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

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DOE/NETL Carbon Storage R&D Project Review Meeting
Pittsburgh, August 22, 2013

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]

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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

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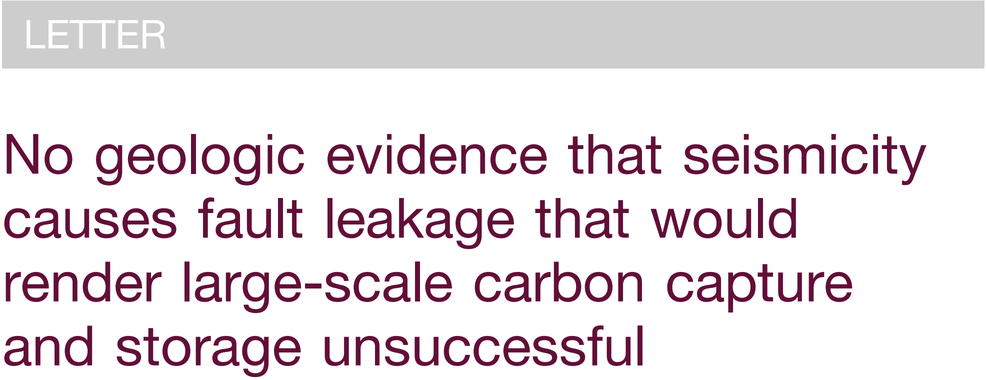
Edited by Pamela A. Matson, Stanford University, Stanford, CA, and approved May 4, 2012 (received for review March 27, 2012)

- ***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?

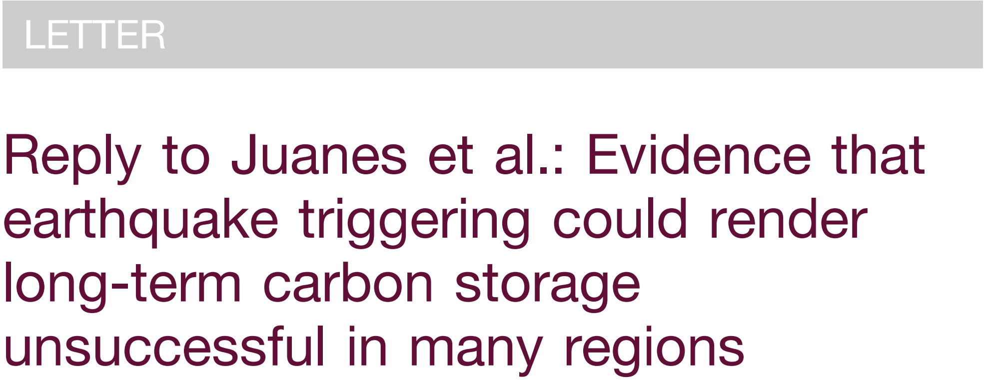
An ongoing debate …



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

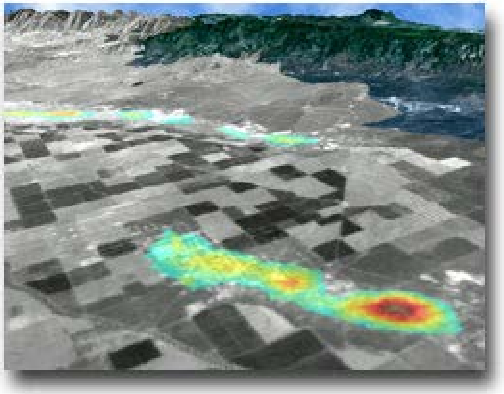
Tasks

- 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

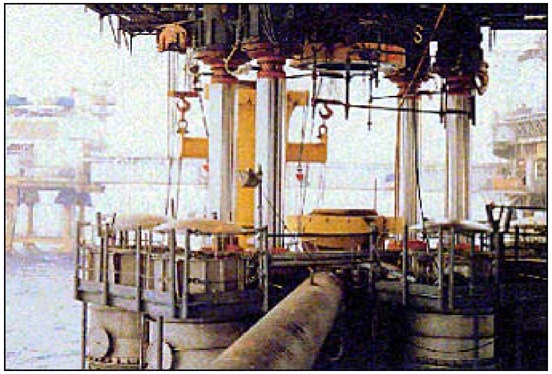
Coupled flow and geomechanics

- ☐ **Reservoir compaction and subsidence**



Belridge oil fields (ATLANTIS)

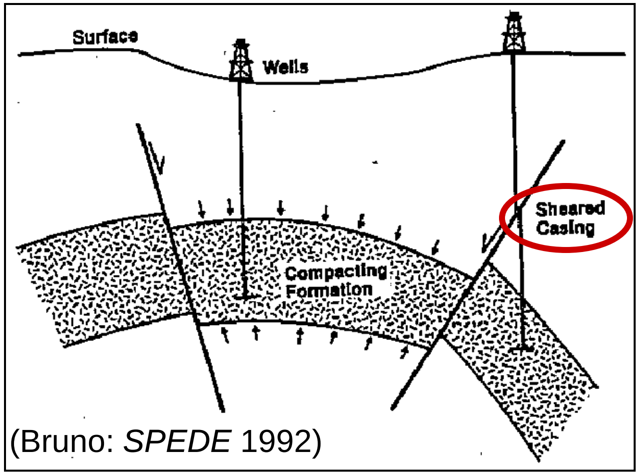
Wilmington field,
Long Beach



Ekofisk oil field (AMESIM)

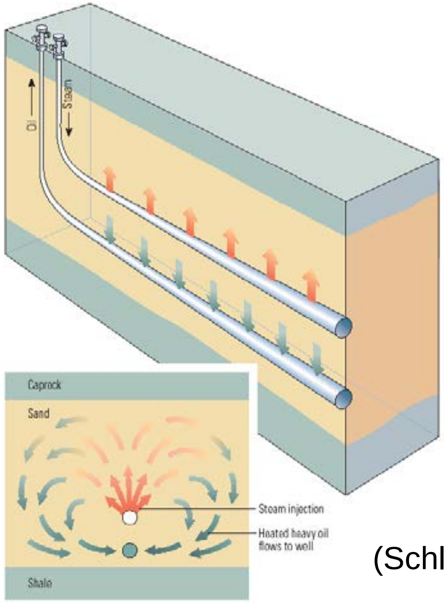
Coupled flow and geomechanics

- ☐ **Wellbore stability**
  - Casing damage
  - Borehole breakout
  - Sand mobilization



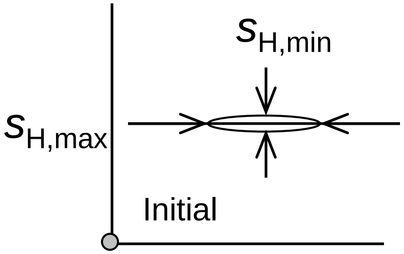
(Bruno: *SPEDE* 1992)

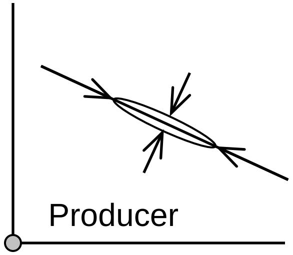
- ☐ **Caprock integrity**
  - SAGD
  - CO_2 sequestration

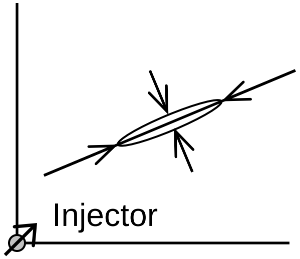


(Schlumberger)

- ☐ **Fluid-induced stress reorientation**
  - Injectors behave as attractors for propagating fractures





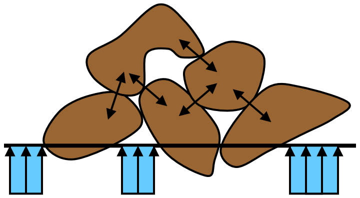


Poromechanical coupling

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

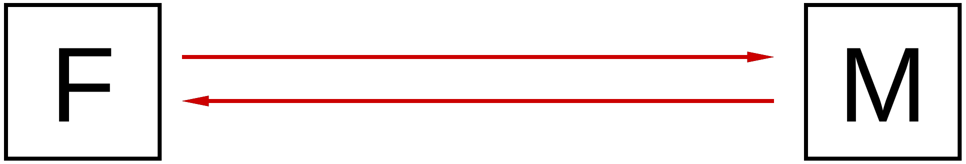
- **Linear momentum balance**
  - Primary unknown: $\boldsymbol{u}$

- **Couplings:**



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

Effective stress



Change in volume

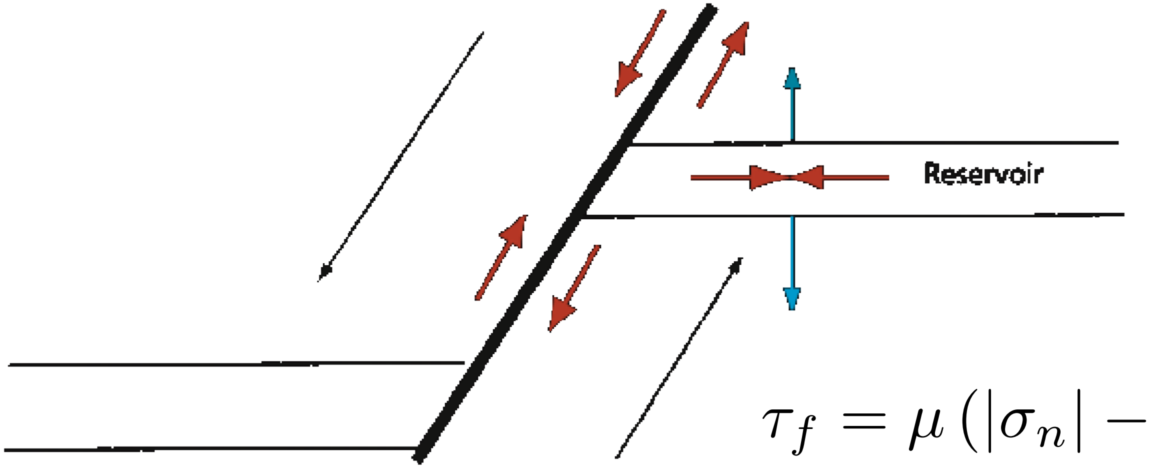
Change in reservoir properties: ϕ, $\boldsymbol{k}$

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



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

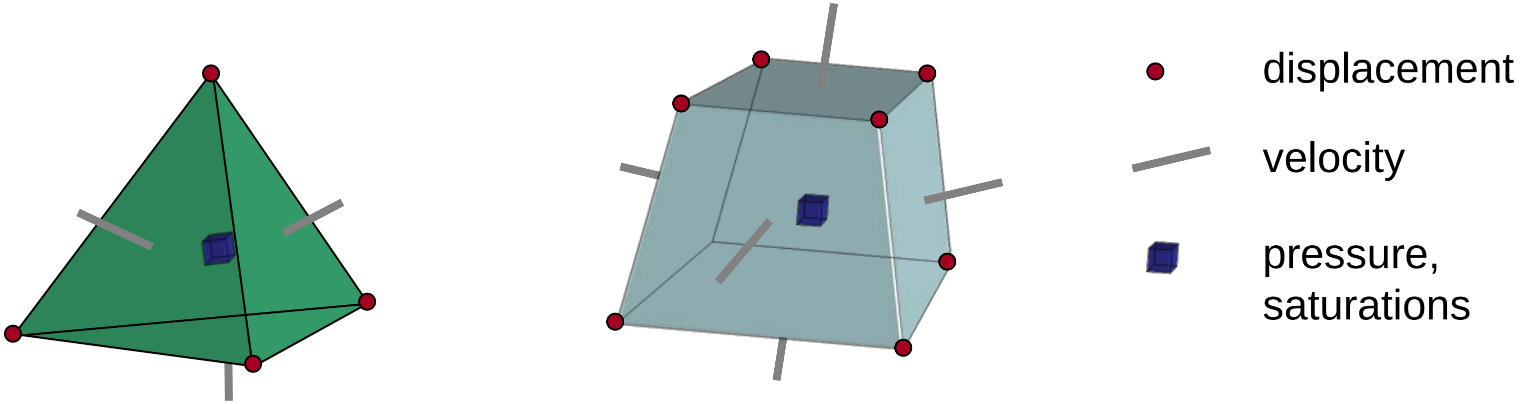
- Increasing the pore fluid pressure within a reservoir tends to promote failure by reducing the failure stress

- Failure above or below the reservoir might depend on fault orientation

- Quantification of the state of deformation and stress of the reservoir is essential for the correct prediction of a number of processes critical to geologic CO2 storage, including pressure evolution, subsidence, seal integrity, hydrofracturing, fault slip and induced seismicity

Geomechanics – computational/modeling issues

- Discretization (Jha and Juanes, *Acta Geotech.* 2007)
  - Stable, convergent scheme
  - Single, unstructured computational grid

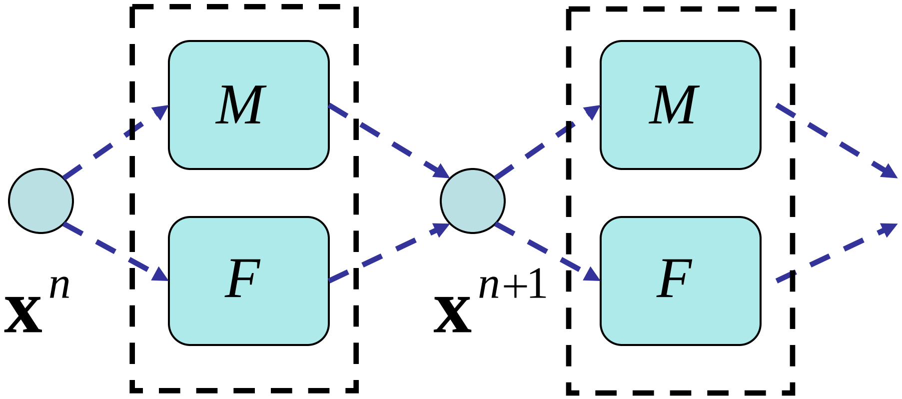


- Coupling strategies (Kim, Tchelepi and Juanes, *SPE J.* 2011; *CMAME* 2011a,b)
  - Efficient, unconditionally stable sequential scheme

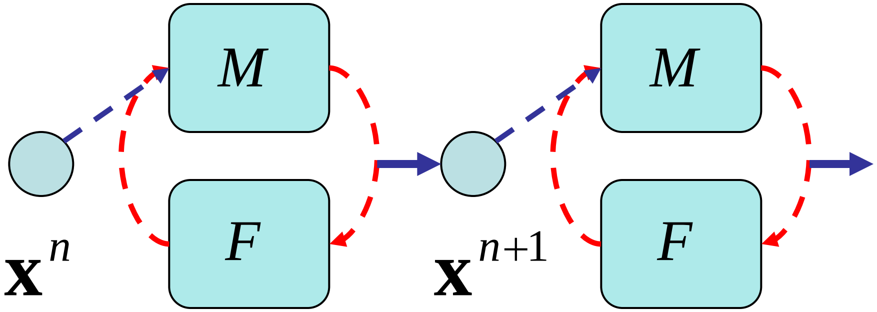
- **Fault slip and fault activation**
  - Flow: reservoir integrity, pressure maintenance, CO_2 leakage
  - Seismic: determinant of induced seismicity

Coupling Strategy

- Fully coupled
  - Solve two problems **simultaneously**



- Iteratively coupled
  - Solve two problems **sequentially**



Two problems communicate through updating the **source terms**

M : *Mechanics*

F : *Flow*

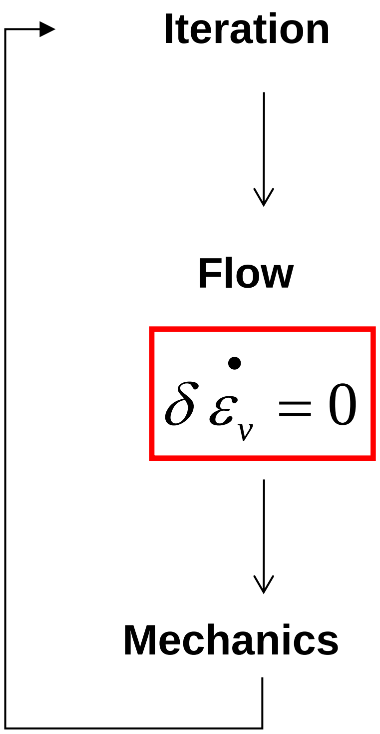
Why a Sequential Method ?

- Make use of the existing robust tool kits
  (mechanics codes and reservoir simulators)
- Implement interface code only
- Must deal effectively with issues related to stability and convergence

One Step Sequential Method

- Flow First -

Fixed strain



Iteration

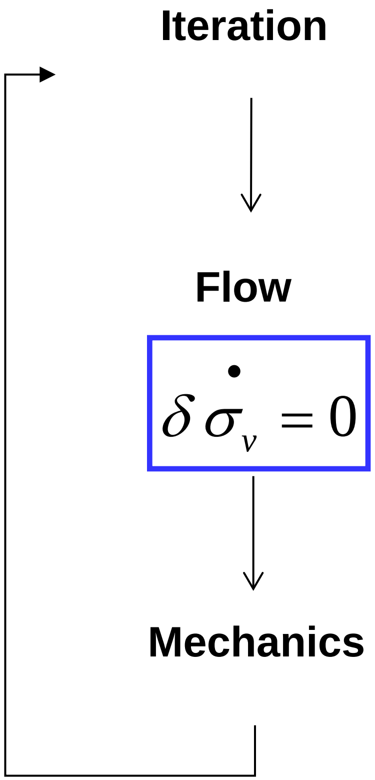
Flow

$$\boxed{\delta \dot{\varepsilon}_v = 0}$$

Mechanics

Conditionally stable
Oscillatory

Fixed stress



Iteration

Flow

$$\boxed{\delta \dot{\sigma}_v = 0}$$

Mechanics

Unconditionally stable
Monotonic

Rock Compressibility

Traditional reservoir simulation

$$\left(\phi_o c_f + \phi_o c_r\right)\frac{\partial p}{\partial t} = \frac{1}{\rho_{f,o}}\left(\mathbf{div}(-\mathbf{q}_f) - q_p\right)$$

Fixed strain split

$$\left(\phi_o c_f + \frac{b-\phi_o}{K_{dr}}\right)\frac{\partial p}{\partial t} + b\frac{\partial \varepsilon_v}{\partial t} = \frac{1}{\rho_{f,o}}\left(\mathbf{div}(-\mathbf{q}_f) - q_p\right)$$

Fixed stress split

$$\left(\phi_o c_f + \frac{b-\phi_o}{K_{dr}} + \frac{b^2}{K_{dr}}\right)\frac{\partial p}{\partial t} + \frac{b}{K_{dr}}\frac{\partial \sigma_v}{\partial t} = \frac{1}{\rho_{f,o}}\left(\mathbf{div}(-\mathbf{q}_f) - q_p\right)$$

Stability, Accuracy, and Efficiency of Sequential Methods for Coupled Flow and Geomechanics

J. Kim, SPE, and **H.A. Tchelepi,** SPE, Stanford University, and **R. Juanes,** SPE, Massachusetts Institute of Technology

June 2011 SPE Journal 249

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journal homepage: www.elsevier.com/locate/cma


Computer
methods in
applied
mechanics
and
engineering

Stability and convergence of sequential methods for coupled flow and geomechanics: Fixed-stress and fixed-strain splits

J. Kim [a,c,*], H.A. Tchelepi [a], R. Juanes [b]

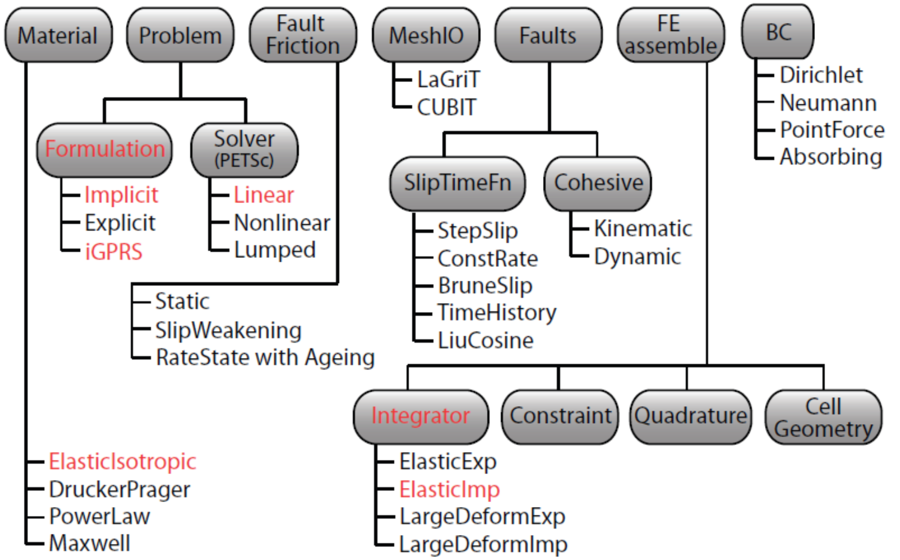
Rigorous Coupling of Geomechanics and Multiphase Flow With Strong Capillarity

J. Kim, SPE, Lawrence Berkeley National Laboratory; **H.A. Tchelepi,** SPE, Stanford University, and
R. Juanes, Massachusetts Institute of Technology

Coupled Fluid Flow and Geomechanics – *PyLith**

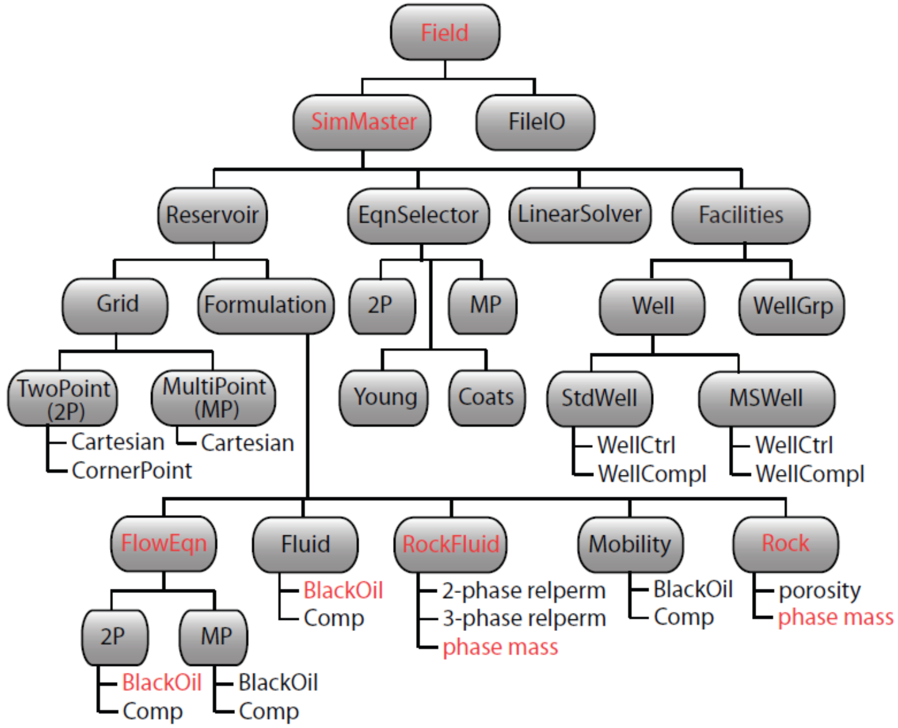
- ❑ PyLith features:
  - A finite element geomechanics code
  - ***Sophisticated formulation for fault deformation and slip***
  - C++, fast, parallel
  - Uses hexahedral (CUBIT) or tetrahedral grid (LaGriT)
  - Viscoelastic and elastoplastic rheology

Pylith modules



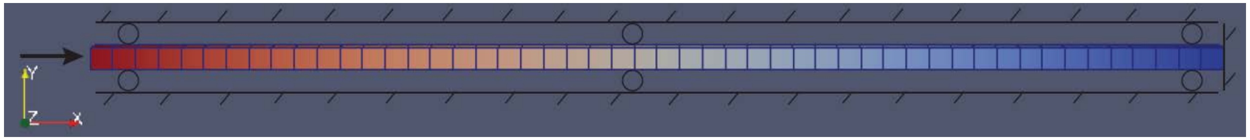
- Material
  - ElasticIsotropic
  - DruckerPrager
  - PowerLaw
  - Maxwell
- Problem
  - Formulation
    - Implicit
    - Explicit
    - iGPRS
  - Solver (PETSc)
    - Linear
    - Nonlinear
    - Lumped
- Fault Friction
  - Static
  - SlipWeakening
  - RateState with Ageing
- MeshIO
  - LaGriT
  - CUBIT
- Faults
  - SlipTimeFn
    - StepSlip
    - ConstRate
    - BruneSlip
    - TimeHistory
    - LiuCosine
  - Cohesive
    - Kinematic
    - Dynamic
- FE assemble
  - Integrator
    - ElasticExp
    - ElasticImp
    - LargeDeformExp
    - LargeDeformImp
  - Constraint
  - Quadrature
  - Cell Geometry
- BC
  - Dirichlet
  - Neumann
  - PointForce
  - Absorbing

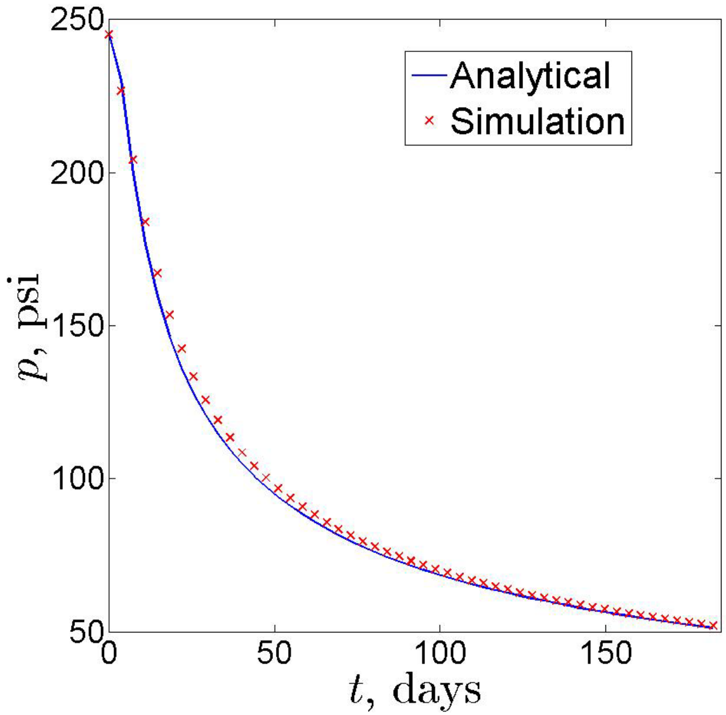
GPRS modules

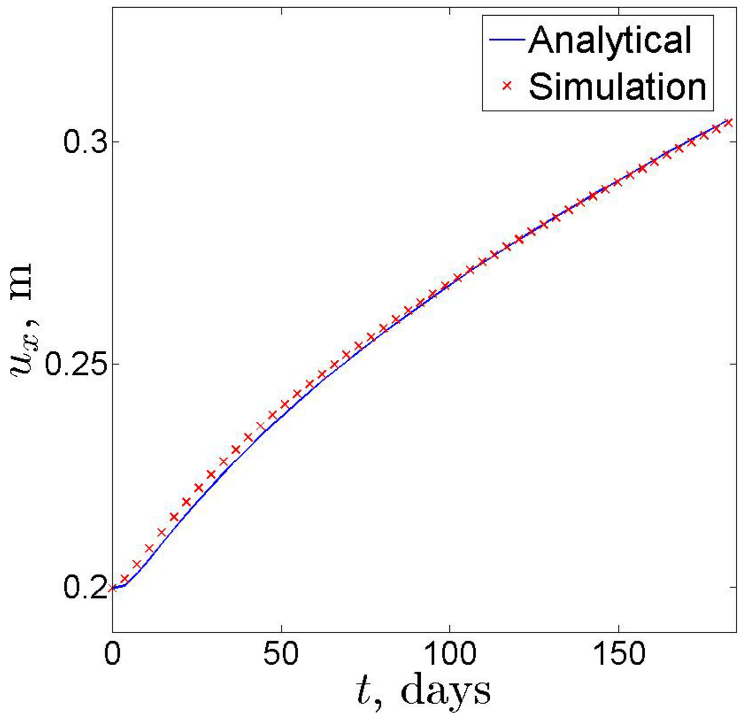


- Field
  - SimMaster
    - Reservoir
      - Grid
        - TwoPoint (2P)
          - Cartesian
          - CornerPoint
        - MultiPoint (MP)
          - Cartesian
      - Formulation
        - FlowEqn
          - 2P
            - BlackOil
            - Comp
          - MP
            - BlackOil
            - Comp
        - Fluid
          - BlackOil
          - Comp
        - RockFluid
          - 2-phase relperm
          - 3-phase relperm
          - phase mass
        - Mobility
          - BlackOil
          - Comp
        - Rock
          - porosity
          - phase mass
    - EqnSelector
      - 2P
      - MP
      - Young
      - Coats
    - LinearSolver
    - Facilities
      - Well
        - StdWell
          - WellCtrl
          - WellCompl
        - MSWell
          - WellCtrl
          - WellCompl
      - WellGrp
  - FileIO

Terzaghi's consolidation problem (One-way coupled)

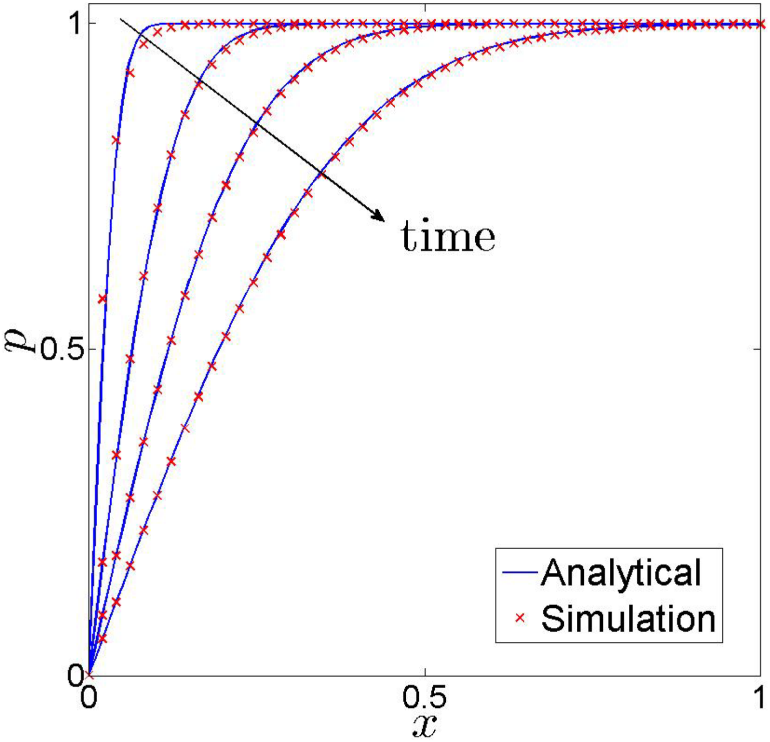




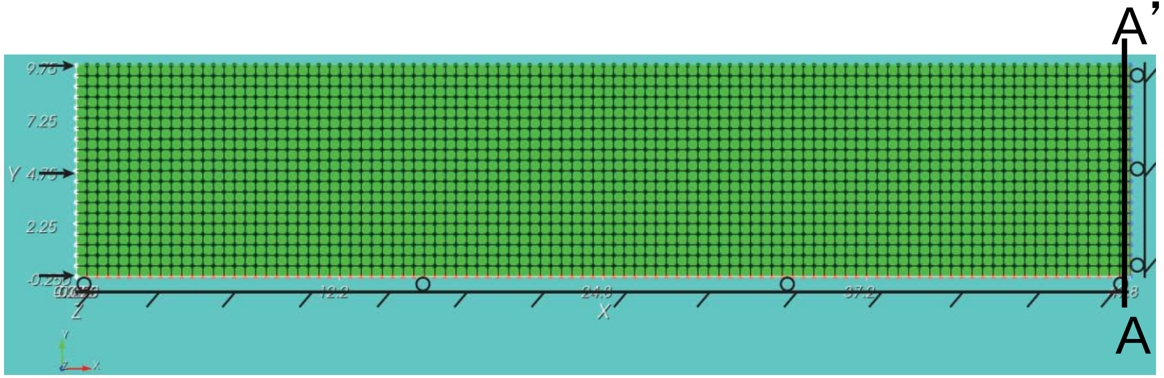


Terzaghi’s consolidation problem (One-way coupled)

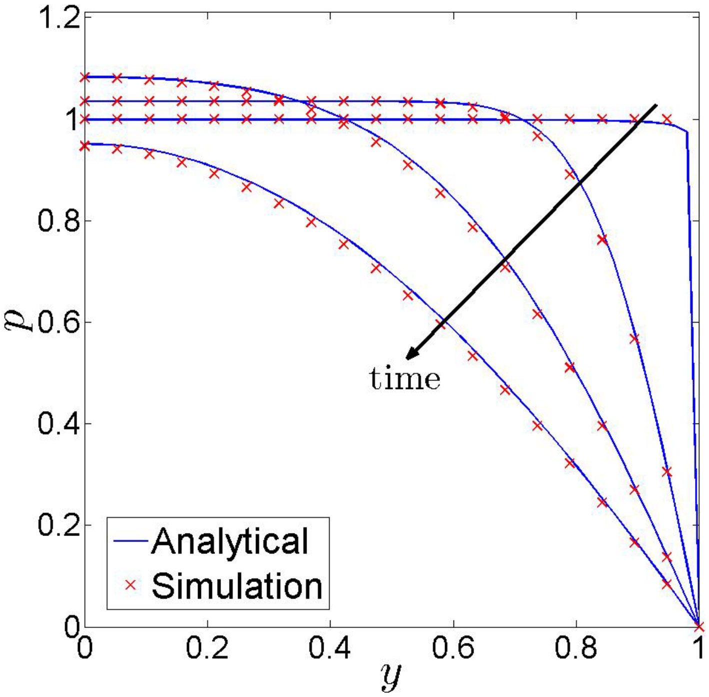
Pressure declines monotonically as the fluid drains out of the column



Mandel’s consolidation problem (Two-way coupled)

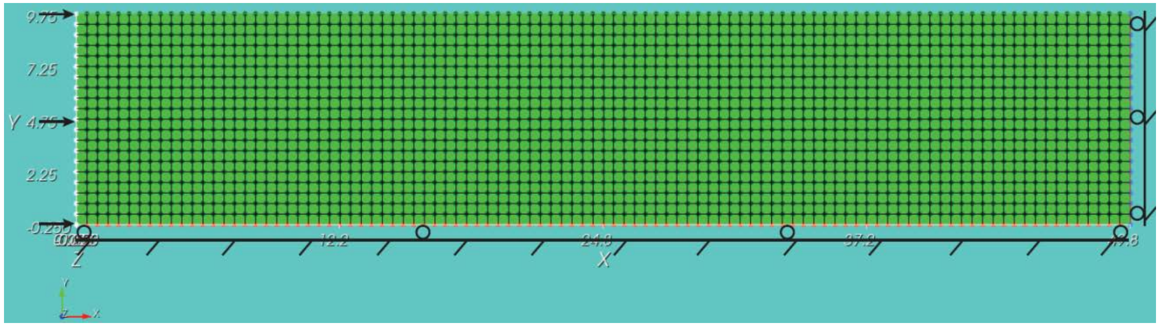


Pressure declines *non-monotonically* as the fluid drains out of the specimen

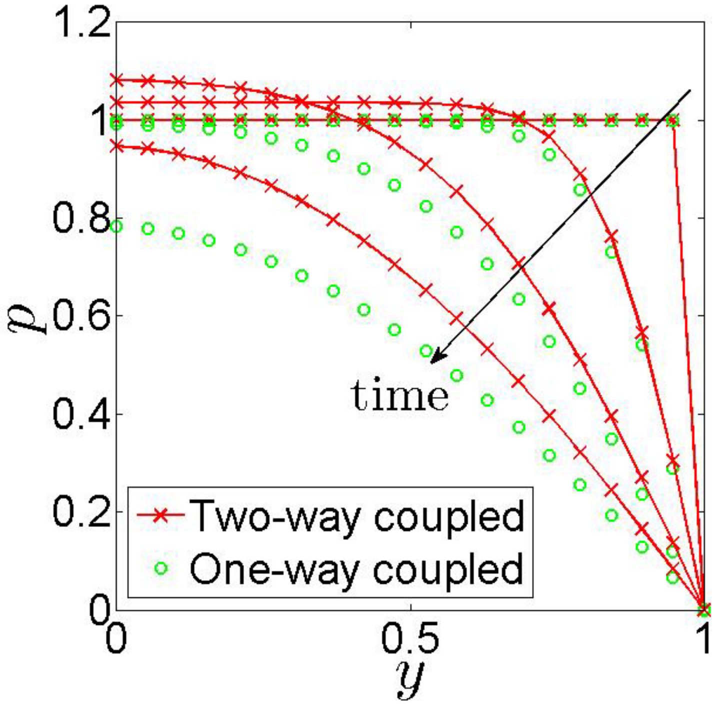


Pressure along AA’

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

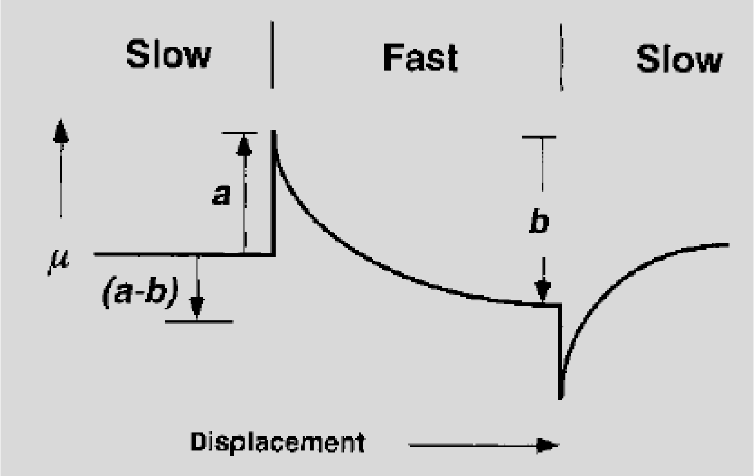


Seismicity – fault friction

- ❑ 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

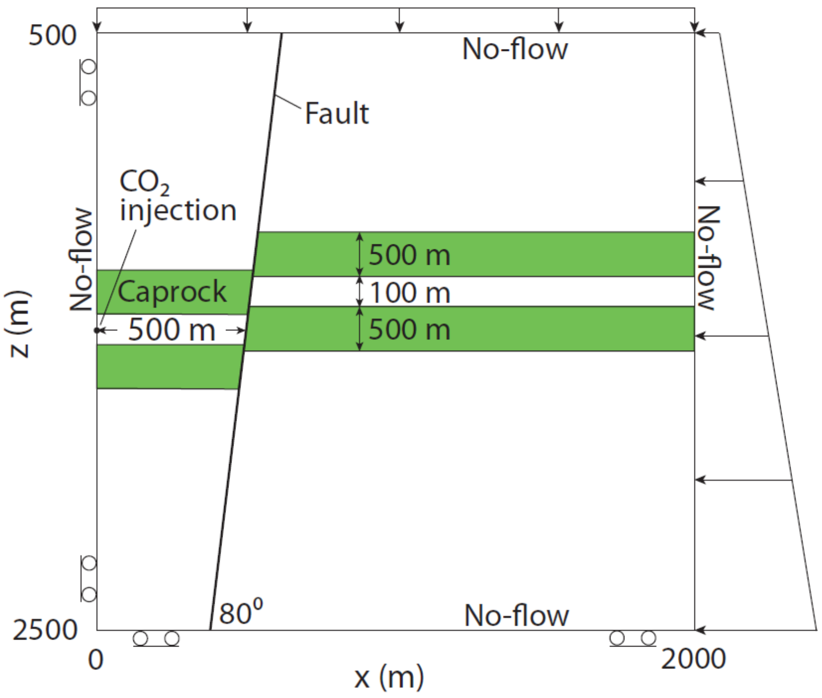
- ❑ Rate and state friction



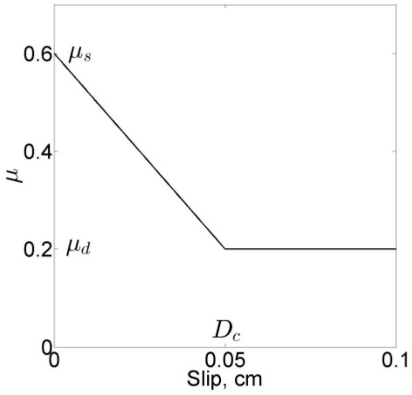
  - (a-b) > 0 : velocity strengthening; stable slip
  - (a-b) < 0 : velocity weakening; potential for earthquake

Faulting induced by CO_2 injection

Plane strain



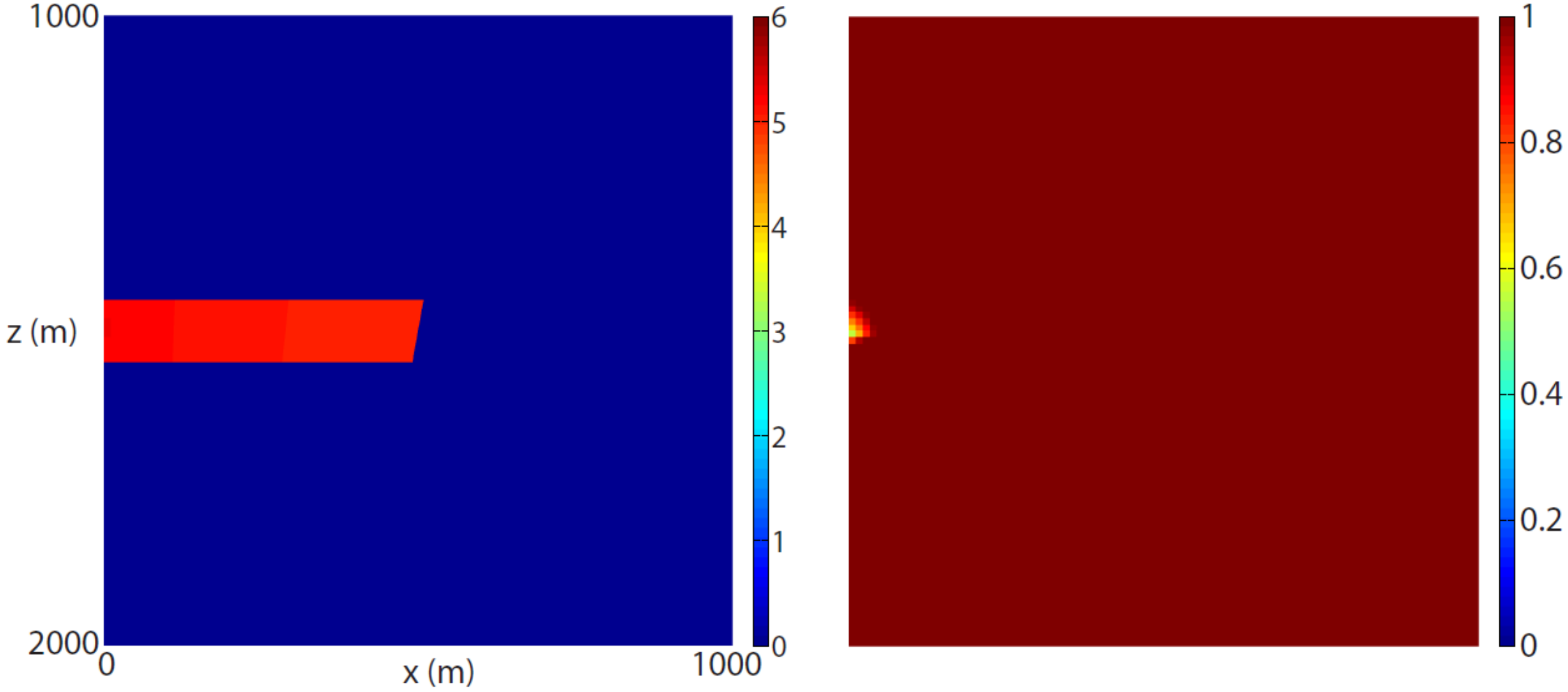
Slip-weakening fault



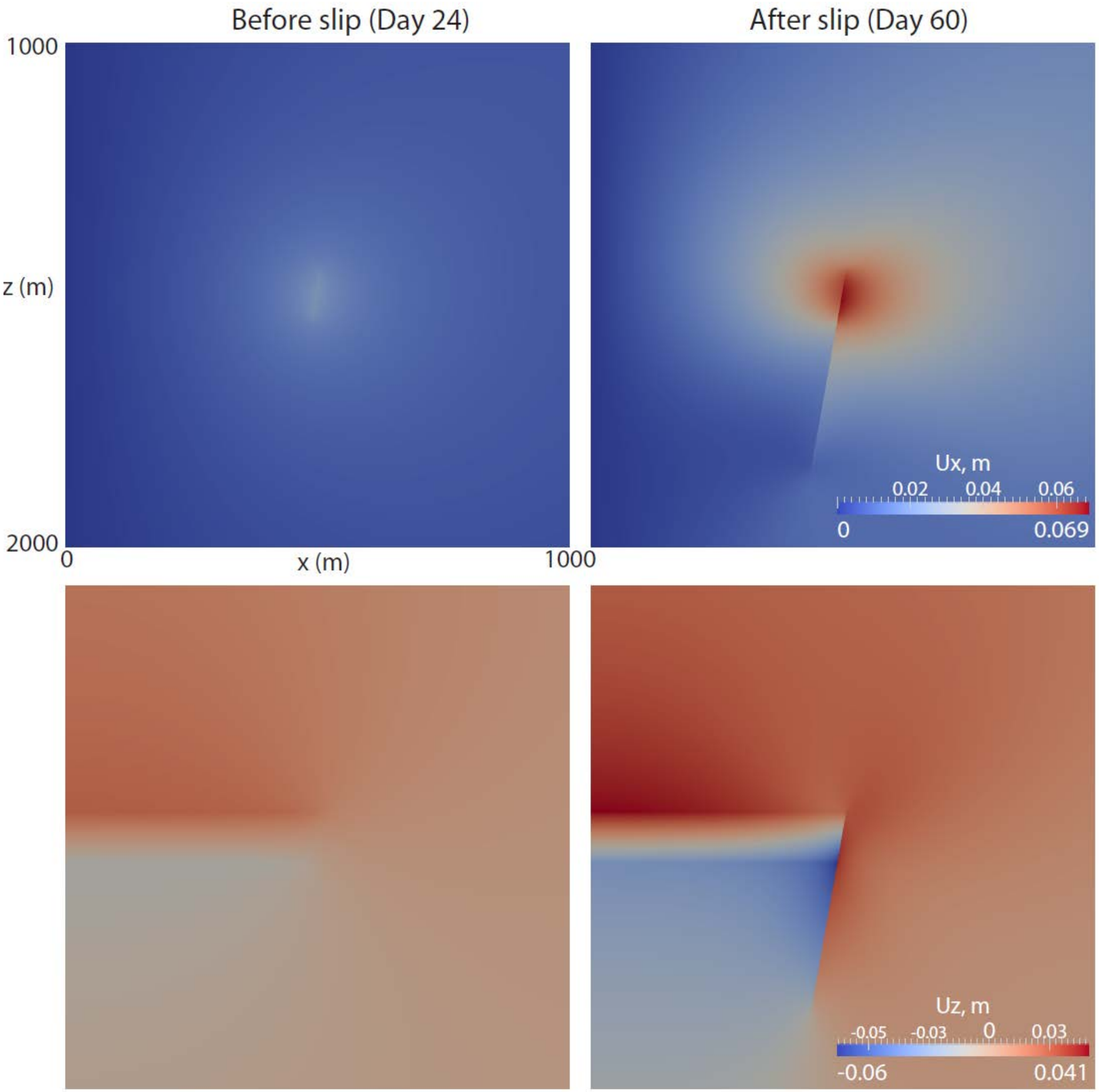
(Cappa and Rutqvist, GRL, 2011

Overpressure and water saturation

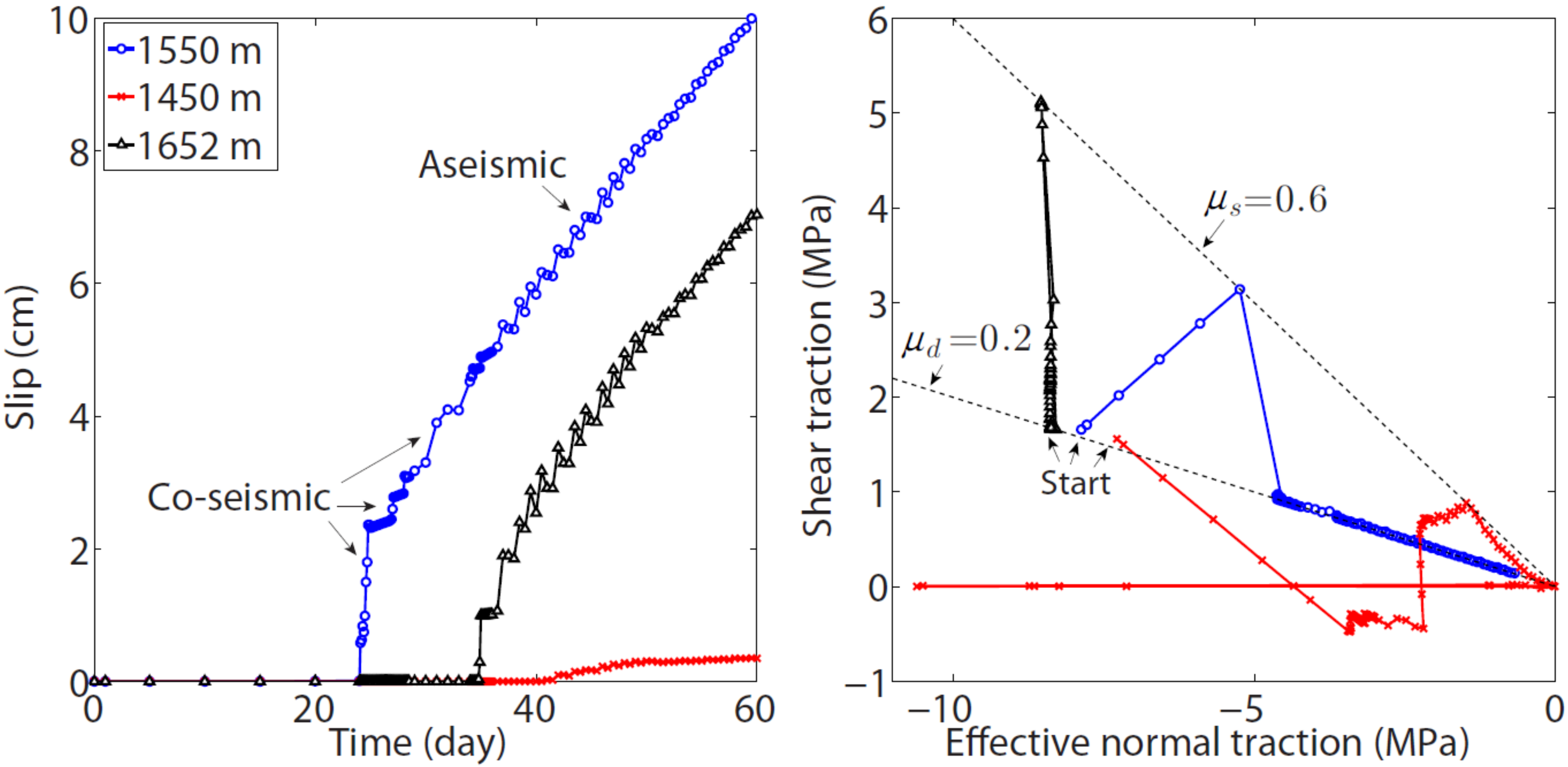
t = 24 day



Displacement fields

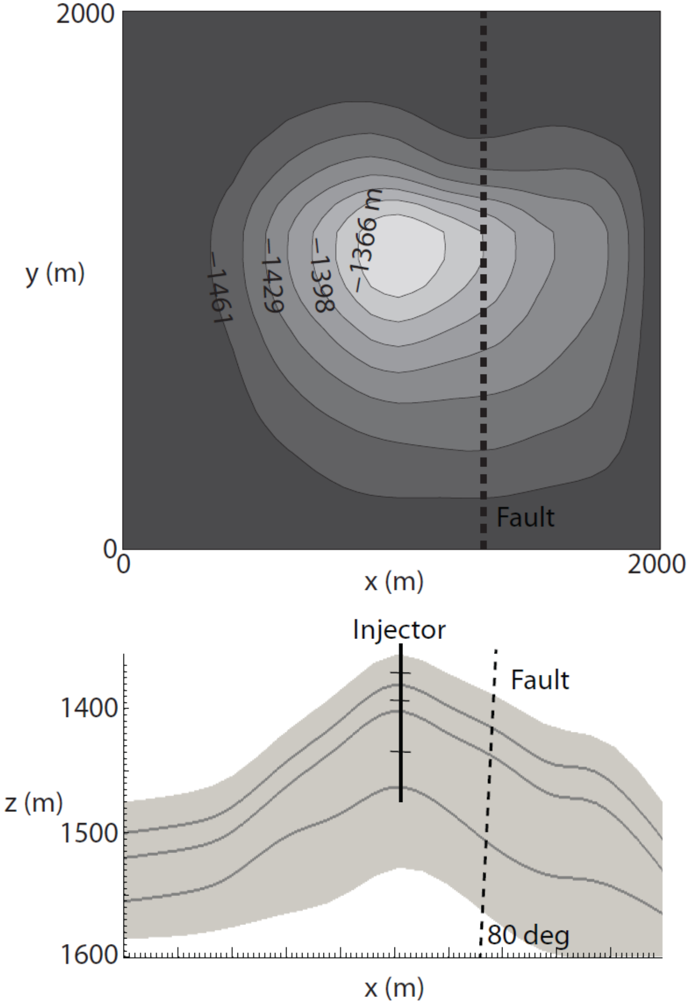


Evolution of stress and slip on the fault

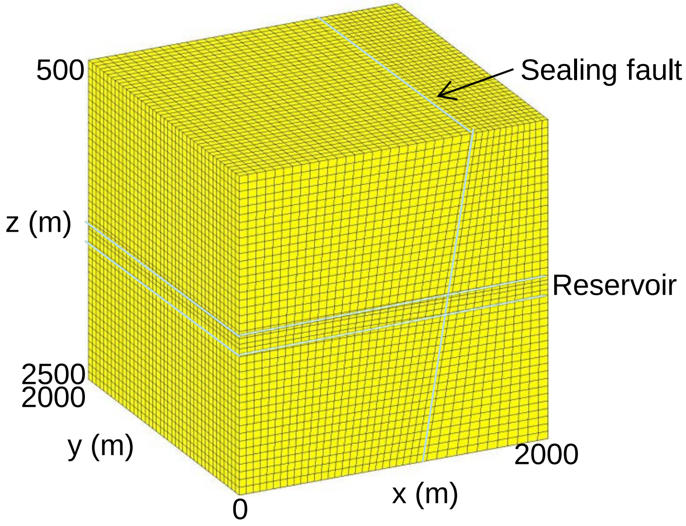


Faulting induced by CO_2 injection: 3D model with Rate- and State- fault

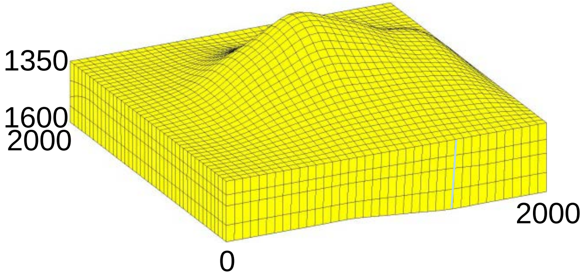
Reservoir model



Geomechanical grid



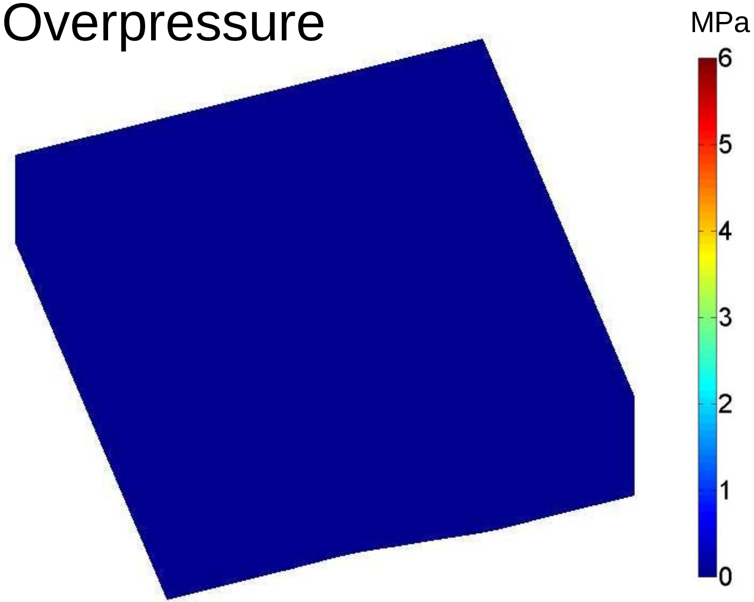
Reservoir grid



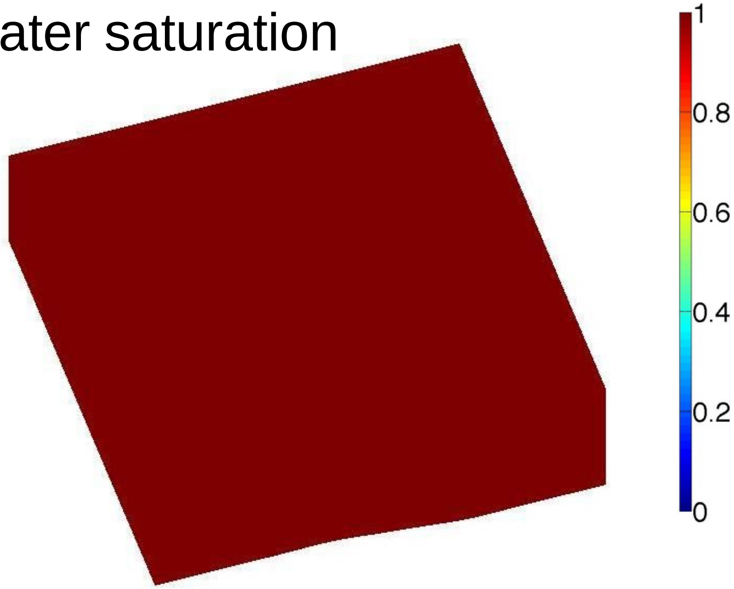
Rate- and State- dependent fault: a = 0.002, b = 0.08, critical slip = 1 c

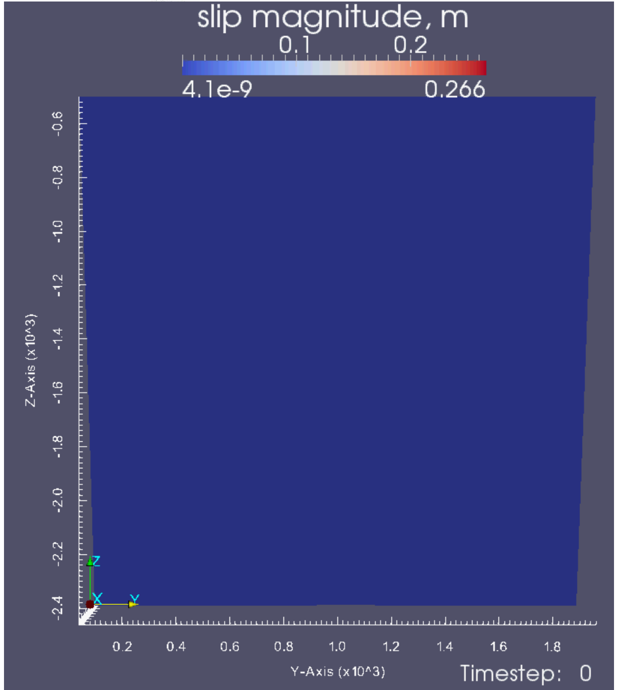
Fault slip due to over-pressurization

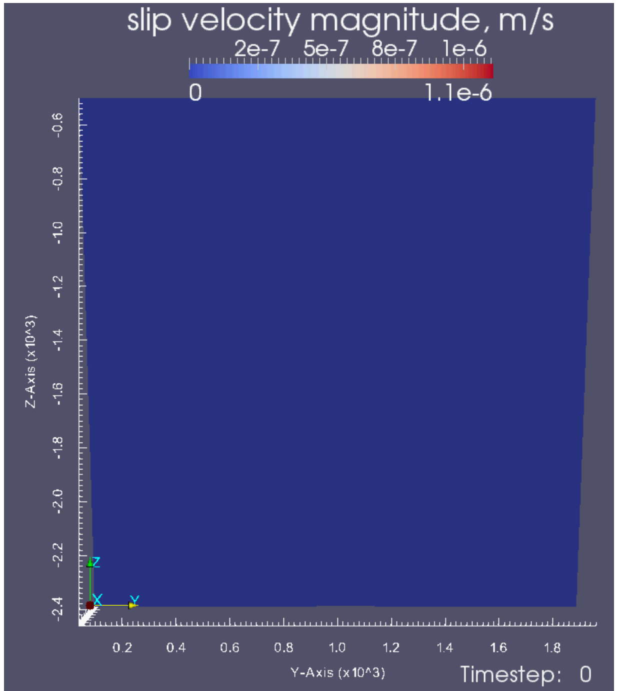
Overpressure



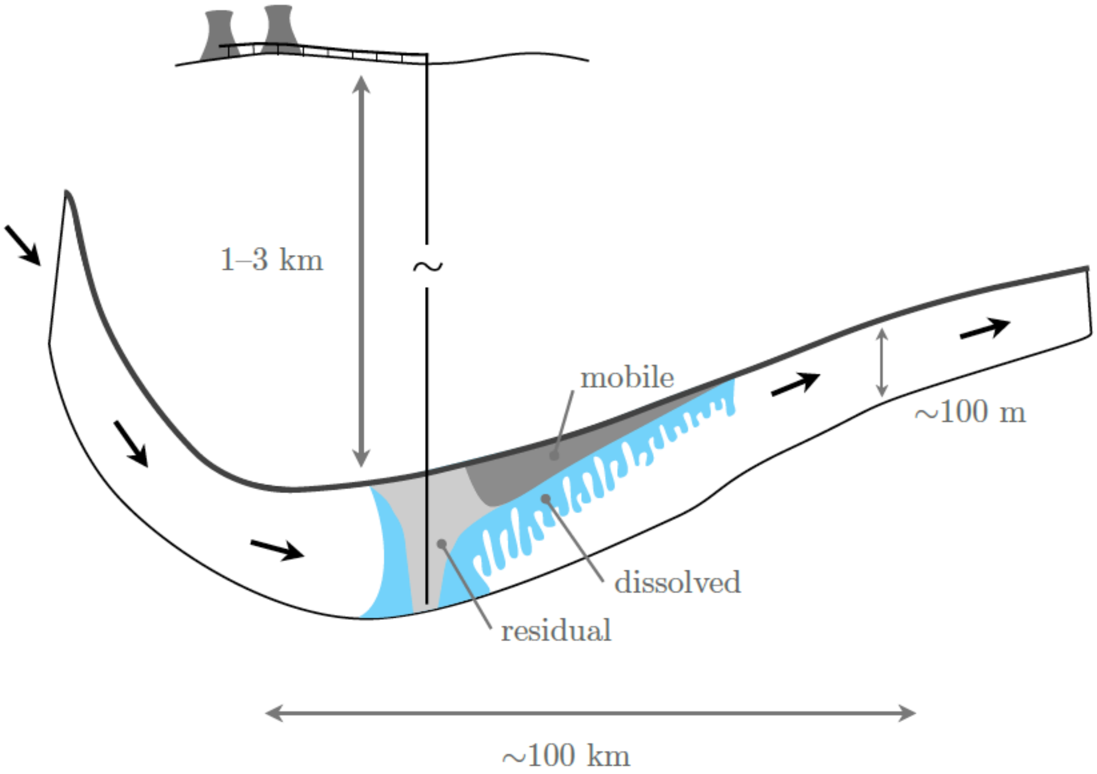
Water saturation







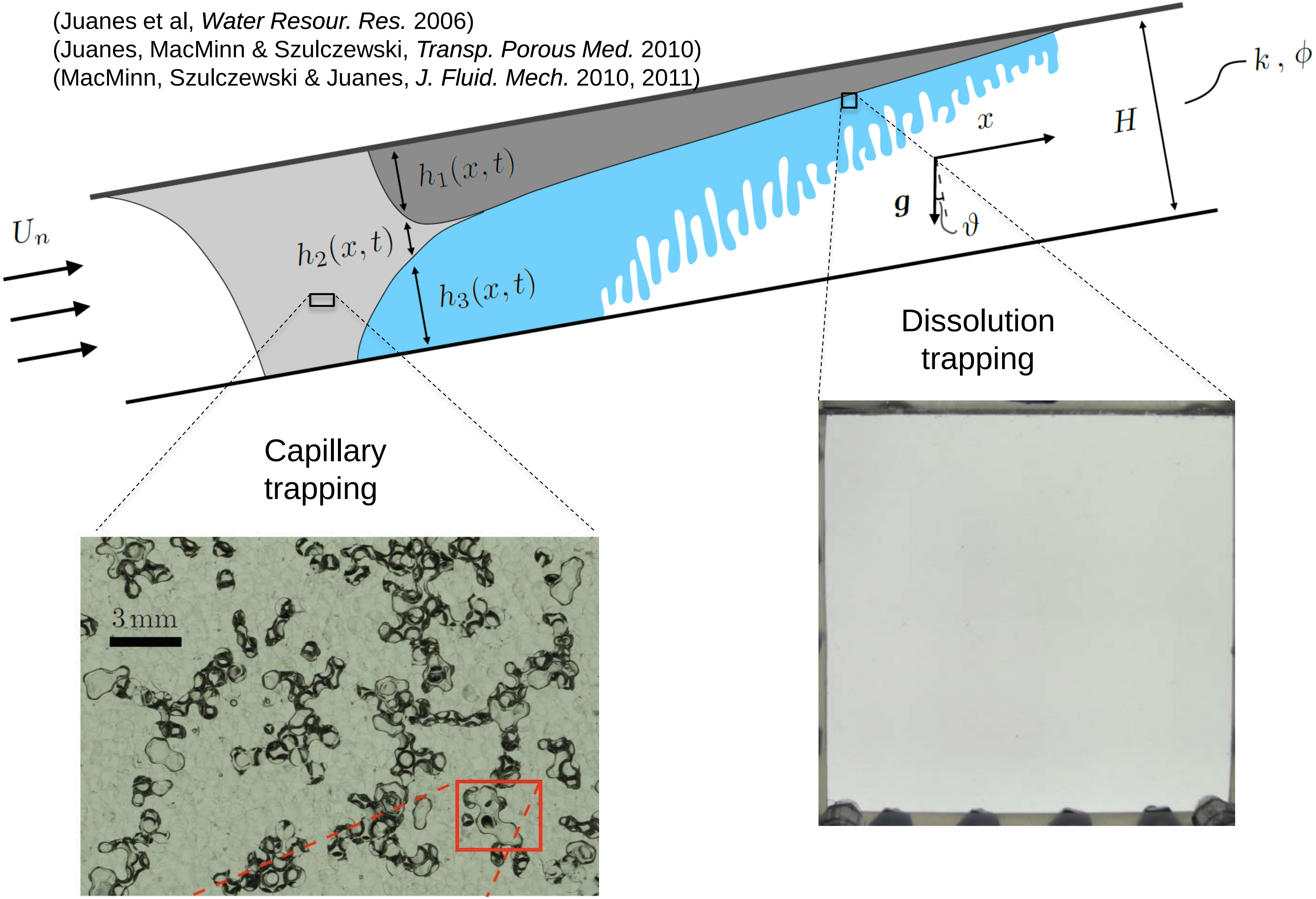
Storage must be understood at the scale of entire geologic basins



- ☐ **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

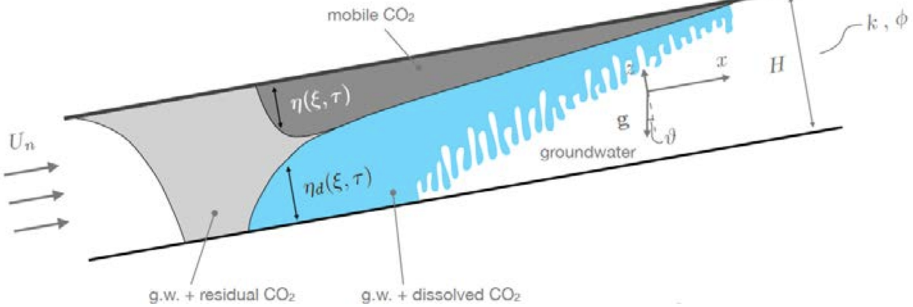
Trapping mechanisms

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



Plume migration with dissolution

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



❑ Theory

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

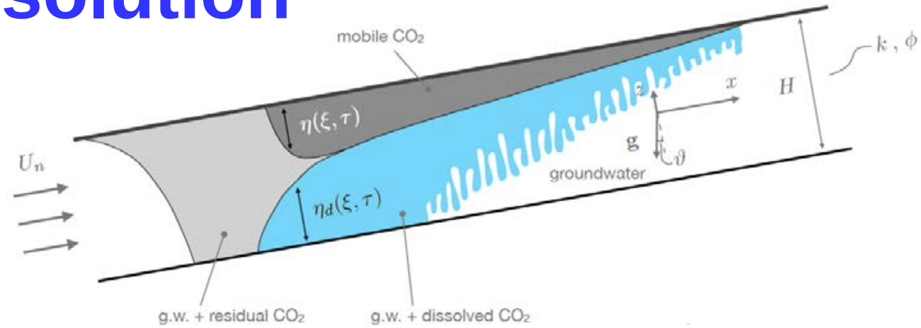
❑ Experiments

(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



advective · diffusive · sink

$$\tilde{\mathcal{R}}\frac{\partial \eta}{\partial \tau} + \boxed{N_f \frac{\partial f}{\partial \xi} + N_s \frac{\partial}{\partial \xi}\left[(1-f)\,\eta\right]} - \boxed{N_g \frac{\partial}{\partial \xi}\left[(1-f)\,\eta\,\frac{\partial \eta}{\partial \xi}\right]} = \boxed{-\tilde{\mathcal{R}}\,N_d}$$

residual trapping · flow · slope · spreading · dissolution

- ❑ Experiments

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

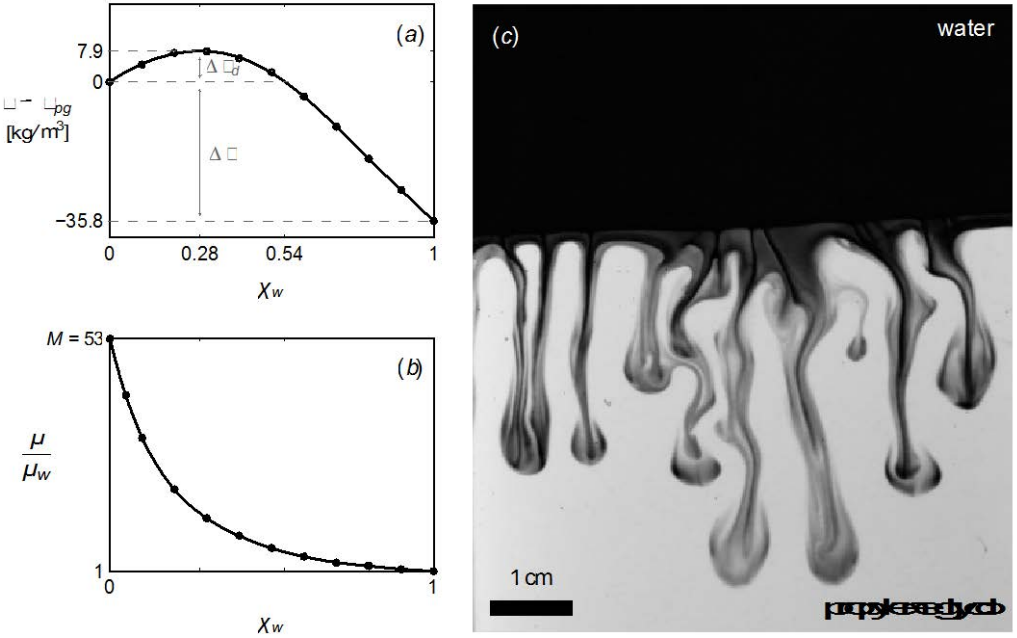
Dissolution by convective mixing

- Dimensionless governing equations

$$r \cdot u = 0; \quad u = -(r\,p - cr\,z),$$

✓ ◆

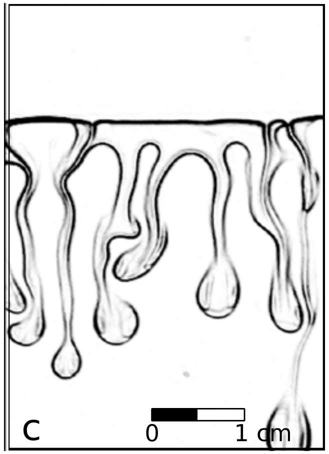
$$@c + r \cdot \; u\,c - \frac{1}{\mathrm{Ra}} r\,c \;\; = 0,$$



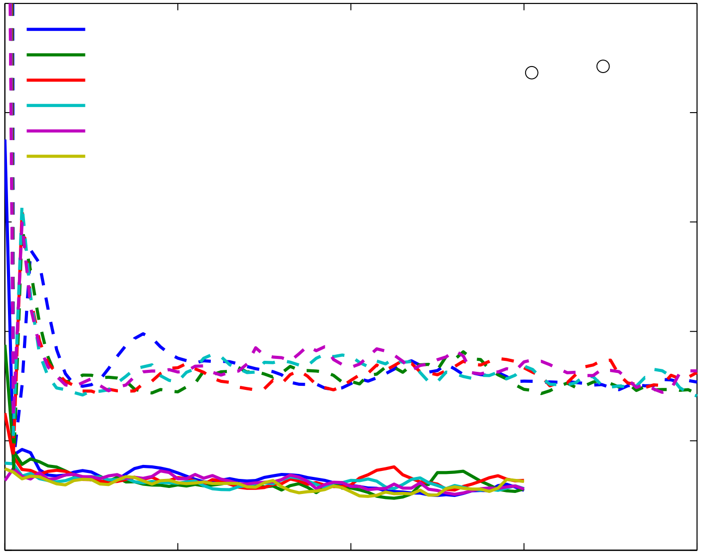
(Hidalgo et al., *Phys. Rev. Lett.*, 2012)

Dissolution by convective mixing

- Mixing controlled by the scalar dissipation rate

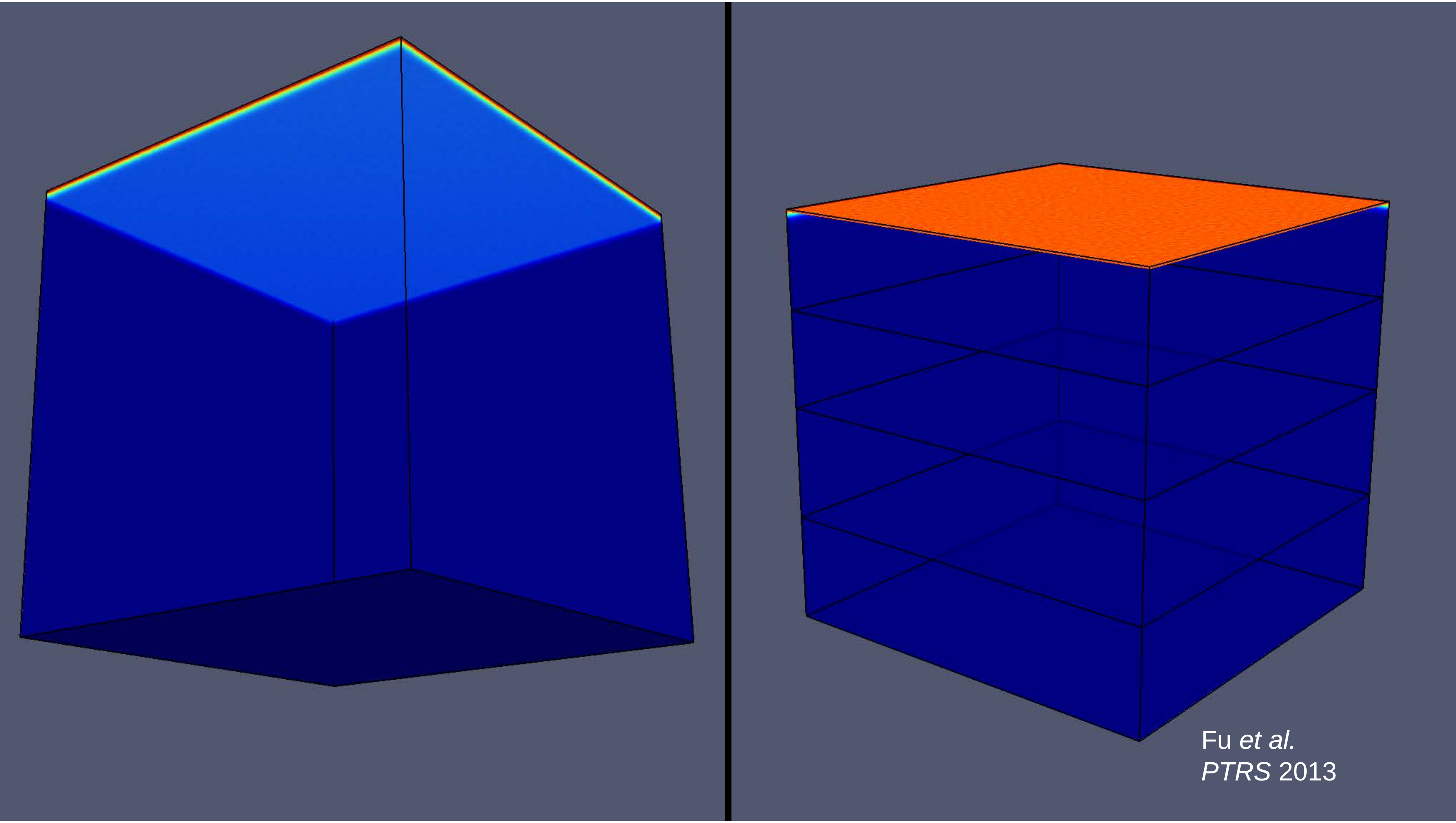


- Dissolution rate is constant and independent of Rayleigh number



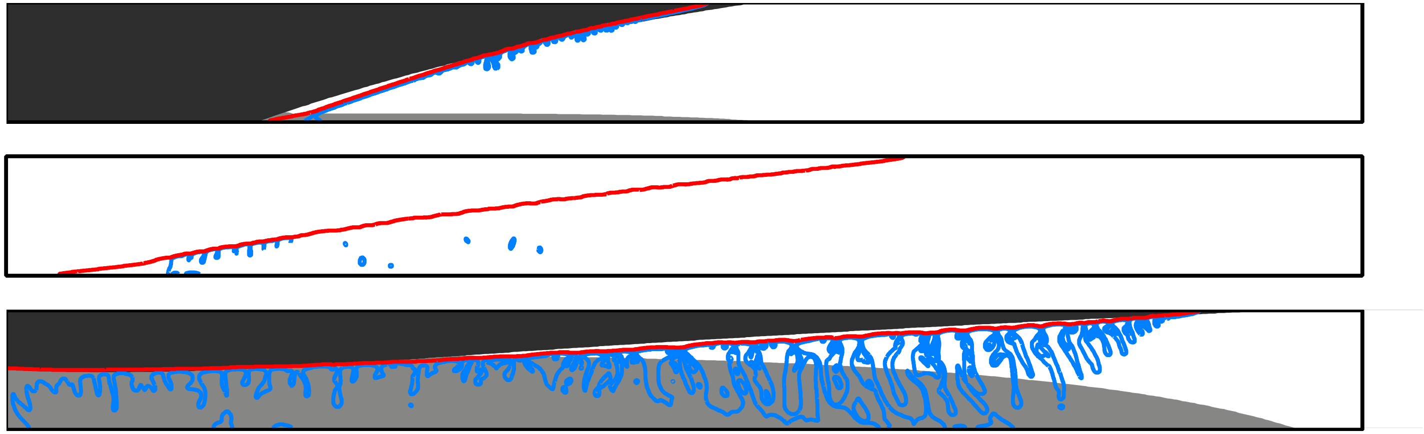
(Hidalgo et al., *Phys. Rev. Lett.*, 2012)

Dissolution by convective mixing



Fu *et al.*
PTRS 2013

Plume migration with dissolution



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

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

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