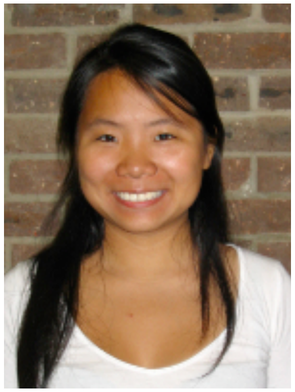
Ruben Juanes

Brad Hager

- All research performed at MIT

- Involves 3 PhD students and 1 postdoctoral associate

Birendra Jha



Xiaojing Fu

Benzhong Zhao

Yuval Tal

An important scientific question

- <u>Can CCS be a bridge solution</u> to a yet-to-be-determined low-carbon energy future?

Lifetime of carbon capture and storage as a climate-change mitigation technology

Michael L. Szulczewski[a], Christopher W. MacMinn[b], Howard J. Herzog[c], and Ruben Juanes[a,d,1]

Departments of [a]Civil and Environmental Engineering and [b]Mechanical Engineering, [c]Energy Initiative, and [d]Center for Computational Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139

Edited by M. Granger Morgan, Carnegie Mellon University, Pittsburgh, PA, and approved February 15, 2012 (received for review September 19, 2011)

- ***CCS is a geologically-viable climate-change mitigation option in the United States over the next century*** (Szulczewski et al., *PNAS* 2012)

Earthquake triggering and large-scale geologic storage of carbon dioxide

Mark D. Zoback[a,1] and Steven M. Gorelick[b]

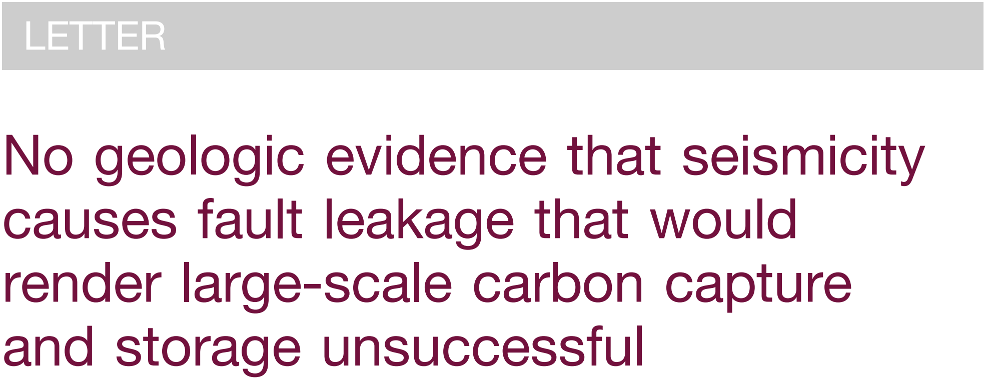
Departments of [a]Geophysics and [b]Environmental Earth System Science, Stanford University, Stanford, CA 94305

Edited by Pamela A. Matson, Stanford University, Stanford, CA, and approved May 4, 2012 (received for review March 27, 2012)

- ***CCS is a risky, and likely unsuccessful, strategy for significantly reducing greenhouse gas emissions*** (Zoback and Gorelick, *PNAS* 2012)

- <u>Is CO_2 leakage really a show-stopping risk?</u>

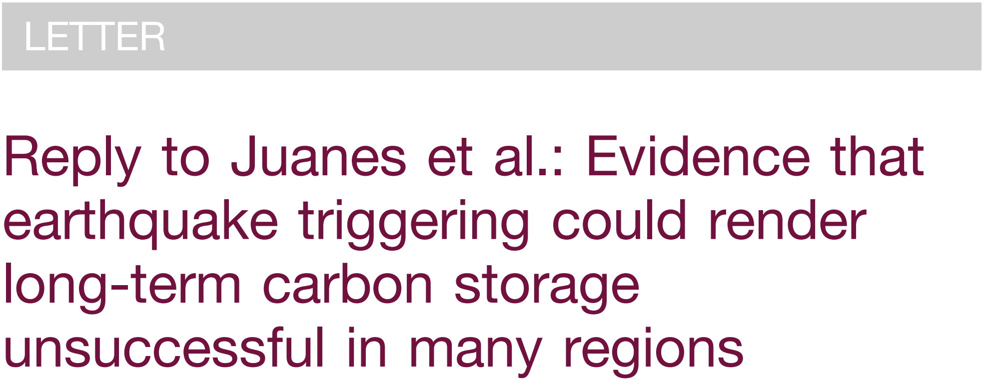
An ongoing debate …



LETTER

No geologic evidence that seismicity causes fault leakage that would render large-scale carbon capture and storage unsuccessful

Juanes et al. (*PNAS* 2012)



LETTER

Reply to Juanes et al.: Evidence that earthquake triggering could render long-term carbon storage unsuccessful in many regions

Zoback and Gorelick (*PNAS* 2012)

An ongoing debate …

Geologic carbon storage is unlikely to trigger large earthquakes and reactivate faults through which CO_2 could leak

Victor Vilarrasa[a,b,1] and Jesus Carrera[c]

Vilarrasa and Carrera (*PNAS* 2015)

To prevent earthquake triggering, pressure changes due to CO_2 injection need to be limited

Zoback and Gorelick (*PNAS* 2015)

Reply to Zoback and Gorelick: Geologic carbon storage remains a safe strategy to significantly reduce CO_2 emissions

Vilarrasa and Carrera (*PNAS* 2015)

Increasing trend of induced earthquakes

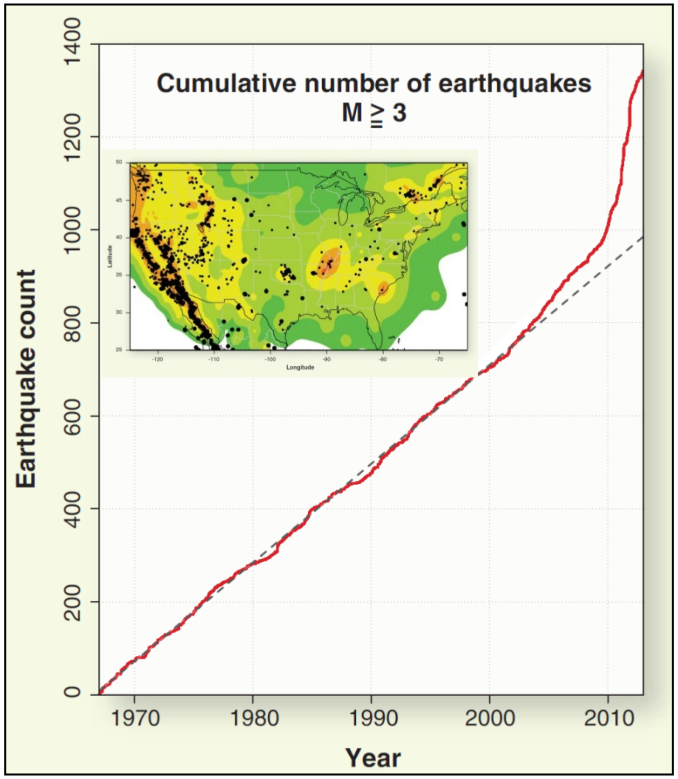
Injection-Induced Earthquakes

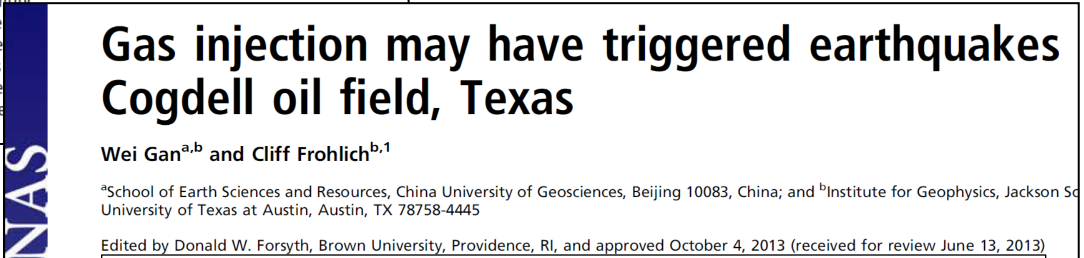
William L. Ellsworth

READ THE FULL ARTICLE ONLINE
http://dx.doi.org/10.1126/science.1225942

Cite this article as W. L. Ellsworth, *Science* **341**, 1225942 (2013).
DOI: 10.1126/science.1225942

Background: Human-induced earthquakes have become an important topic of political and scientific
discussion, owing to the concern that these events may be responsible for widespread damage
an overall increase in seismicity. It has long been known that impoundment of reservoirs, surface
underground mining, withdrawal of fluids and gas from the subsurface, and injection of fluids
underground formations are capable of inducing earthquakes. In particular, earthquakes cause
injection have become a focal point, as new drilling and well-completion technologies enable
extraction of oil and gas from previously unproductive formations.





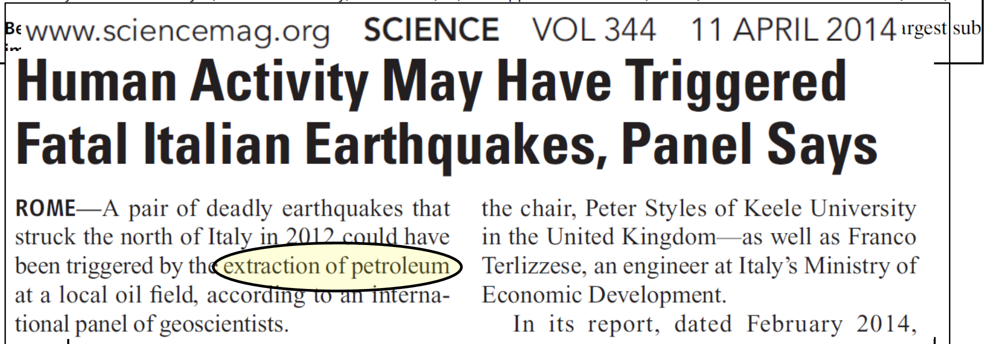
PNAS

Gas injection may have triggered earthquakes 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 Geophysics, Jackson Sc
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 review June 13, 2013)



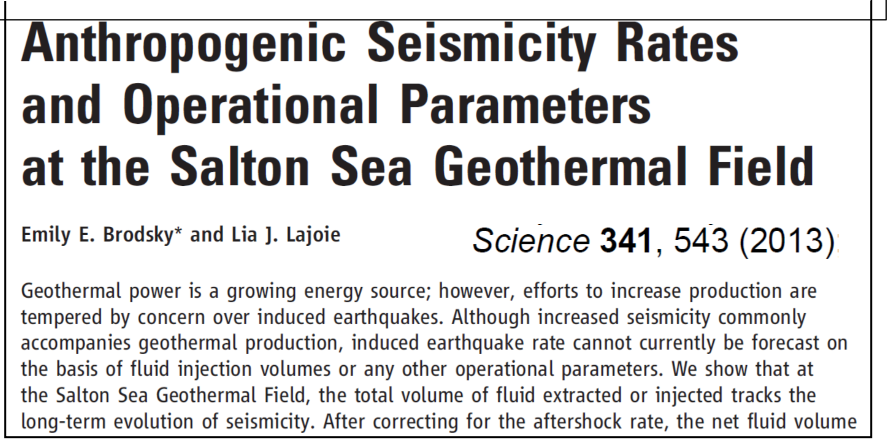
www.sciencemag.org SCIENCE VOL 344 11 APRIL 2014

Human Activity May Have Triggered Fatal Italian Earthquakes, Panel Says

ROME—A pair of deadly earthquakes that struck the north of Italy in 2012 could have been triggered by the extraction of petroleum at a local oil field, according to an international panel of geoscientists.

the chair, Peter Styles of Keele University in the United Kingdom—as well as Franco Terlizzese, an engineer at Italy's Ministry of Economic Development.

In its report, dated February 2014,



Anthropogenic Seismicity Rates and Operational Parameters at the Salton Sea Geothermal Field

Emily E. Brodsky* and Lia J. Lajoie

Science **341**, 543 (2013)

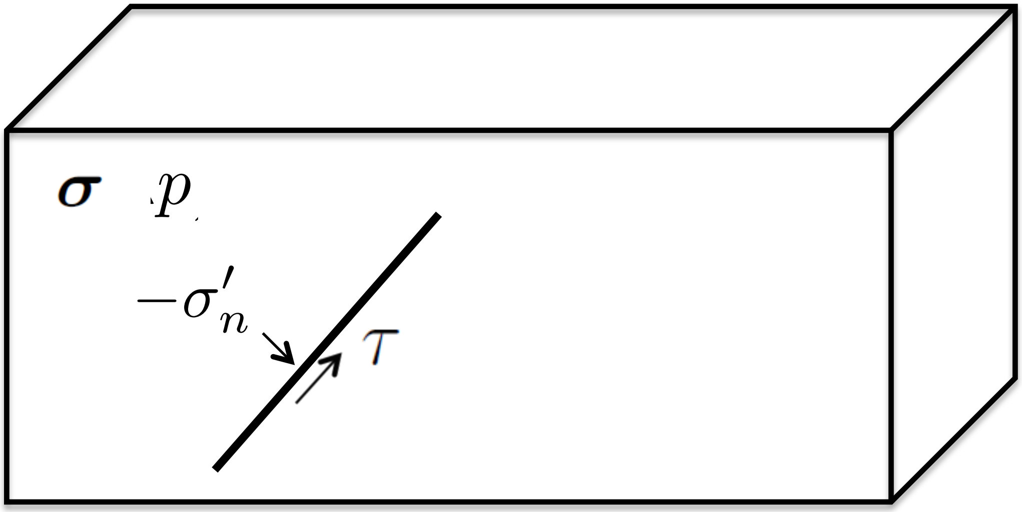
Geothermal power is a growing energy source; however, efforts to increase production are tempered by concern over induced earthquakes. Although increased seismicity commonly accompanies geothermal production, induced earthquake rate cannot currently be forecast on the basis of fluid injection volumes or any other operational parameters. We show that at the Salton Sea Geothermal Field, the total volume of fluid extracted or injected tracks the long-term evolution of seismicity. After correcting for the aftershock rate, the net fluid volume

Key questions in subsurface technologies

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

Geomechanical modeling of faults
is essential

What is the mechanism?

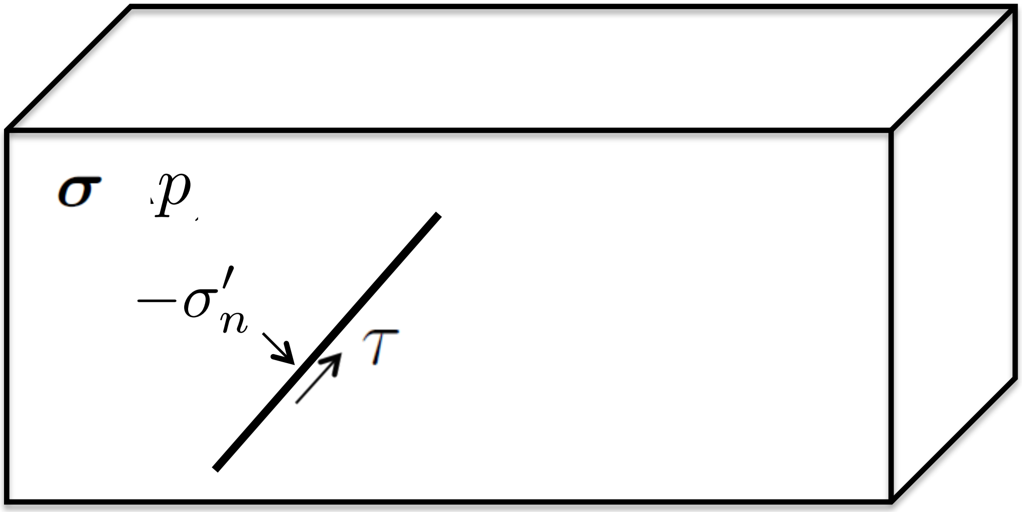


Effective stress on the fault: $(-\sigma_n') = (-\sigma_n) - bp$

Failure shear stress: $\tau_f = \tau_0 + \mu_f(-\sigma_n')$

Coulomb Force Function: $\mathrm{CFF} := \tau - \mu_f(-\sigma_n')$

What is the mechanism?



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

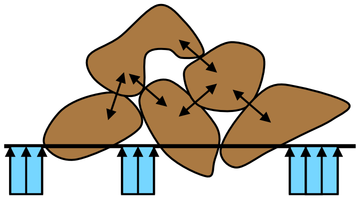
$$\Rightarrow \begin{cases} \Delta\tau > 0 & \text{(increase tectonic shear)} \\ \Delta\mu_f < 0 & \text{(fault weakening)} \\ \Delta(-\sigma_n) < 0 & \text{(poroelastic unloading)} \\ \Delta p > 0 & \text{(fluid injection)} \end{cases}$$

Multiphase poromechanics

- **Fluid mass conservation**
  - Primary unknowns: p, S

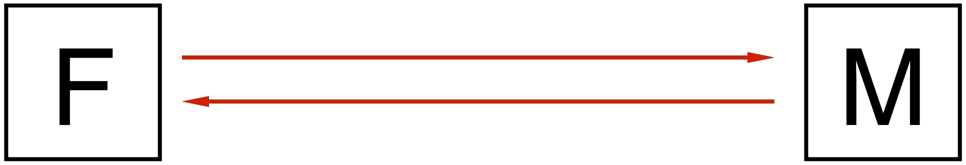
- **Linear momentum balance**
  - Primary unknown: $\boldsymbol{u}$

- **Couplings:**



$$(-\boldsymbol{\sigma}') = (-\boldsymbol{\sigma}) - bp\boldsymbol{1}$$

Effective stress

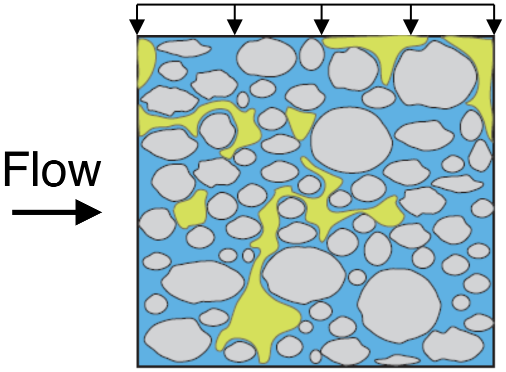


Change in volume

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

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

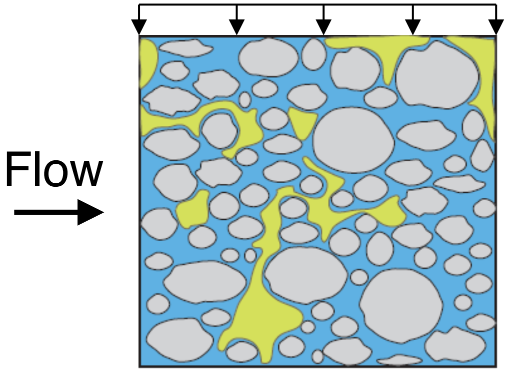
Multiphase poromechanics



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

Fluid mass balance: $\dfrac{dm_\alpha}{dt} + \nabla \cdot \boldsymbol{w}_\alpha = \rho_\alpha f_\alpha$

Multiphase poromechanics



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

Fluid mass balance: $\dfrac{dm_\alpha}{dt} + \nabla \cdot \boldsymbol{w}_\alpha = \rho_\alpha f_\alpha$

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

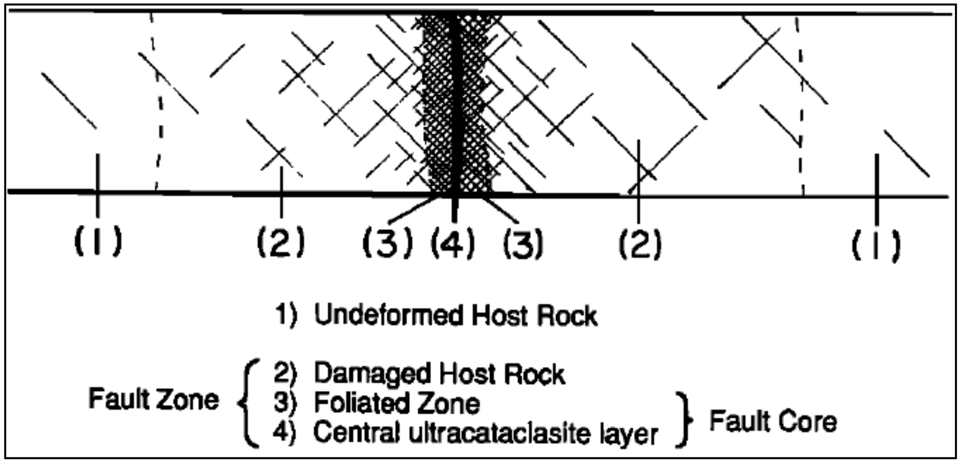
Multiphase effective stress: $\delta\boldsymbol{\sigma} = \delta\boldsymbol{\sigma}' - b\delta p_E \mathbf{1}, \quad \delta\boldsymbol{\sigma}' = \boldsymbol{C}_{dr} : \boldsymbol{\varepsilon}$

Coussy, 1995; Kim et al., *SPE J.* 2013

Earthquakes happen due to rupture of a fault

Interpretation of a fault – *Structural*

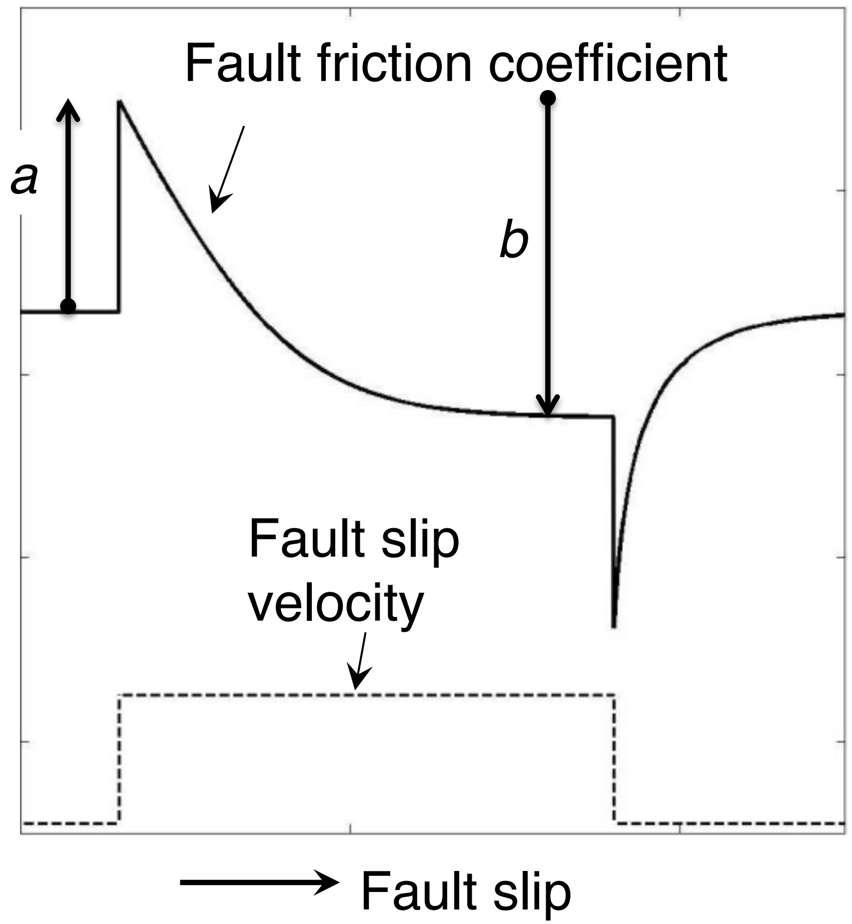
surface of discontinuity



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

Interpretation of a fault – *Functional*

Rate and state friction law



$$\tau_f = \tau_0 + \underbrace{\mu_f}(-\sigma'_n)$$

Fault friction coefficient

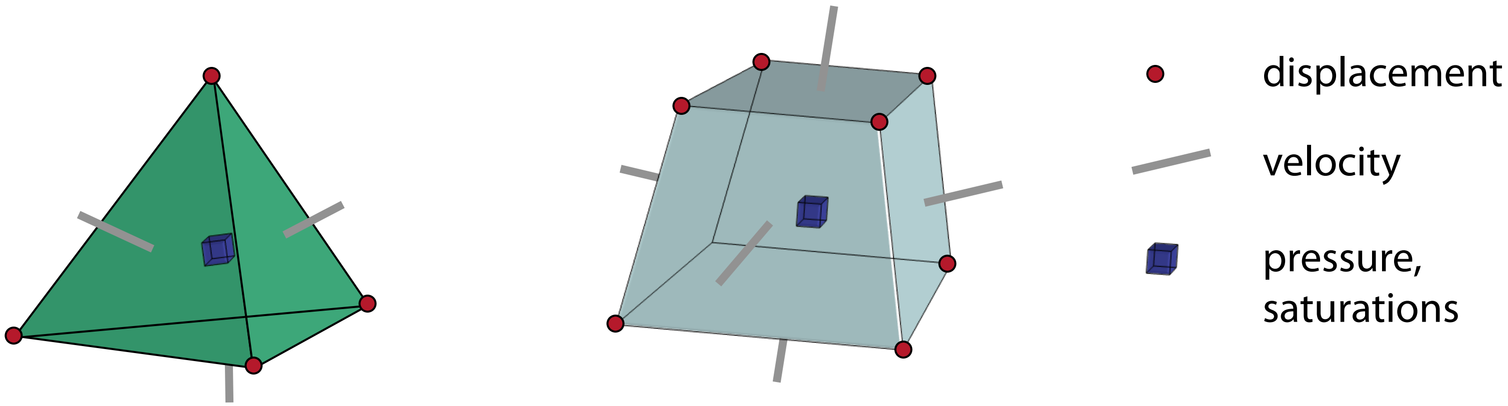
Fault friction and strength evolve dynamically

- (a-b) > 0 : velocity strengthening;
  stable slip
- (a-b) < 0 : velocity weakening;
  runaway slip;
  potential for earthquake

Marone, *Ann. Rev. EPS*, 1998

Computational modeling of flow-geomechanics

- **Discretization** (Jha and Juanes, *Acta Geotech.* 2007)
  - Finite elements for mechanics; finite volumes for flow
  - Stable, convergent scheme
  - Single, unstructured computational grid

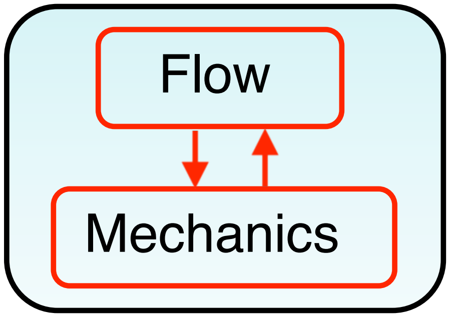


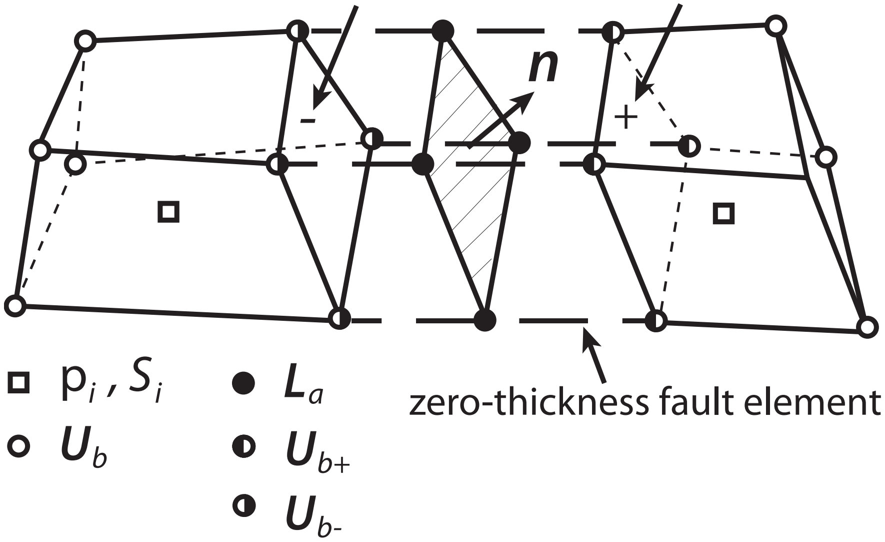
- **Coupling strategies** (Kim, Tchelepi and Juanes, *SPE J.* 2011; *CMAME* 2011a,b; *SPE J.* 2013)
  - Fixed-stress operator split
  - Efficient, unconditionally stable sequential scheme
  - Recently, generalized to a class of iterative schemes

(Castelleto, White, et al., *IJNAMG* 2015, *CMAME* 2016)

Coupled fluid flow and geomechanics simulator

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

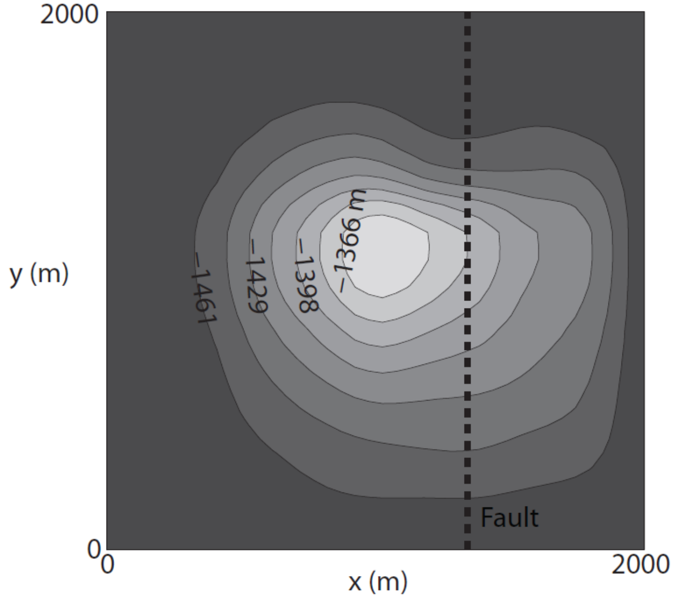


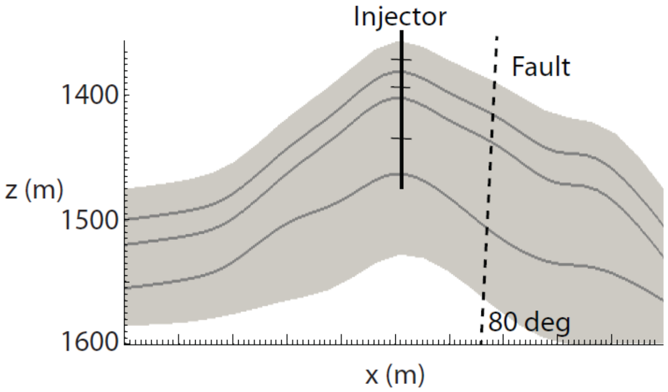


- Features of the coupled code:
  - Finite element geomechanics code (PyLith)
  - Finite volume multiphase-flow reservoir simulator (GPRS)
  - ***Sophisticated formulation for fault deformation and slip***
  - C++, fast, parallel
  - Uses hexahedral or tetrahedral grid
  - Viscoelastic and elastoplastic rheology; rate- and state- fault friction

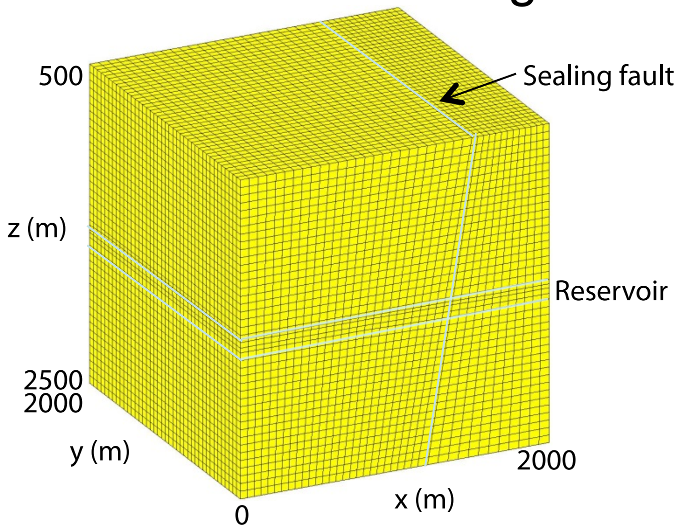
Synthetic case: faulting induced by CO_2 injection

Dome-shaped aquifer

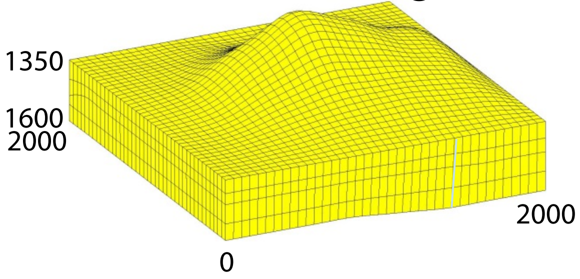




Geomechanical grid



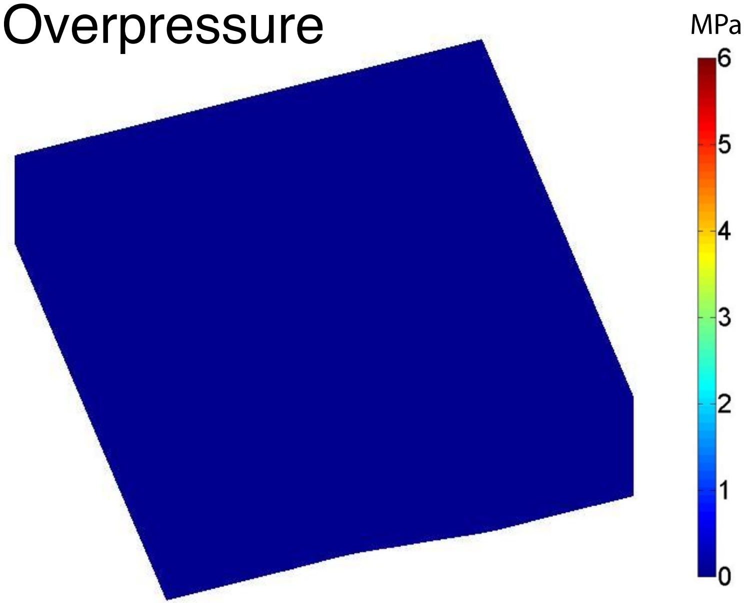
Reservoir grid



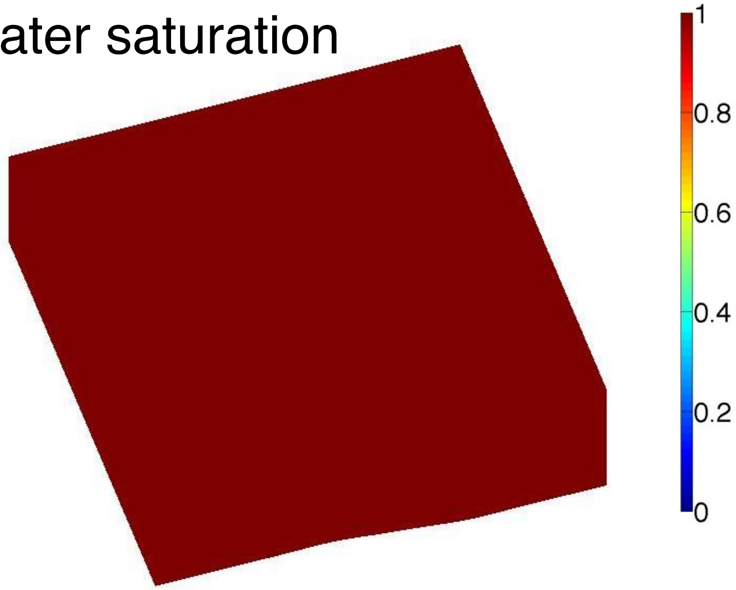
- Normal faulting regime
- Rate- and State- friction law: *a* = 0.002, *b* = 0.08, critical slip = 1 cm

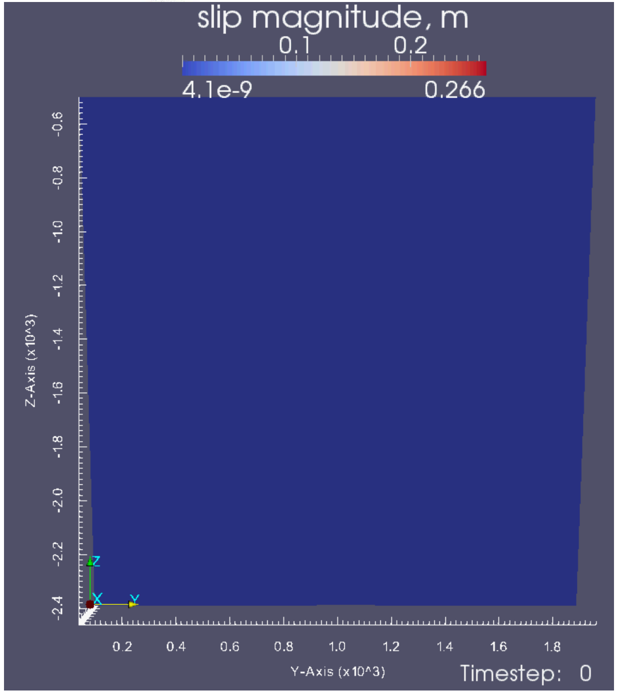
Fault slip due to over-pressurization

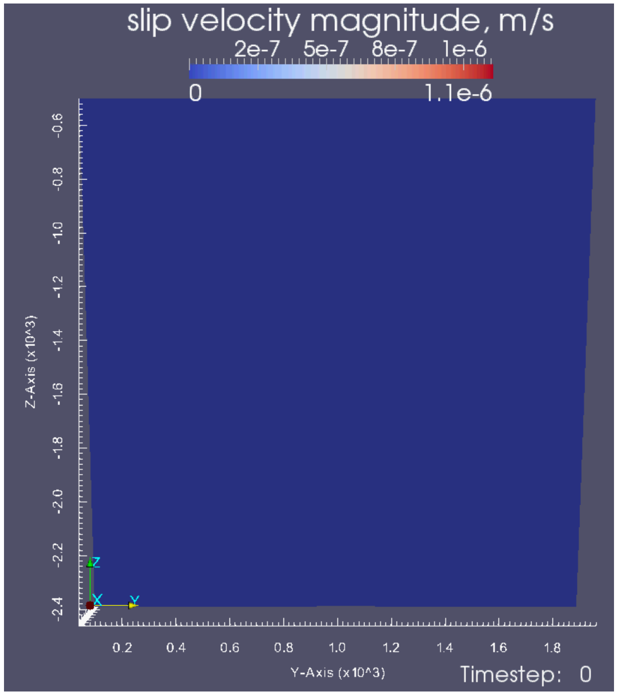
Overpressure



Water saturation







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Water Resources Research

RESEARCH ARTICLE

10.1002/2013WR015175

Key Points:

- New computational approach to coupled multiphase flow and geomechanics
- Faults are represented as surfaces, capable of simulating runaway slip
- Unconditionally stable sequential solution of the fully coupled

Coupled multiphase flow and poromechanics: A computational model of pore pressure effects on fault slip and earthquake triggering

Birendra Jha[1] and Ruben Juanes[1]

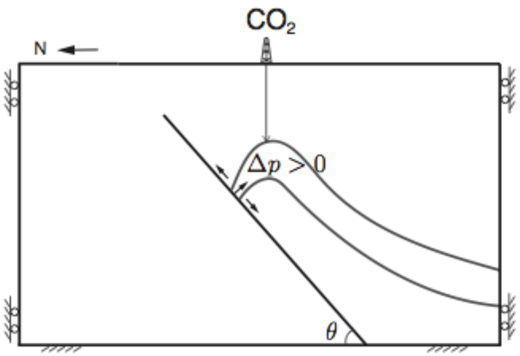
[1] Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

Effect of tectonic stress on fault stability

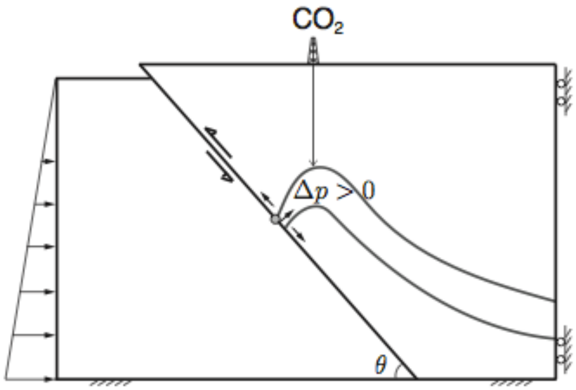
Tectonic regime

- determines preferred failure mode
- interacts with injection-induced stress changes to control onset and magnitude of seismicity

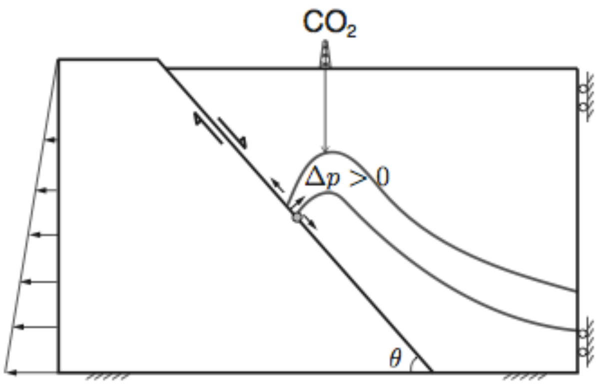
Lithostatic



Reverse-faulting



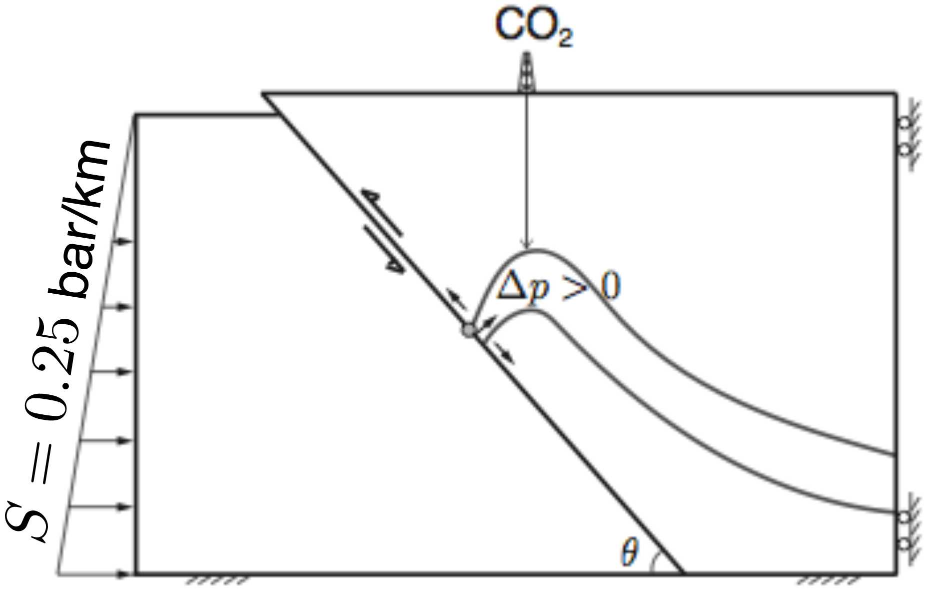
Normal-faulting



Question:

- What is the best injection strategy in a given tectonic regime?
- For example, is CO_2 injection with brine production a safe strategy in reverse-faulting regime?

Isolate tectonic contribution from injection-induced perturbation



At a point at depth z km,

$$\boldsymbol{\sigma} = (0, -zS, 0)$$

$$\boldsymbol{T} = \boldsymbol{\sigma n} = [0, zS\sin\theta, 0]$$

$$\Delta\sigma_n^{\text{tec}} = \boldsymbol{T}\cdot\boldsymbol{n} = -zS\sin^2\theta$$

$$\Delta\boldsymbol{\tau}^{\text{tec}} = [0, zS\sin\theta\cos^2\theta, \\ zS\sin^2\theta\cos\theta]$$

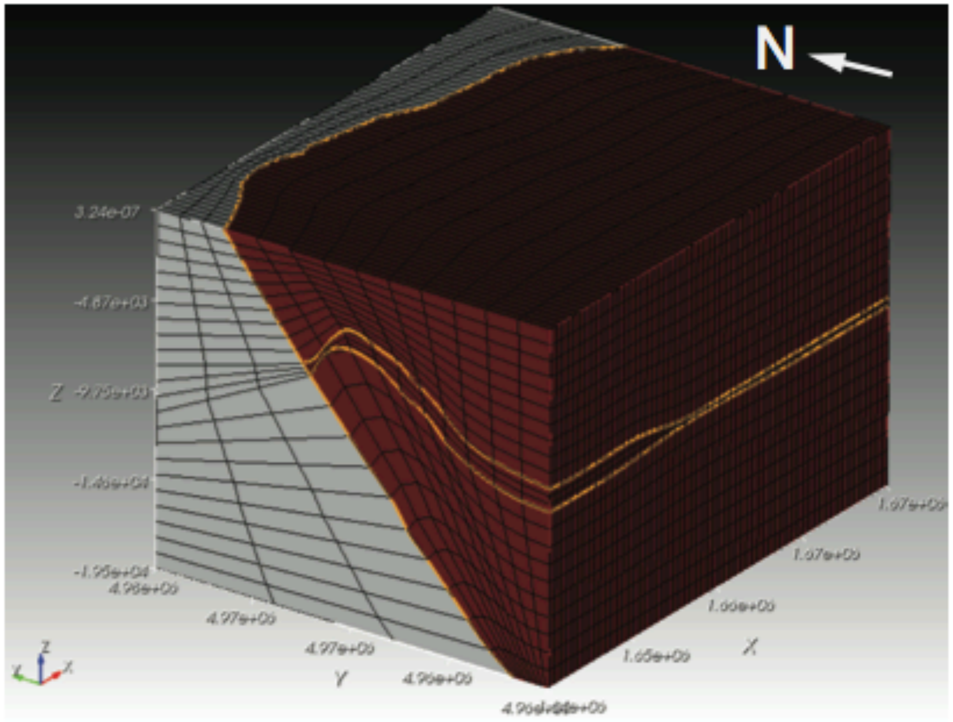
$$\begin{aligned}\Delta\text{CFF} &= [\Delta\tau + \mu_f\Delta\sigma_n]^{\text{tec}} + [\Delta\tau + \mu_f(\Delta\sigma_n + b\Delta p)]^{\text{ind}} \\ &= \Delta\text{CFF}^{\text{tec}} + \Delta\text{CFF}^{\text{ind}}\end{aligned}$$

Increase in Coulomb stress with depth,

$$\Delta\text{CFF}^{\text{tec}}/z = S\sin\theta(\cos\theta - \mu_f\sin\theta)$$

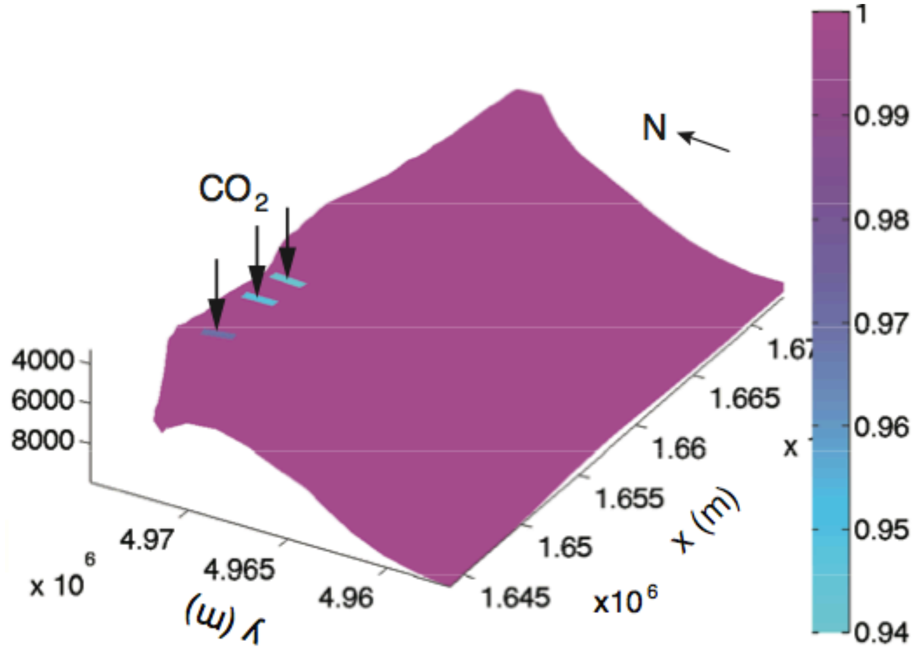
A case study: CO_2 injection in a reservoir

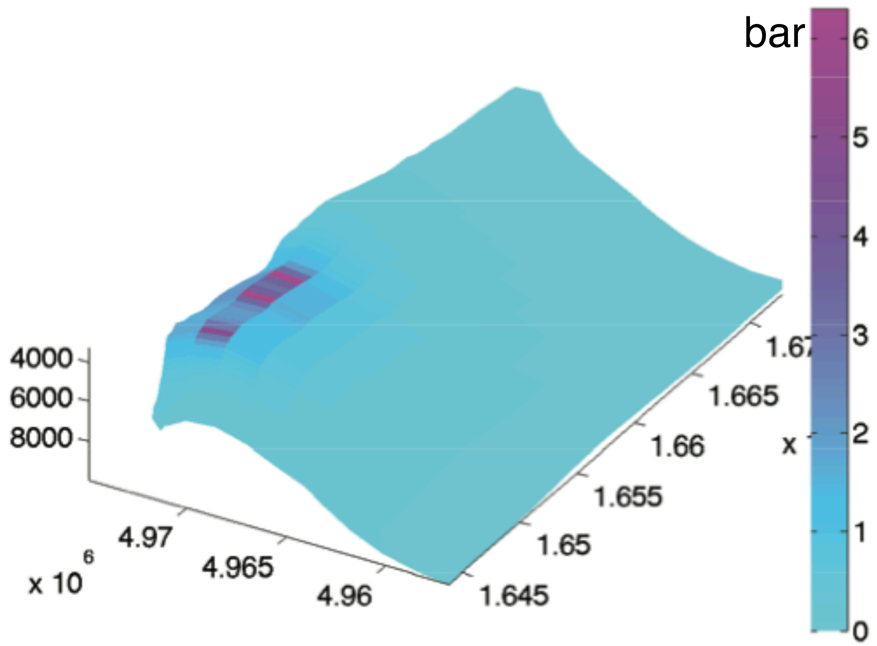
- ☐ 3D model of a depleted oilfield in an anticline with a bounding fault
- ☐ CO_2 injection for 20 years under three different stress regimes



Coupled flow and geomechanical modeling

- CO_2 accumulates near the top of the anticline (left figure), pressurizing the reservoir (right)

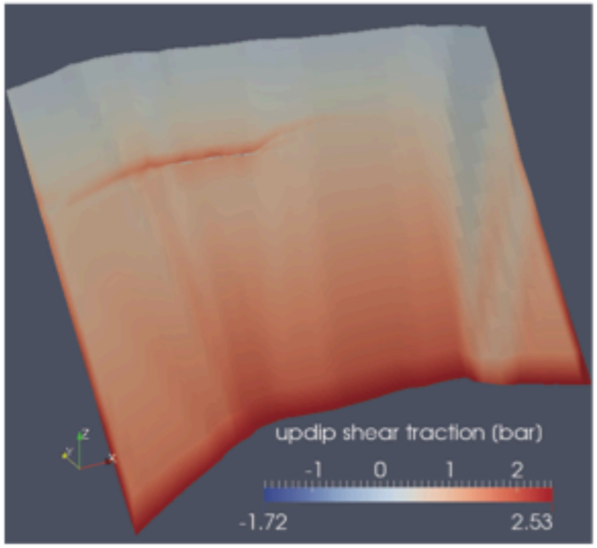




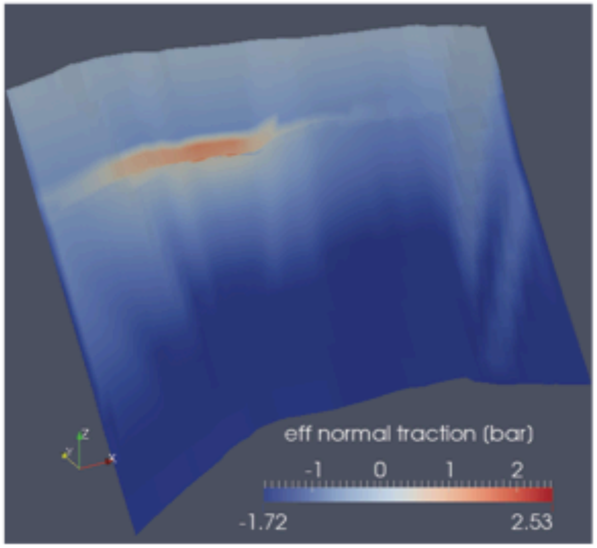
Fault stability in reverse-faulting regime

- Shear increases due to reservoir expansion.
- Fault unclamps due to pressure-induced drop in effective compressive stress

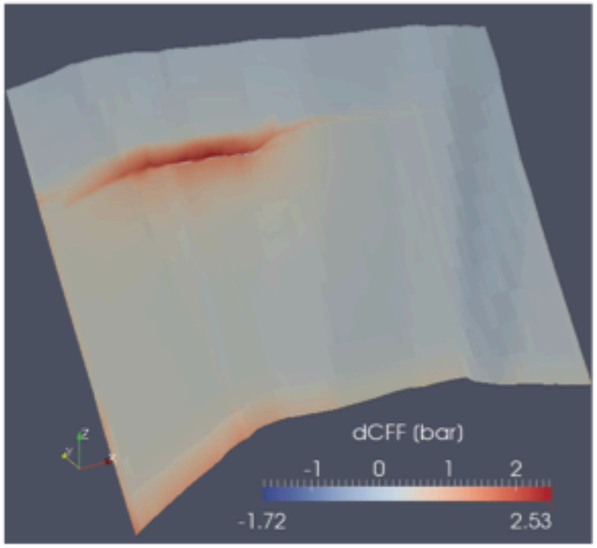
Up-dip shear



Effective normal

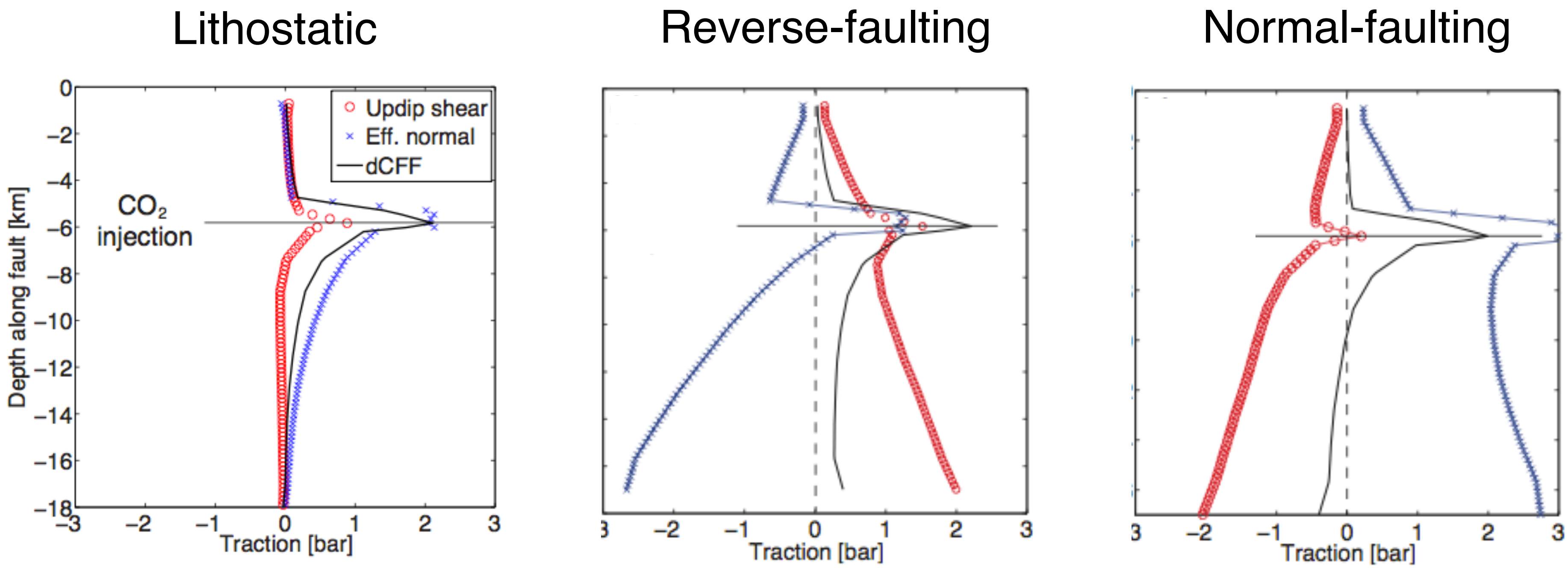


Coulomb stress



Conclusions

- ❑ Size of destabilized region depends on tectonic regime
- ❑ Traction-dependent changes in fault permeability, relevant for leakage, varies with tectonic regime



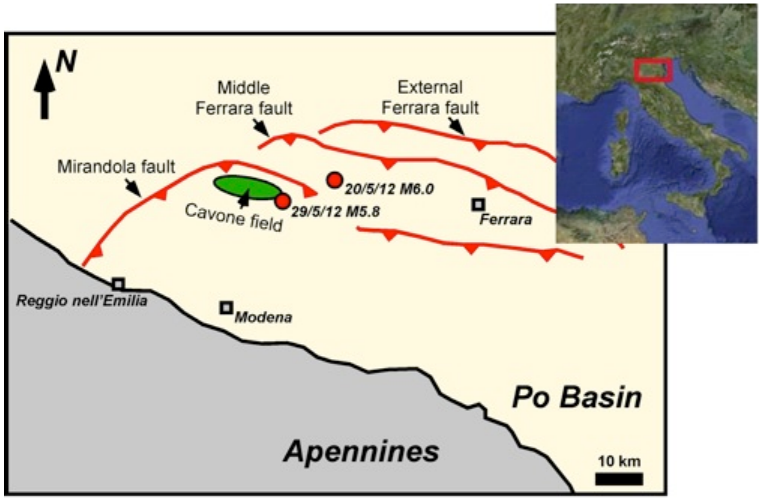
Lithostatic

Reverse-faulting

Normal-faulting

The 2012 Emilia Romagna earthquake sequence

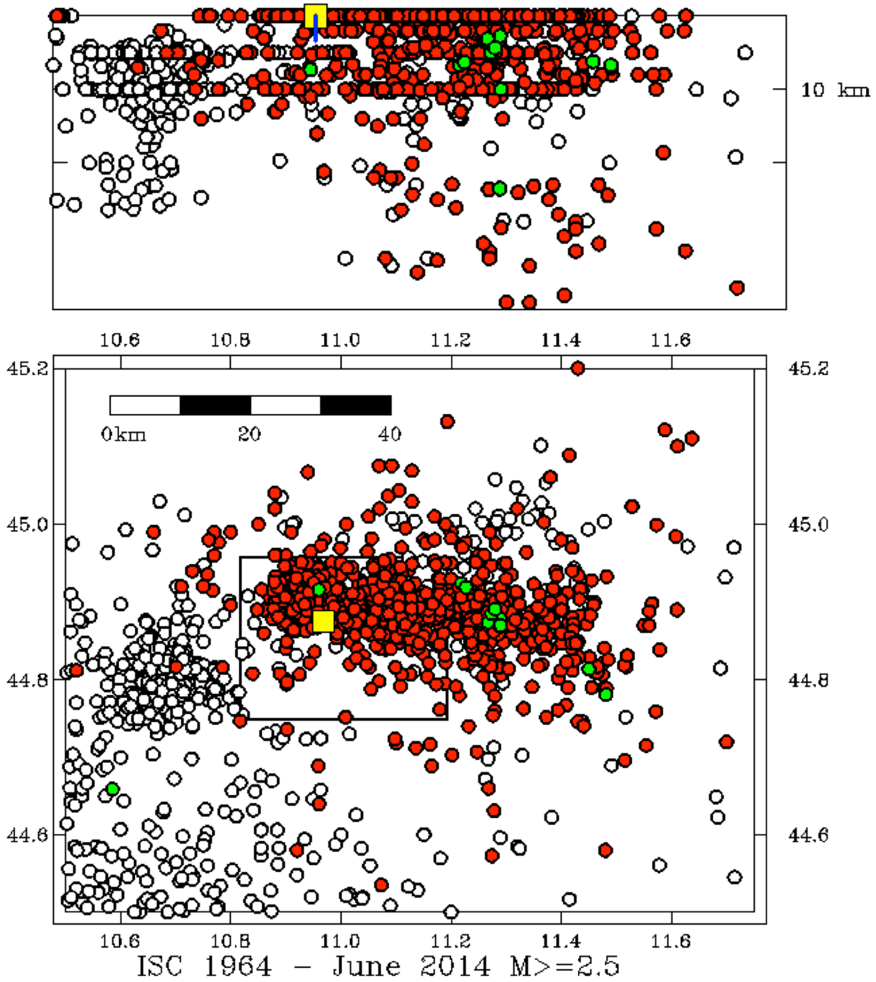
- ☐ A sequence of damaging earthquakes ($M_w = 6.0$, $M_w = 5.8$) in May 2012, near the Cavone oil field, in northern Italy



  - Raised the question: was it induced by reservoir operations?
  - We address this question by means of computational modeling of coupled flow and geomechanics, which integrates geologic constraints and seismic observations

Historic seismicity

- ❑ This is a tectonically active region: here, earthquakes of M > 2.5



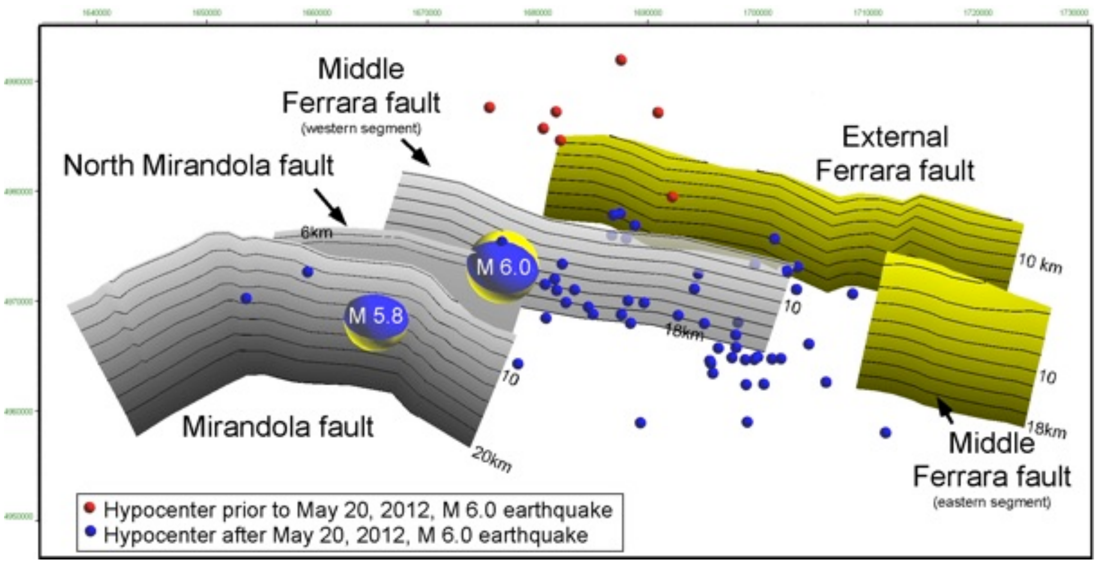
○ 1964 – Apr 2012

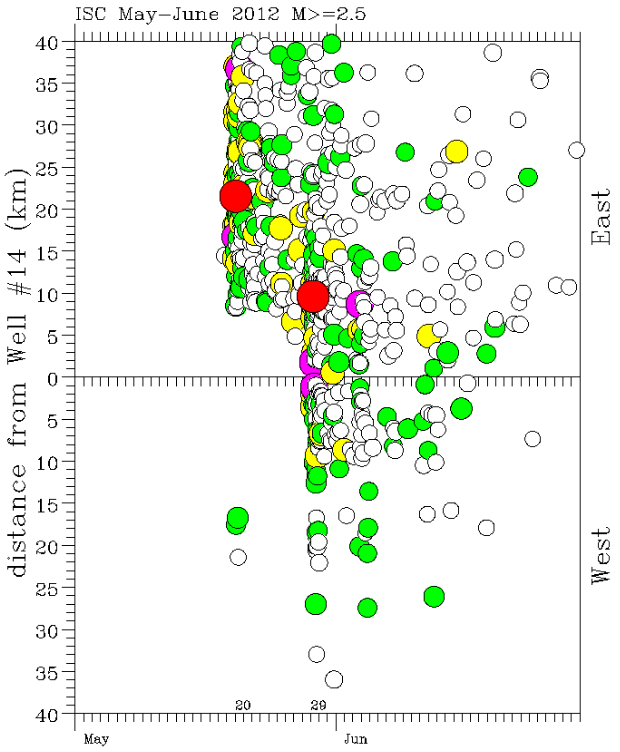
🔴 May – Jun 2012

🟢 Jul 2012 – Jun 2014

Seismotectonic analysis

- Two events: May 20 (M_w = 6.0) and May 29 (M_w = 5.8) sourced on close but separate faults – Middle Ferrara fault and Mirandola fault

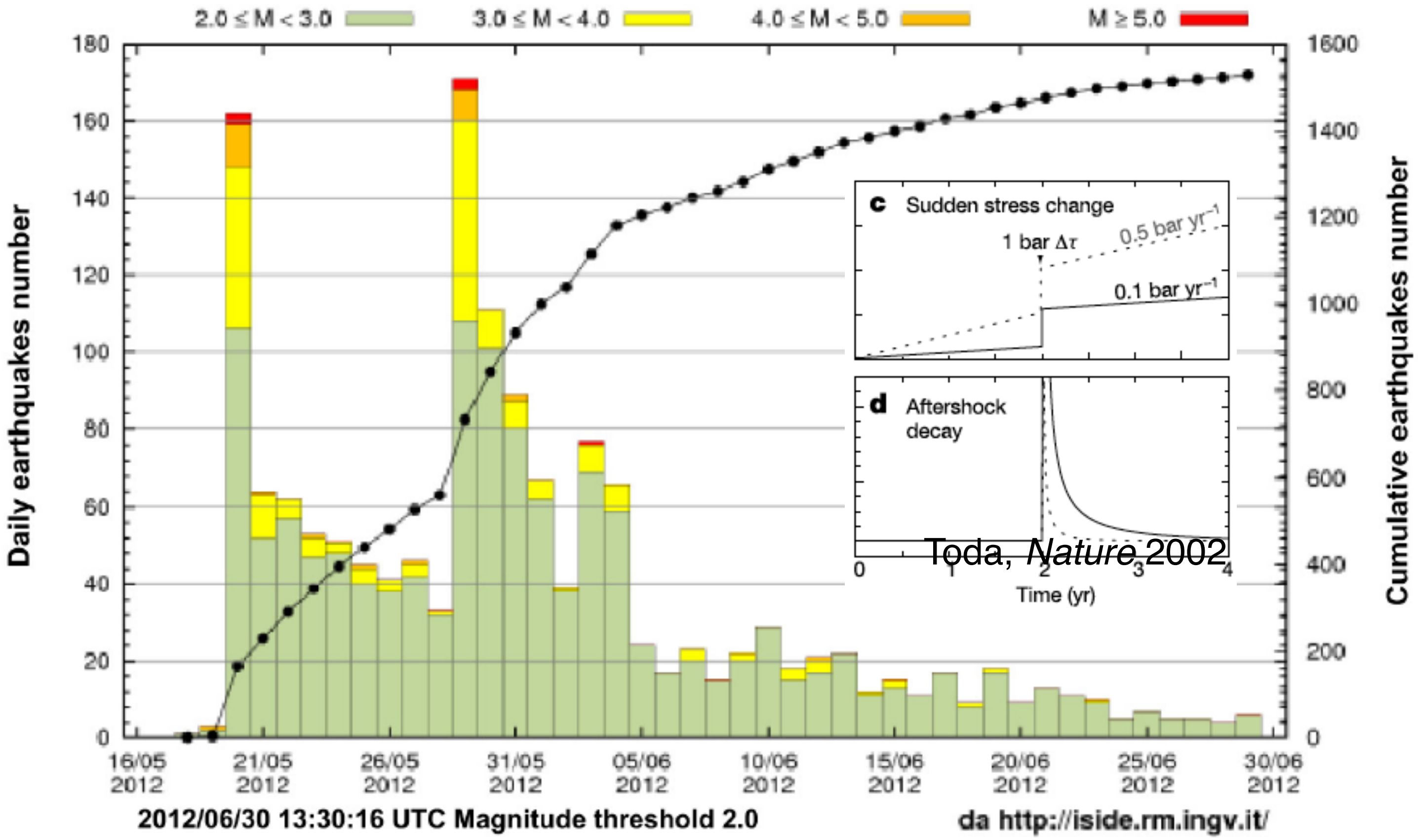




- Increased stress from May 20 shock large enough to trigger May 29 main aftershock (Mw = 5.8) on the Mirandola fault near Cavone field

Observed seismicity in the Emilia-Romagna sequence

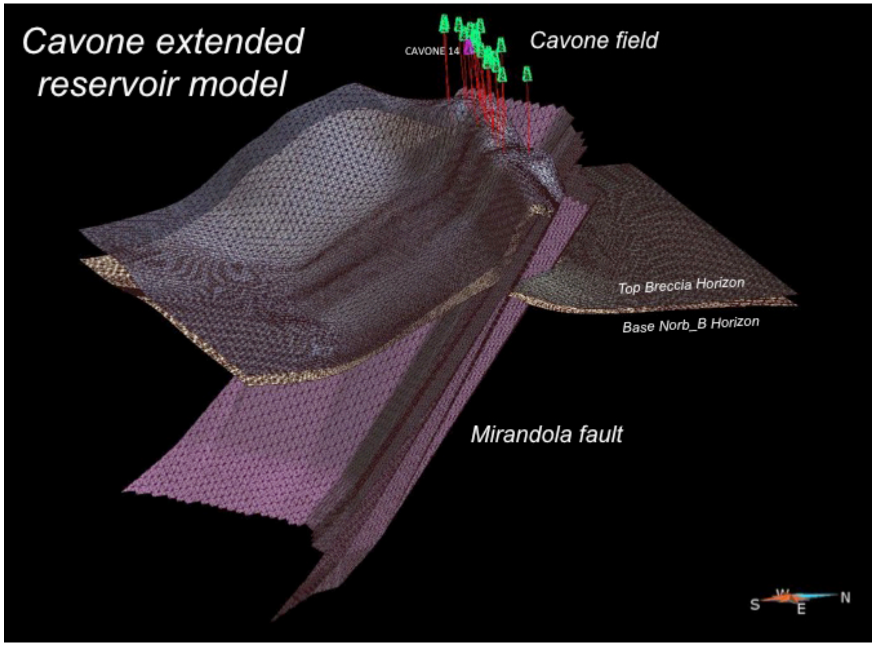
- The earthquake sequence has properties of a cascading series of foreshocks and aftershocks common with tectonic earthquakes



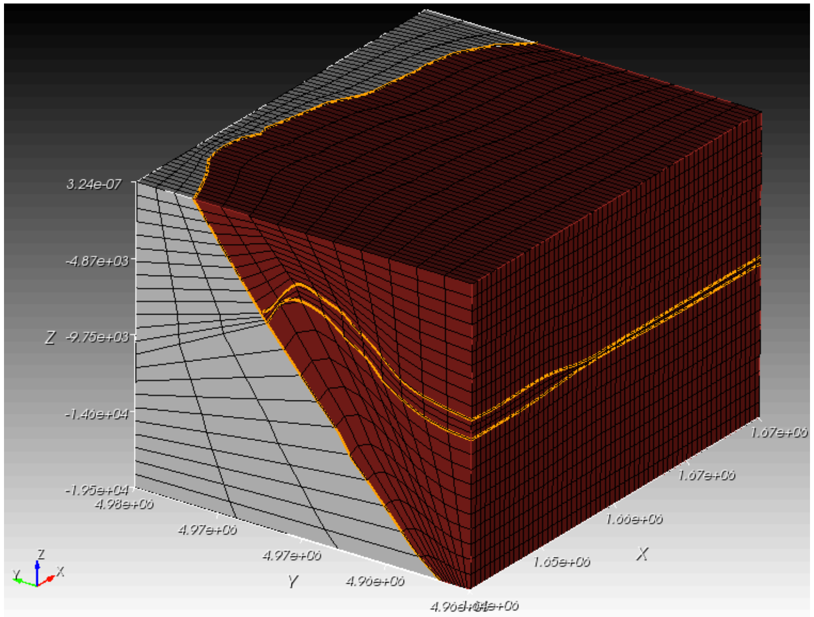
Toda, *Nature* 2002

Coupled flow and geomechanical modeling

- ❑ Stratigraphic model



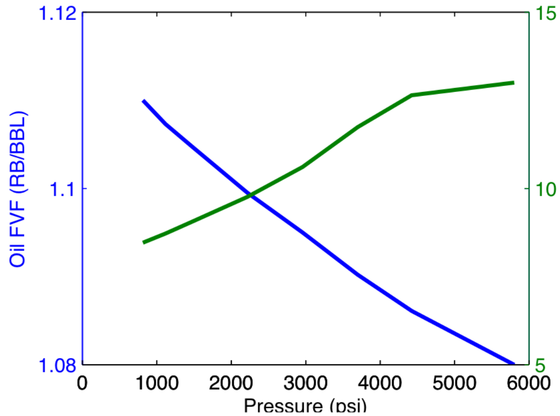
- ❑ Geomechanical grid

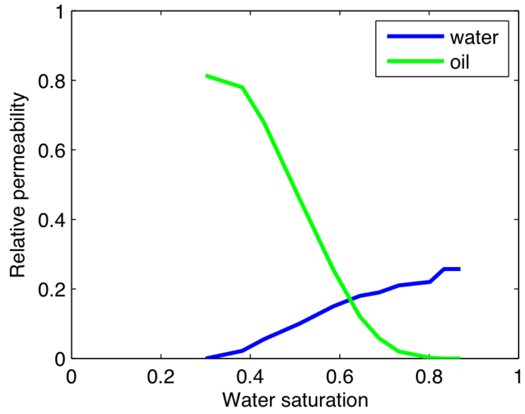


Coupled flow and geomechanical modeling

❑ Modeling choices

- Two-phase black-oil fluid system

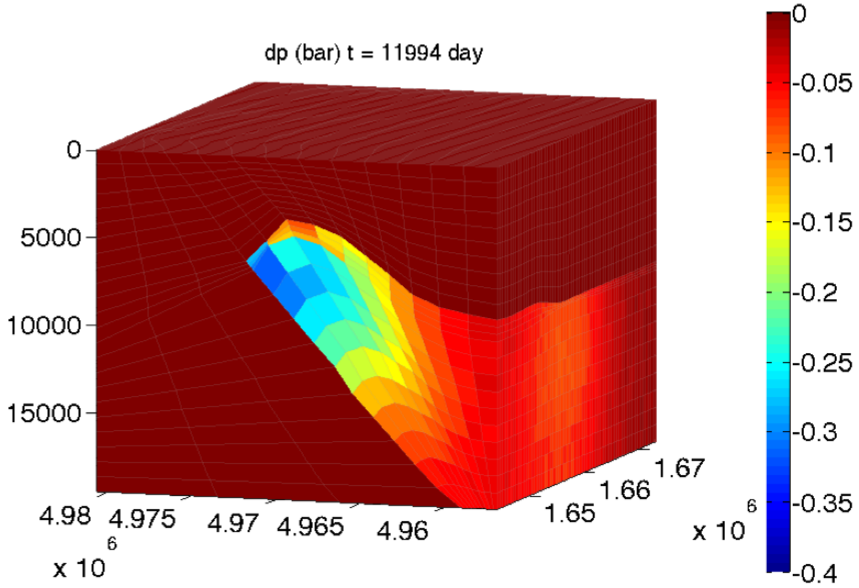




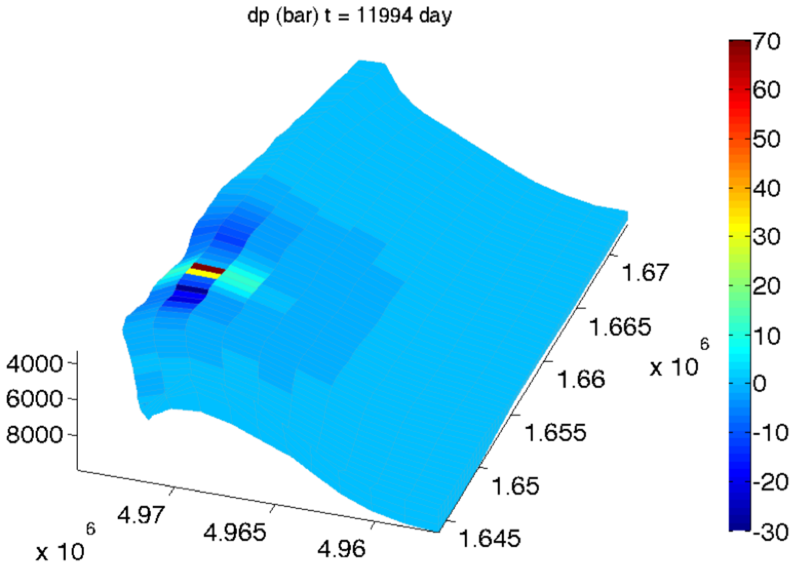
- Hydrostatic initial pressures; strong aquifer support
- Uniform permeability that captures well-test and field-scale pressures
- Linear poroelasticity with depth-dependent compressibility
- Lithostatic vertical stress; reverse faulting conditions
- Dynamic simulation from March 1980 – Dec 2012 (11,994 days)
- 19 wells with their actual production/injection rates and completions

Simulation results – changes in pressure

Whole computational domain



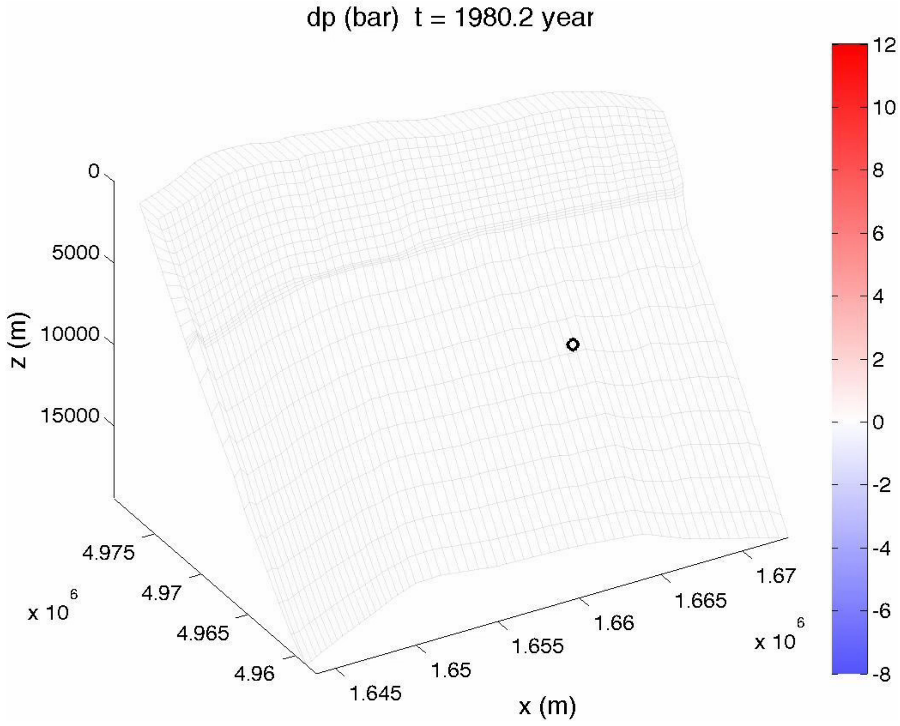
Within reservoir



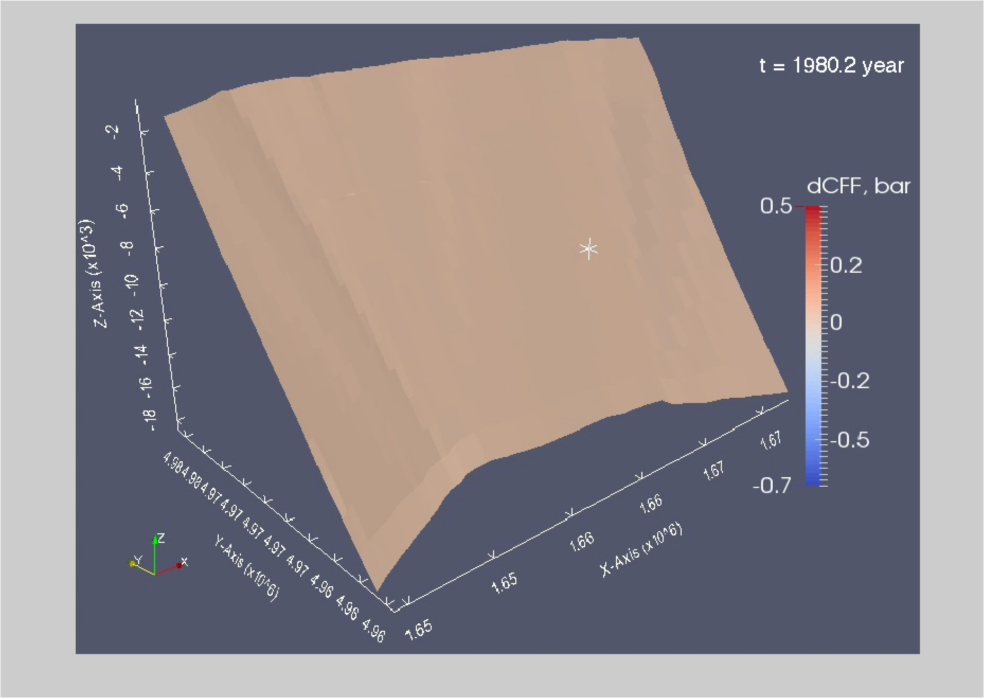
- Pressure changes extend downwards into supporting aquifer
- General pressure decline due to net production
- Localized increase in pore pressure due to water injection (well #14)

Simulation results – fault stability

Variation in pore pressure



Variation in Coulomb stress

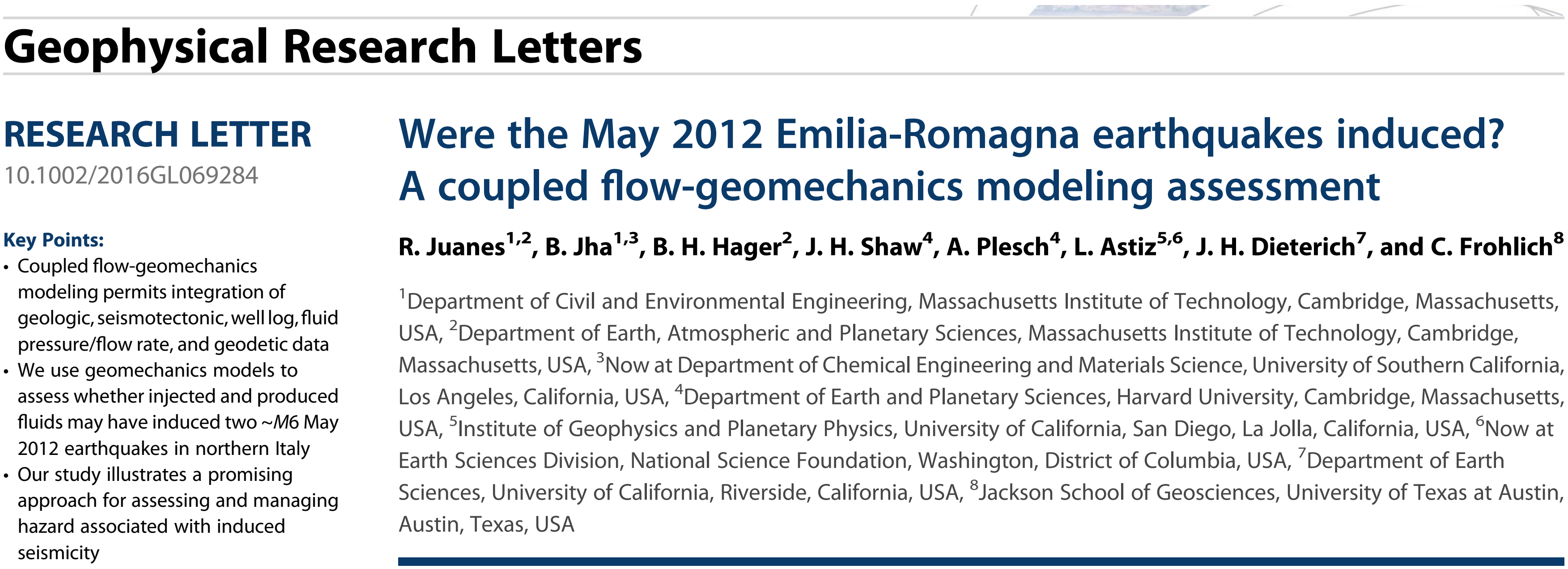


- Localized increase in pore pressure due to water injection (well #14)
- Variations in Coulomb stress on the fault require careful consideration

The 2012 Emilia Romagna earthquake sequence

- **Conclusions:**
  - Injection has a stabilizing effect on the Mirandola fault
  - Areas of de-stabilization are very small (~ 10 km^2) compared with the slip areas required for an event of magnitude 6.0 (~ 250 km^2)
  - Changes in pressure and Coulomb stress are non-negligible only in the vicinity of the reservoir, in an area with no recorded seismicity
  - Coupled flow-geomechanics model suggests that reservoir operations in the Cavone field are <u>not</u> an important driver for the observed seismicity

The 2012 Emilia Romagna earthquake sequence



Geophysical Research Letters

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10.1002/2016GL069284

Key Points:

- Coupled flow-geomechanics modeling permits integration of geologic, seismotectonic, well log, fluid pressure/flow rate, and geodetic data
- We use geomechanics models to assess whether injected and produced fluids may have induced two ~*M*6 May 2012 earthquakes in northern Italy
- Our study illustrates a promising approach for assessing and managing hazard associated with induced seismicity

Were the May 2012 Emilia-Romagna earthquakes induced? A coupled flow-geomechanics modeling assessment

R. Juanes[1,2], B. Jha[1,3], B. H. Hager[2], J. H. Shaw[4], A. Plesch[4], L. Astiz[5,6], J. H. Dieterich[7], and C. Frohlich[8]

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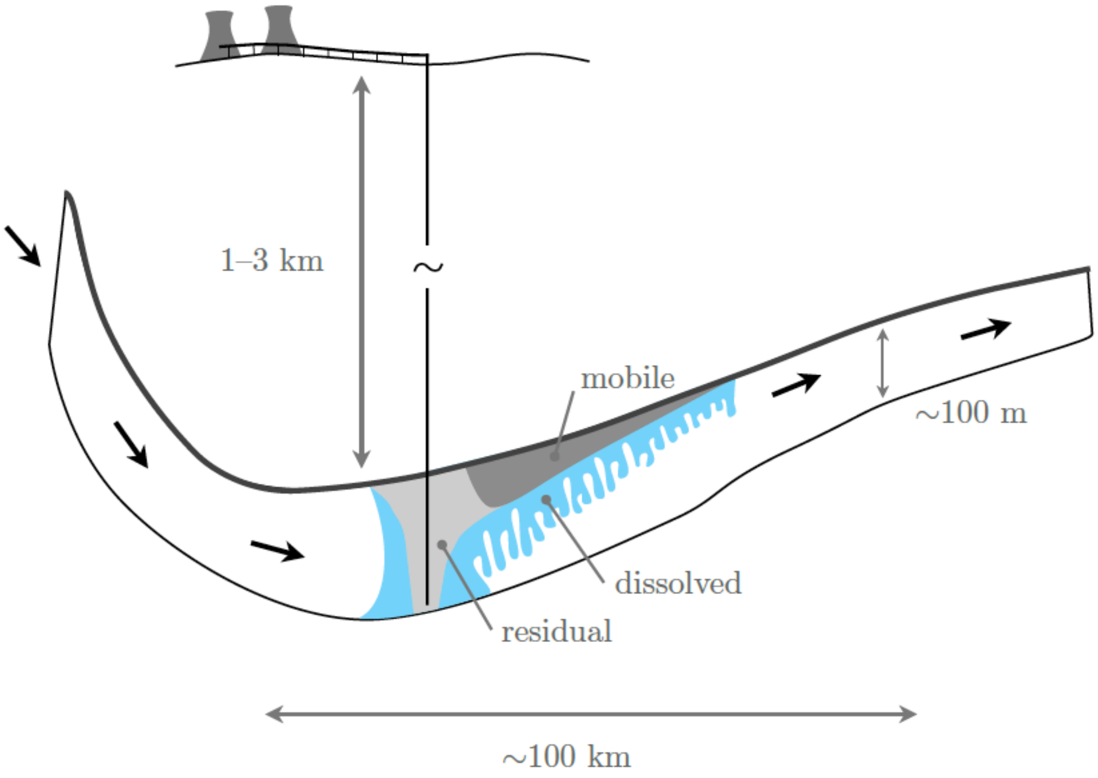
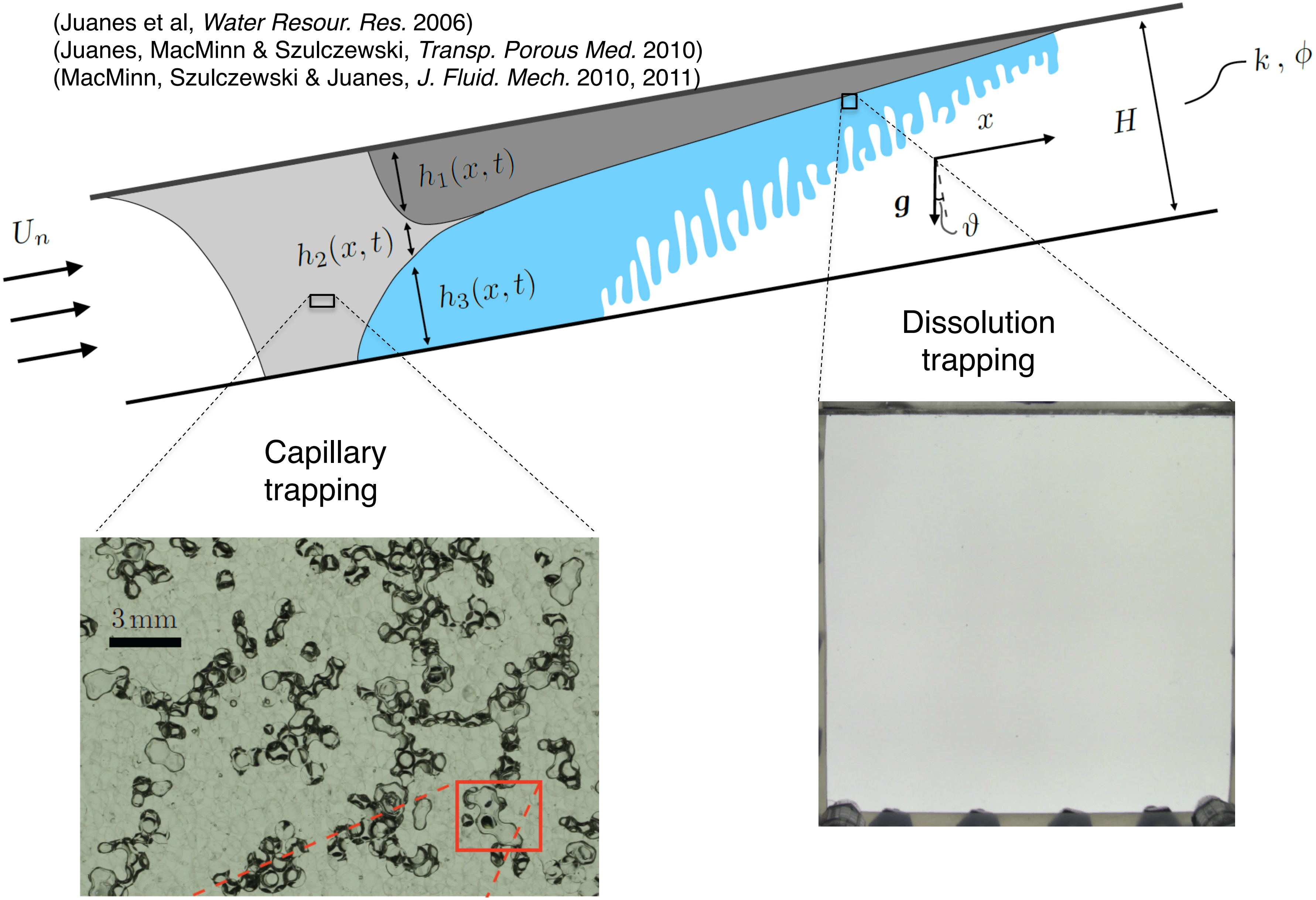
Storage must be understood at the scale of entire geologic basins



- ☐ **Two constraints**
  - The <u>footprint</u> of the migrating CO_2 plume must fit in the basin
  - The <u>pressure</u> induced by injection must not fracture the rock

Trapping mechanisms

(Juanes et al, *Water Resour. Res.* 2006)
(Juanes, MacMinn & Szulczewski, *Transp. Porous Med.* 2010)
(MacMinn, Szulczewski & Juanes, *J. Fluid. Mech.* 2010, 2011)

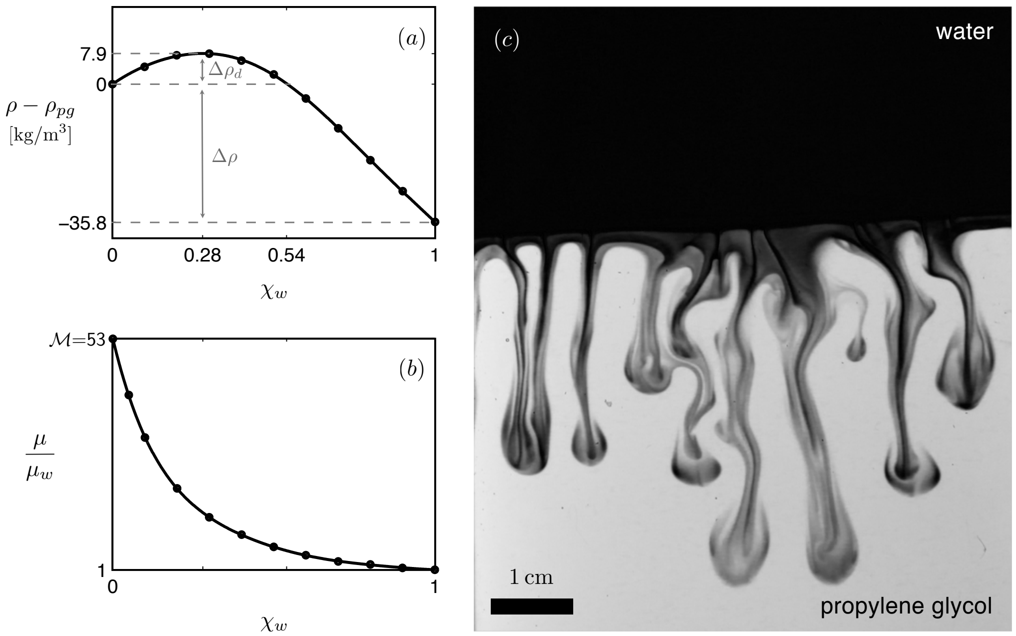


Dissolution by convective mixing

- Dimensionless governing equations

$$\nabla \cdot \boldsymbol{u} = 0; \quad \boldsymbol{u} = -(\nabla p - c\nabla z),$$

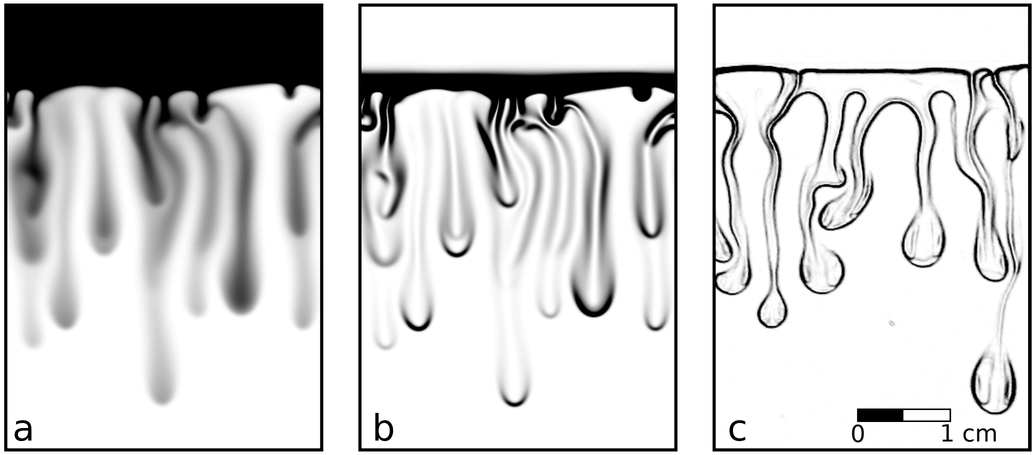
$$\partial_t c + \nabla \cdot \left(\boldsymbol{u} c - \frac{1}{\mathrm{Ra}} \nabla c \right) = 0,$$



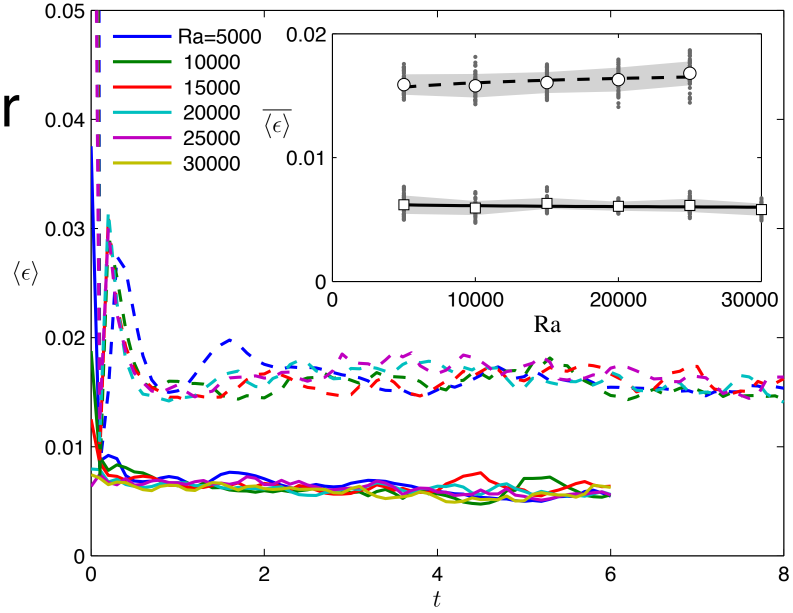
(Hidalgo et al., *Phys. Rev. Lett.,* 2012)

Dissolution by convective mixing

- Mixing controlled by the scalar dissipation rate

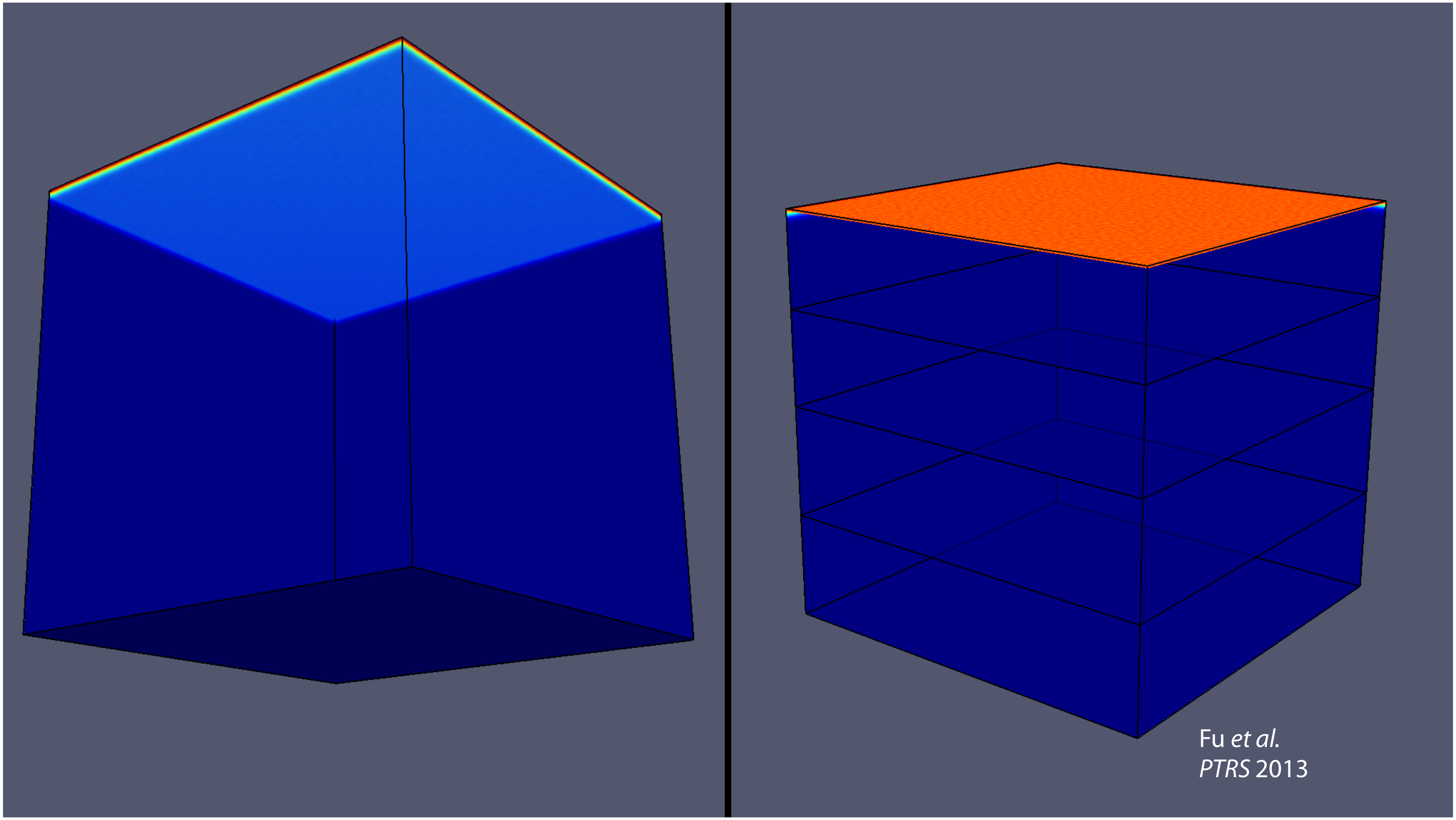


- Dissolution rate is constant and independent of Rayleigh number



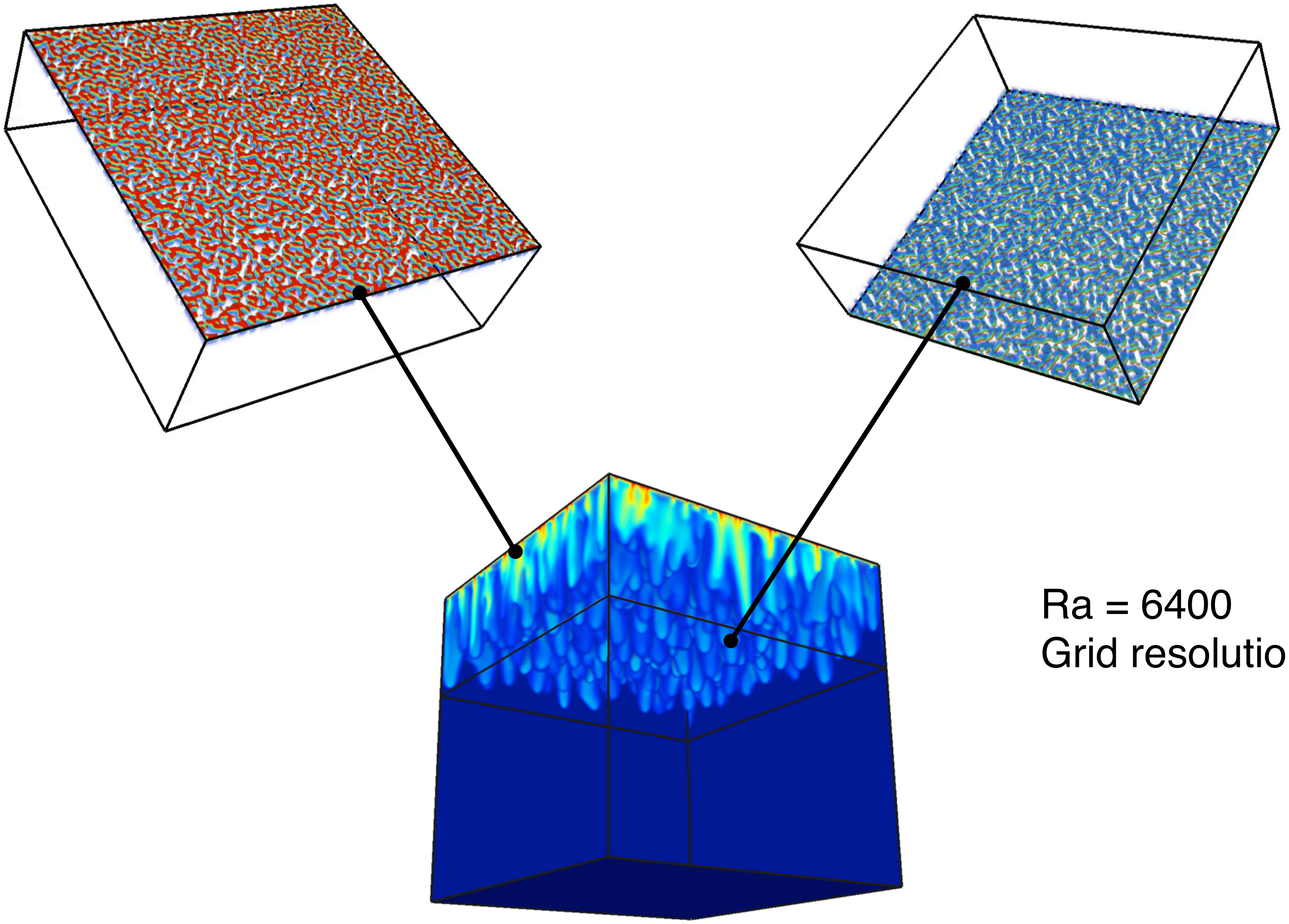
(Hidalgo et al., *Phys. Rev. Lett.,* 2012)

Dissolution by convective mixing



Fu *et al.*
PTRS 2013

3D dynamics of CO2 convective mixing

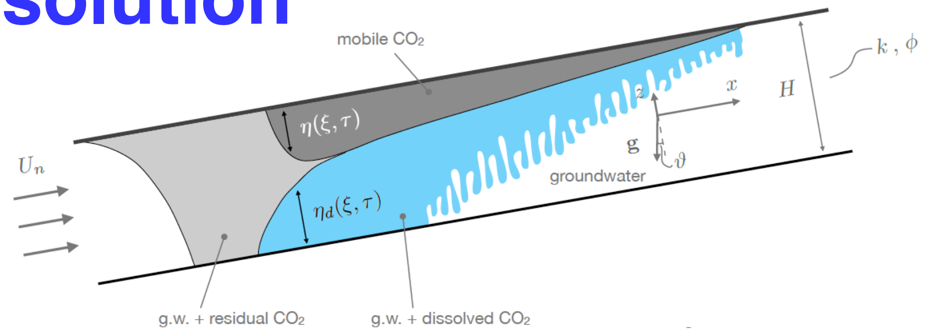


Ra = 6400
Grid resolution: 512^3

Fu, Cueto-Felgueroso & Juanes (*Phil. Trans. R. Soc. A.* 2013)

Plume migration with dissolution

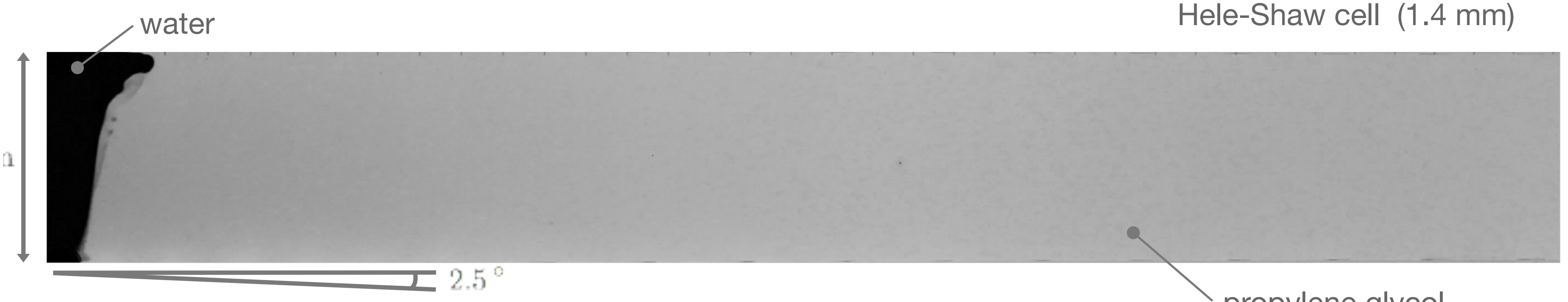
(Juanes, MacMinn & Szulczewski, *Transp. Porous Med.* 2010)
(MacMinn, Szulczewski & Juanes, *J. Fluid. Mech.* 2010, 2011)



- ☐ Theory

$$\underbrace{\widetilde{\mathcal{R}}\,\frac{\partial \eta}{\partial \tau}}_{\text{residual trapping}} + \overset{\text{advective}}{\boxed{\underbrace{N_f\,\frac{\partial f}{\partial \xi}}_{\text{flow}} + \underbrace{N_s\,\frac{\partial}{\partial \xi}\Big[(1-f)\,\eta\Big]}_{\text{slope}}}} - \overset{\text{diffusive}}{\underbrace{\boxed{N_g\,\frac{\partial}{\partial \xi}\left[(1-f)\,\eta\,\frac{\partial \eta}{\partial \xi}\right]}}_{\text{spreading}}} = \overset{\text{sink}}{\underbrace{\boxed{-\widetilde{\mathcal{R}}\,N_d}}_{\text{dissolution}}}$$

- ☐ Experiments

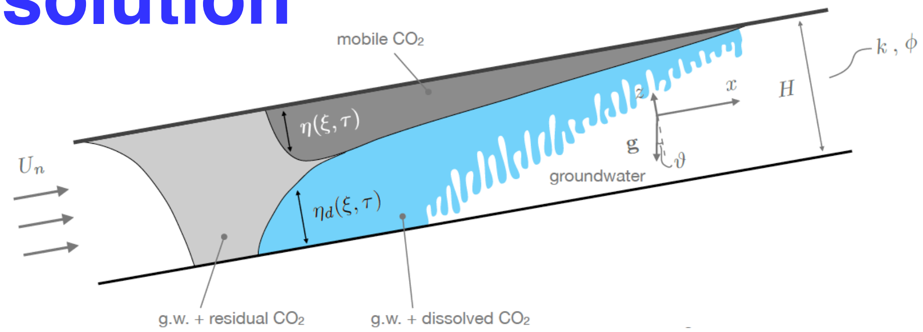


(MacMinn & Juanes, *Geophys. Res. Lett.*, 2013)

Plume migration with dissolution

(Juanes, MacMinn & Szulczewski, *Transp. Porous Med.* 2010)
(MacMinn, Szulczewski & Juanes, *J. Fluid. Mech.* 2010, 2011)

- ❑ Theory

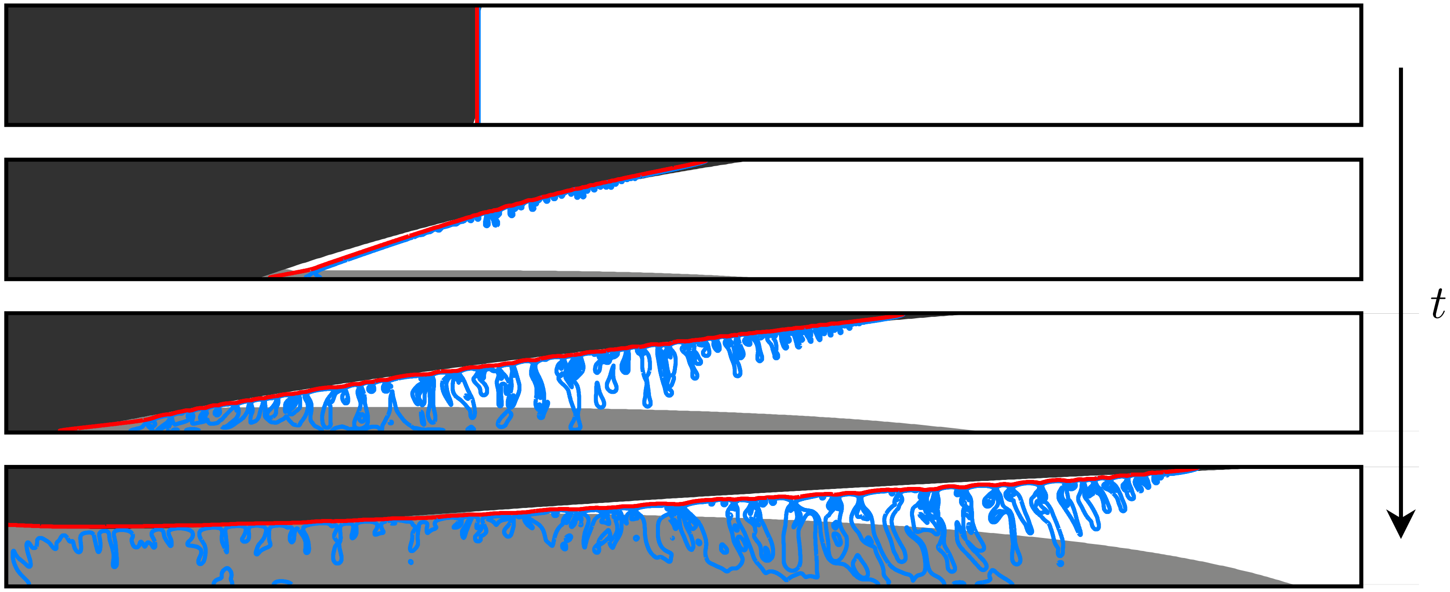


$$\underset{\text{residual trapping}}{\widetilde{\mathcal{R}}}\,\frac{\partial\eta}{\partial\tau} + \overset{\text{advective}}{\boxed{\underset{\text{flow}}{N_f\,\frac{\partial f}{\partial\xi}} + \underset{\text{slope}}{N_s\,\frac{\partial}{\partial\xi}\Big[(1-f)\,\eta\Big]}}} - \overset{\text{diffusive}}{\underset{\text{spreading}}{\boxed{N_g\,\frac{\partial}{\partial\xi}\Big[(1-f)\,\eta\,\frac{\partial\eta}{\partial\xi}\Big]}}} = \overset{\text{sink}}{\underset{\text{dissolution}}{\boxed{-\widetilde{\mathcal{R}}\,N_d}}}$$

- ❑ Experiments

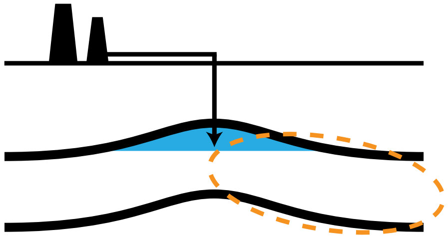
(MacMinn & Juanes, *Geophys. Res. Lett.*, 2013)

Plume migration with dissolution

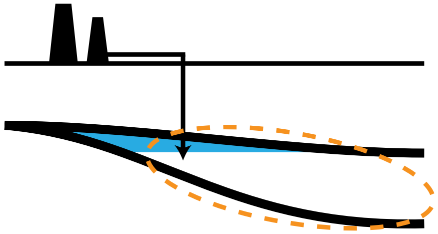


(Hidalgo, MacMinn & Juanes, *Adv. Water Resour.*, 2013)

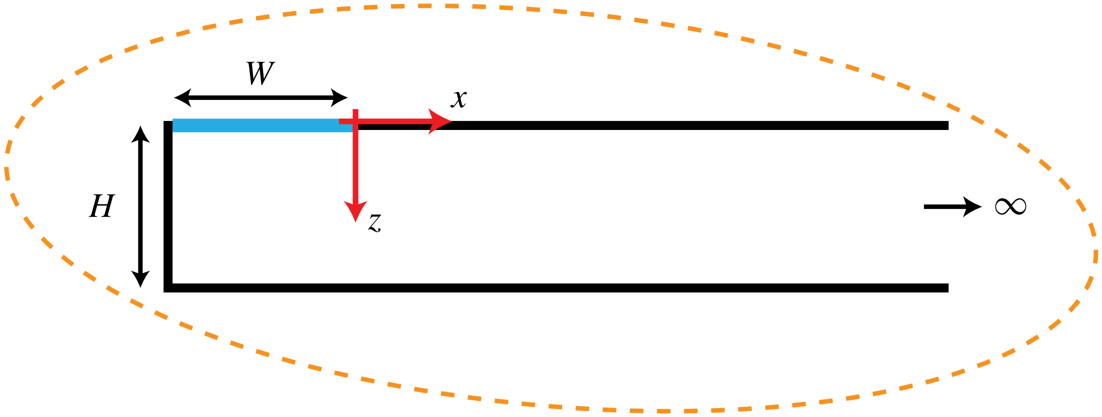
CO2 dissolution in structural traps



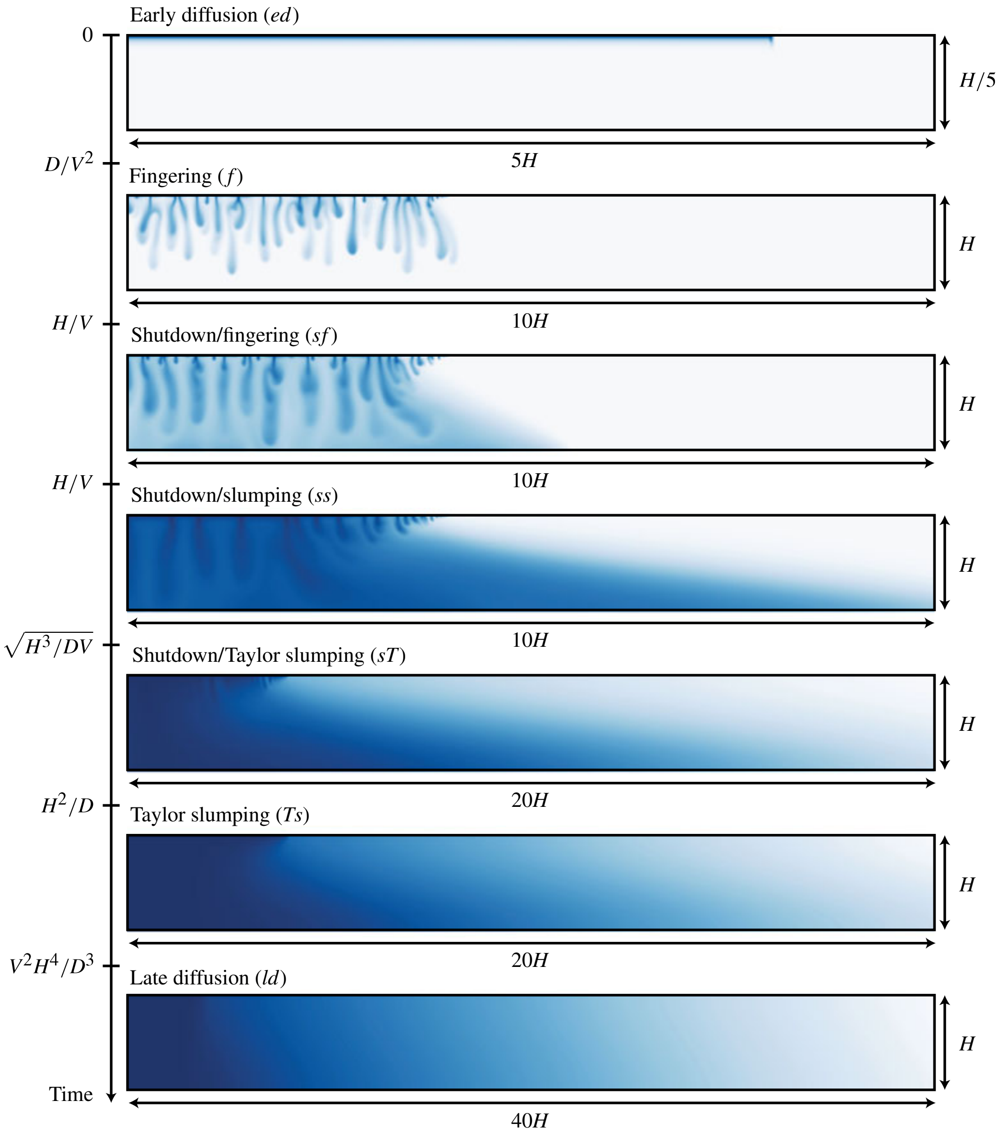
Anticline

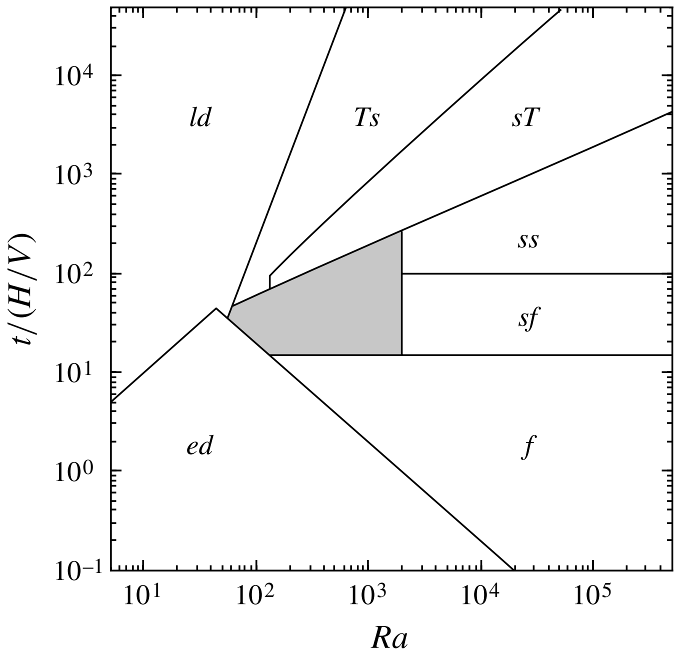


Pinchout



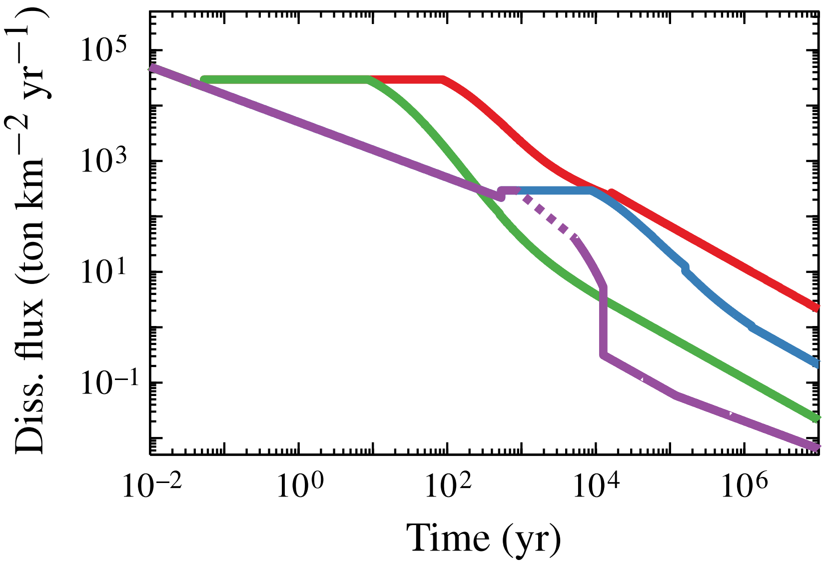
CO2 dissolution in structural traps





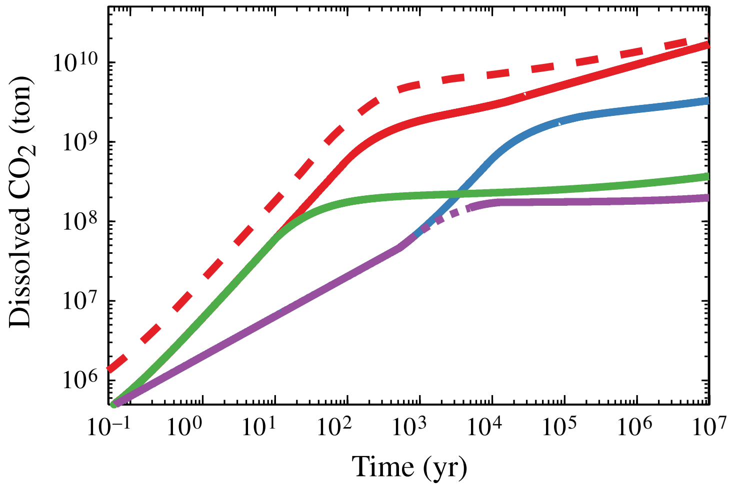
CO2 dissolution in structural traps

- Dissolution flux



	H (m)	*k* (mD)	*Ra*
🟥	200,	1000,	2×10^5
🟩	20,	1000,	2×10^4
🟦	200,	10,	2×10^3
🟪	20,	10,	2×10^2

- Cumulative dissolution mass



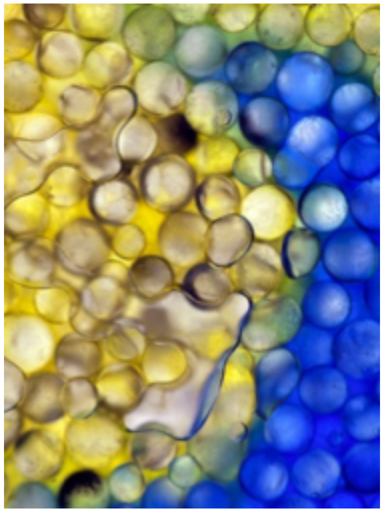
(Szulczewski, Hesse & Juanes,
J. Fluid Mech., 2013)

Miscibility of two fluids

oil/water

immiscible

CO_2/water



partially miscible

[Szulczewski et. al,
Proc. Natl. Acad. Sci. 2012]

milk/coffee

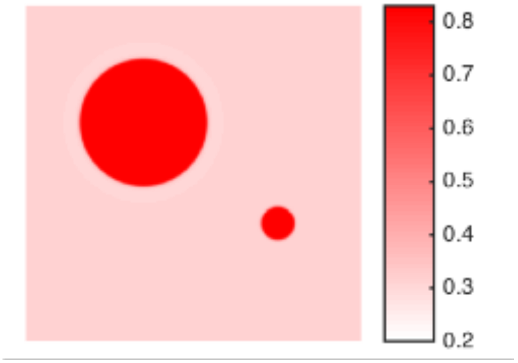
fully miscible

partially miscible:
two fluids have limited but non-zero solubility into each other

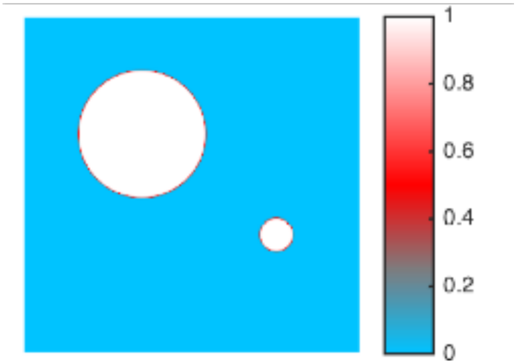
Modeling a partially miscible fluid system:

Introduce two variables to describe a two-phase two-component system

Example: CO_2 gas in liquid water



$c =$ CO_2 concentration



$\phi =$ gas volume fraction

(phase variable)

[Fu et. al, *in review*]

A phase-field model coupling thermodynamics with hydrodynamics: governing equations

$$\frac{\partial \phi}{\partial t} + \nabla \cdot (\mathbf{u}\phi) + \frac{1}{\mathrm{Ca}}\lambda\frac{\delta F}{\delta \phi} = 0$$

advection

thermodynamic
driven diffusion

$$\frac{\partial c}{\partial t} + \nabla \cdot (\mathbf{u}c) - \frac{1}{\mathrm{Pe}}\nabla \cdot \left[\lambda\nabla\left(\frac{\delta F}{\delta c}\right)\right] = 0.$$

advection

thermodynamic
driven phase change

$$\mathbf{u} = -\frac{k(\phi)}{\mu(\phi)}\nabla P;$$

Darcy velocity

$$\nabla \cdot \mathbf{u} = 0;$$

incompressibility

$$\mu = e^{R(1-\phi)}$$

phase-dependent
viscosity

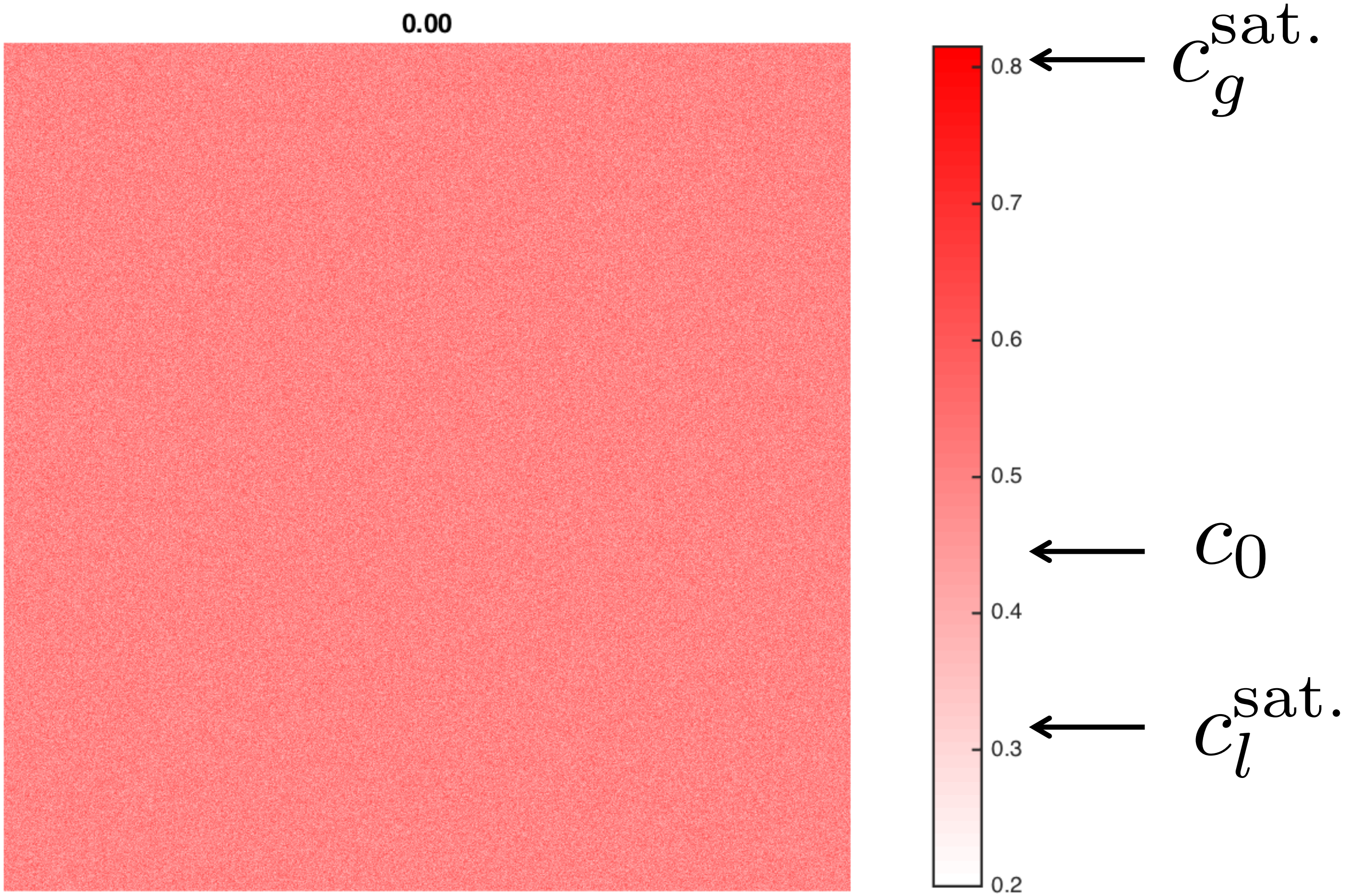
Assumptions:

- incompressible fluids
- viscosity depends on phase variable only

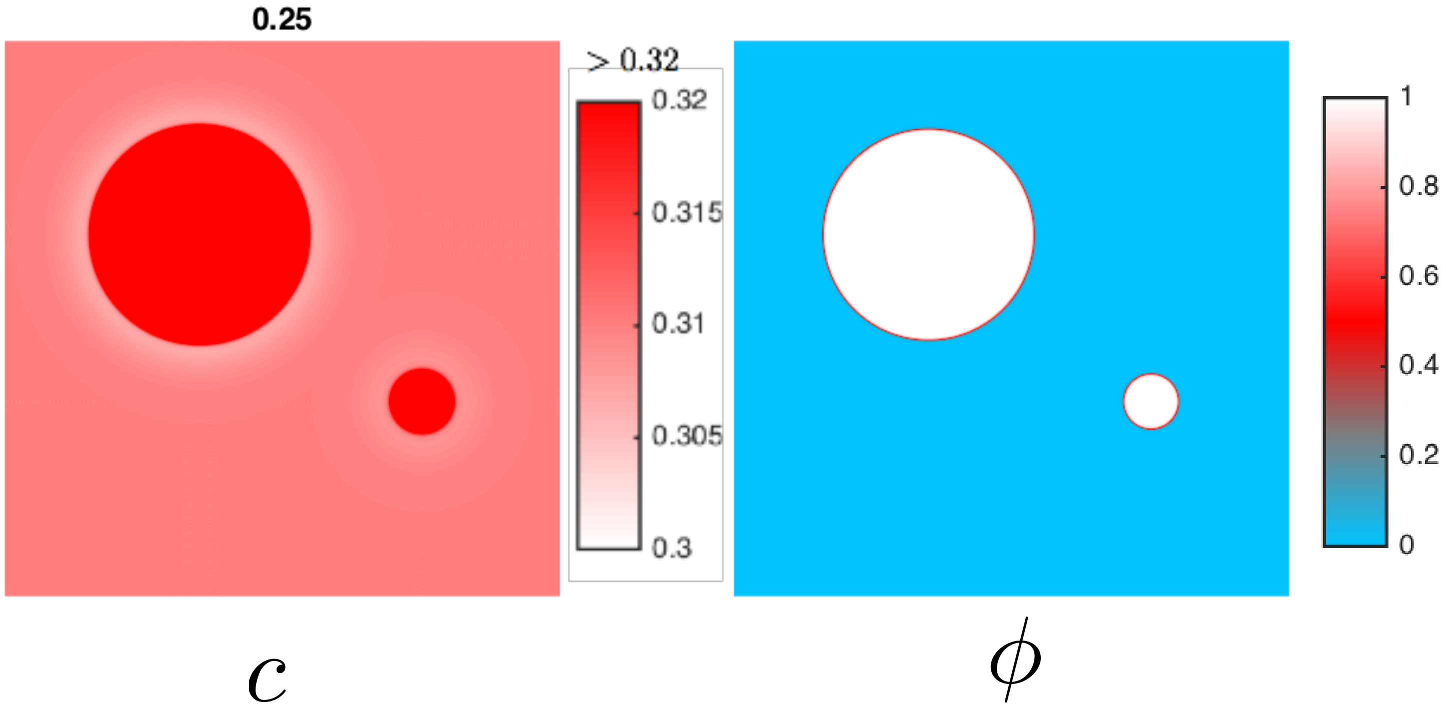
Free energy as a function of c and ϕ describes the thermodynamic behavior of the two fluids.

$$F = \overbrace{\frac{1}{2}\epsilon_c^2 T(\nabla c)^2 + \frac{1}{2}\epsilon_\phi^2 T(\nabla \phi)^2}^{\text{interfacial energy}} + \overbrace{\underbrace{\omega T W(\phi)}_{\text{double-well}} + \underbrace{\omega_{\text{mix}} T \left[f_l(c)(1-g(\phi)) + f_g(c)g(\phi)\right]}_{\text{mixing energy (between phases)}}}^{\text{bulk energy}}$$

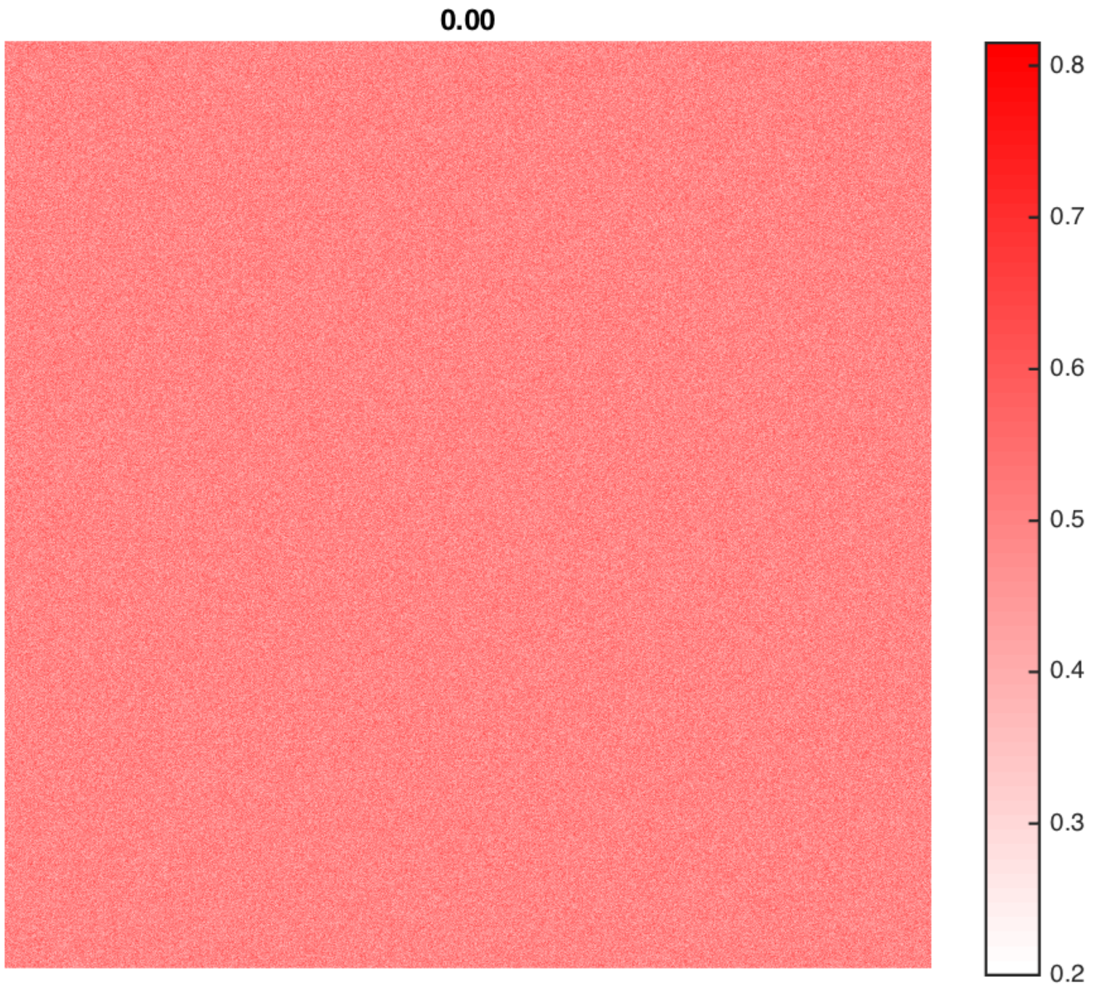
In an initially supersaturated liquid, vapor bubbles will first nucleate, phase-separating the fluid into gas and liquid



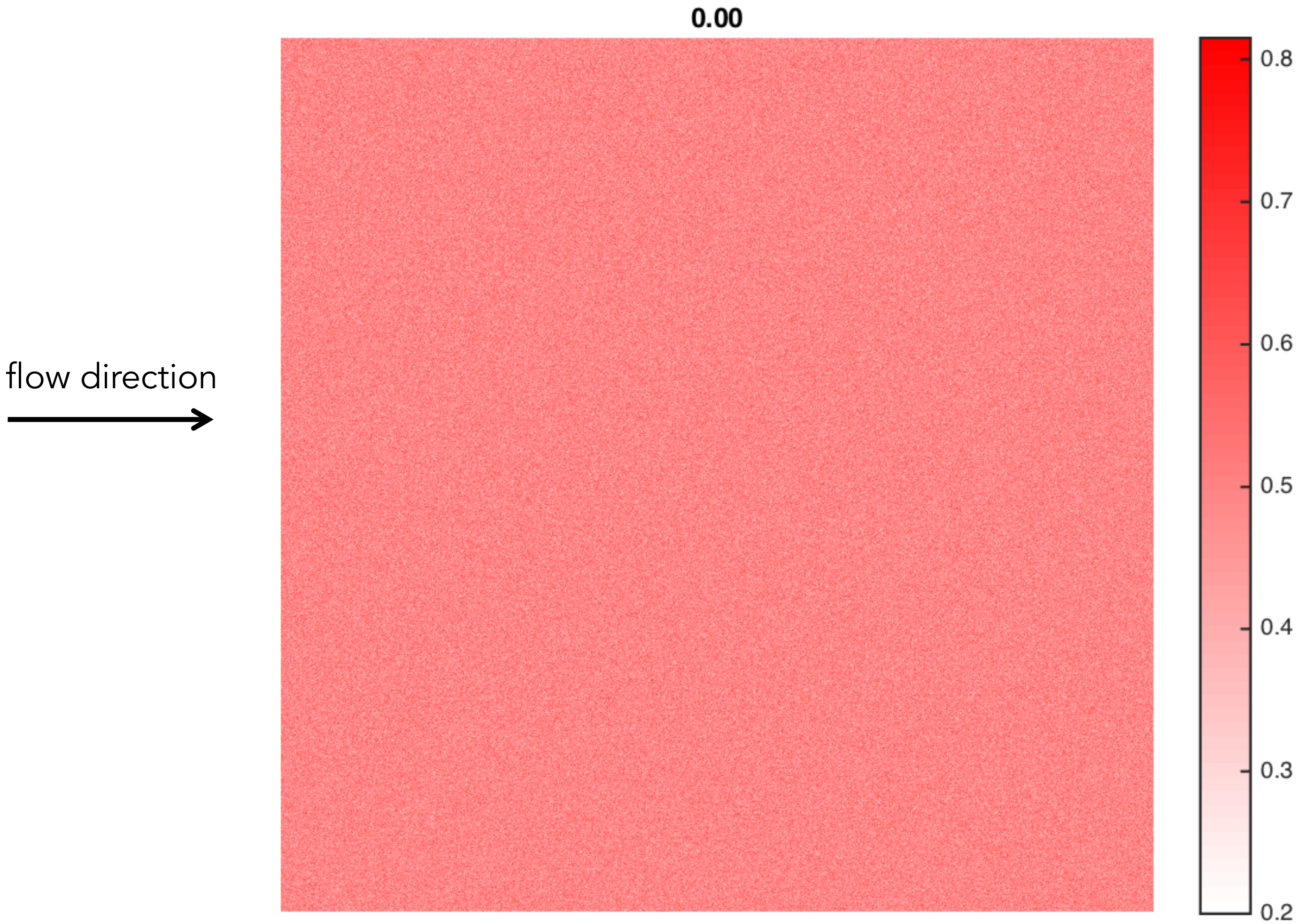
- After nucleation stage, bubbles interact through liquid.
- Ostwald ripening: to minimize interfacial energy, large bubbles grow in the expense of small bubbles. [Ostwald, W. Z., Phys. Chem. 1900]



Without external flow, Ostwald ripening leads to continued coarsening.



Under periodic flow, gas bubbles undergo repeated breakup and coalescence



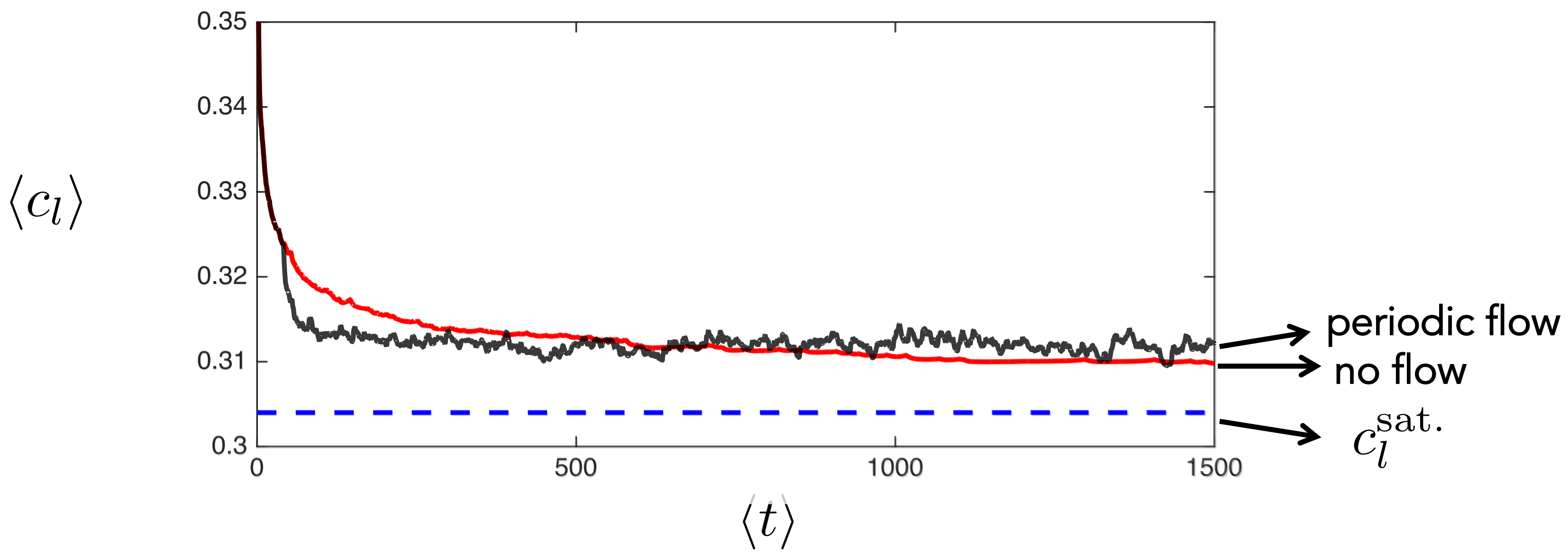
viscosity contrast=20.8
flow imposed at t=40

$\mathrm{Ca} = 2$ $\mathrm{Pe} = 32$

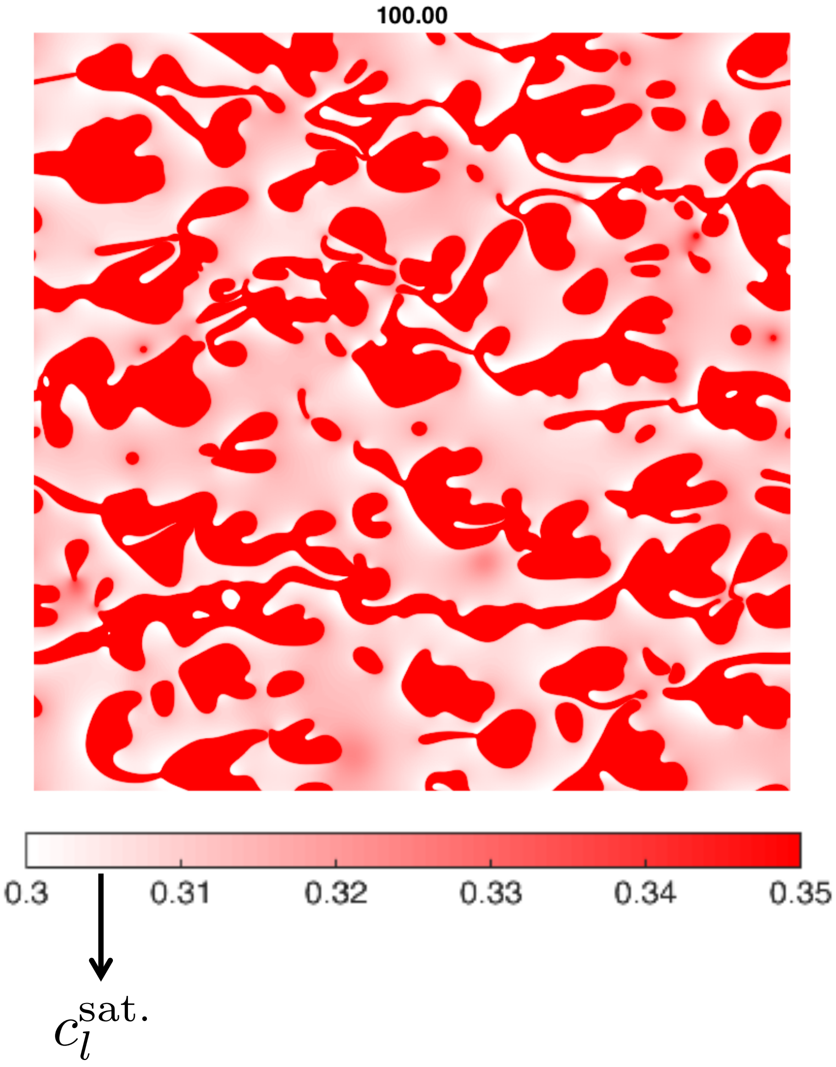
Infer thermodynamic equilibrium from liquid phase concentration:

- with no flow, the system approaches equilibrium asymptotically.
- with periodic flow, the system is permanently out-of-equilibrium.

average concentration of CO_2 in liquid



Under viscous instability, small bubbles are constantly created, and they quickly dissolve into the liquid due to Ostwald ripening. This results in a permanently supersaturated liquid.



Summary – outcomes and impact

- The proposed work addresses some key aspects of CCS at scale
- In particular, public acceptance of CCS will require that concerns about leakage and seismicity triggered by CO2 injection be addressed
- Predicting leakage and induced fault slip requires new tools
  - Computational model of coupled multiphase/compositional flow and fault poromechanics
- This project contributes to the future deployment of this technology by analyzing the impact of CCS at the commercial-injection scale on storage security in the decade time period (CO2 leakage and induced seismicity), and in the century time period (long-term CO2 migration and trapping)

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