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

DOE/NETL Carbon Storage R&D Project Review Meeting
Pittsburgh, August 12, 2014

Benefit to the Program

- **Area of Interest 4:** Enhanced simulation tools to improve predictions and enhance performance of geologic storage

- Support the Goal of development of Best Practices Manuals, and contribute to the Goal of demonstrating 99% storage permanence, by providing advanced simulation tools to understand and predict fault motion, fault transmissivity, and induced seismicity.

- Develop technologies to estimate storage capacity and to improve storage efficiency making substantial advances in understanding capillary and solubility trapping during the post-injection period, and the impacts of aquifer heterogeneity and hydrodynamic instabilities on migration distance.

Key questions

- How can CO2 injection be conducted without inducing fractures or activating faults that could channel CO2 toward the surface?

- Under what conditions could injection induce fault slip and associated induced seismicity? How can this process be forecast, monitored, and mitigated?

- How far will thin layers of mobile CO2 migrate? Where will displaced water exit the basin? Will dense CO2-saturated water sink? How does aquifer heterogeneity affect migration and trapping?

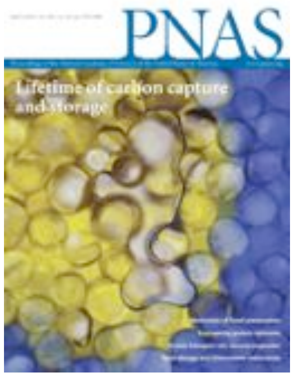
Project objectives

- **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

An important scientific question

- Can CCS be a bridge solution to a yet-to-be-determined low-carbon energy future?



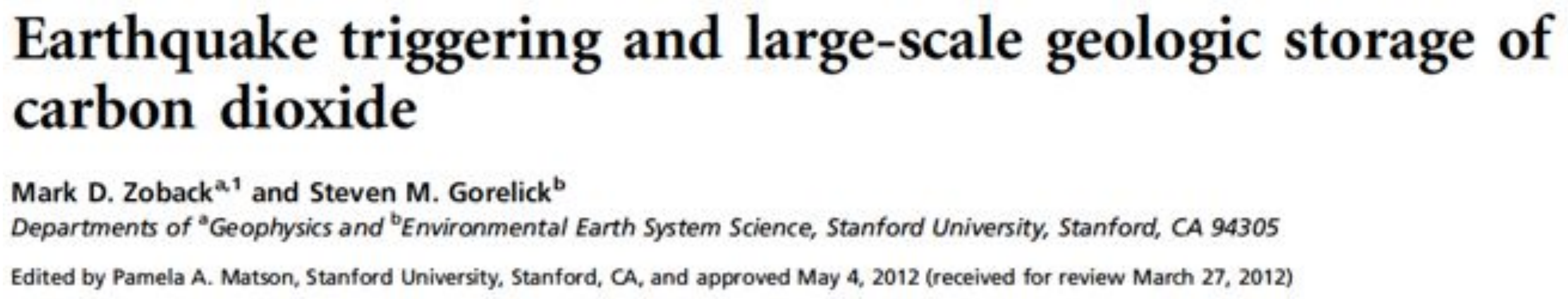
Lifetime of carbon capture and storage as a climate-change mitigation technology

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)

- Is CO_2 leakage really a show-stopping risk?

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)

Tasks

- ☐ Task 1: Project Management, Planning and Reporting

- ☐ Task 2: Technology Status Assessment

- ☐ Task 3: Coupled modeling of flow and fault geomechanics
  1. Sequential scheme for CO2-brine flow and geomechanics
  2. Theoretical and computational framework for flow along 2D faults
  3. Theoretical and computational framework of fault poromechanics
  4. Application to synthetic and actual geologic formations in the continental United States

- ☐ Task 4: Investigation of effects of fault rheology, pre-existing stress, and fluid pressure changes on triggered fault slip and induced seismicity
  1. Dependence of coefficient of friction on fault slip rate and state
  2. Testing of alternative descriptions of fault rheology
  3. Application to synthetic and actual formations to evaluate production scenarios and risk of induced seismicity

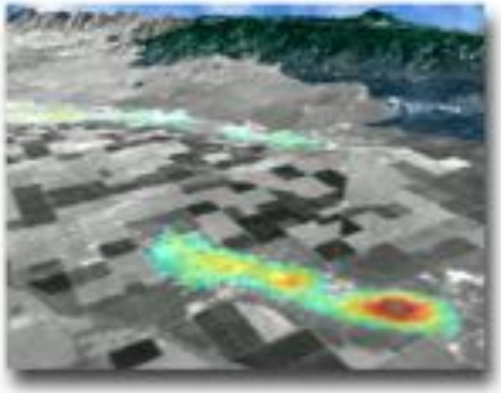
Tasks

- Task 5: High-resolution simulation of CO2 migration and trapping
  1. 2D gravity currents with analogue fluids in homogeneous media
  2. Heterogeneous media
  3. 3D simulations of an analogue system
  4. High-resolution simulation of gravity currents of actual system (such as CO2–brine system)

Coupled modeling of flow and geomechanics: evaluating the risk of CO2 leakage

Coupled flow and geomechanics

- **Reservoir compaction and subsidence**



Belridge oil fields (ATLANTIS)

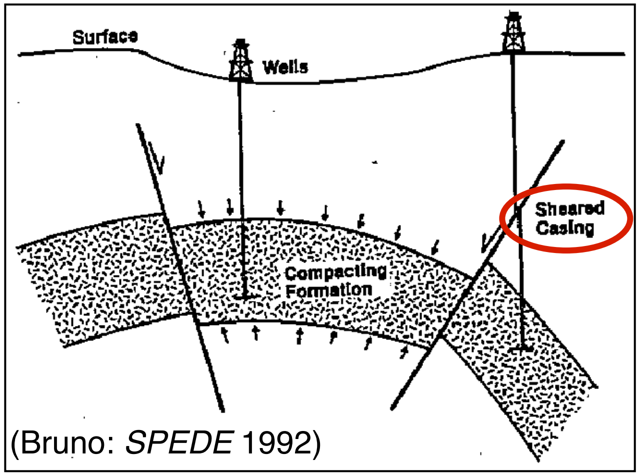
Wilmington field,
Long Beach

Ekofisk oil field (AMESIM)

Coupled flow and geomechanics

Wellbore stability

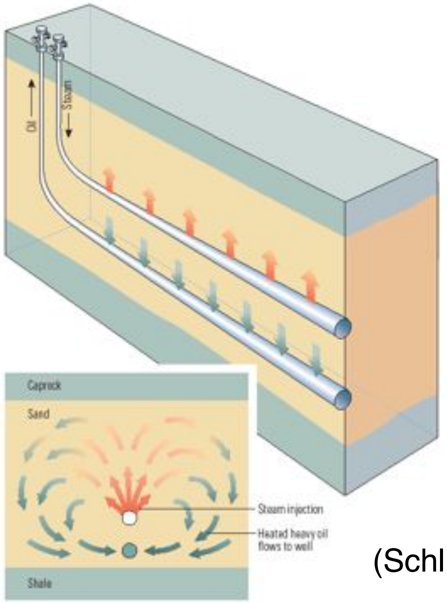
- Casing damage
- Borehole breakout
- Sand mobilization



(Bruno: *SPEDE* 1992)

Caprock integrity

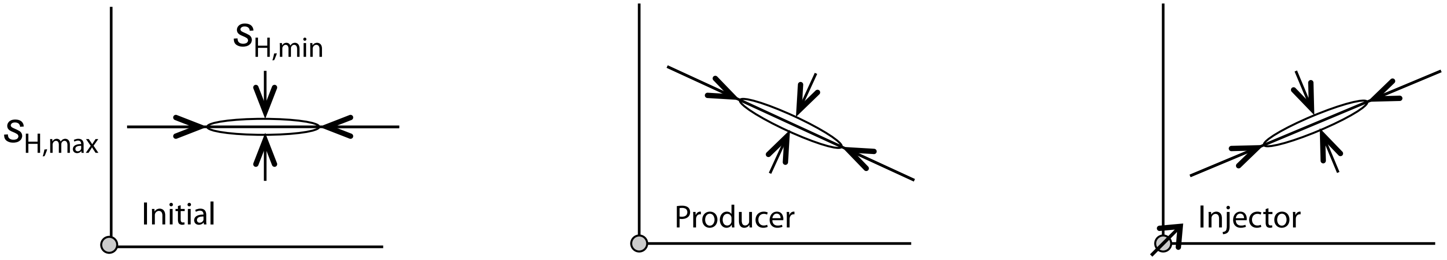
- SAGD
- CO_2 sequestration



(Schlumberger)

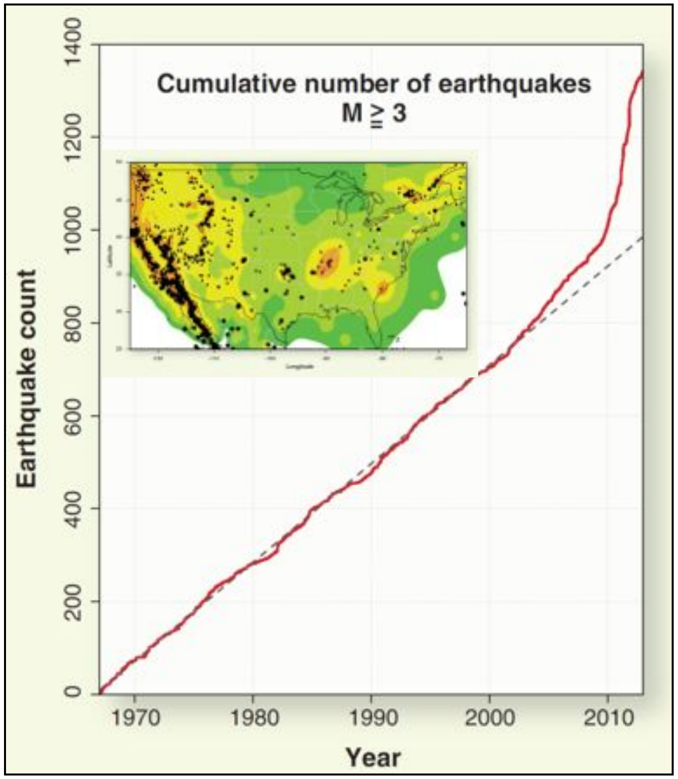
Fluid-induced stress reorientation

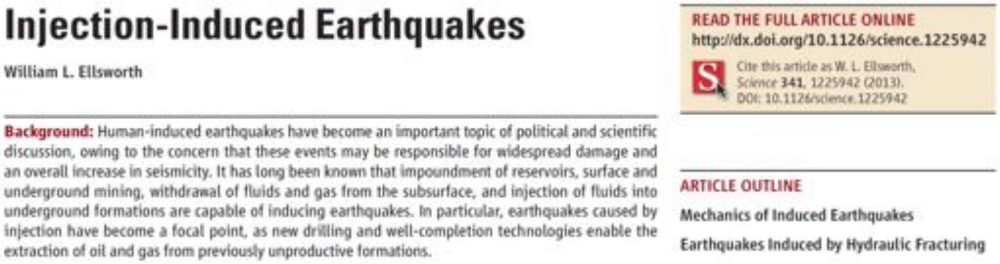
- Injectors behave as attractors for propagating fractures



Coupled flow and geomechanics

- ❑ **Induced seismicity**





Injection-Induced Earthquakes

William L. Ellsworth

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 and an overall increase in seismicity. It has long been known that impoundment of reservoirs, surface and underground mining, withdrawal of fluids and gas from the subsurface, and injection of fluids into underground formations are capable of inducing earthquakes. In particular, earthquakes caused by injection have become a focal point, as new drilling and well-completion technologies enable the extraction of oil and gas from previously unproductive formations.

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

ARTICLE OUTLINE

Mechanics of Induced Earthquakes

Earthquakes Induced by Hydraulic Fracturing

Enhanced Remote Earthquake Triggering at Fluid-Injection Sites in the Midwestern United States

Nicholas J. van der Elst,[1*] Heather M. Savage,[1] Katie M. Keranen,[2†] Geoffrey A. Abers[1]

A recent dramatic increase in seismicity in the midwestern United States may be related to increases in deep wastewater injection. Here, we demonstrate that areas with suspected anthropogenic earthquakes are also more susceptible to earthquake-triggering from natural transient stresses generated by the seismic waves of large remote earthquakes. Enhanced triggering susceptibility suggests the presence of critically loaded faults and potentially high fluid pressures. Sensitivity to remote triggering is most clearly seen in sites with a long delay between the start of injection and the onset of seismicity and in regions that went on to host moderate magnitude earthquakes within 6 to 20 months. Triggering in induced seismic zones could therefore be an indicator that fluid injection has brought the fault system to a critical state.

Earthquakes can be induced by underground fluid injection, which increases pore pressure and allows faults to slide under preexisting shear stress (*1*). The increase in wastewater disposal from natural gas development and other sources has been accompanied by an increase in fluid-induced earthquakes in recent years (*2*). These earthquakes include widely felt earthquakes in

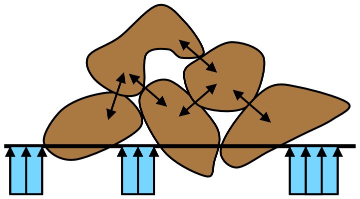
2013 VOL 341 **SCIENCE** www.sciencemag.org

Poromechanical coupling

- **Fluid mass conservation**
  - Primary unknown: p

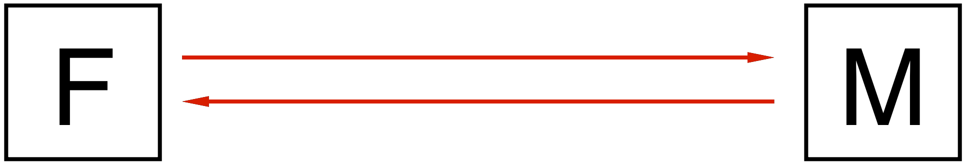
- **Linear momentum balance**
  - Primary unknown: $\boldsymbol{u}$

- **Couplings:**



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

Effective stress



Change in volume

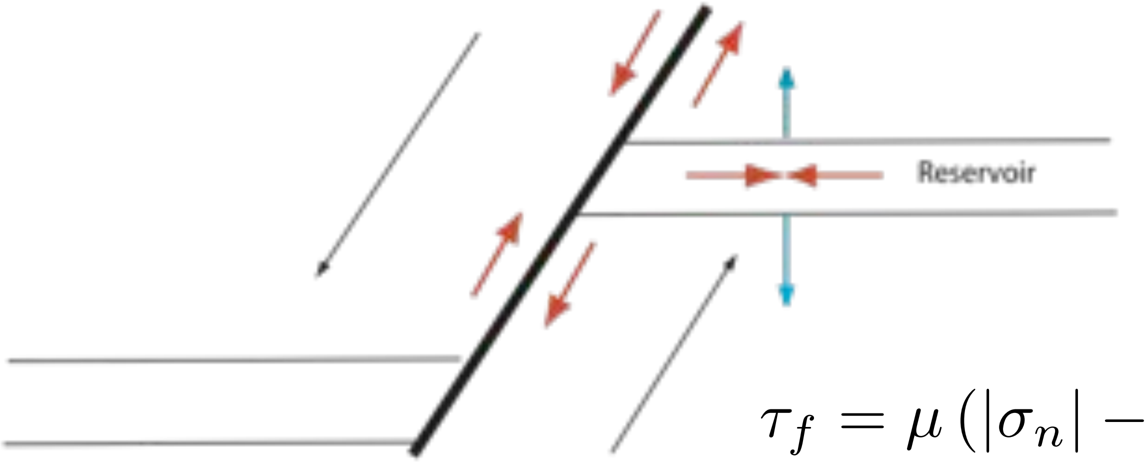
Change in reservoir properties: ϕ, $\boldsymbol{k}$

Coupled modeling of flow and geomechanics: evaluating the risk of CO2 leakage

- ☐ Injection of CO2 into a saline aquifer changes the state of stress, both within and outside of the aquifer, affecting the stability of preexisting faults, the permeability of existing fractures, and potentially creating new fractures

- ☐ The effects are not always intuitively obvious and should be quantified using geomechanical models. This requires the development of a new generation of geomechanical models that include coupling between fluid flow through the medium and along faults and fault motion

A “simple” scenario



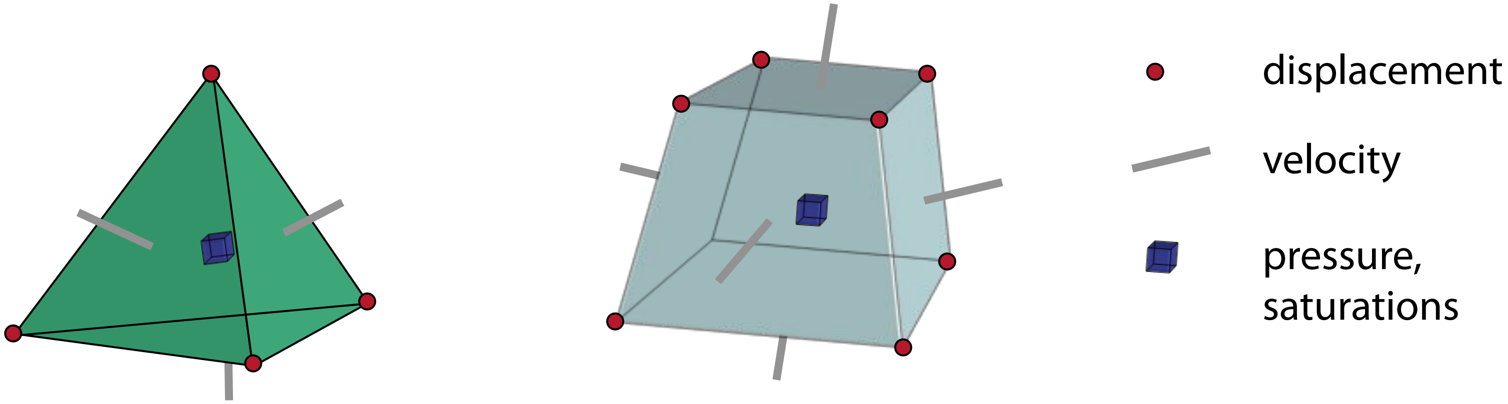
$$\tau_f = \mu \left(|\sigma_n| - p \right) + \tau_0$$

- Increasing the pore fluid pressure within a reservoir tends to promote failure by reducing the failure stress
- Failure above or below the reservoir depends on fault orientation and on tectonic stress regime (normal faulting, reverse faulting)

Geomechanics – computational/modeling issues

❑ Discretization (Jha and Juanes, *Acta Geotech.* 2007)

- Stable, convergent scheme
- Single, unstructured computational grid



❑ Coupling strategies (Kim, Tchelepi and Juanes, *SPE J.* 2011; *CMAME* 2011a,b; *SPE J.* 2013)

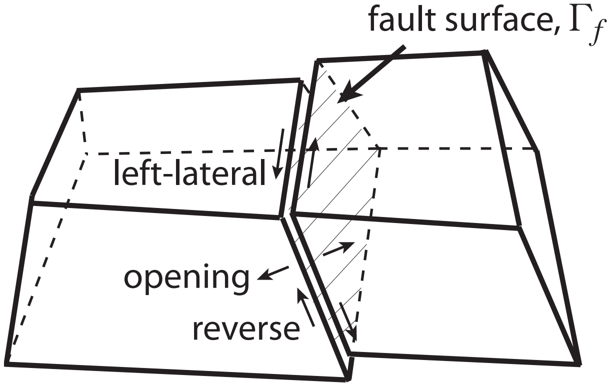
- Efficient, unconditionally stable sequential scheme

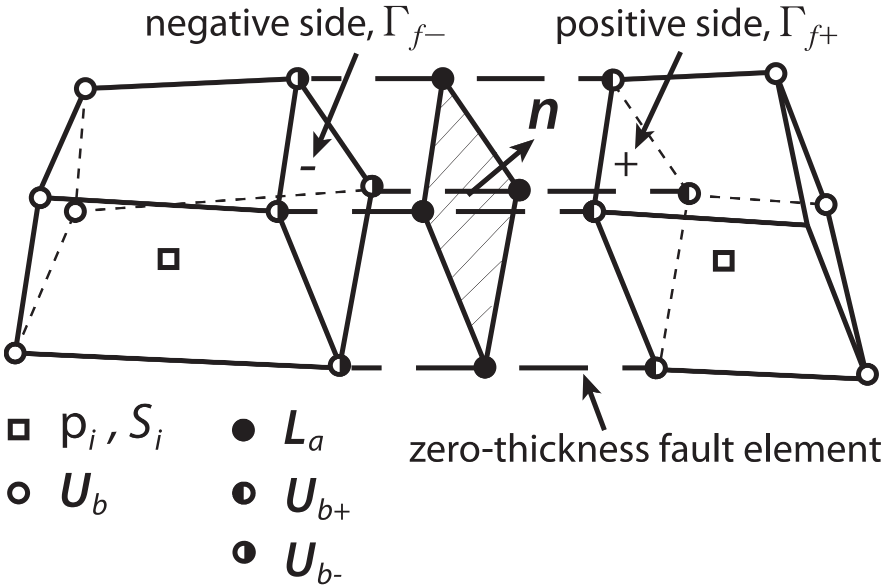
❑ **Fault slip and fault activation**

- Flow: reservoir integrity, pressure maintenance, CO_2 leakage
- Slip: determinant of induced seismicity

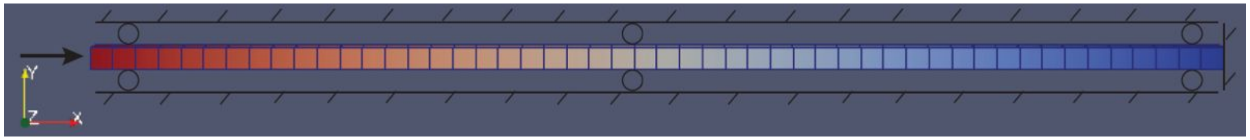
Coupled Fluid Flow and Geomechanics Simulator

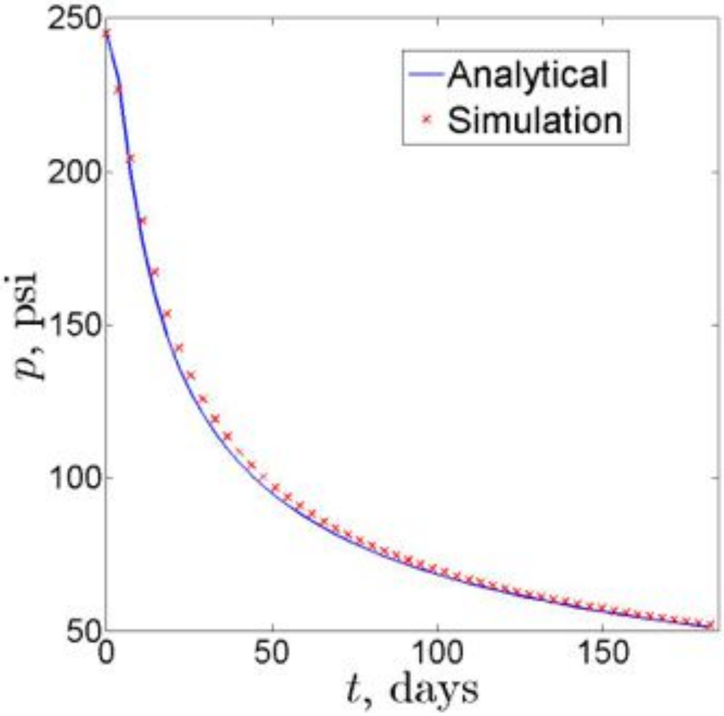
- Features of the coupled code:
  - Finite element geomechanics code
  - Finite volume multiphase-flow reservoir simulator
  - ***Sophisticated formulation for fault deformation and slip***
  - C++, fast, parallel
  - Uses hexahedral (CUBIT) or tetrahedral grid (LaGriT)
  - Viscoelastic and elastoplastic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

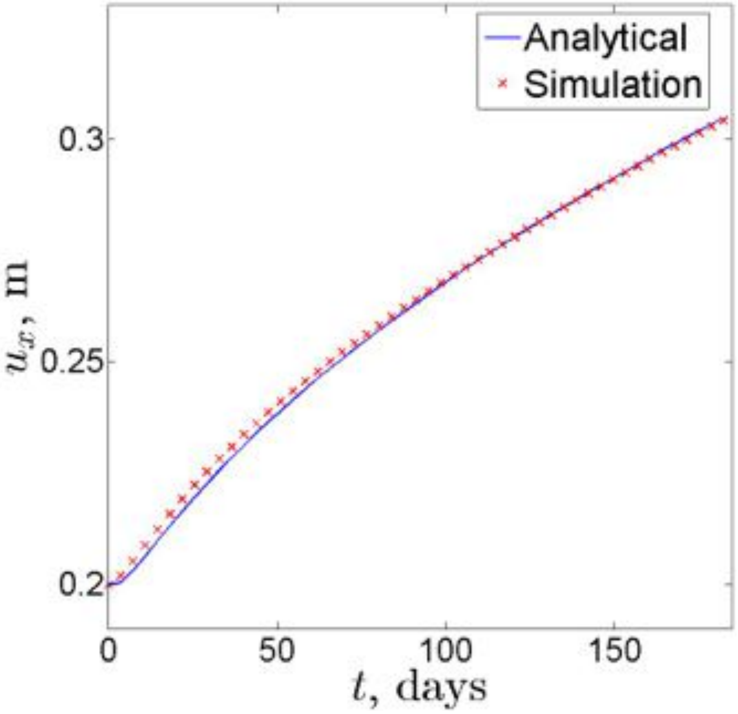




Terzaghi's consolidation problem (One-way coupled)

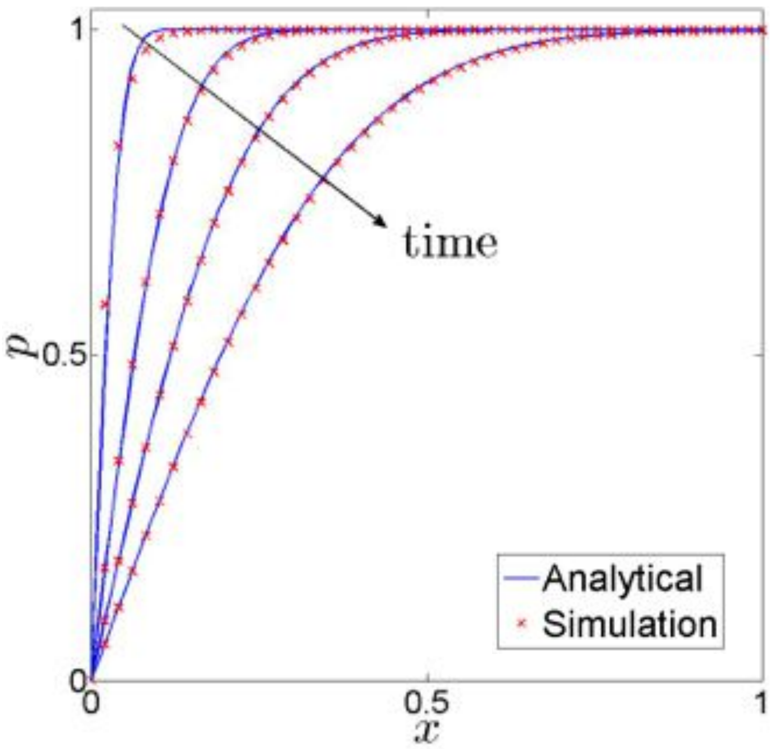




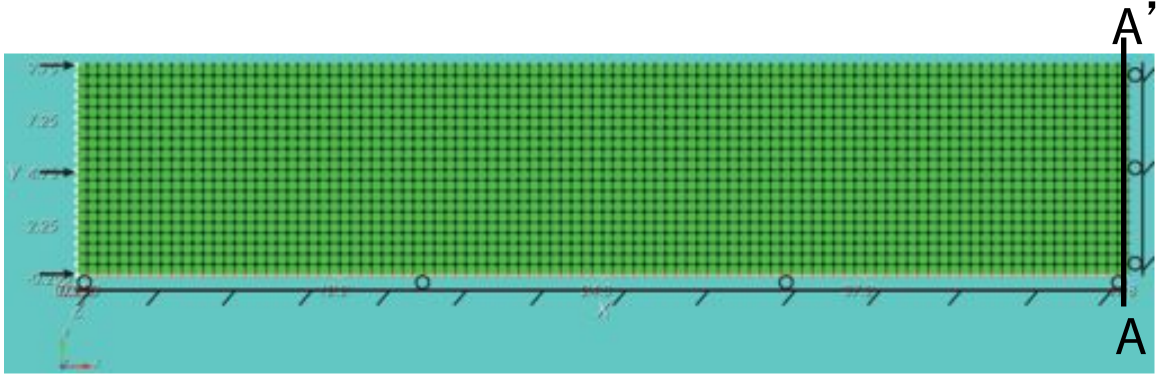


Terzaghi's consolidation problem (One-way coupled)

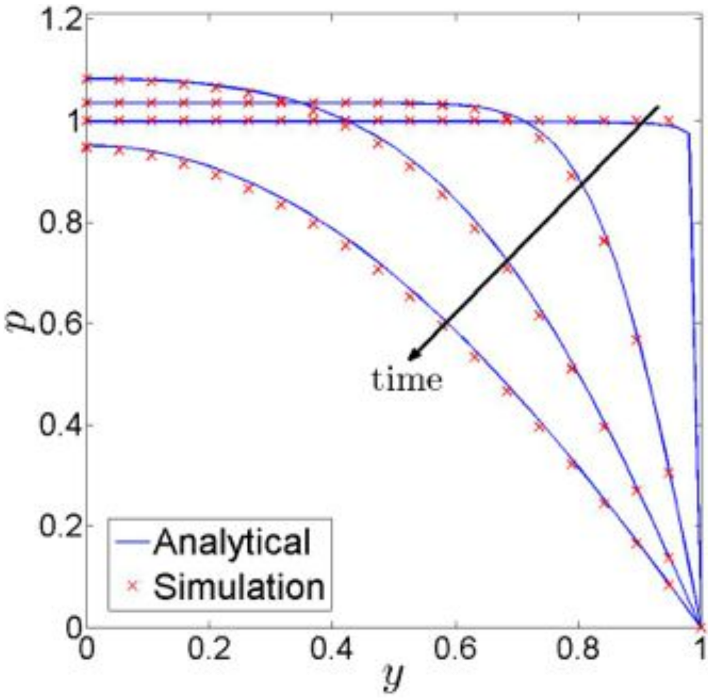
Pressure declines monotonically as the fluid drains out of the column



Mandel's consolidation problem (Two-way coupled)

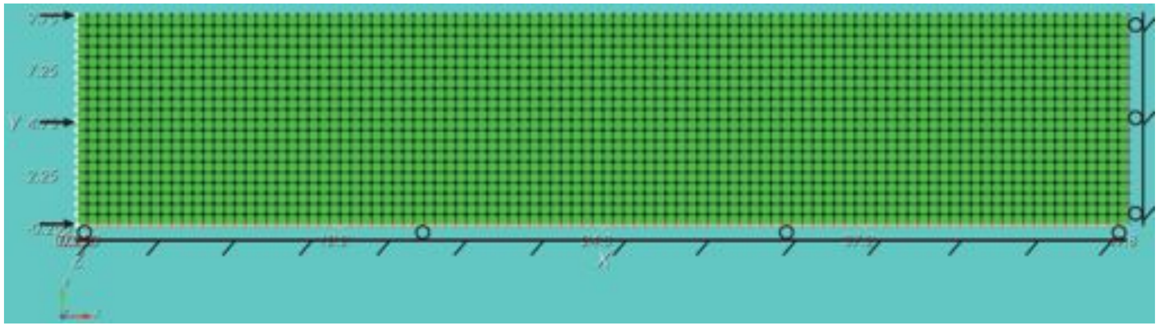


Pressure declines *non-monotonically* as the fluid drains out of the specimen

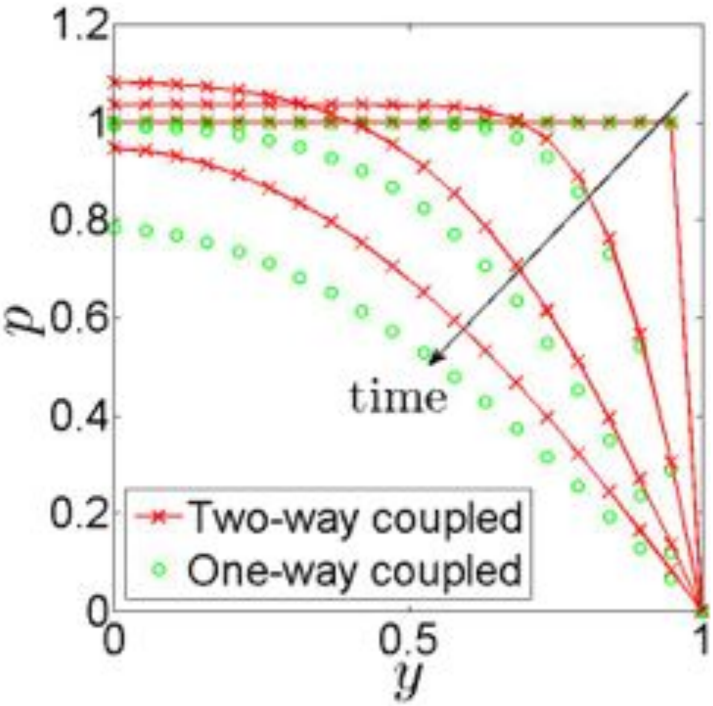


Pressure along AA'

Compare with one-way coupled



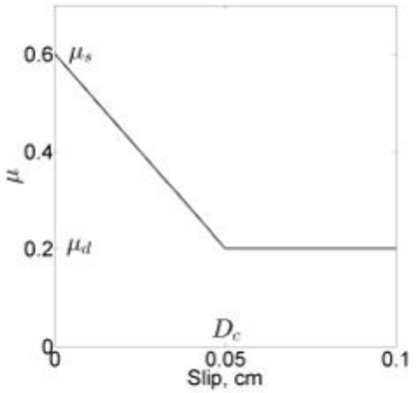
Pressure cannot rise in the one-way coupled scheme because the effect of volume contraction at the drained edge is not fed back into the pressure



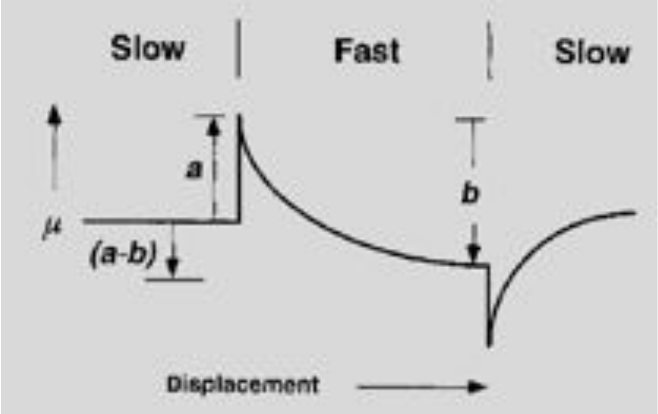
Seismicity – fault friction

- Fault slip at critical effective stress: $\tau_f = \mu\left(|\sigma_n| - p\right) + \tau_0$

- First-order model: dynamic friction coefficient μ
  - Static friction > dynamic friction (slip weakening)
  - Allows for stick-slip behavior



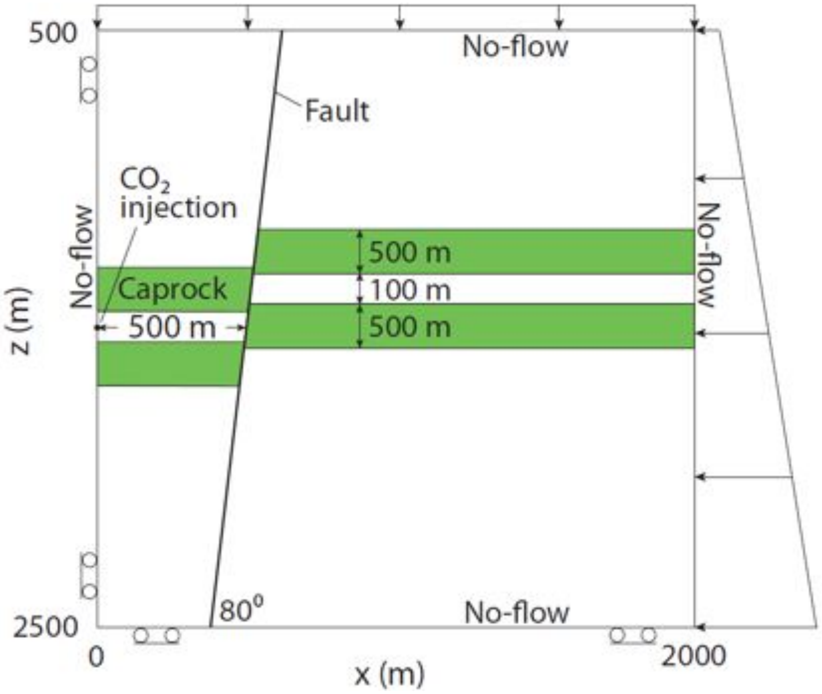
- Rate and state friction



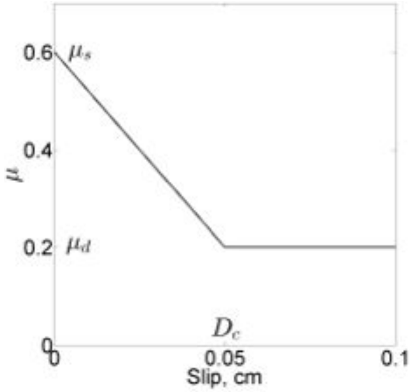
  - (a-b) > 0 : velocity strengthening; stable slip
  - (a-b) < 0 : velocity weakening; potential for earthquake

Faulting induced by CO_2 injection

Plane strain

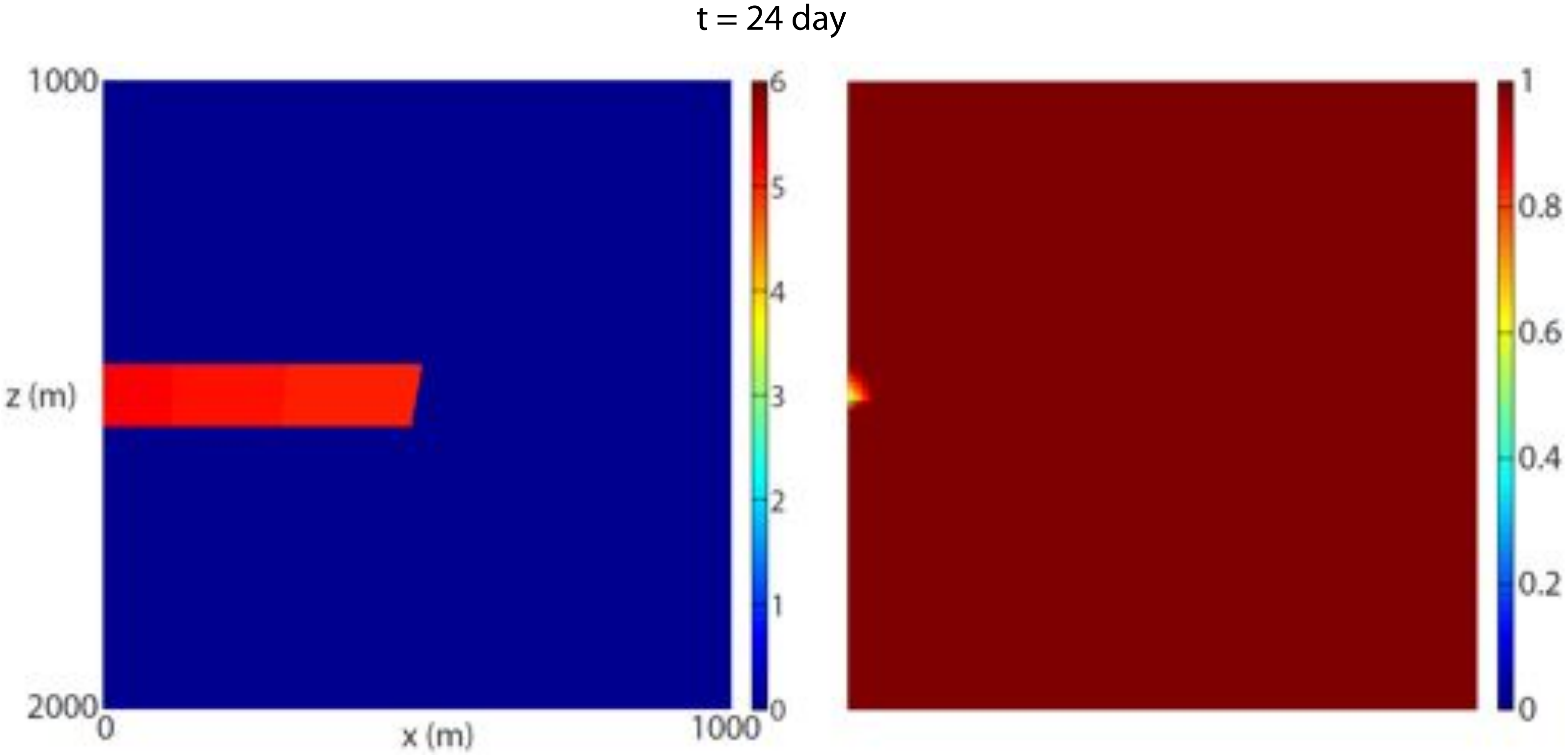


Slip-weakening fault

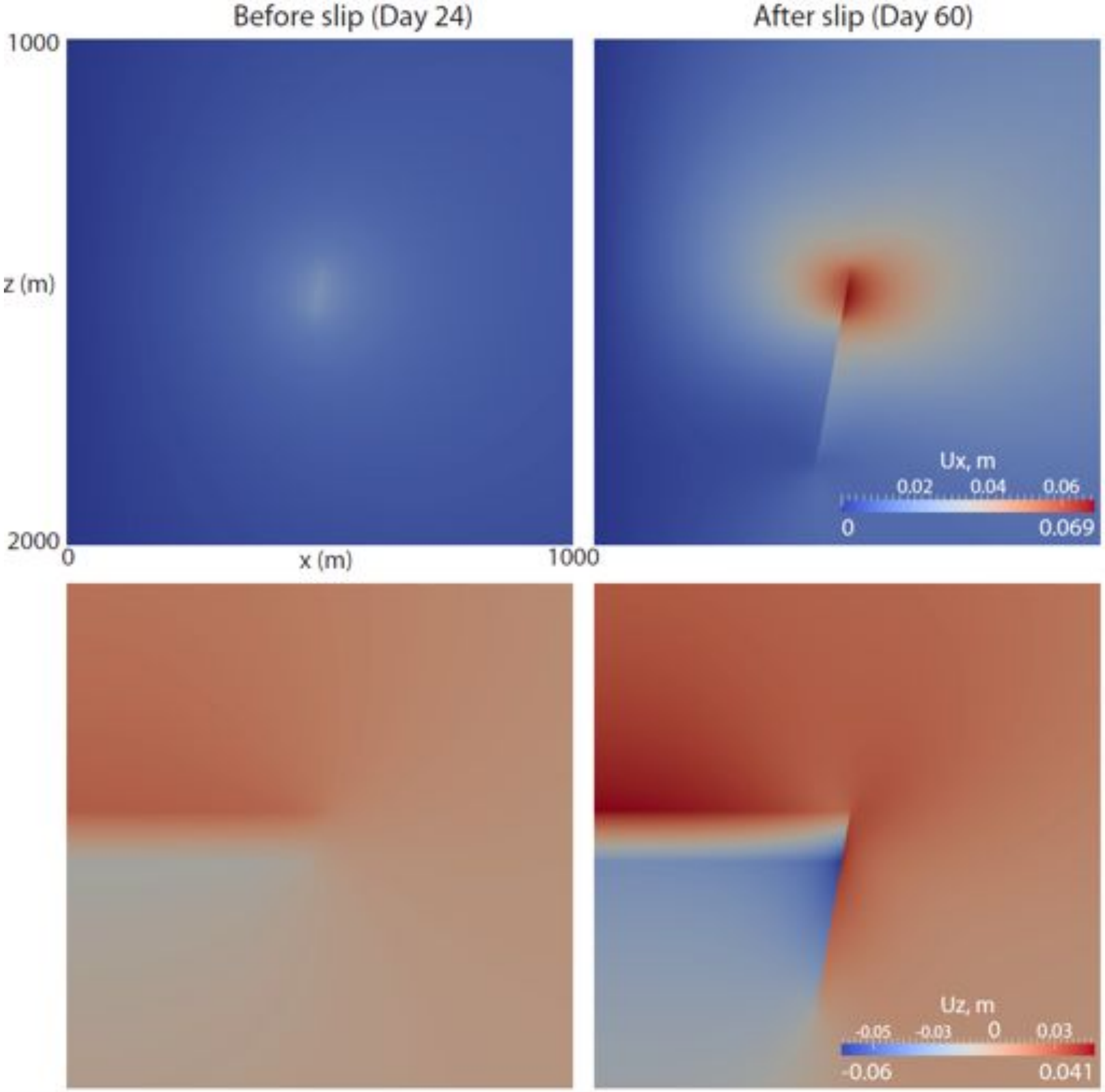


(Cappa and Rutqvist, GRL, 2011)

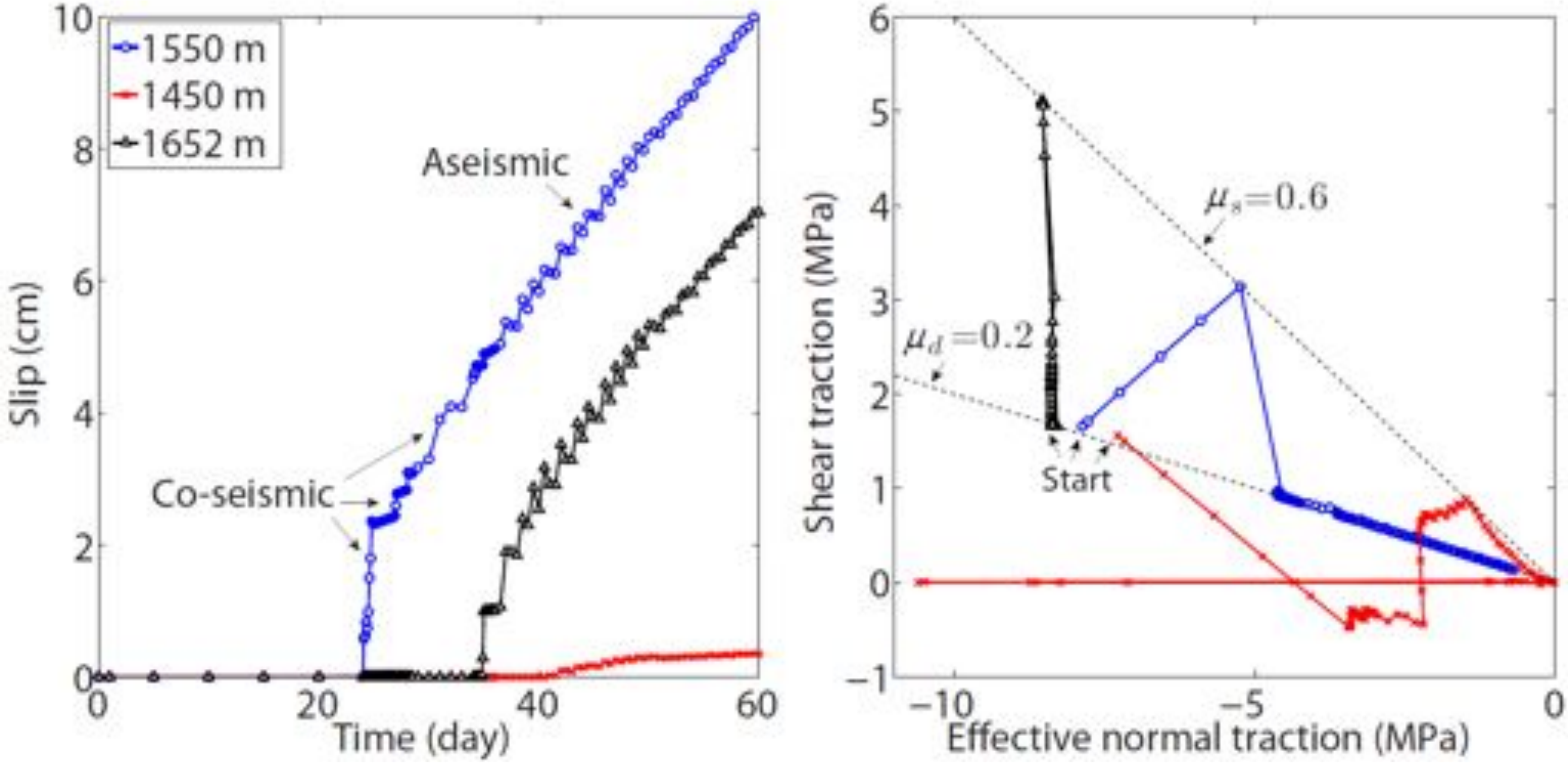
Overpressure and water saturation



Displacement fields

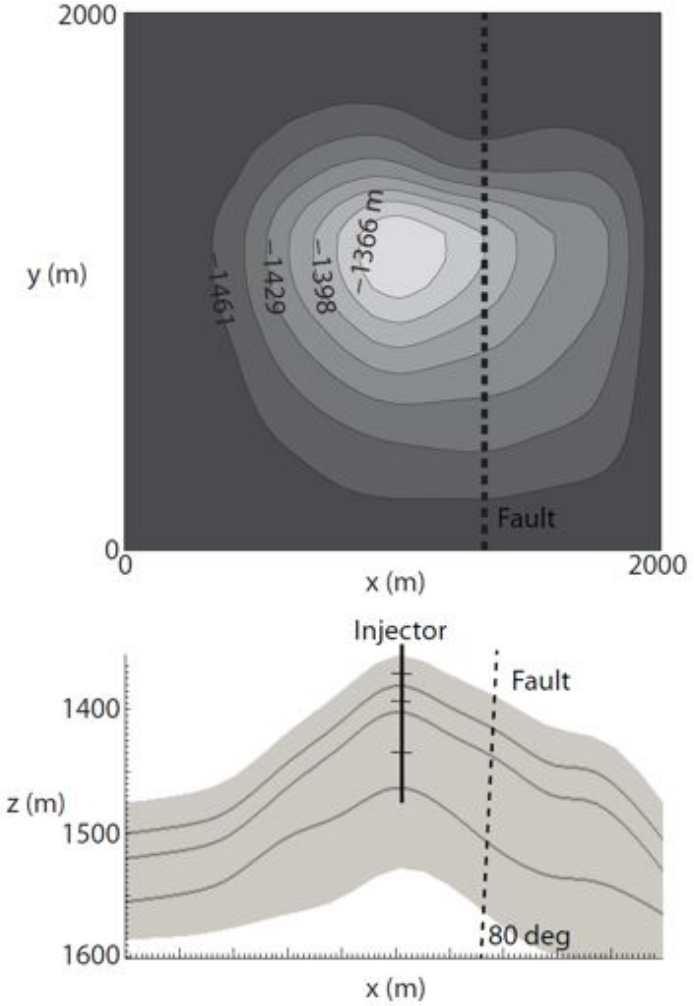


Evolution of stress and slip on the fault

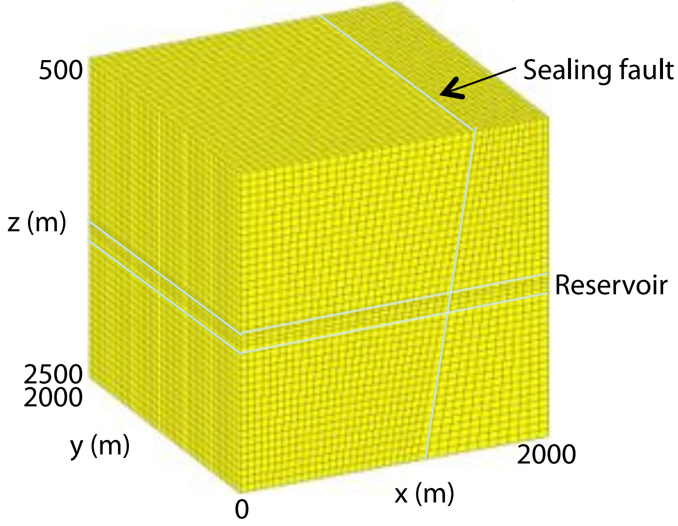


Faulting induced by CO_2 injection: 3D model with Rate- and State- fault

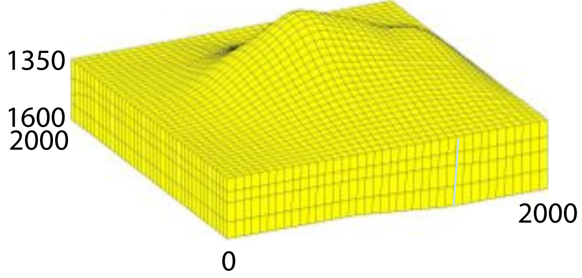
Reservoir model



Geomechanical grid



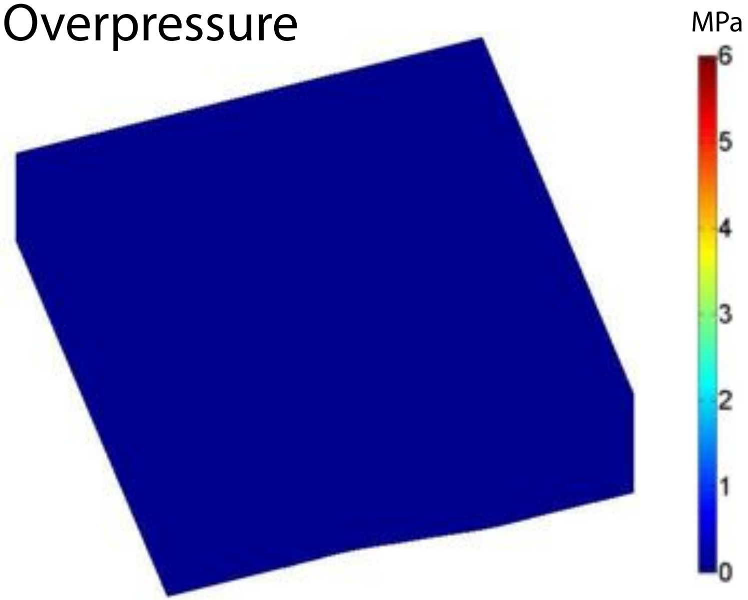
Reservoir grid



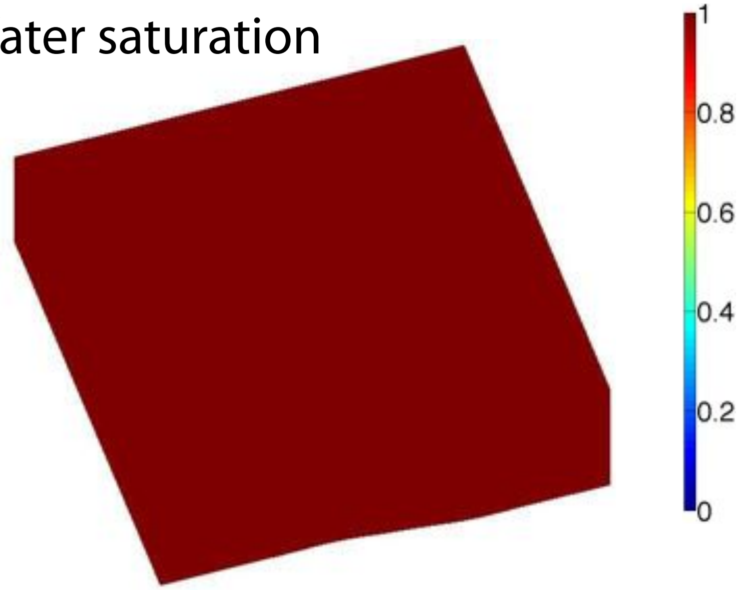
Rate- and State- dependent fault: $a = 0.002$, $b = 0.08$, critical slip = 1 cm

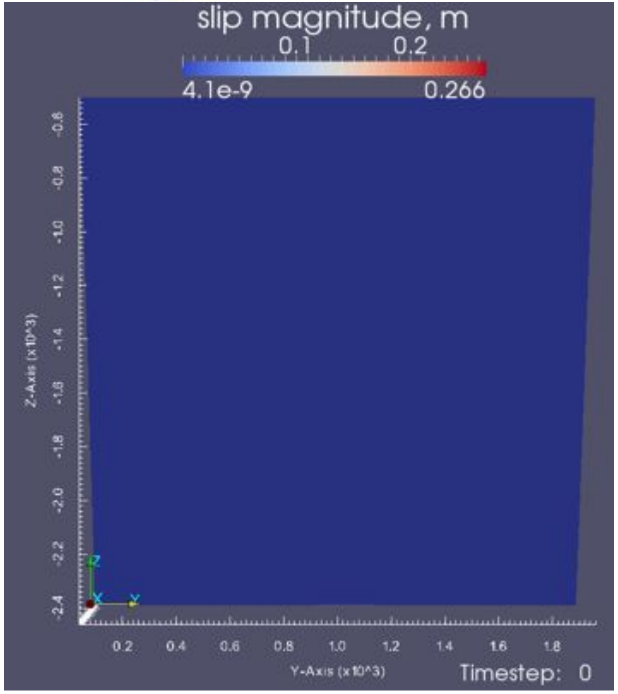
Fault slip due to over-pressurization

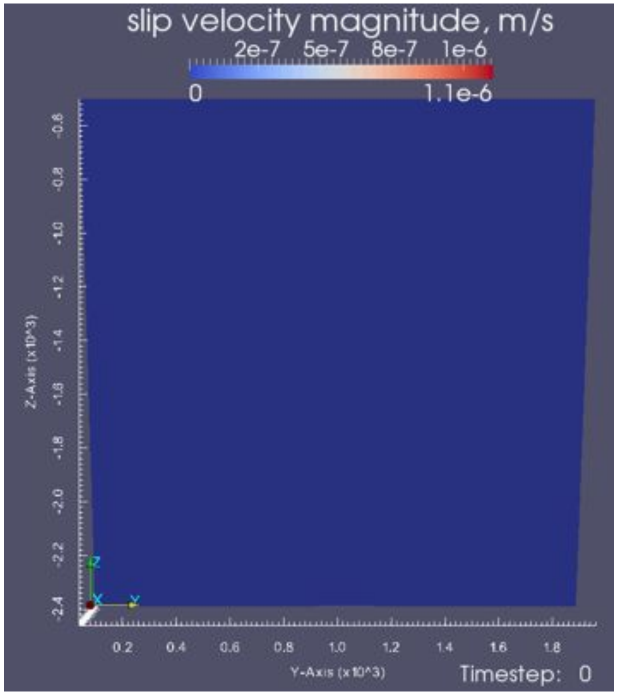
Overpressure



Water saturation







AGU PUBLICATIONS

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 equations

Supporting Information:

- Readme
- Videos S1 and S2

Correspondence to:

R. Juanes,
juanes@mit.edu

Citation:

Jha, B., and R. Juanes (2014), Coupled multiphase flow and poromechanics: A computational model of pore pressure effects on fault slip and earthquake triggering, *Water Resour. Res.*, *50*, doi:10.1002/2013WR015175.

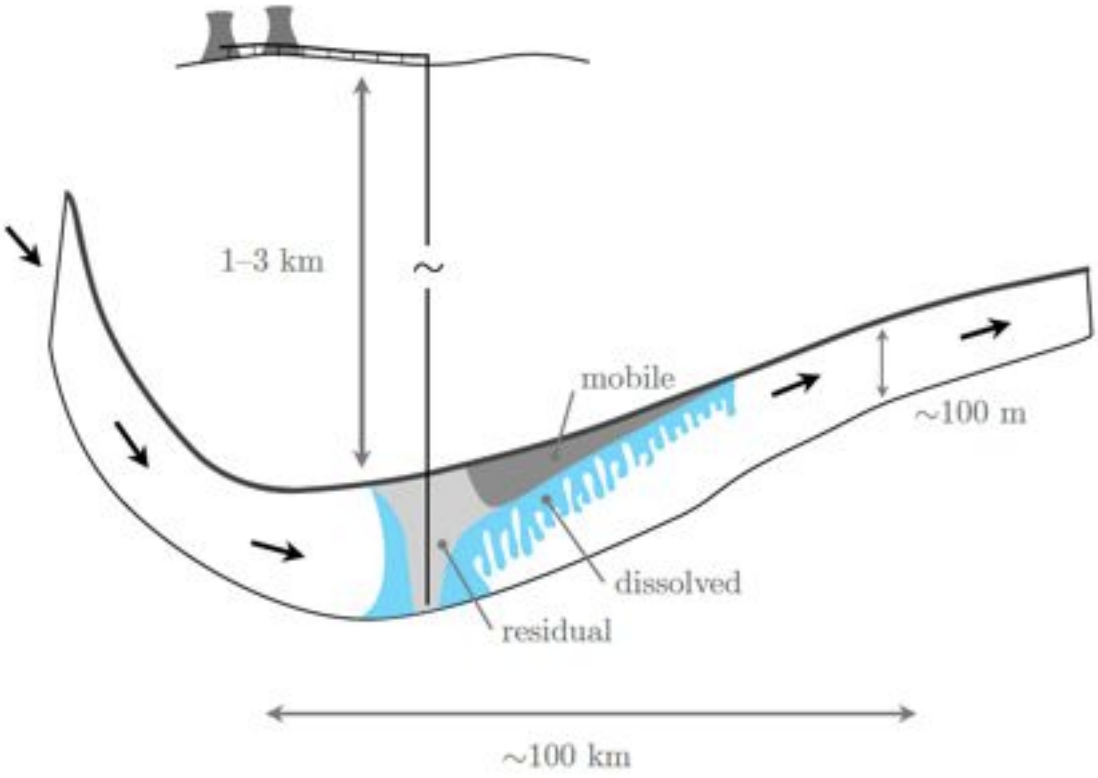
Coupled multiphase flow and poromechanics: A computational model of pore pressure effects on fault slip and earthquake triggering

Birendra Jha[1] and Ruben Juanes[1]

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

Abstract The coupling between subsurface flow and geomechanical deformation is critical in the assessment of the environmental impacts of groundwater use, underground liquid waste disposal, geologic storage of carbon dioxide, and exploitation of shale gas reserves. In particular, seismicity induced by fluid injection and withdrawal has emerged as a central element of the scientific discussion around subsurface technologies that tap into water and energy resources. Here we present a new computational approach to model coupled multiphase flow and geomechanics of faulted reservoirs. We represent faults as surfaces embedded in a three-dimensional medium by using zero-thickness interface elements to accurately model fault slip under dynamically evolving fluid pressure and fault strength. We incorporate the effect of fluid pressures from multiphase flow in the mechanical stability of faults and employ a rigorous formulation of nonlinear multiphase geomechanics that is capable of handling strong capillary effects. We develop a numerical simulation tool by coupling a multiphase flow simulator with a mechanics simulator, using the unconditionally stable fixed-stress scheme for the sequential solution of two-way coupling between flow and geomechanics. We validate our modeling approach using several synthetic, but realistic, test cases that illustrate the onset and evolution of earthquakes from fluid injection and withdrawal.

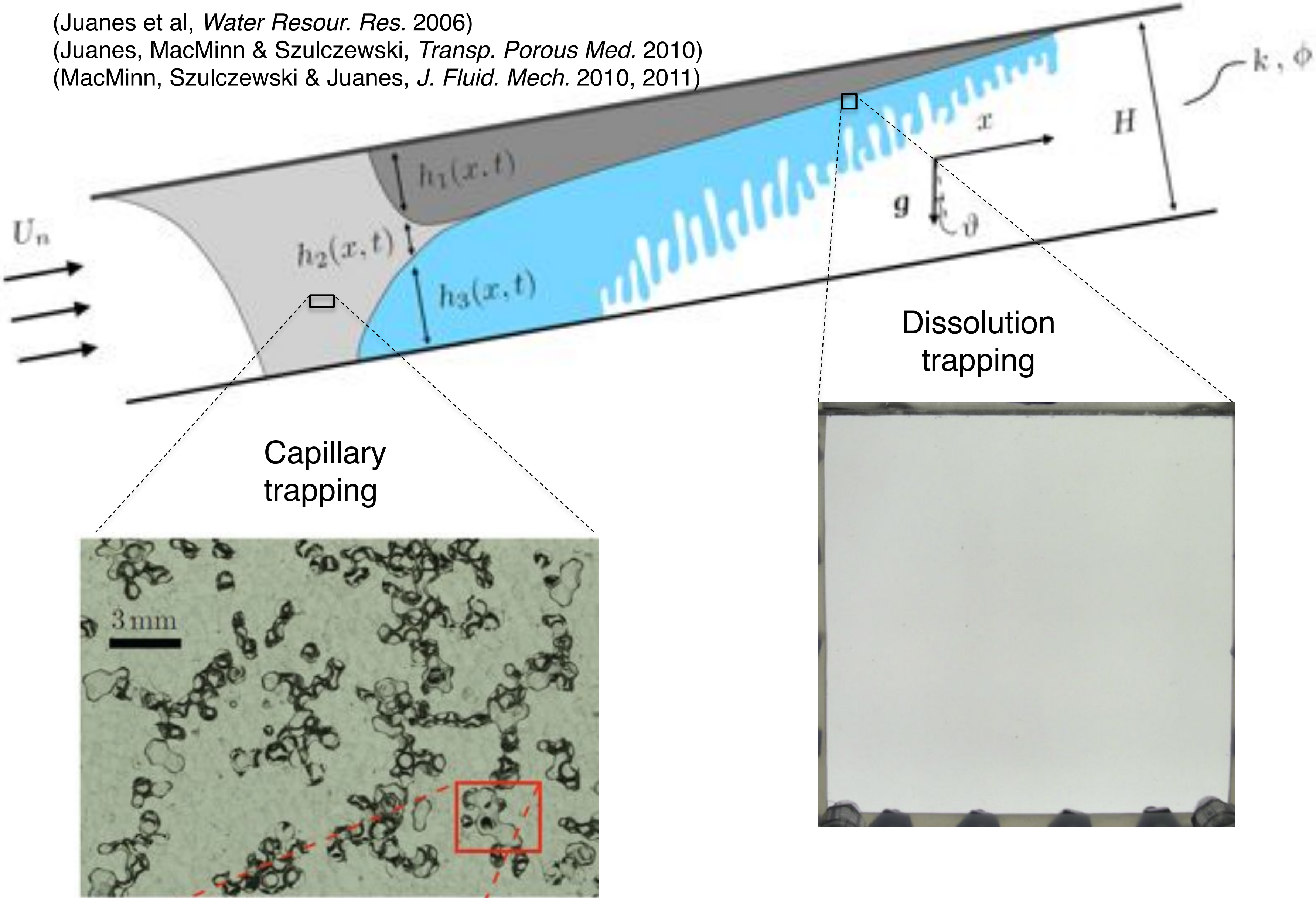
Storage must be understood at the scale of entire geologic basins



- ☐ **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)

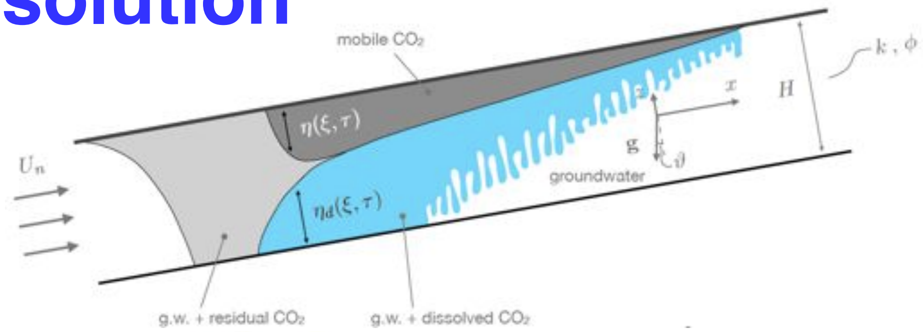


Capillary trapping

Dissolution trapping

Plume migration with dissolution

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



- Theory

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

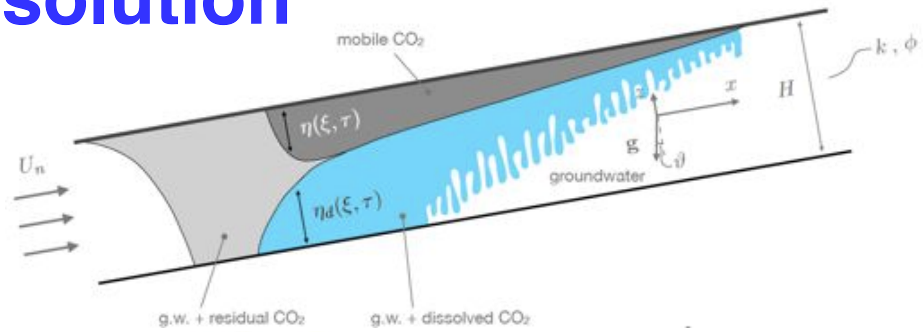
- Experiments

(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



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

- ❑ Experiments

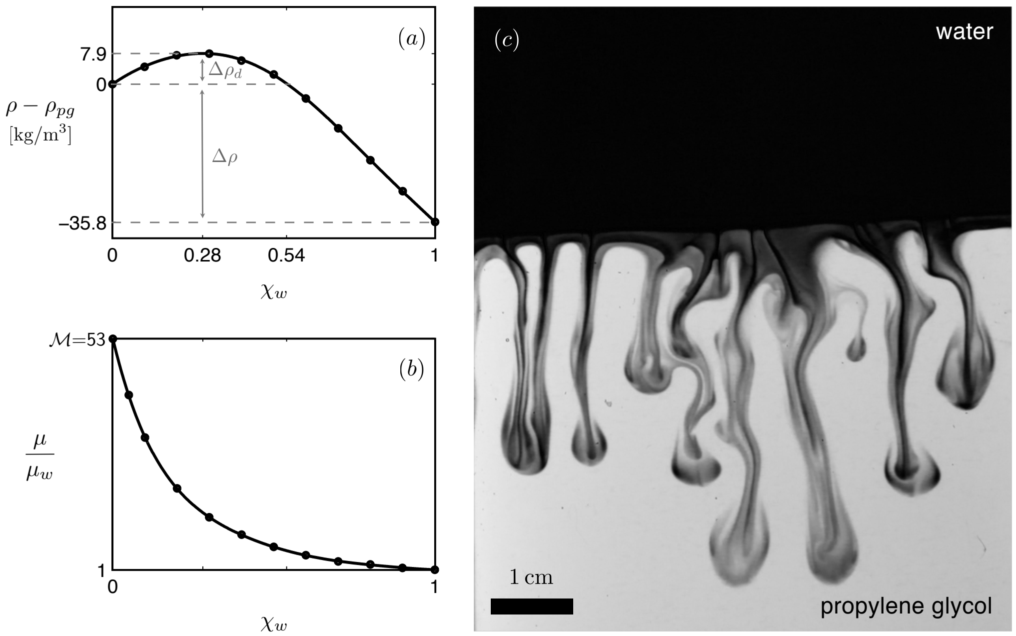
(MacMinn & Juanes, *Geophys. Res. Lett.*, 2013)

Dissolution by convective mixing

- Dimensionless governing equations

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

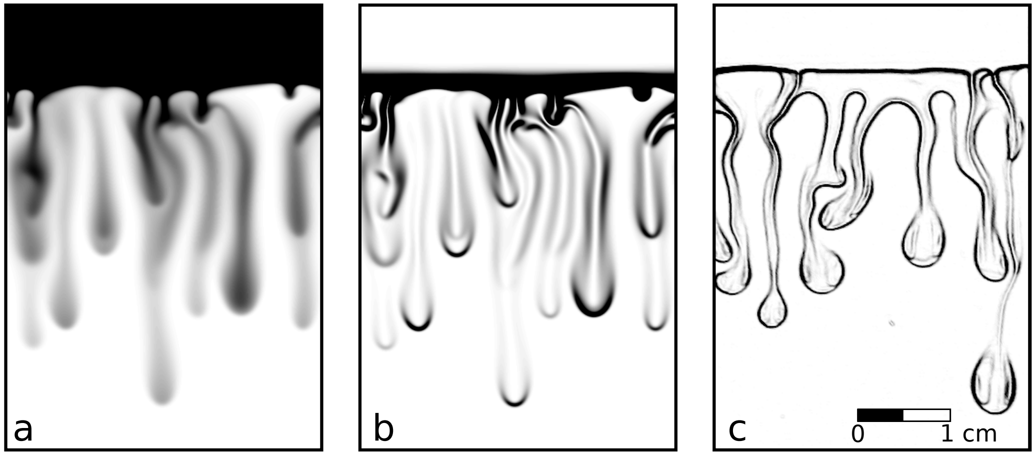
$$\partial_t c + \nabla \cdot \left(\boldsymbol{u}c - \frac{1}{\mathrm{Ra}} \nabla c \right) = 0,$$



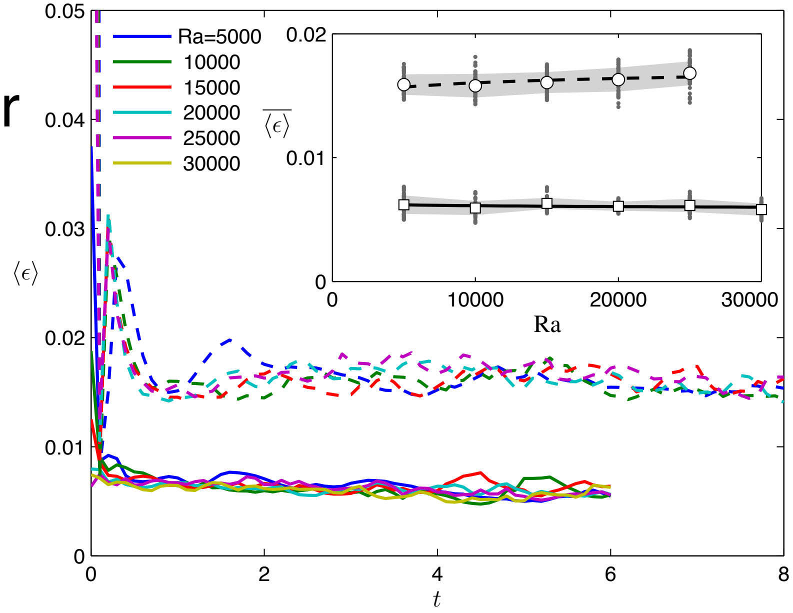
(Hidalgo et al., *Phys. Rev. Lett.,* 2012)

Dissolution by convective mixing

- Mixing controlled by the scalar dissipation rate

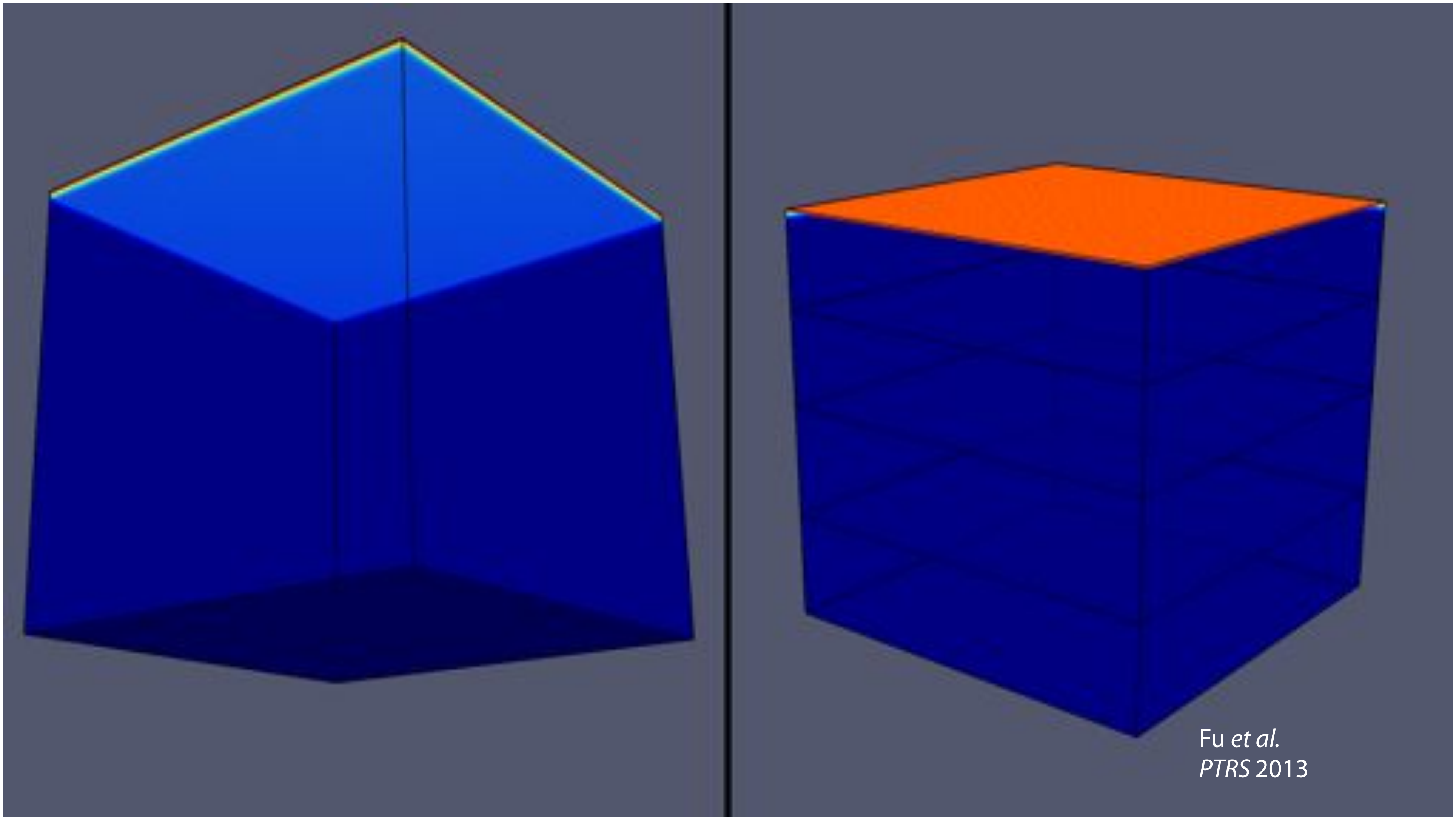


- Dissolution rate is constant and independent of Rayleigh number



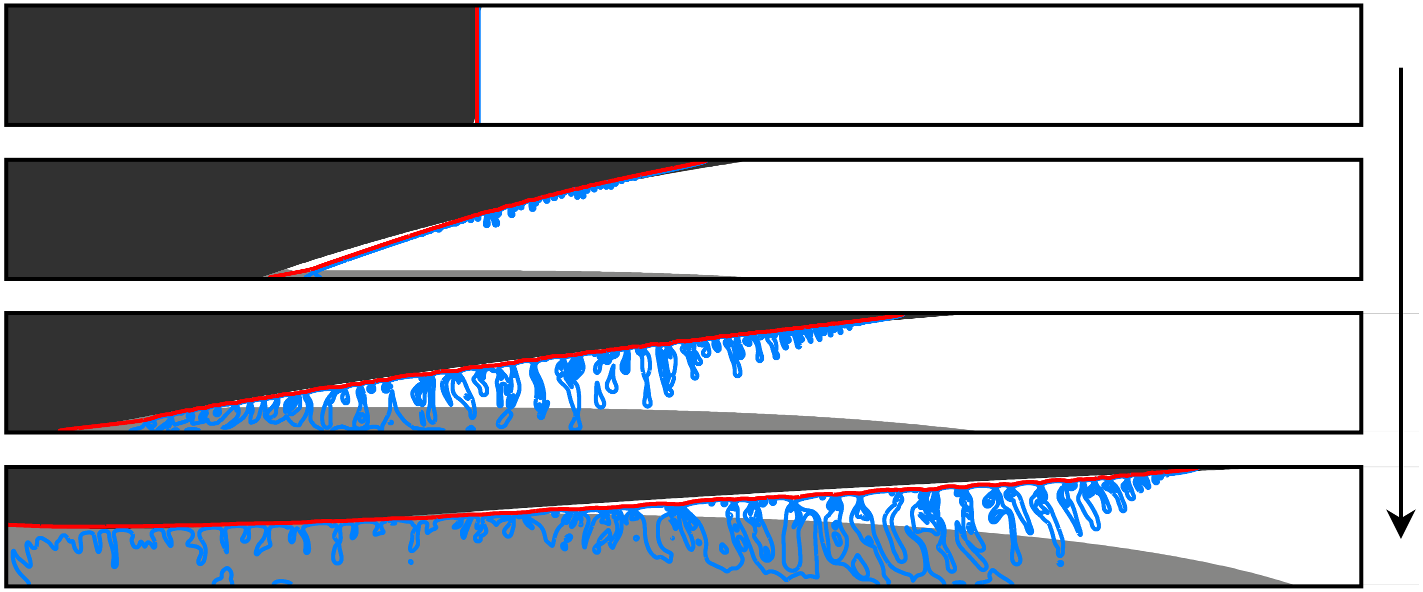
(Hidalgo et al., *Phys. Rev. Lett.,* 2012)

Dissolution by convective mixing



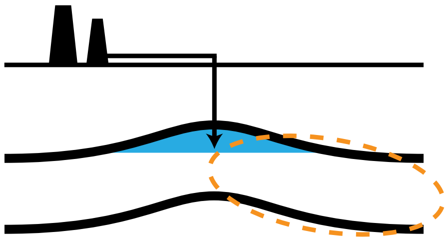
Fu *et al.*
PTRS 2013

Plume migration with dissolution

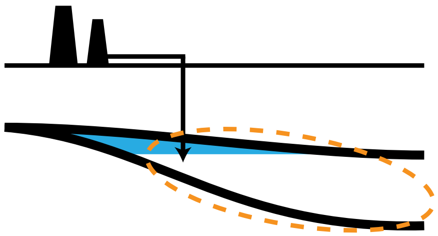


(Hidalgo, MacMinn & Juanes, *Adv. Water Resour.*, 2013)

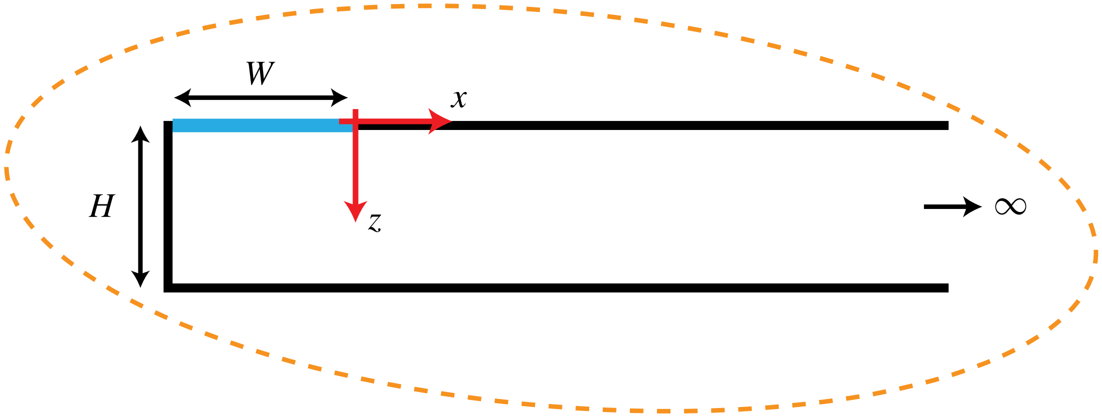
CO2 dissolution in structural traps



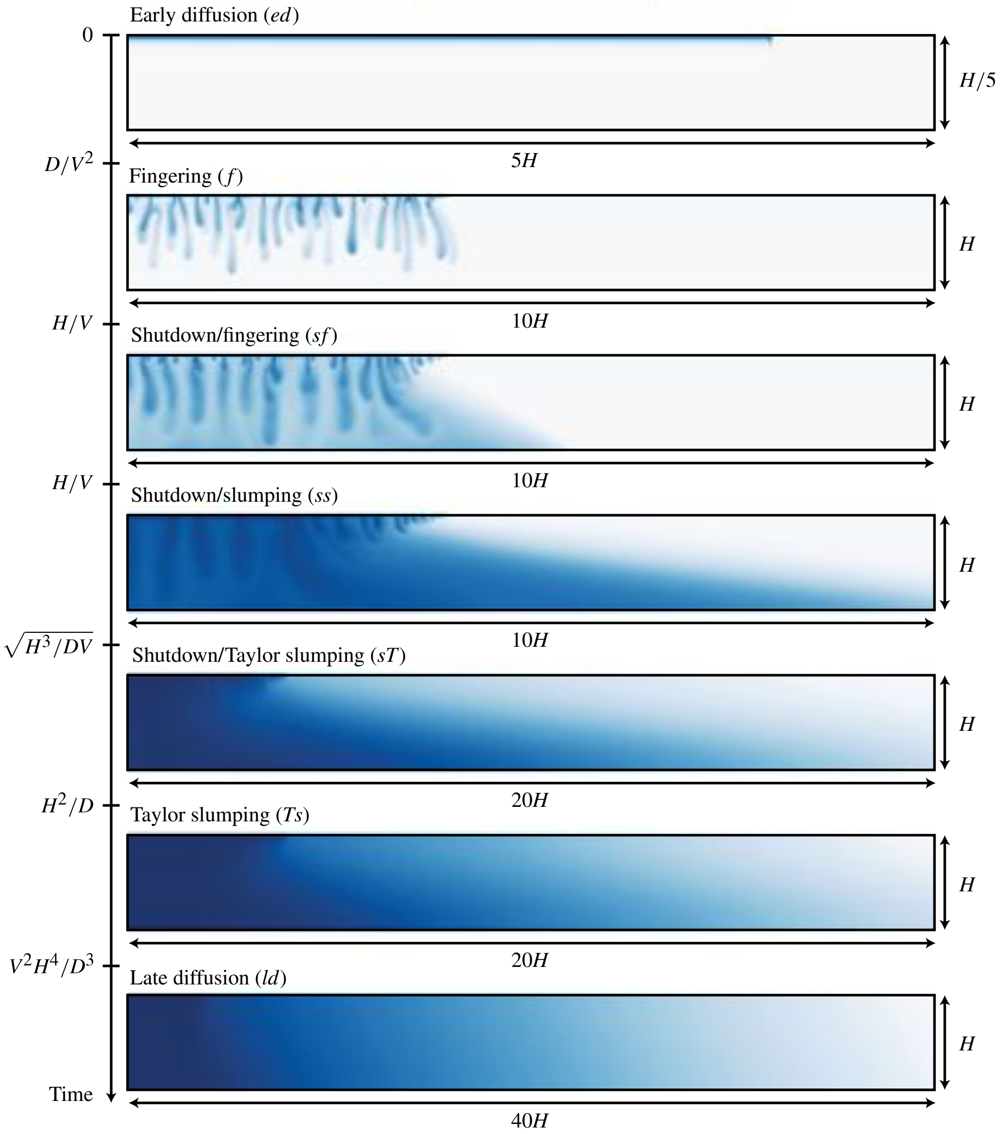
Anticline

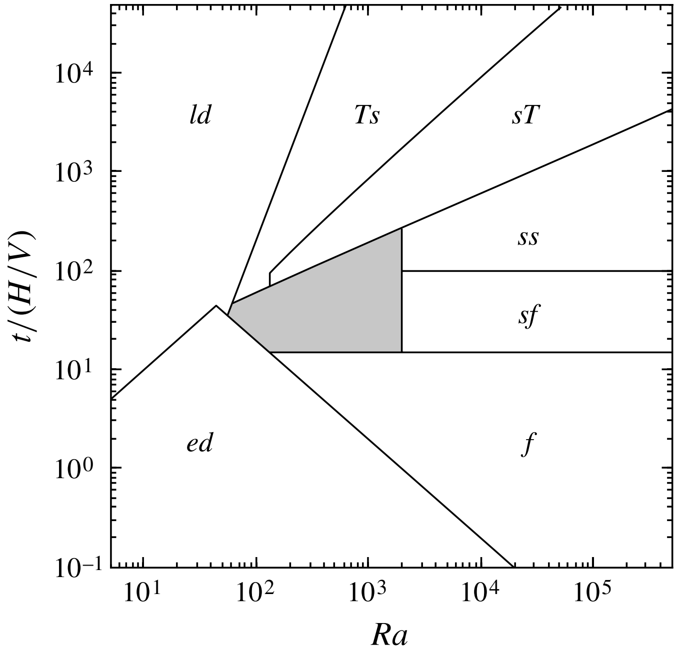


Pinchout



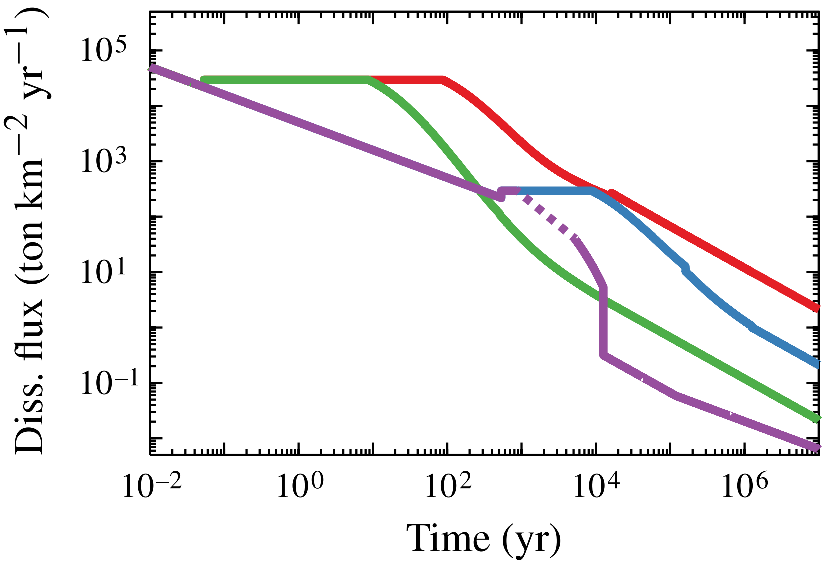
CO2 dissolution in structural traps





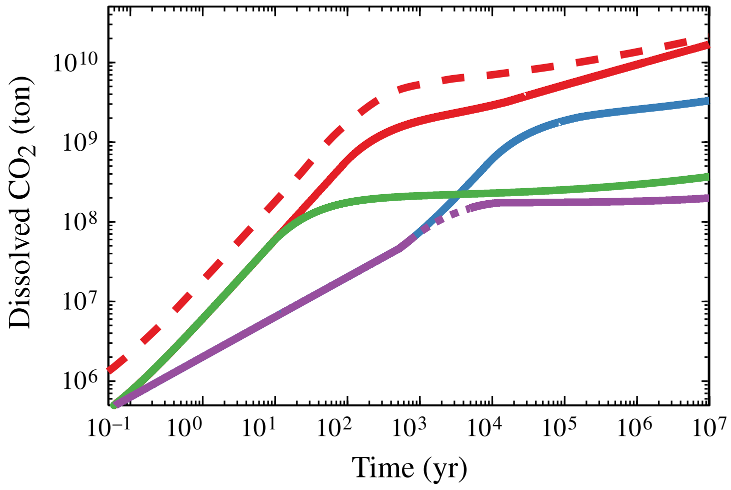
CO2 dissolution in structural traps

- 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)

Summary – expected 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
- This project contributes to the future deployment of this technology by analyzing the impact of CCS at the gigatonne-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)

Organization chart

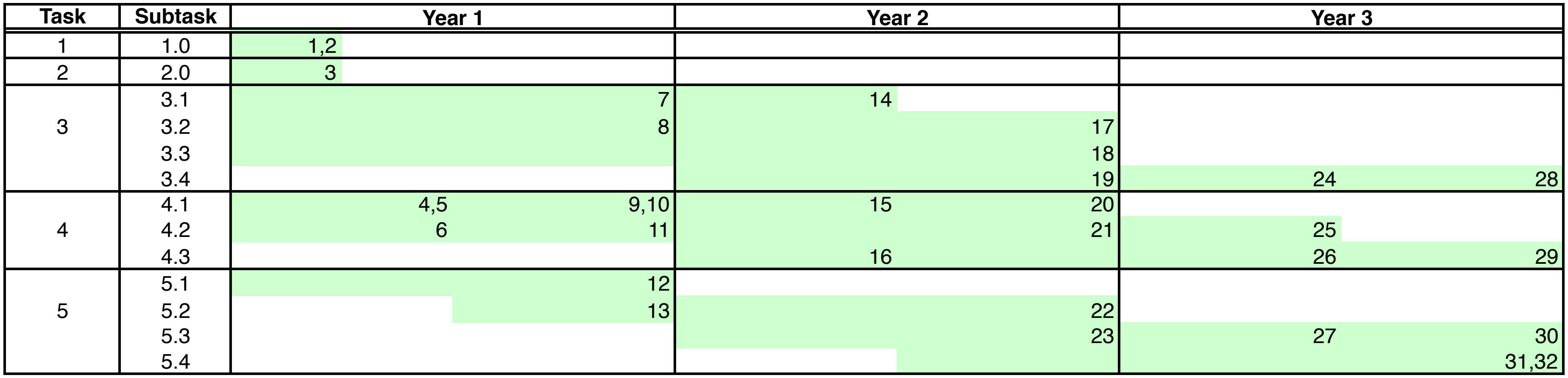
- Key personnel:

Ruben Juanes

Brad Hager

- All research performed at MIT
- Involves 2 PhD students and 1 postdoctoral associate

Gantt chart



Task	Subtask	Year 1	Year 2	Year 3
1	1.0	1,2		
2	2.0	3		
3	3.1	7	14	
	3.2	8	17	
	3.3		18	
	3.4		19	24 28
4	4.1	4,5 9,10	15 20	
	4.2	6 11	21	25
	4.3		16	26 29
5	5.1	12		
	5.2	13	22	
	5.3		23	27 30
	5.4			31,32

Bibliography

- ❑ B. Jha and R. Juanes, Coupled multiphase flow and poromechanics: a computational model of pore-pressure effects on fault slip and earthquake triggering. Water Resources Research, 50, doi:10.1002/2013WR015175 (2014).

- ❑ B. Zhao, C. W. MacMinn, H. E. Huppert, and R. Juanes, Capillary pinning and blunting of immiscible gravity currents in porous media. Water Resources Research, 50, doi: 10.1002/2014WR015335 (2014).

- ❑ M. L. Szulczewski, C. W. MacMinn and R. Juanes, Theoretical analysis of how pressure buildup and CO2 migration both constrain storage capacity in deep saline aquifers. International Journal of Greenhouse Gas Control, 23, 113-118 (2014), doi:10.1016/j.ijggc.2014.02.006.

- ❑ M. L. Szulczewski, M. A. Hesse, and R. Juanes, Carbon dioxide dissolution in structural and stratigraphic traps. Journal of Fluid Mechanics, 736, 287-315 (2013), doi:10.1017/jfm.2013.511.

- ❑ J. J. Hidalgo, C. W. MacMinn and R. Juanes, Dynamics of convective dissolution from a migrating current of carbon dioxide. Advances in Water Resources, 62, 511-519 (2013), doi: 10.1016/j.advwatres.2013.06.013.

- ❑ J. Kim, H. A. Tchelepi and R. Juanes, Rigorous coupling of geomechanics and multiphase flow with strong capillarity. SPE Journal, 18(6), 1123-1139 (2013), doi:10.2118/141268-PA.

Bibliography

- X. Fu, L. Cueto-Felgueroso, and R. Juanes, Pattern formation and coarsening dynamics in three-dimensional convective mixing in porous media. Philosophical Transactions of the Royal Society A, 371, 20120355 (2013), doi:10.1098/rsta.2012.0355.

- C. W. MacMinn and R. Juanes, Buoyant currents arrested by convective dissolution. Geophysical Research Letters, 40(10), 2017-2022 (2013), doi:10.1002/grl.50473.

- M. L. Szulczewski and R. Juanes, The evolution of miscible gravity currents in horizontal porous layers. Journal of Fluid Mechanics, 719, 82-96 (2013), doi:10.1017/jfm.2012.631.

- B. Zhao, C. W. MacMinn, M. L. Szulczewski, J. A. Neufeld, H. E. Huppert, and R. Juanes, Interface pinning of immiscible gravity-exchange flows in porous media. Physical Review E, 87, 023015 (2013), doi:10.1103/PhysRevE.87.023015.

- J. J. Hidalgo, J. Fe, L. Cueto-Felgueroso and R. Juanes, Scaling of convective mixing in porous media. Physical Review Letters, 109, 264503 (2012), doi:10.1103/PhysRevLett.109.264503.

- R. Juanes, B. H. Hager, and H. J. Herzog, No geologic evidence that seismicity causes fault leakage that would render large-scale carbon capture and storage unsuccessful. Proc. Natl. Acad. Sci. U.S.A., 109(52), E3623 (2012), doi:10.1073/pnas.1215026109.