Modeling Leakage of Carbon Dioxide along a Fault for Risk Assessment

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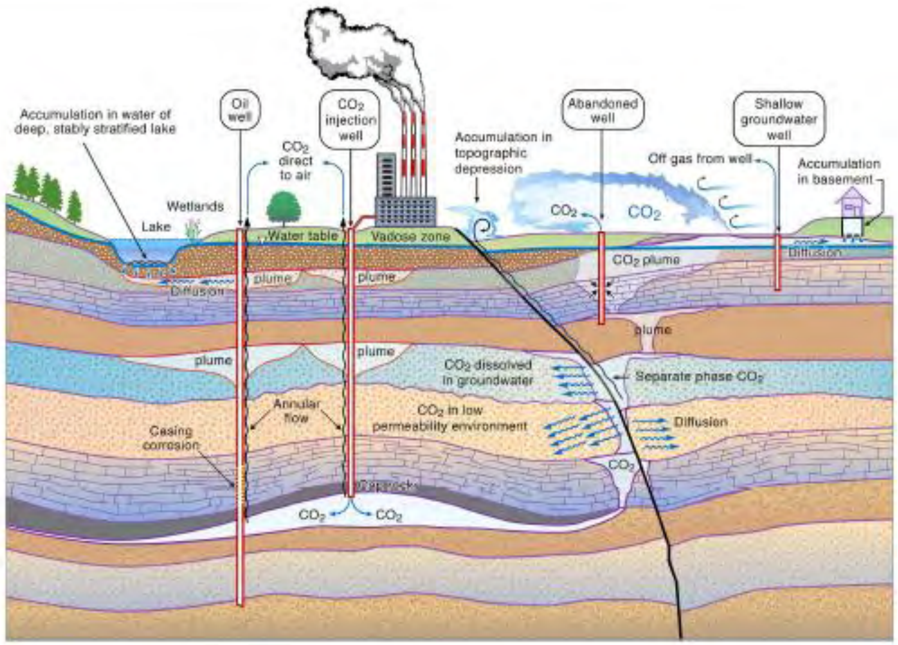
Presented By: Nicolas J. Huerta, UT Austin

Outline

- Discussion of Certification Framework
- Mathematical Modeling of Simple Fault Leakage
- Preliminary Results
- Conclusions

Certification Framework

Objective: to develop a simple framework to allow regulators to evaluate leakage risk for certifying operation and abandonment of geologic CO_2 storage sites.



• Project funded by the Carbon Capture Project Phase 2 (CCP2). PI's are Curt Oldenburg at LBNL and Steve Bryant at UT Austin.

Certification Framework

Definition

CO_2 leakage risk is migration across the boundary of the storage volume (3D region of the subsurface intended to contain injected CO_2).

Risk is the probability that negative impacts will occur to:

1. Health, Safety, and the Environment (HSE)
2. Potable Groundwater (USDW)
3. Hydrocarbon and Mineral Resources (HMR)
4. Emission Credits and Atmosphere (ECA)

Example Cross Section

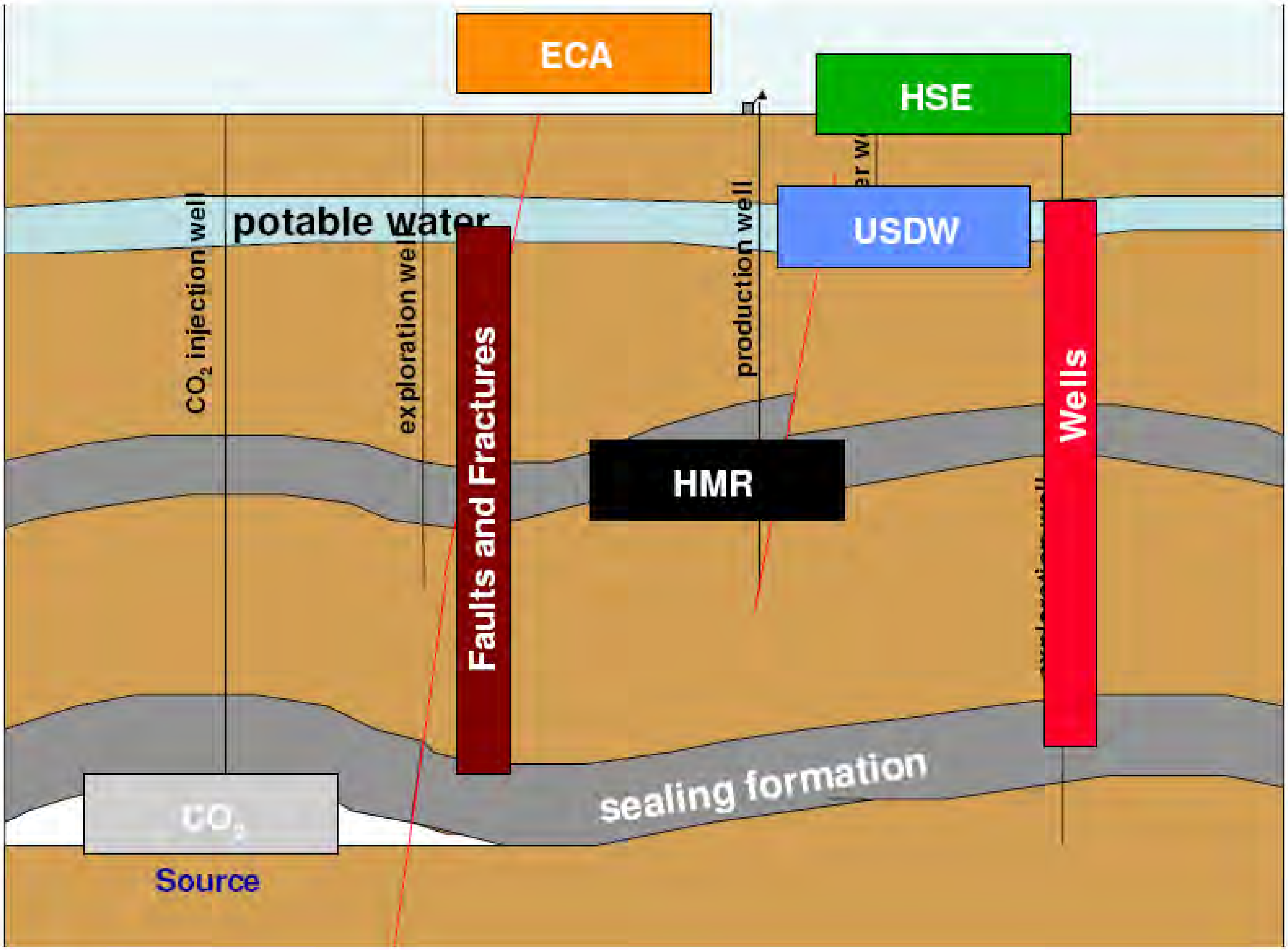


Figure courtesy of Oldenburg

Motivation for Certification Framework

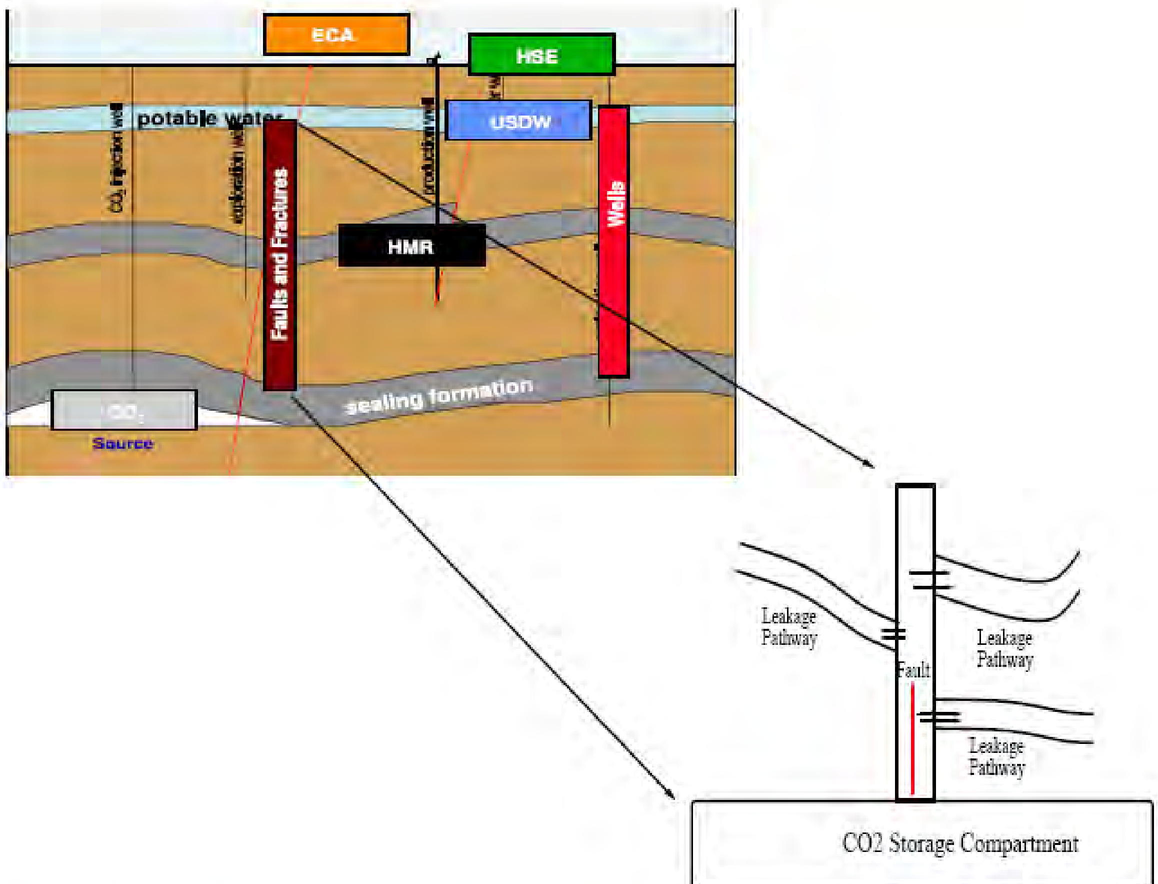
- There is an urgent need for a framework to certify and permit CO_2 injection and eventual closure of thousands of sites.
- CF aims to develop a simple, transparent, and accepted basis for regulators and stakeholders to certify that risks of CCS projects to environment are acceptable.

Needs for Framework:

1. Simplicity: data will always be limited in subsurface systems.
2. Transparency: reservoir models are inherently complicated, not well understood which leads to suspicion.
3. Acceptance: regardless of inherent value, no framework will be used unless it is accepted (by regulators, stakeholders and public).

Fault Leakage Model Schematic

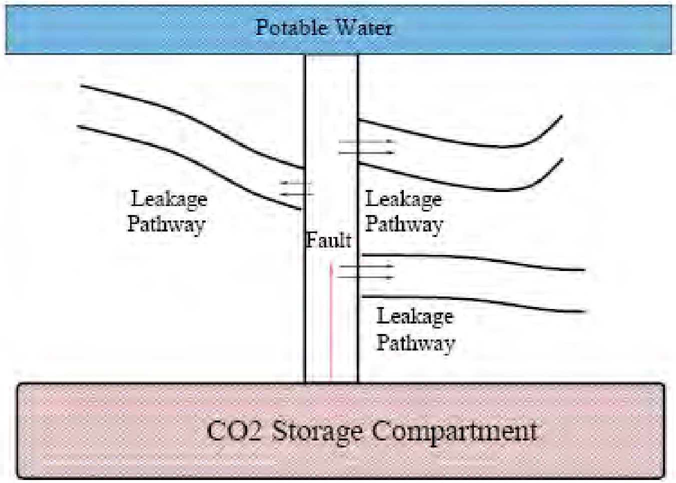
Supercritical CO_2 is lighter than brine. Buoyancy becomes a driving force (causing upward migration of fluid).



Mathematical Modeling of Simple Fault Leakage

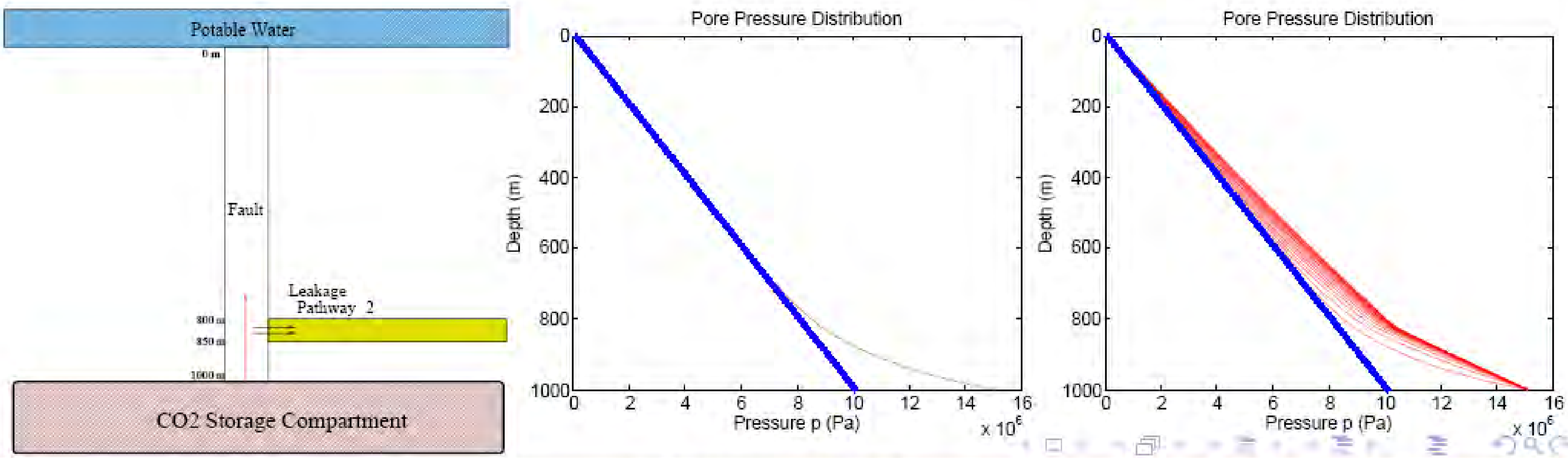
Assumptions:

- Fault is one-dimensional (vertical).
- Single-phase flow (supercritical fluid)
- Fluid is only slightly compressible
- Leakage into neighboring (lateral) strata modeled by source term.
- Fault initially contains water (initial condition is hydrostatic).
- Bottom boundary condition for fault is higher than hydrostatic.
- Value of bottom bc depends on thickness of CO_2 storage compartment.



Example

- 1000 m long vertical fault
- Fault properties: $\phi = .2$; $k = 100$ mD; $c = 10^{-6}$ Pa^{-1}; $\rho = 733$ kg/m^3
- Bottom BC for CO_2 storage compartment with 5 MPa pressurization.
- Single leak between 800–850 m depth. Leakoff coefficient $= -1.5 \times 10^{-4}$.
- Blue curve is hydrostatic pressure. Red curve is pore pressure in fault.



Numerical Experiments

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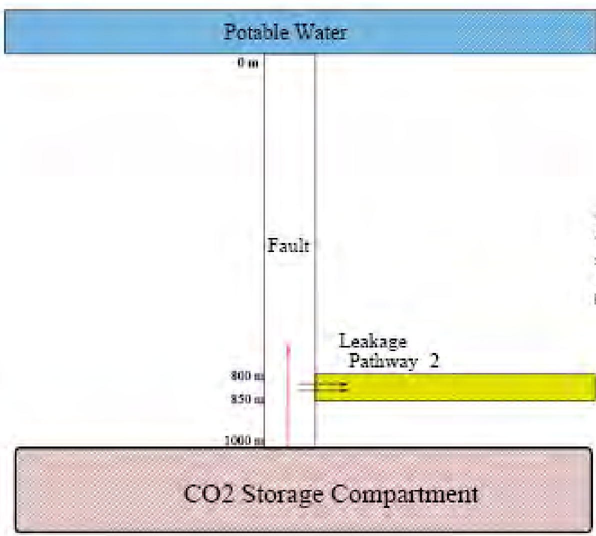
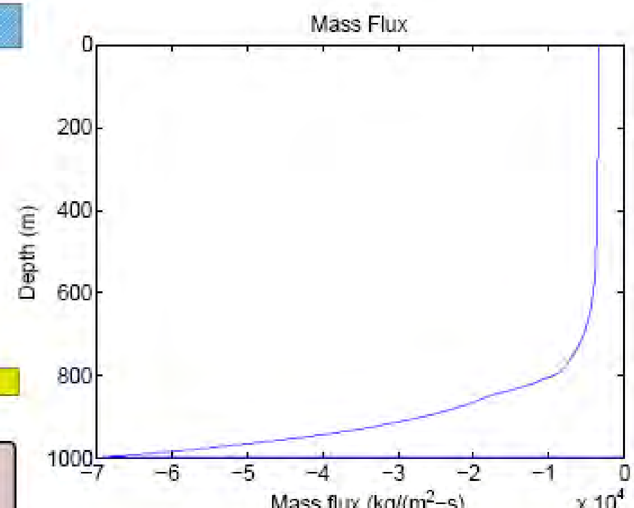
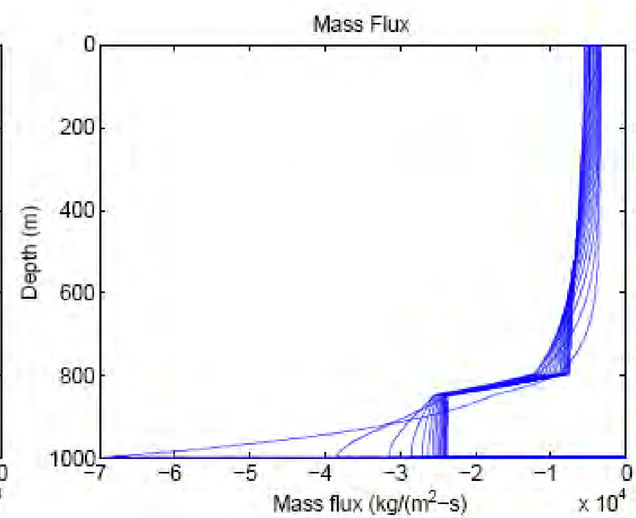


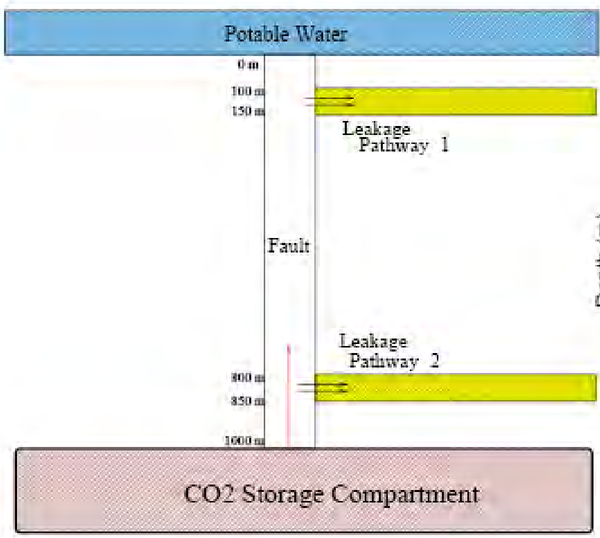


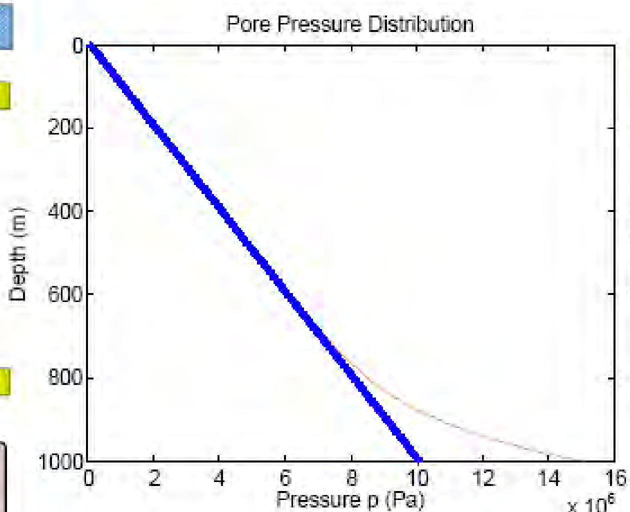


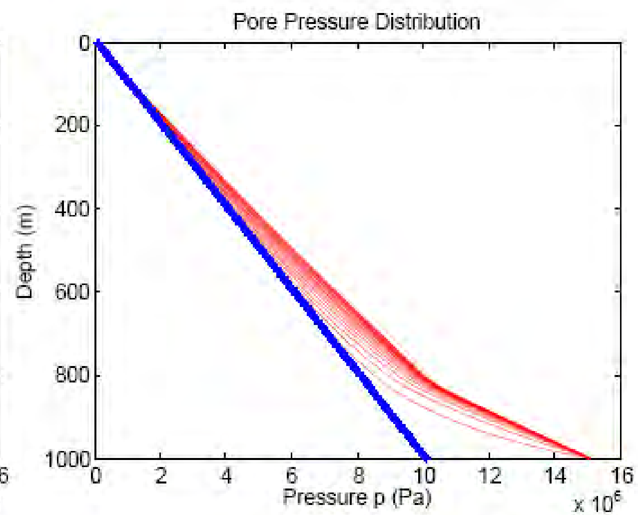
Numerical Experiments

Example

- 1000 m long vertical fault
- Bottom BC for 500 m deep CO_2 storage compartment
- Two leaks: first between 100–150 m; second from 800–850 m
- Leakoff coefficient for both leaks of size -1.5×10^{-4}







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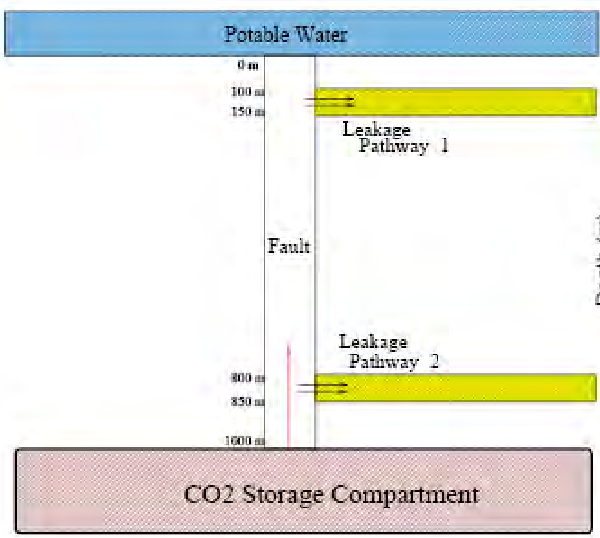

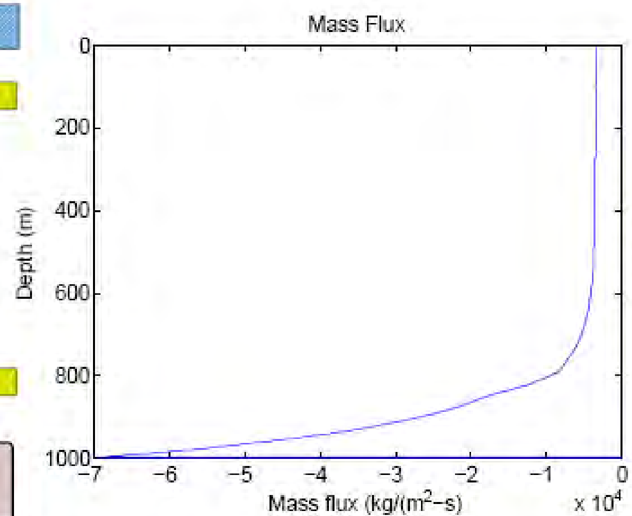

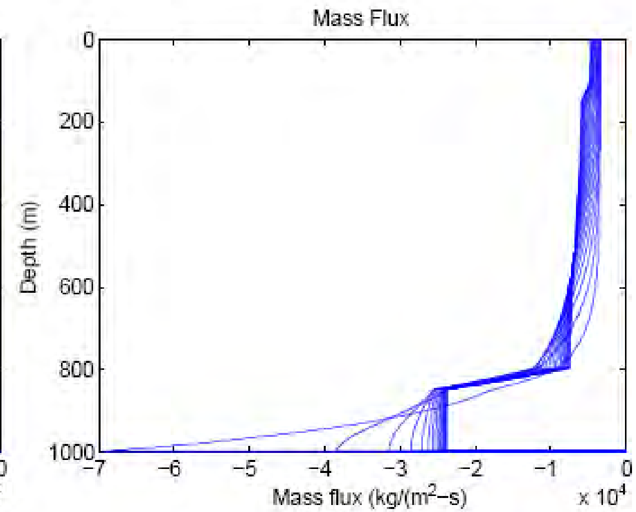

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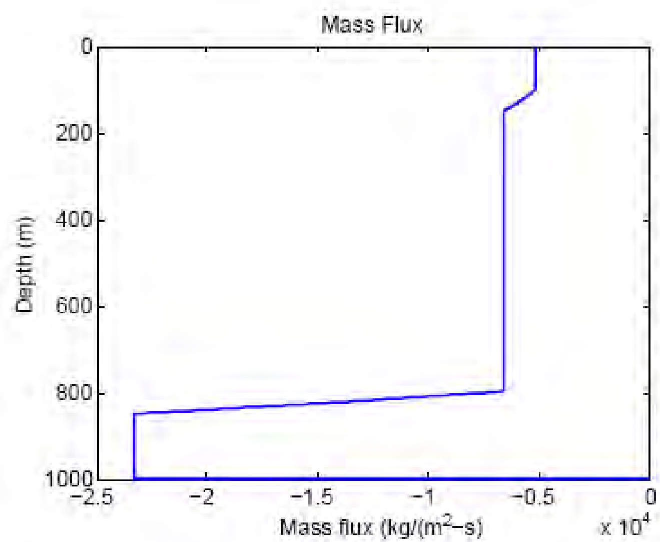
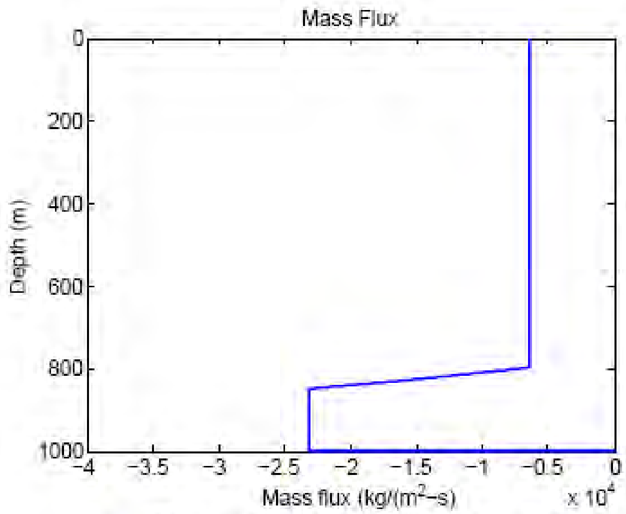


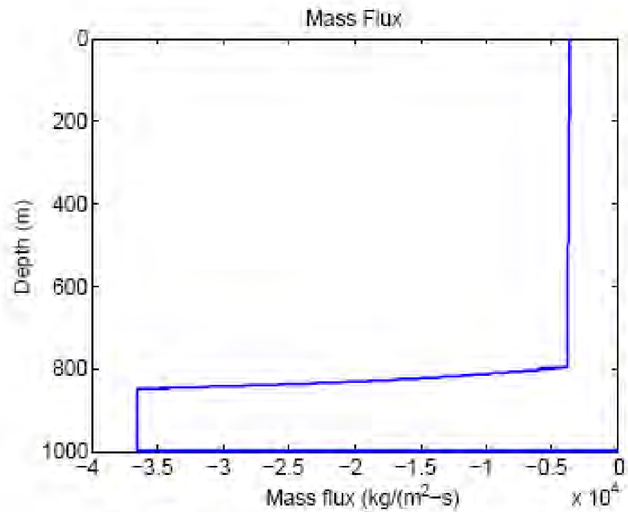
Numerical Experiments

Results

- Most important leaks are those near source of CO_2 (aquifer).
- Flux through the fault is not linearly related to size of leakoff coefficient.



- One leak at 800–850 m
- leakoff of -1.5×10^{-4}.

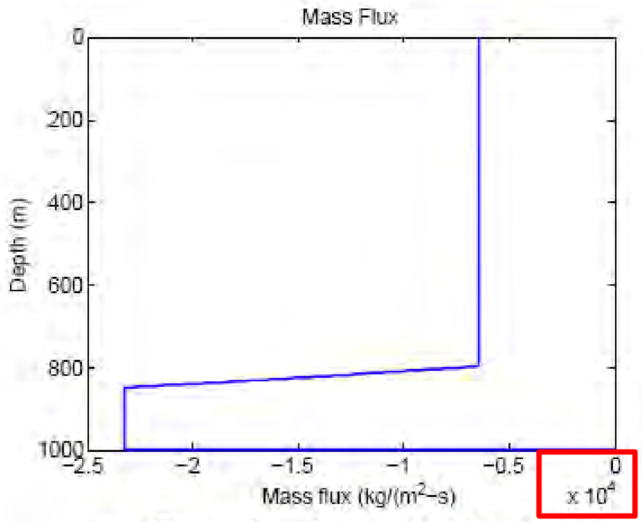


- One leak at 800–850 m
- leakoff of -1.5×10^{-3}.

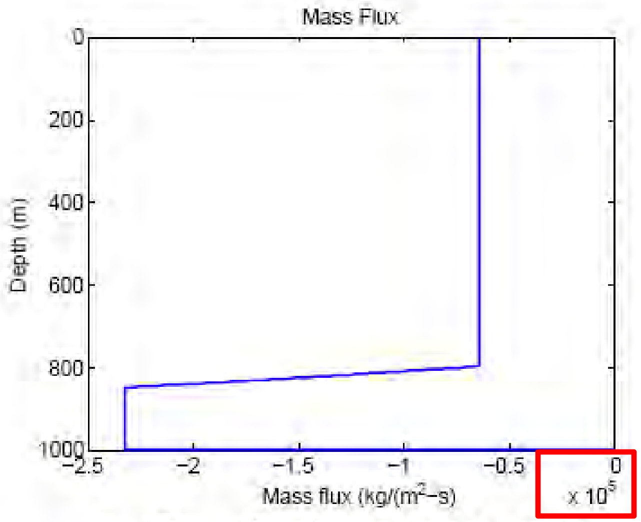
Numerical Experiments

Results

- Percentage which attenuates (leaks off) is proportional to k/q_{leak}.



- One leak at 800–850 m
- leakoff of -1.5×10^{-4}, $k = 100$ mD.



- One leak at 800–850 m
- leakoff of -1.5×10^{-3}, $k = 1000$ mD.

Numerical Experiments

Pressing Questions:

- How do we relate the leakoff coefficient to the geology on either side of the fault?
- What combinations of leaks cause the fluids to attenuate completely before reaching a compartment in our model such as a source of drinking water?
- How might mechanical deformation affect the leakage through faults?

Conclusions

- Carbon sequestration is the process of injecting CO_2 into the ground or ocean to remove it from the atmosphere.
- For carbon sequestration to be acceptable to regulators and the public, underground storage sites will need to be certified. The sites must be demonstrated to be able to contain the majority of the CO_2 for a few hundred years.
- The two primary pathways for leakage will be faults and abandoned wells.
- A simple leakage model of a fault indicates that leaks closer to the storage reservoir are the most important to fluid migration out of the container.
- Nonlinear behavior has been demonstrated between the amount of fluid which attenuates and the size of leakoff coefficient, the width of the leak, the number of leaks, and their relative sizes.
- For this model to be useful for the certification framework, we need to relate the leakoff coefficient to geological properties of the surrounding rocks.

Acknowledgements

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Appendix: Fault Flow Model

Conservation of mass and Darcy's law give the single-phase flow equation:

$$\frac{\partial}{\partial t}(\phi\rho) = \nabla \cdot \frac{\rho k}{\mu}(\nabla p - \rho g \nabla D) + q,$$
$$\overrightarrow{x} \in \Omega, \quad t \in [t_0, T]$$

Where:

- ϕ = porosity
- ρ = density of fluid
- p = pore pressure
- k = vertical permeability of fault
- μ = viscosity of fluid
- g = gravitational constant
- D = depth vector
- q = source/sink term
- c = fluid compressibility

Appendix: Fault Leakage Model

Using the Equation of State

$$\frac{\partial \rho}{\partial t} = c\rho \frac{\partial p}{\partial t}$$

we arrive at a single equation in one unknown (pressure).
Let p_z denote hydrostatic pressure.

- Initial condition is $p(z, t_0) = p_z(z)$.
- Top boundary condition is $p(z_{top}, t) = p_z(z_{top})$.
- Bottom boundary condition is $p(z_{bottom}, t) = p_z(z_{bottom}) + X$ where X is an additional pressure due to the CO_2 storage compartment below the fault.
- Source term $q(z, t) = q_{leak}(z)(p(z, t) - p_z(z))$.

Appendix: Numerical Solution of Leakage Model

If we discretize the spatial derivatives using Galerkin finite elements, then we have the following variational problem to solve for pressure p:

$$\left\langle \frac{\partial(\phi p)}{\partial t}, v \right\rangle = -\left\langle \frac{k}{\mu c} \nabla p, \nabla v \right\rangle + \left\langle \frac{k}{\mu c} \rho_0 g \nabla D, \nabla v \right\rangle + \langle \tilde{q}_{leak}(p - p_z), v \rangle \quad \forall v \in V$$

Using piecewise linear basis functions Ψ_i, we look for a finite dimensional solution $p(z,t) = \sum_{i=1}^{n-1} \alpha_i(t)\Psi_i(z)$ to

$$\sum_{i=1}^{n-1} \frac{\partial \alpha_i(t)}{\partial t} \langle \phi \Psi_i, \Psi_j \rangle = -\sum_{i=1}^{n-1} \alpha_i \left\langle \frac{k}{\mu c} \frac{\partial \Psi_i}{\partial z}, \frac{\partial \Psi_j}{\partial z} \right\rangle - \left\langle \frac{k}{\mu c} \frac{\partial g_n}{\partial z}, \frac{\partial \Psi_j}{\partial z} \right\rangle$$
$$+ \left\langle \frac{k}{\mu c} \rho_0 g, \frac{\partial \Psi_j}{\partial z} \right\rangle + \sum_{i=1}^{n-1} \alpha_i \langle \tilde{q}_{leak} \Psi_i, \Psi_j \rangle + \langle \tilde{q}_{leak}(g_n - p_z), \Psi_j \rangle$$

Appendix: Numerical Solution of Leakage Model

$$\sum_{i=1}^{n-1} \frac{\partial \alpha_i(t)}{\partial t} \underbrace{\langle \phi \Psi_i, \Psi_j \rangle}_{M} = -\sum_{i=1}^{n-1} \alpha_i \underbrace{\left\langle \frac{k}{\mu c} \frac{\partial \Psi_i}{\partial z}, \frac{\partial \Psi_j}{\partial z} \right\rangle}_{K1} - \underbrace{\left\langle \frac{k}{\mu c} \frac{\partial g_n}{\partial z}, \frac{\partial \Psi_j}{\partial z} \right\rangle}_{Q1}$$

$$+ \underbrace{\left\langle \frac{k}{\mu c} \rho_0 g, \frac{\partial \Psi_j}{\partial z} \right\rangle}_{Q2} + \sum_{i=1}^{n-1} \alpha_i \underbrace{\langle \tilde{q}_{leak} \Psi_i, \Psi_j \rangle}_{K2} + \underbrace{\langle \tilde{q}_{leak}(g_n - p_z), \Psi_j \rangle}_{Q3}$$

Using Backward Euler for the time discretization, we solve the following linear system for each unknown coefficient α_i at each time n:

$$\alpha_i^{n+1} = (M + \Delta t K1 - \Delta t K2)^{-1} [\alpha_i^n M + \Delta t(-Q1 + Q2 + Q3)]$$

Note that term $K2$ (from the source) contributes to the stiffness matrix.