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
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, Christopher W. MacMinn, Howard J. Herzog, and Ruben Juanes

Departments of Civil and Environmental Engineering and Mechanical Engineering, Energy Initiative, and Center for Computational Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139

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- **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 and Steven M. Gorelick

Departments of Geophysics and Environmental Earth System Science, Stanford University, Stanford, CA 94305

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

- Is CO₂ leakage really a show-stopping risk?
An ongoing debate ...

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

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

Juanes et al. (PNAS 2012)

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

- **Caprock integrity**
  - SAGD
  - CO$_2$ sequestration

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

![Diagram showing wellbore stability and caprock integrity with SAGD and CO$_2$ sequestration](Schlumberger)
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.

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

Nicholas J. van der Elst,1,2 Heather M. Savage,1 Katie M. Keranen,1,3 Geoffrey A. Albers

A recent dramatic increase in seismicity in the midwestern United States may be related in part to increases in deep wastewater injection. Here, we demonstrate that areas with suspected anthropogenic earthquakes are also those with critical stress changes caused by fluid injection. High fluid pressures near injection points can lead to induced or remote triggering. These areas may have experienced high fluid pressures for years, with no apparent increase in seismicity. Enhanced triggering susceptibility suggests the presence of critically oriented faults and potentially high fluid pressures. Seismicity or remote triggering is most clearly seen in areas with a long history of injection and the onset of seismicity by and in regions that went on to host moderate magnitude earthquakes within 1 to 30 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 slip under pre-existing shear stress. The increase in occurrence of seismic events can result from the increased pressure within the reservoirs. The induced seismicity in these areas is often associated with the injection of water or other fluids into the subsurface, leading to increased pore pressures and stress changes in the surrounding rock. These changes can trigger seismic events in previously quiescent regions, highlighting the importance of monitoring and managing fluid injection practices to minimize seismic risks.
Poromechanical coupling

- Fluid mass conservation
  - Primary unknown: \( p \)

- Linear momentum balance
  - Primary unknown: \( u \)

- Couplings:

\[
(-\sigma') = (-\sigma) - bp1
\]

Effective stress

Change in volume

Change in reservoir properties: \( \phi, k \)
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

- 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).

\[ \tau_f = \mu (|\sigma_n| - p) + \tau_0 \]
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

![Diagram of coupled fluid flow and geomechanics simulator](image-url)
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 \( \mu \)
  - 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

\( t = 24 \text{ day} \)
Displacement fields
Evolution of stress and slip on the fault
Faulting induced by CO$_2$ injection: 3D model with Rate- and State- fault

Rate- and State- dependent fault: $a = 0.002$, $b = 0.08$, critical slip = 1 cm
Fault slip due to over-pressurization

Overpressure

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

Birendra Jha¹ and Ruben Juanes¹

¹Department 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 footprint of the migrating CO$_2$ plume must fit in the basin
  - The pressure induced by injection must not fracture the rock
Trapping mechanisms

Plume migration with dissolution


- **Theory**

\[
\begin{align*}
\tilde{R} \frac{\partial \eta}{\partial \tau} + N_f \frac{\partial f}{\partial \xi} + N_s \frac{\partial}{\partial \xi} \left[ (1 - f) \eta \right] - N_g \frac{\partial}{\partial \xi} \left[ (1 - f) \eta \frac{\partial \eta}{\partial \xi} \right] &= -\tilde{R} N_d \\
\end{align*}
\]

- **Experiments**

Hele-Shaw cell (1.4 mm)


- propylene glycol
- water
Plume migration with dissolution


- Theory

- Experiments

Dissolution by convective mixing

- Dimensionless governing equations

\[ \nabla \cdot \mathbf{u} = 0; \quad \mathbf{u} = -(\nabla p - c \nabla z), \]

\[ \partial_t c + \nabla \cdot \left( \mathbf{u} c - \frac{1}{Ra} \nabla c \right) = 0, \]

Dissolution by convective mixing

- Mixing controlled by the scalar dissipation rate

- Dissolution rate is constant and independent of Rayleigh number

Dissolution by convective mixing
Plume migration with dissolution

CO2 dissolution in structural traps

We study CO2 dissolution in a porous layer that exhibits features of structural traps such as anticlines and stratigraphic traps such as pinchouts between low-permeability rock. The layer is semi-infinite to represent the large lateral extent of a deep, geologic reservoir. A portion of the top boundary (grey line in print/blue line online) is held at the saturated CO2 concentration to represent the finite CO2–groundwater interface.

Structural and stratigraphic traps are attractive sites for CO2 sequestration (Gunter, Bachu & Benson 2004). Their low-permeability seal inhibits the upward migration of CO2, reducing the risk of leakage to a shallower formation or the surface. While a low-permeability seal can be present at many locations in a reservoir, structural and stratigraphic traps are particularly appealing because their concave-down geometry also constrains the lateral spread of CO2, reducing the risk that it will migrate away from the injection site to potential leakage pathways such as non-sealing faults or abandoned wells. Another attractive feature is that many traps have proven seals. When the trap is located in an oil and gas field, for example, the seal quality is confirmed by the fact that it has retained buoyant hydrocarbons for millions of years.

While structural and stratigraphic traps reduce the risk of CO2 leakage, they do not eliminate it. The seal may contain small fractures or faults that allow leakage but that are not identified in the characterization stage of a sequestration project. In the injection stage, the seal may be compromised by accidentally overpressurizing the reservoir, which could hydraulically fracture the seal or cause slip along a pre-existing fault in the seal (Grasso 1992; Rutqvist & Tsang 2002; Chiaramonte et al. 2008; Mathias et al. 2009). After the injection well has been closed, the seal may be damaged by seismic activity or human activity in the subsurface close to the reservoir.

Dissolution of the CO2 into the groundwater mitigates the risk of leakage from an imperfect or compromised seal. This is because water with dissolved CO2 is more dense than the ambient groundwater, and will tend to sink rather than rise through a leakage pathway. Estimating the dissolution rate will help constrain the quantity of CO2 that will remain in the target reservoir, and the quantity that will escape.
CO2 dissolution in structural traps

![Diagram of dissolution regimes and phase diagram]

**Figure 2.** (Colour online) Dissolution evolves through the seven regimes shown here \((Ra = 3000)\). The colour scale represents the concentration of CO\(_2\), \(c\), normalized to the saturated concentration, \(c_s\). The scalings of the transition times between the regimes are shown in terms of the layer thickness, \(H\), the effective diffusion coefficient, \(D\), and the characteristic velocity, \(V = 1\times 10^5 \text{g} \times k\times \mu\) (see §2). When \(Ra = V H \times D\) is sufficiently small, the first and final transition times become equal, the duration of the intermediate regimes becomes zero, and the system transitions directly to the late diffusion regime.

**Figure 10.** Phase diagram of the dissolution regimes. Tracing a vertical line through the diagram illustrates the regimes that occur for a particular Rayleigh number. The grey region in the centre represents conditions for which we did not model dissolution. The sharp angle on the border between the Taylor slumping \((Ts)\) and shutdown/Taylor slumping \((sT)\) regimes occurs at \(Ra = 133\), the leftmost extent of the fingering regime \((f)\), due to uncertainty about the validity of the convective shutdown mechanism for lower Rayleigh numbers.

Such as lenses and layers of fine-grained rock. In addition, the length of the CO\(_2\)-brine interface in a real trap continually decreases as the CO\(_2\) dissolves, whereas the interface length in our system is constant (figure 1). Due to the large number of differences and their complexity, we cannot, at this stage, rigorously evaluate the accuracy of our models in real traps or determine whether they provide upper or lower bounds on the dissolution rates. Some features of real traps, such as slope and natural groundwater flow, will likely lead to higher dissolution rates in practice, but the effect of other features such as heterogeneity is more difficult to predict. Consequently, we emphasize that the main contribution of the study is, strictly speaking, the elucidation of how dissolution is affected by the finite CO\(_2\)-brine interface that exists during storage in geologic traps.

While our models are based on several assumptions, applying them to real geologic traps can be useful. Since the models are all analytical, they can quickly provide rough estimates of the dissolution rates that can be expected in practice, and can help constrain the time required to completely dissolve a volume of injected CO\(_2\). While highly uncertain, these estimates are useful because there are currently several sequestration projects worldwide either injecting or planning to inject CO\(_2\) into structural and stratigraphic traps, but there are limited techniques available to quickly predict dissolution rates over the lifetime of the project. While large simulations incorporating site-specific geometry and geology play an important role in quantifying these rates, they are time-consuming to develop, and the information they provide is also highly uncertain due to uncertainty in the subsurface properties. In addition, uncertainty arises from the inability of conventional simulations to resolve the small length scales associated with the fingering instability, which plays a key role in the dissolution process.

With their limitations in mind, we apply the models to a few simplified geologic traps. The traps are characterized by six dimensional parameters: the layer...
CO2 dissolution in structural traps

- Dissolution flux

![Graph showing dissolution flux over time for different trap thicknesses and permeabilities.]

- Cumulative dissolution mass

![Graph showing cumulative dissolved CO2 over time for different trap thicknesses and permeabilities.]

\[
\begin{array}{ccc}
H (m) & k (mD) & Ra \\
200, & 1000, & 2 \times 10^5 \\
20, & 1000, & 2 \times 10^4 \\
200, & 10, & 2 \times 10^3 \\
20, & 10, & 2 \times 10^2 \\
\end{array}
\]

(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
The following chart shows the resource loaded schedule for the project, broken down by task and subtask as described in the SOPO. The start and end date of each task is shown by Quarter. The timeline shows the proper interdependencies between tasks and subtasks. The numbers in within the tasks refer to the milestones that are identified in the Milestones Log (Section D of this document). The cost of each task (including the government funds and cost-sharing portion) is as follows: Task 1: $12,195; Task 2: $12,195; Task 3: $365,854; Task 4: $317,073; Task 5: $292,683.

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Bibliography


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