RISK ASSESSMENT FOR CO_2 SEQUESTRATION

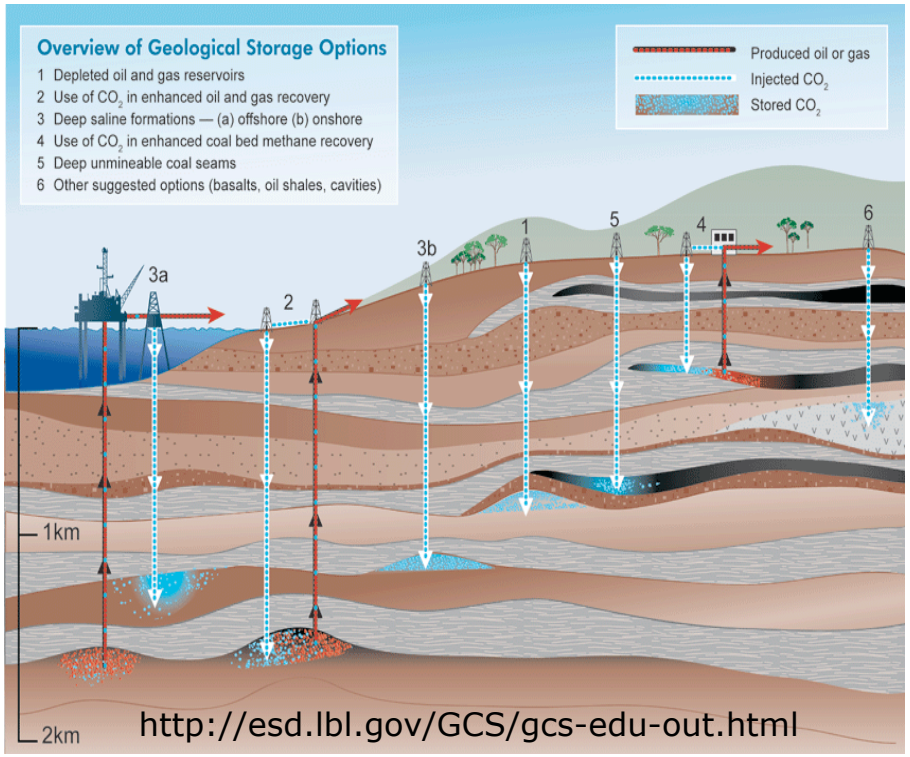
Yan Zhang
Department of Chemical Engineering
Carnegie Mellon University

Panagiotis Vouzis
Department of Chemical Engineering
Carnegie Mellon University

Nick Sahinidis
National Energy Technology Laboratory
Department of Chemical Engineering
Carnegie Mellon University
sahinidis@cmu.edu

INTRODUCTION TO CO_2 SEQUESTRATION

- Effect of anthropogenic CO_2 on global warming
- Carbon mitigation portfolio
  - Improved efficiency vehicles
  - Decarbonization
    - renewable, nuclear
  - Sequestration
- CO_2 sequestration options
  - Ocean
    - large capacity, ecological impact
  - Mineral
    - permanently, energy penalty
  - Geological: mature technology
    - oil/ gas reservoir
    - deep saline formation
    - deep coal seam

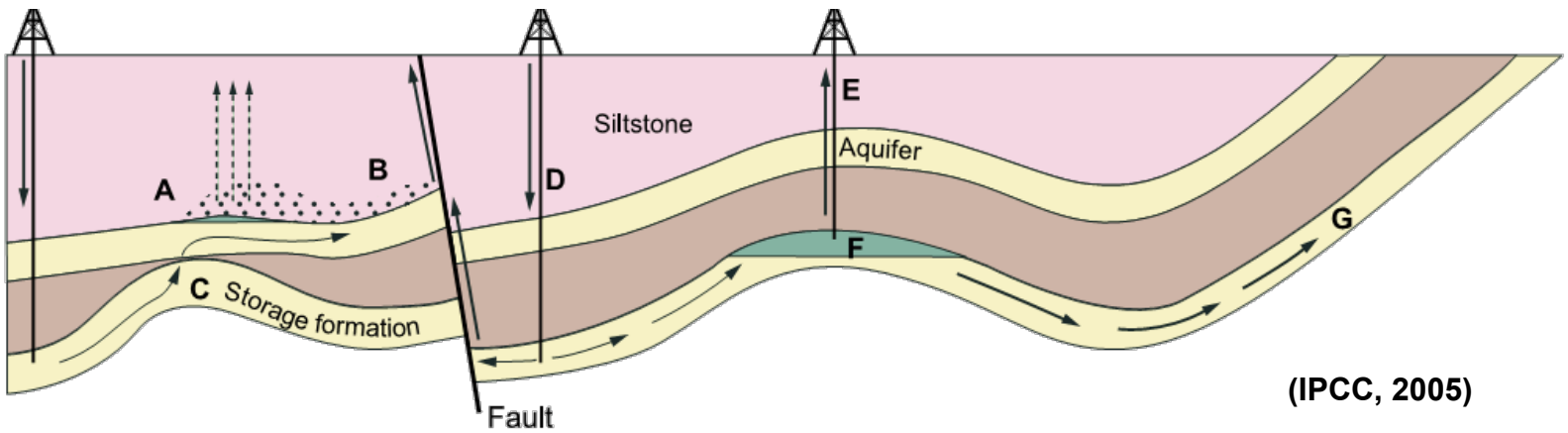


http://esd.lbl.gov/GCS/gcs-edu-out.html

RISKS IN CO_2 GEOLOGIC STORAGE

- **Risks**
  - Massive release of CO_2 to the atmosphere
  - Contamination of local environment: soil, water
- **Risk = Probability * Severity (impact)**

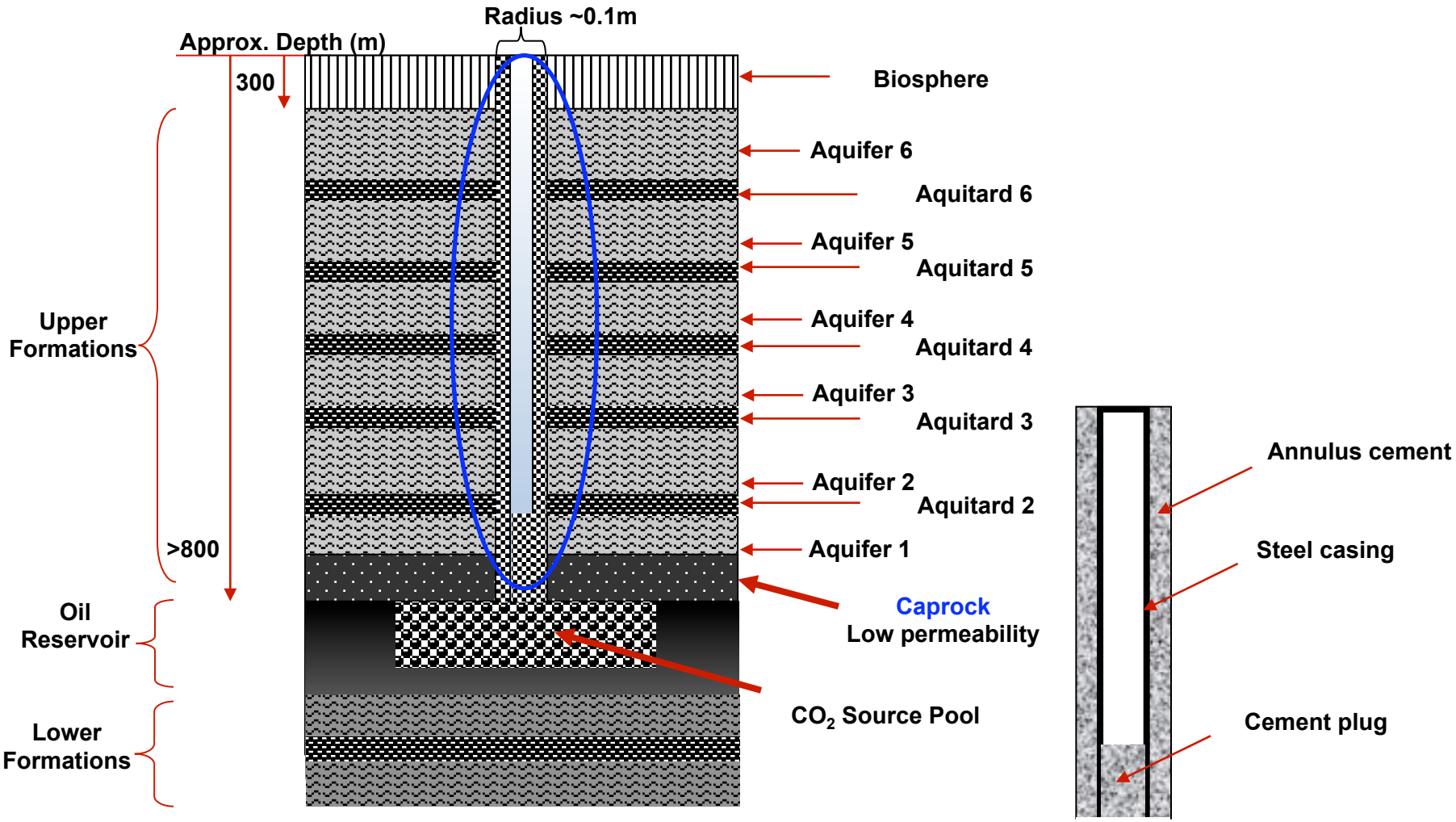
Identification of events/scenarios → Estimation of likelihood/probability → Evaluation of impact/ consequences



(IPCC, 2005)

A. CO_2 gas pressure exceeds capillary pressure	B&D. CO_2 leaks through faults	C. CO_2 escapes through 'gap' in caprock	E. CO_2 leaks through broken wells	F&G. CO_2 leaks through open aquifer

PHYSICAL SYSTEM



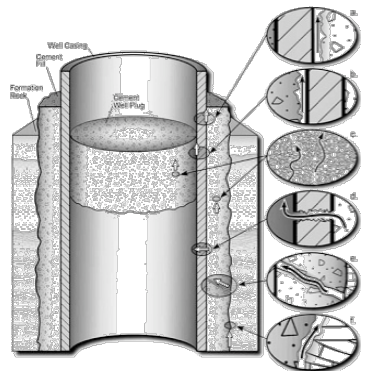
Simplified geological structure

PROCESS DESCRIPTION

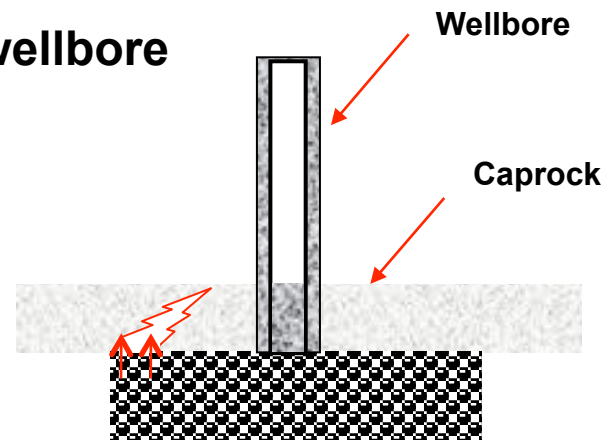
- **Viability of a sequestration system:**

Leakage

Failed seals of wellbore



Celia et al., 2004



Open fractures and faults

vs .

Sequestration

Dissolution of source pool

Migration of CO_2 into surrounding formations

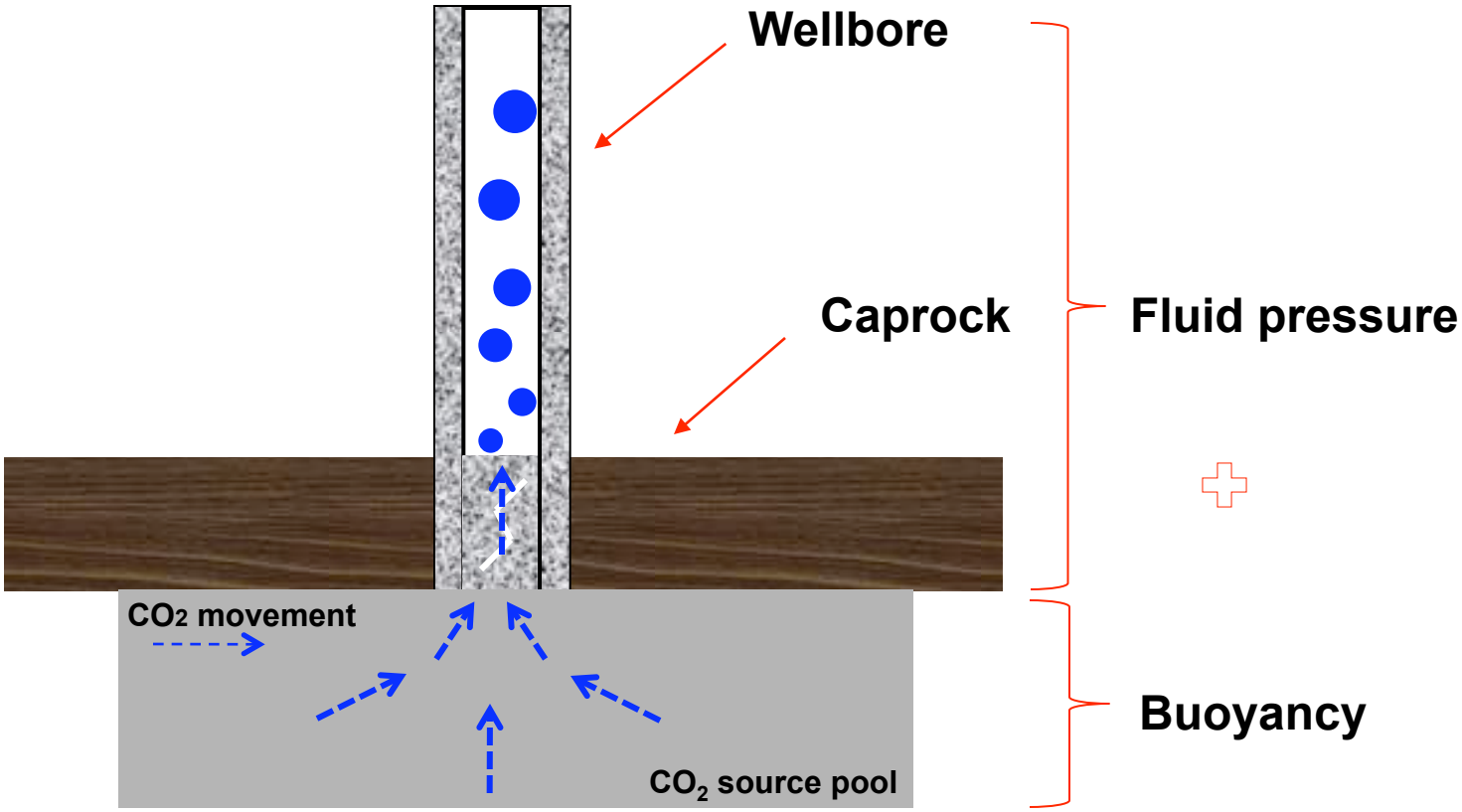
Mineralization

$$\frac{dM}{dt} = F_i - F_o$$

M: CO_2 mass
F_i: inflow rate = 0
F_o: outflow rate = leakage + sequestration

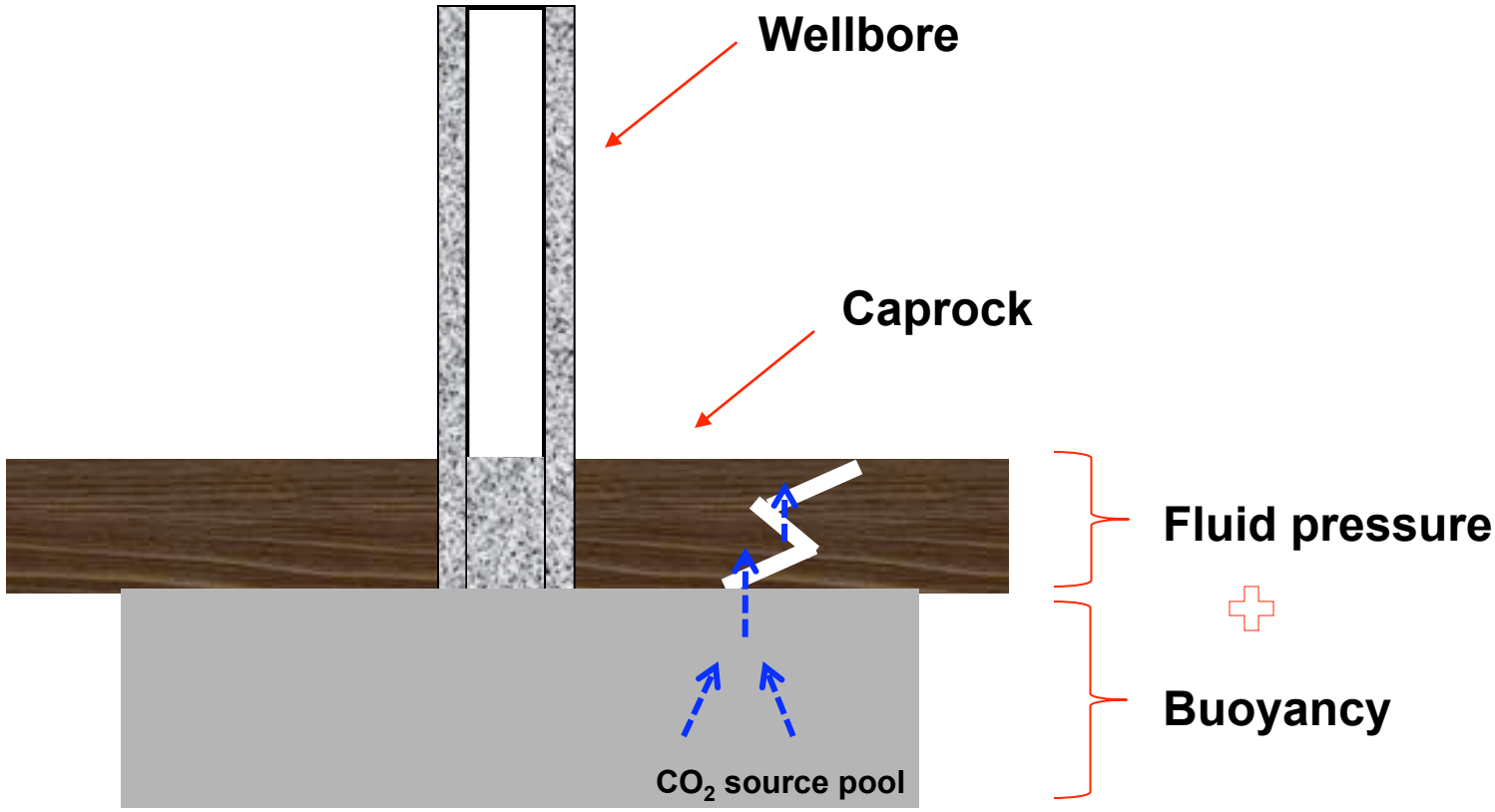
MOVEMENT THROUGH WELLBORE

- **Non-penetrating well equation**



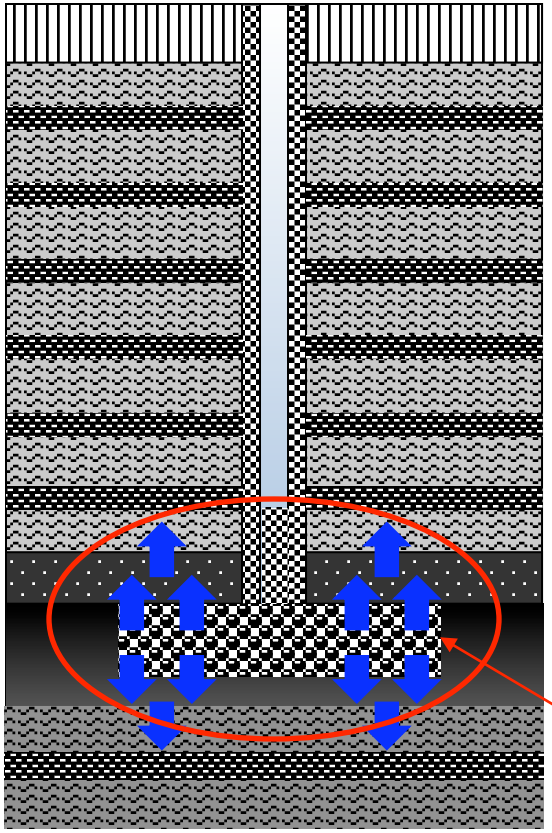
MOVEMENT THROUGH CAPROCK

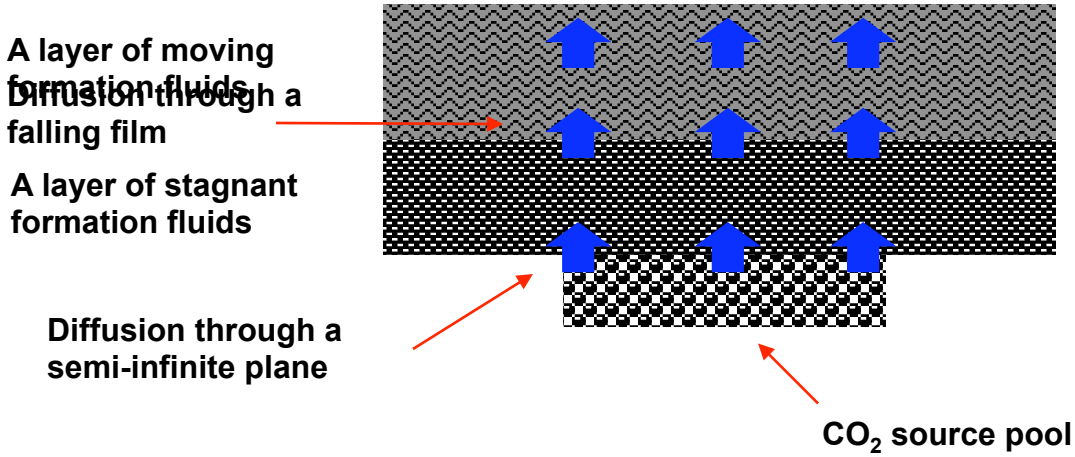
- **Equation for drainage in tunnels**



DISSOLUTION OF SOURCE POOL

- **Dissolution of source pool to the formations below or above the source**





Steady state dissolution rate =

Diffusion through a semi-infinite plane

+

Diffusion through a falling film

MIGRATION THROUGH FAILED SEALS

- **Migration of CO_2 to surrounding formations through failed seals on the way of rising up**
  - **Failure times are unpredictable**
    - **If the cement annulus fails first…**
    - **If the cement plug fails first…**
  - **Physical model**

    Heat conduction from a thin wire
    - **Aquifer with advection, dispersion and reaction**
    - **Aquitard with diffusion and reaction**

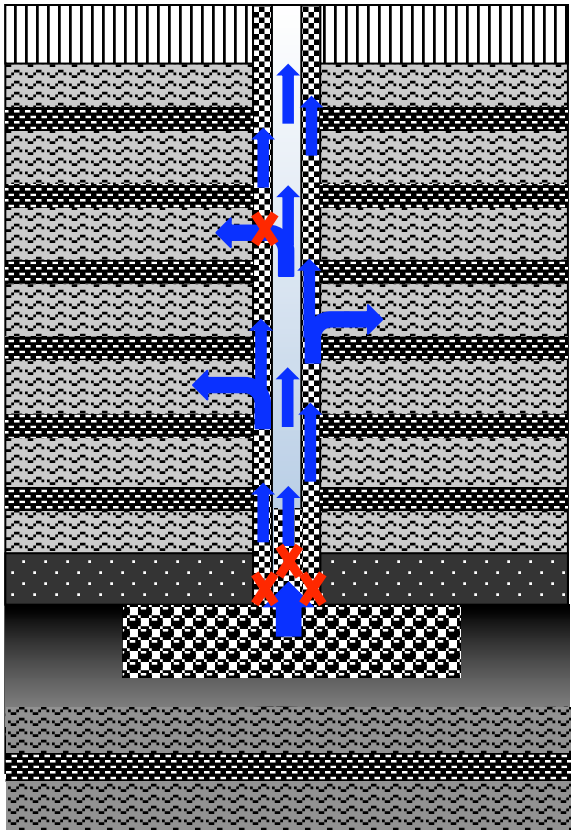
    ➔ Apply solution for temperature profile

    ➔ Get CO2 concentration in the formation

    ➔ Obtain steady state flux at the wall of the wellbore

$$\lim_{t \to \infty} \left(\frac{\partial C(r,t)}{\partial r} \Big|_{r=r_b} \right)$$

➔ Migration rate = steady state flux * concentration at the wall * thickness



OVERALL MASS BALANCE

- **The mass left in the reservoir pool as time goes by:**

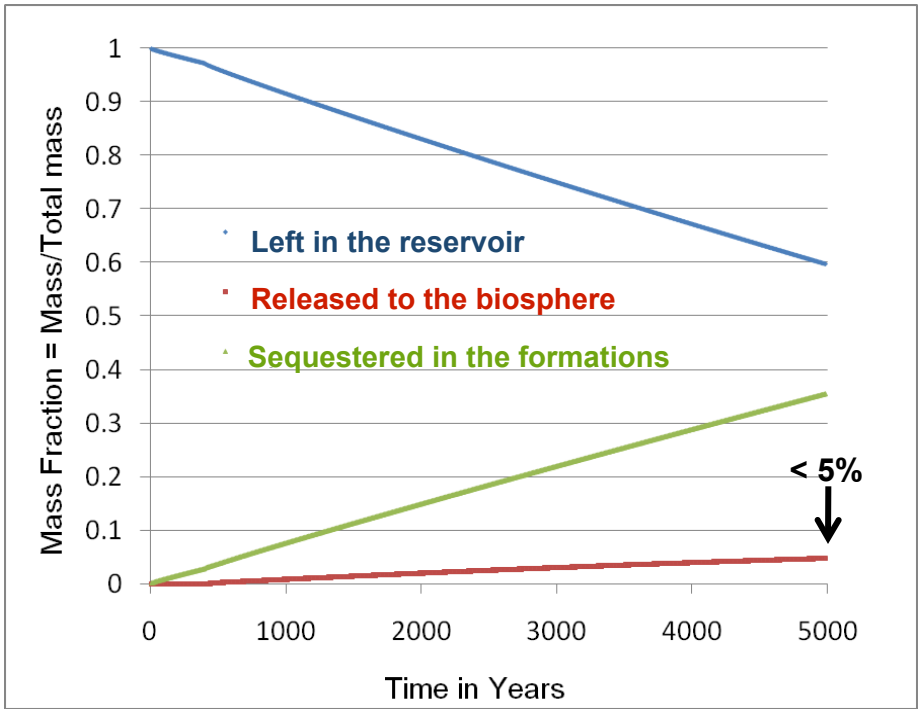
$$M = \underbrace{M_0 exp(-\beta t)}_{\text{Leakage through wellbores and/or faults}} - \underbrace{\frac{F_D}{\beta}[1 - exp(-\beta t)] - \frac{2\alpha exp(-\beta t)}{\sqrt{\pi\beta}} \int_0^{\sqrt{\beta t}} exp(\xi^2)\, d\xi}_{\text{Sequestration Dissolution + Mineralization}}$$

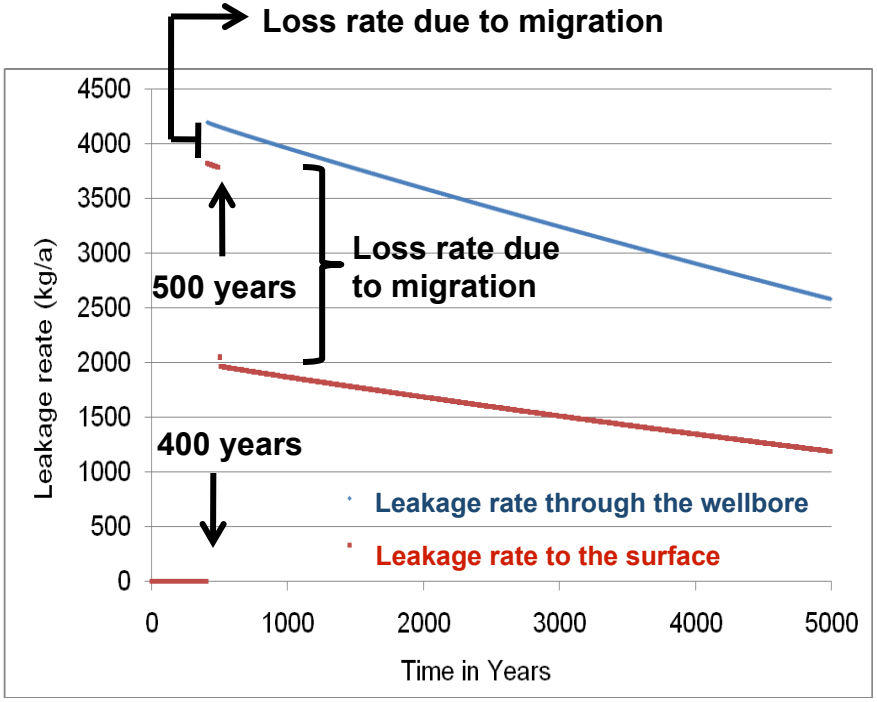
$$\beta = \frac{\left[2\pi N_w K_s r_b \left(1 + \frac{\rho_s \varphi_s}{\rho_w - \rho_s}\right) + \frac{N_F K_F L_F}{\ln\left(h_0/w_F\right)}\left(1 + \frac{\rho_s \varphi_F}{\rho_w - \rho_s}\right)\right](\rho_w - \rho_s)}{A_s \rho_s \varepsilon_s S_s}$$

Depends on the failure times of wellbore components

$$\alpha = A_s \varepsilon_s S_s C_o (D\tau)^{1/2}$$

RESULTS FOR ONE SET OF PARAMETERS





CO_2 mass fractions vs. time

CO_2 leakage rate (kg/a) vs. time

MODEL PARAMETERS

- **Parameters:**
  - **Main independent parameters**

Formation	Brine water	CO_2 phase	Wellbore
•Depth •Thickness •Permeability •Porosity •Tortuosity •Mineralization rate •…	•Salinity •Pressure •Surface tension of the free phase •Temperature gradient •Darcy velocity •Capillary pressure in reservoir •Dispersion coefficients •…	•Mass •Composition •Thermo-property •Permeability •Effective saturation •…	•Cement seal failure times •Casing failure times •Permeability of degraded cement •Effective crack diameter of degraded cement •Surface tension •Wellbore radius

  - **Main calculated parameters:**

    formation fluid density, free phase density, viscosity, solubility, etc.

PROBABILISTIC RISK ASSESSMENT

Input:
Randomly Sampled from probability distribution function of independent parameters

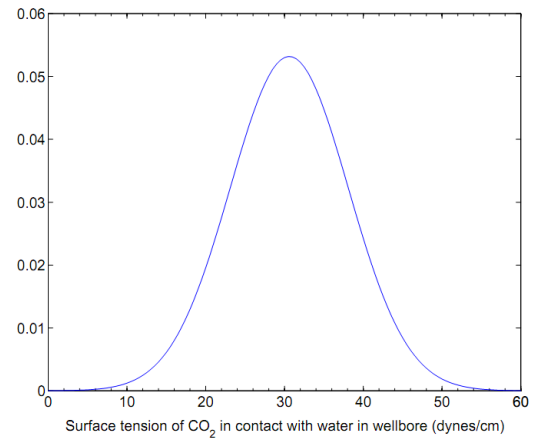
Monte Carlo simulation →

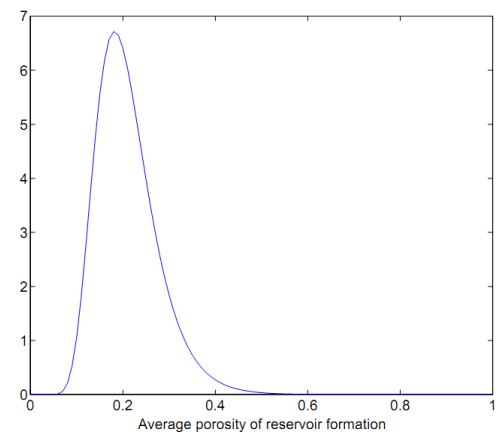
Output:
Statistical Analysis

Simulator

Generated inputs with independent parameters				
sample #	x_1	x_2	…	x_n
	Permeability	Porosity	…	
1				
2				
…				
4000				

Model Outputs			
y_1	y_2	…	y_m
Mass left	Mass leaked		



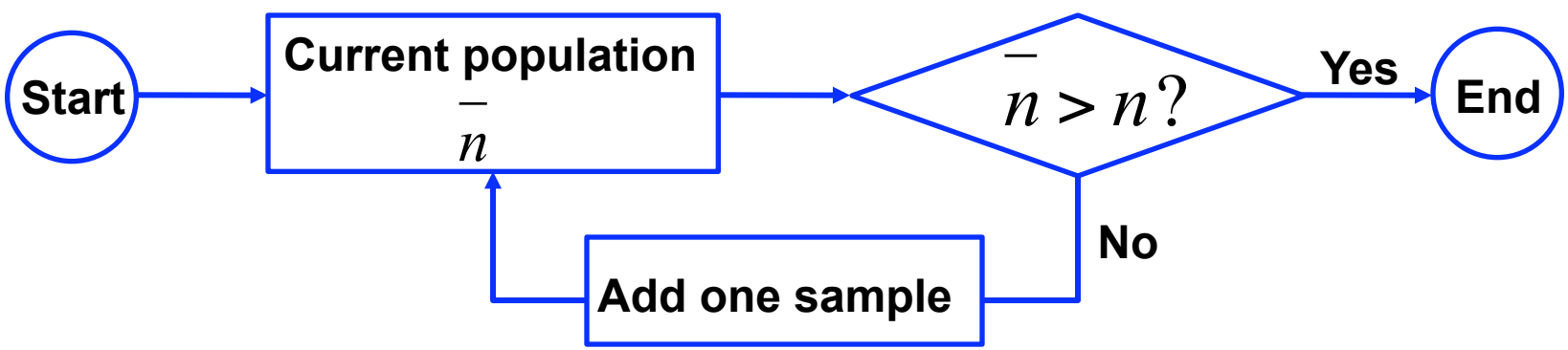


MINIMUM MC SAMPLING SIZE

- **95% confidence interval for the average of the output:**

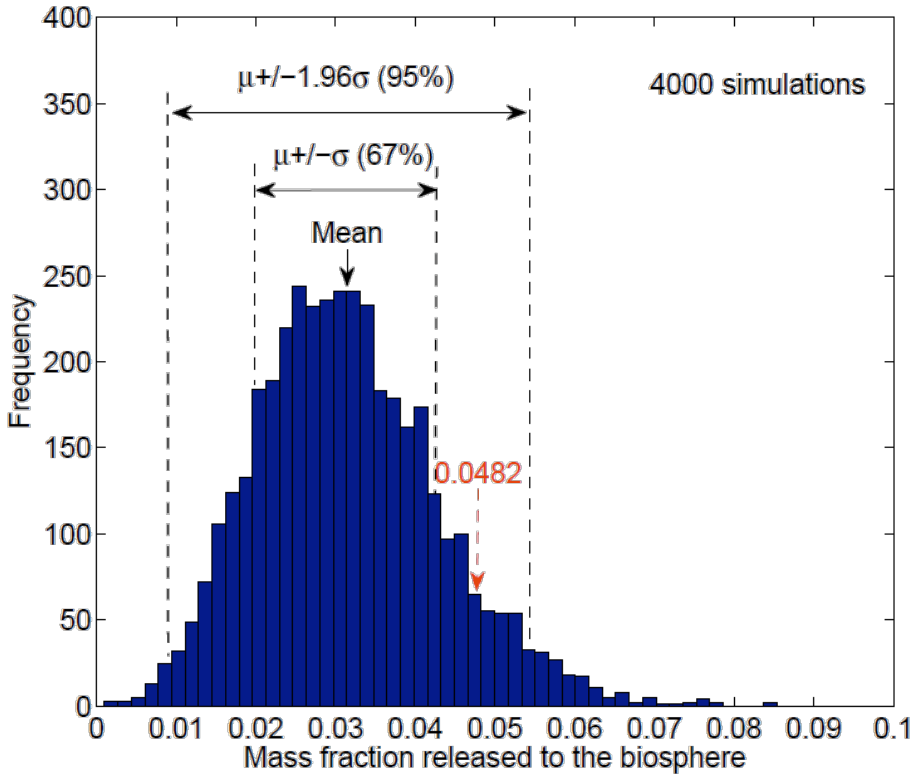
$$\overline{X} \pm \underbrace{1.96 \frac{s}{\sqrt{n}}}_{B} \Rightarrow n = \frac{1.96^2 s^2}{B^2}$$

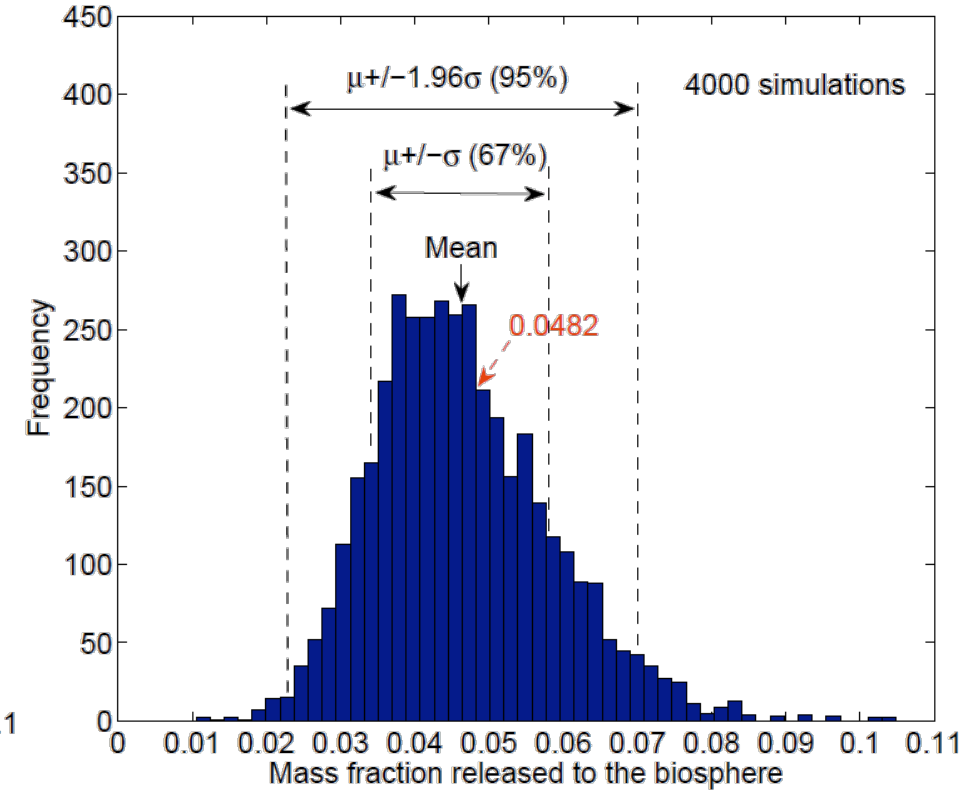
- **Algorithm:**



- **Effect of number of input parameters on minimum sampling size**

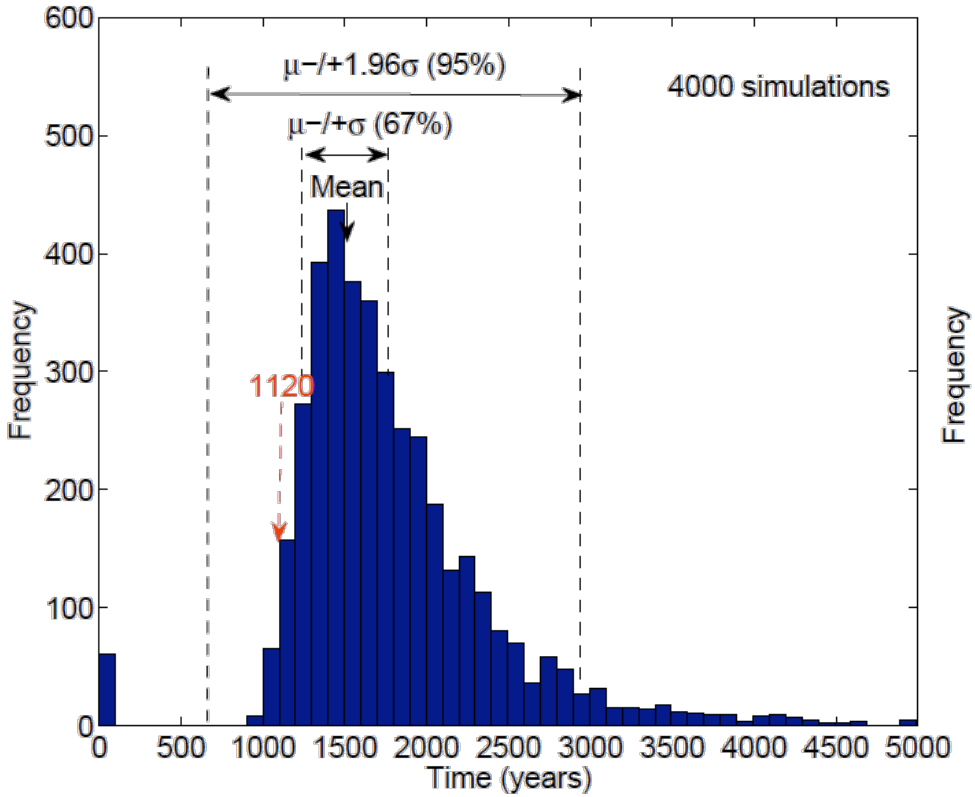
RESULTS FOR MONTE CARLO SIMULATION

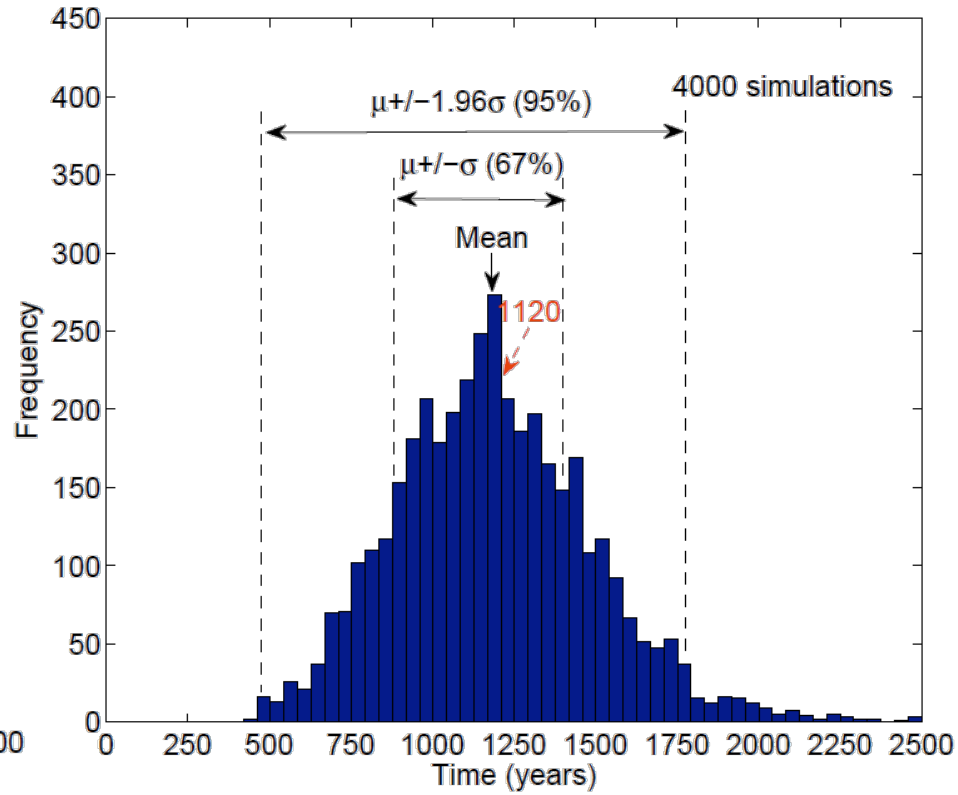




Frequency histogram showing fraction released to the biosphere at 5000 years with normal (left) and lognormal (right) inputs

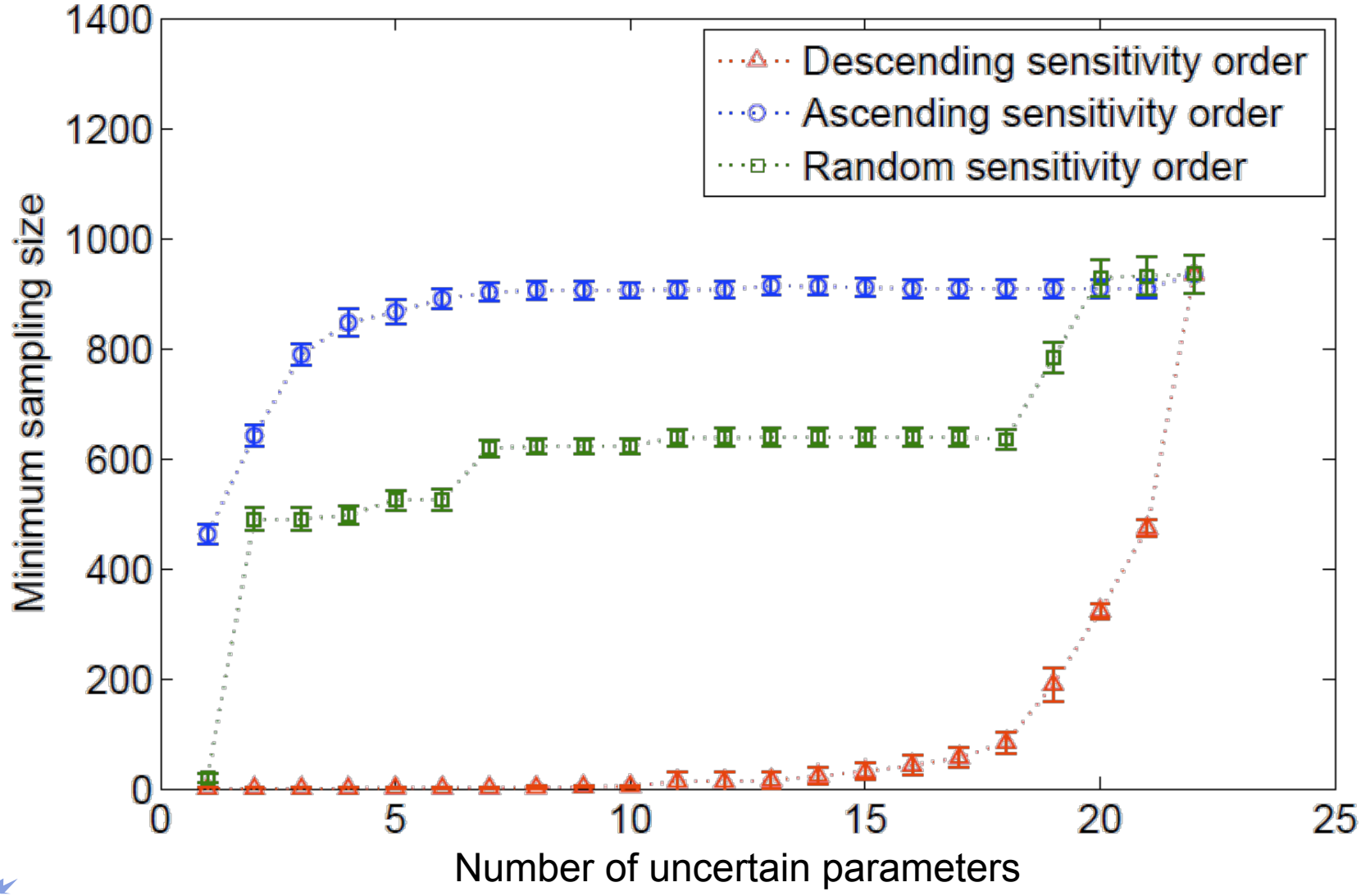
RESULTS FOR MONTE CARLO SIMULATION



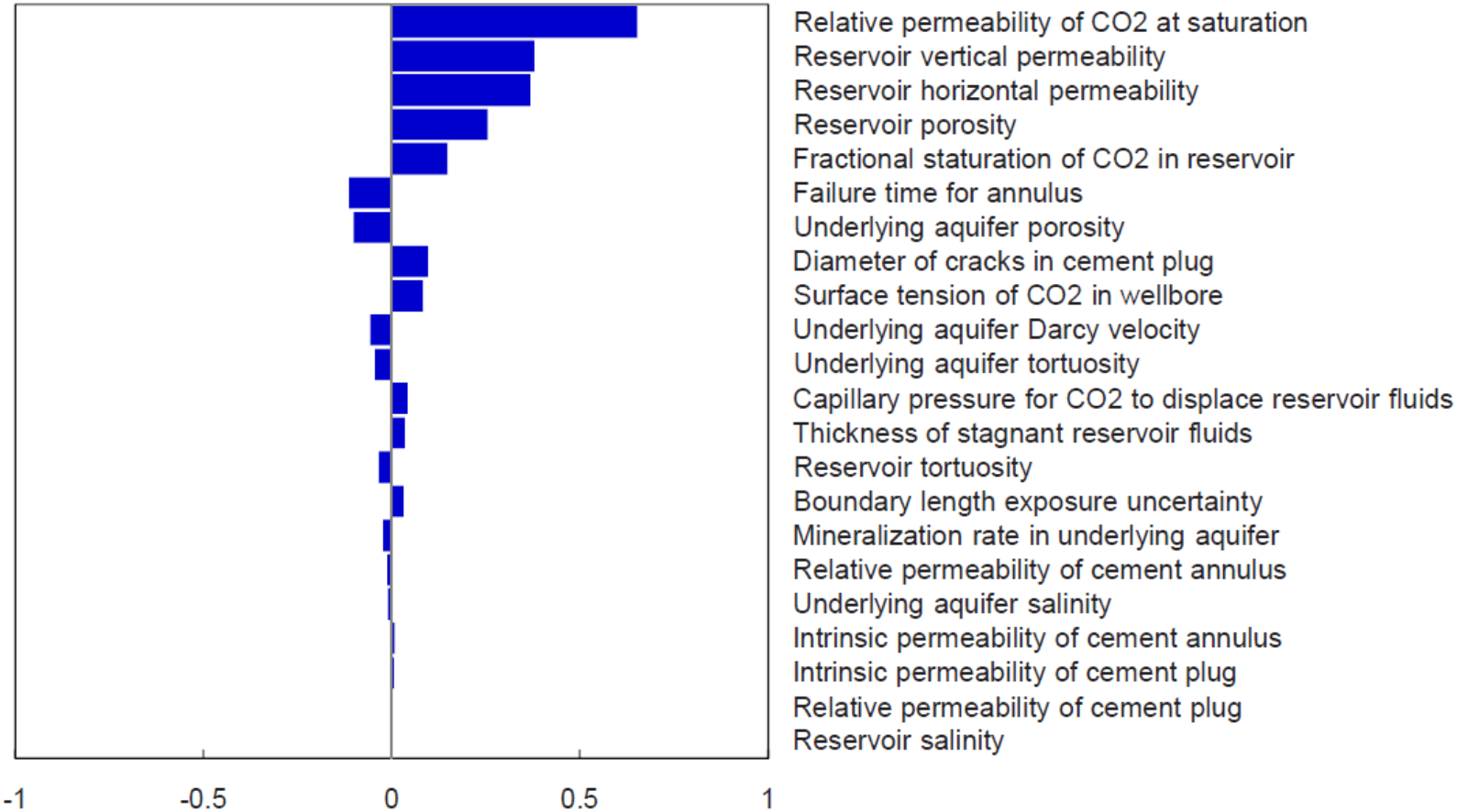


Frequency histogram showing various times when 1% of total injected CO_2 mass leakage occurs with normal (left) and lognormal (right) inputs

SAMPLING SIZE VS NUMBER OF PARAMETERS

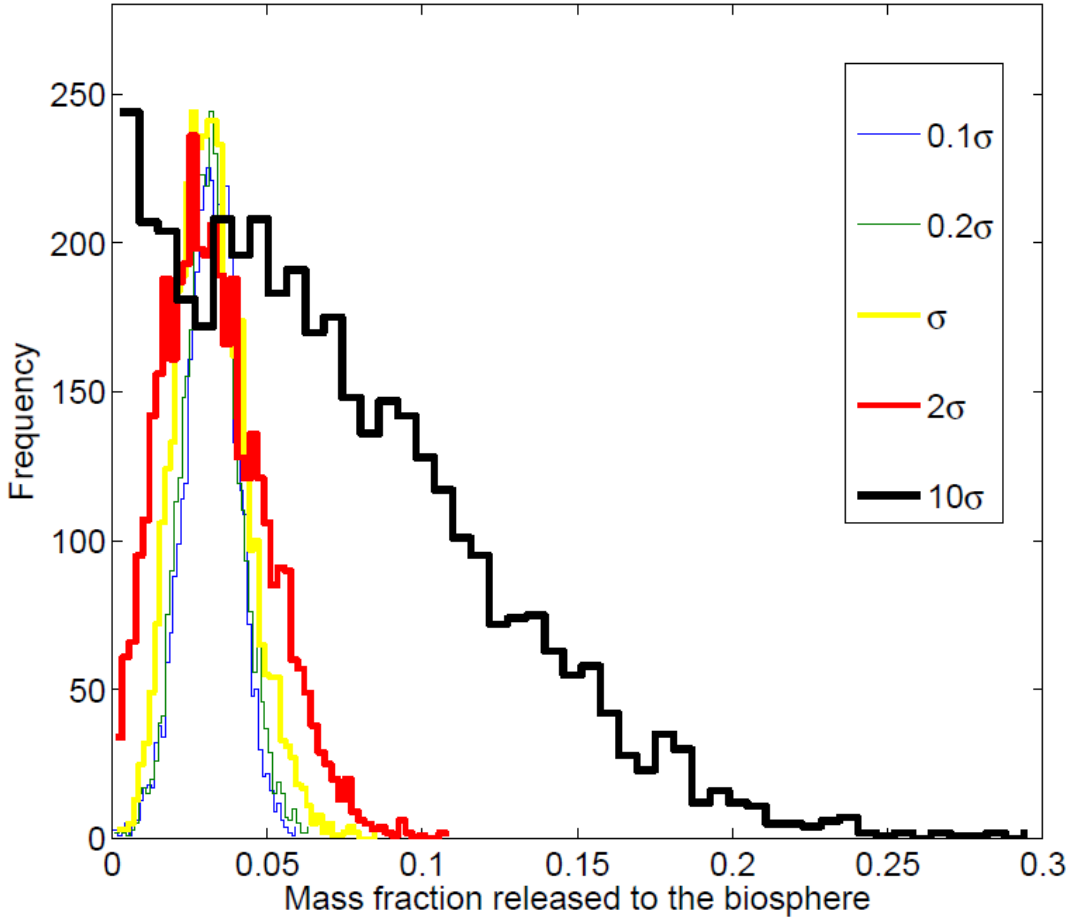


SENSITIVITY ANALYSIS



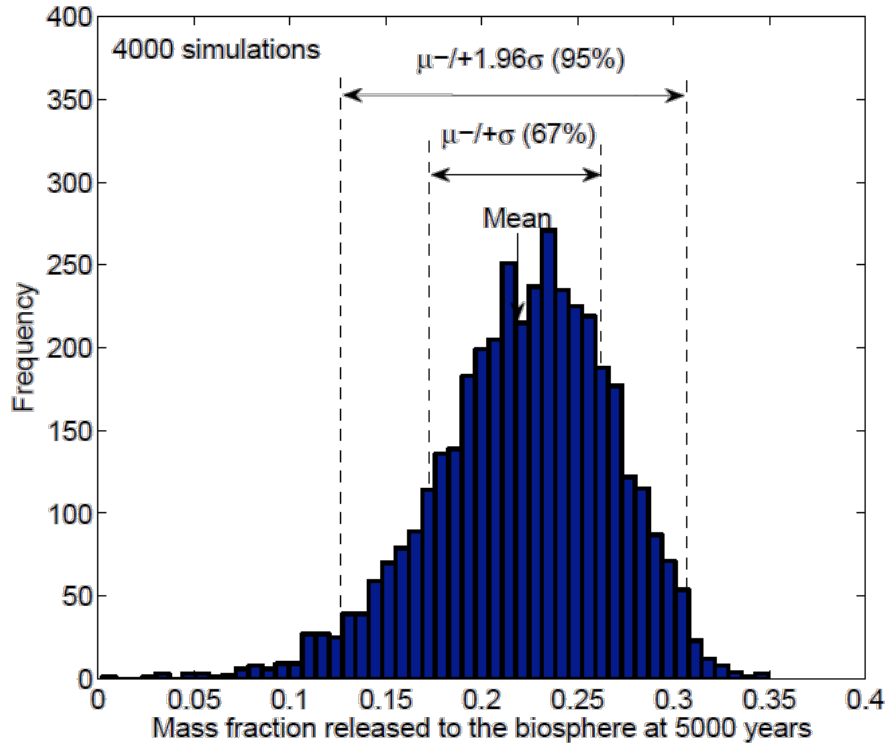
Spearman's rank correlation between the mass fraction of leakage and normally distributed independent input parameters

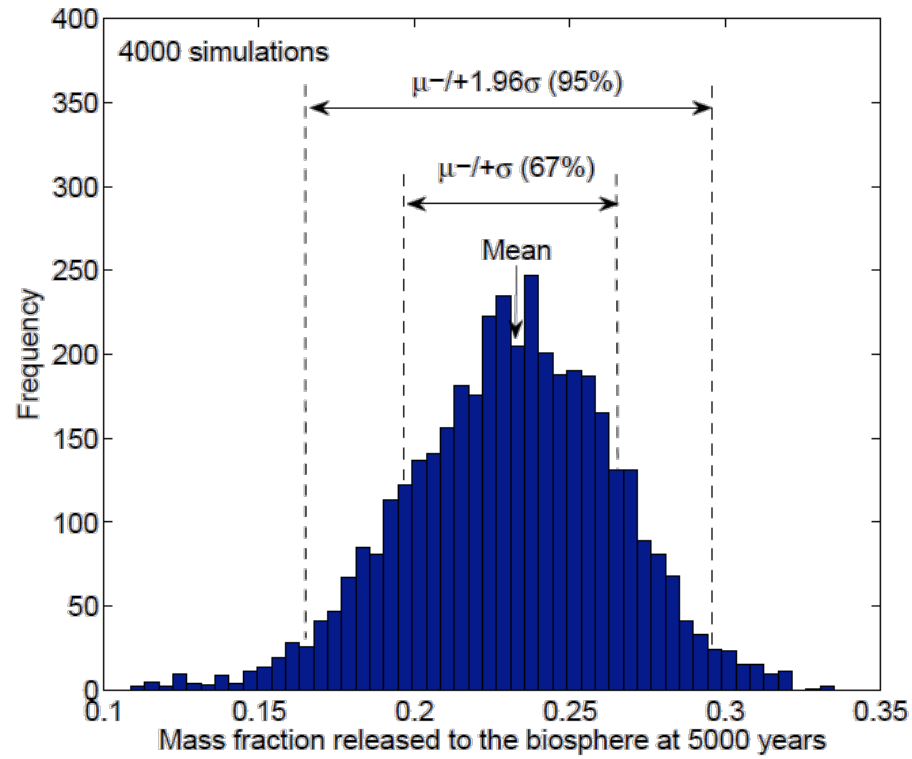
SENSITIVITY ANALYSIS



Frequency histogram showing fractions released to the biosphere in 5000 years with different variances of the distribution of relative permeability

MUTIPLE LEAKY WELLS SIMULATION



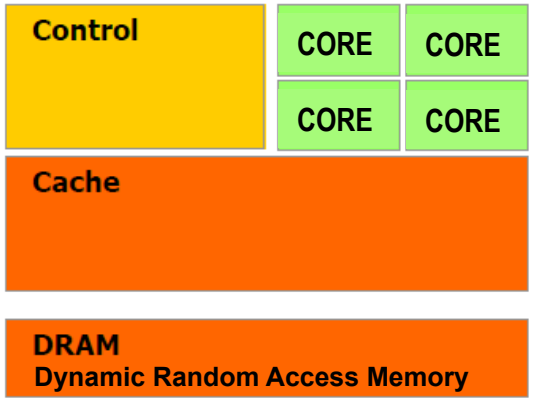


Frequency histogram showing mass fraction released to the bio-sphere in 5000 years with ten leaky wells under snormal (left) and lognormal (right) inputs

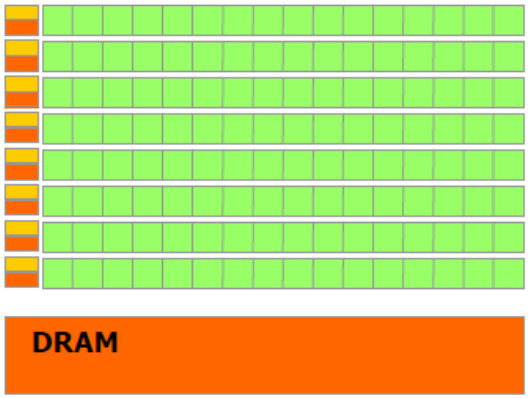
GPU PARALLEL COMPUTING

- Multi-core and many-core

CPU



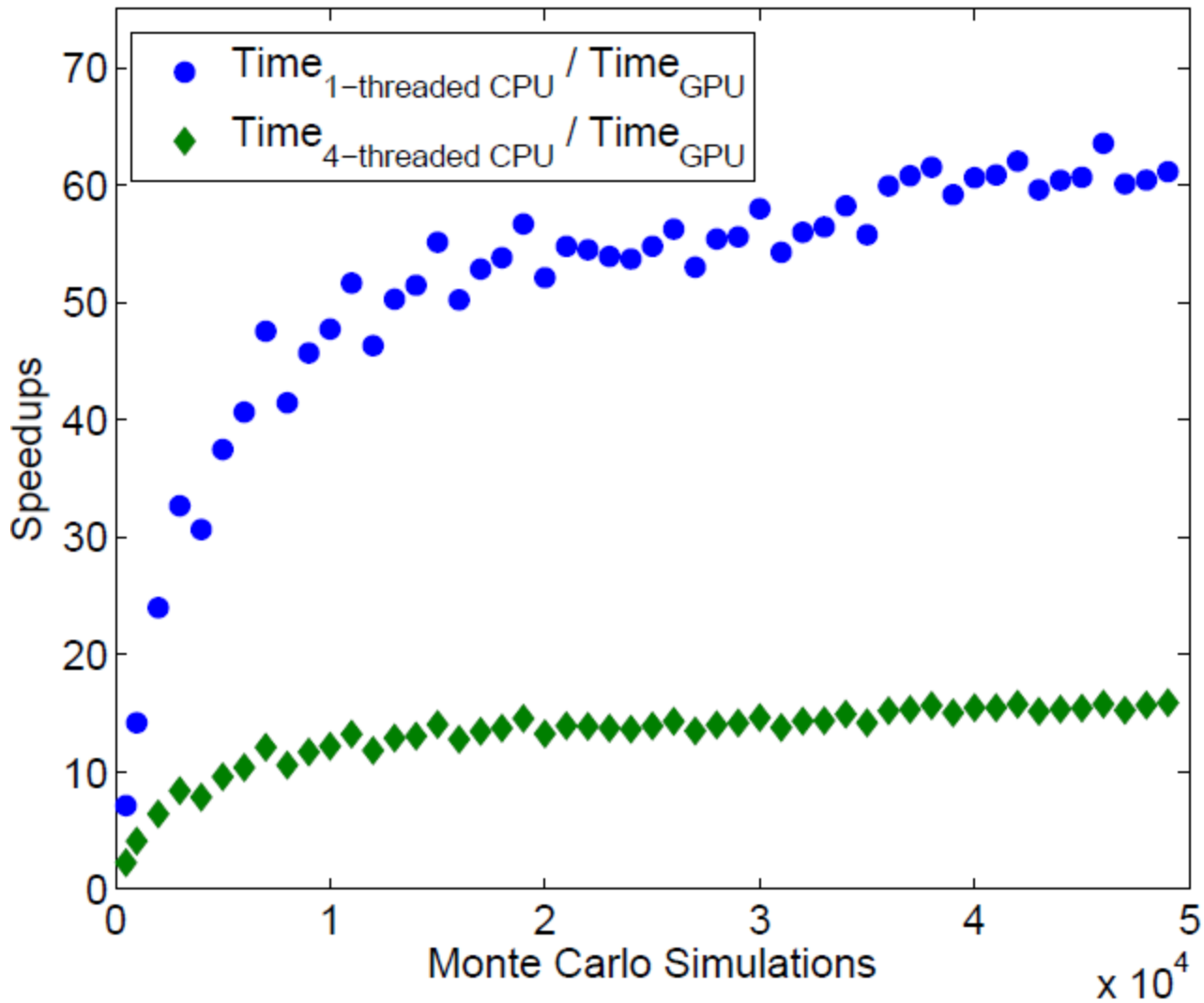
GPU



http://www.nvidia.com/object/GPU_Computing.html

Lecture Notes, David Kirk/NVIDIA and Wen-mei Hwu, 2006-2008

FASTER THAN CONVENTIONAL CPU IMPLEMENTATION

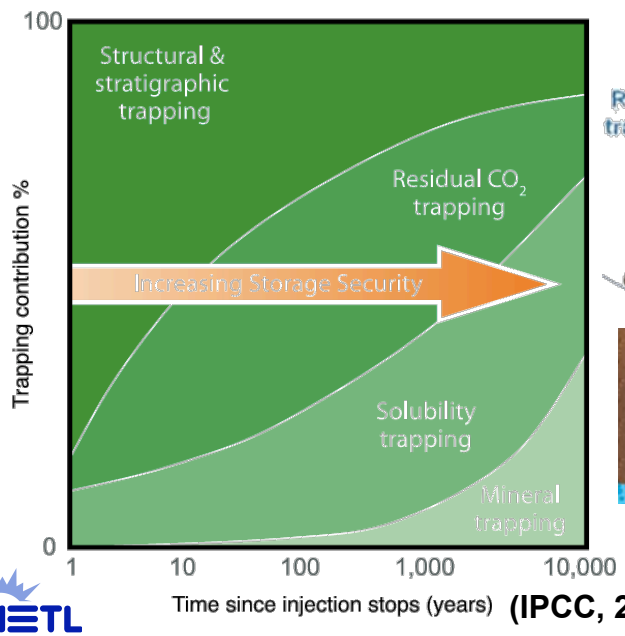


CONCLUSIONS

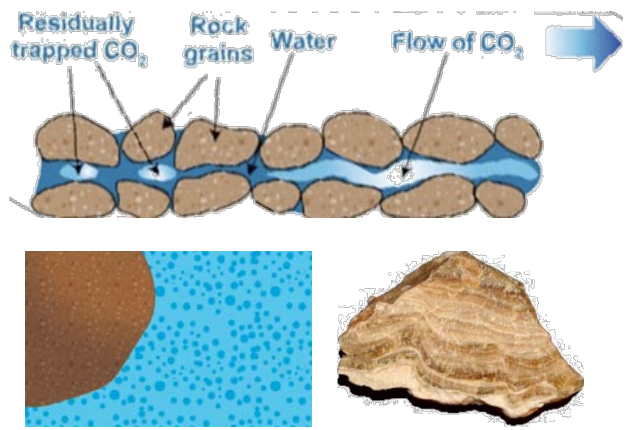
- **Developed a CO_2 sequestration simulator**
  - **Based mostly on the ideas of the CQUESTRA model**
- **Performed deterministic simulation and probabilistic risk assessment**
  - **Over 90% of the injected CO_2 is safely trapped underground after 5000 years in our simulations**
- **Parallel implementation of Monte Carlo simulation on GPUs**
  - **64 times speedups**

FUTURE WORK: CO_2 STORAGE IN DEEP SALINE AQUIFER

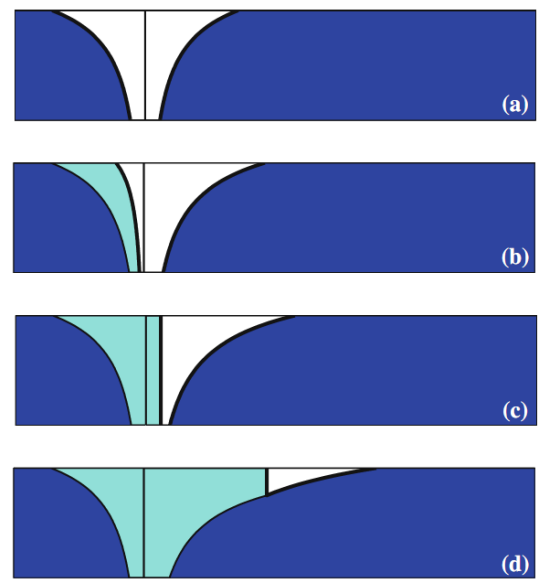
Formation	**Deep saline aquifer**	**Depleted oil/gas reservoir**
Time scale	10 — 100 — 1000 — Time (years) Injection | Post-injection Mobile | Immobile	
Trapping mechanisms	**Structural trapping** **Residual trapping**	**Solubility trapping** **Mineral trapping**



(IPCC, 2005)



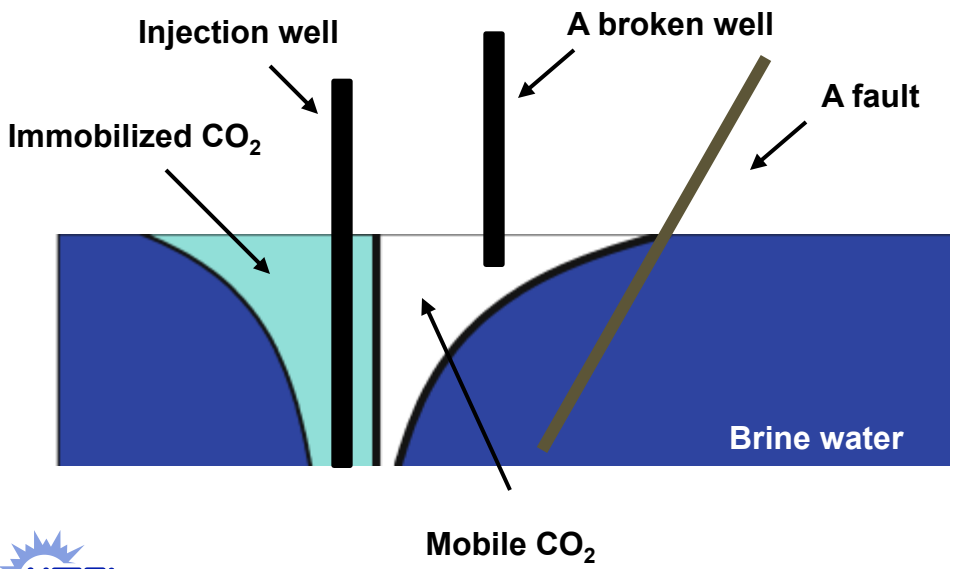
(Kaldi, 2010)

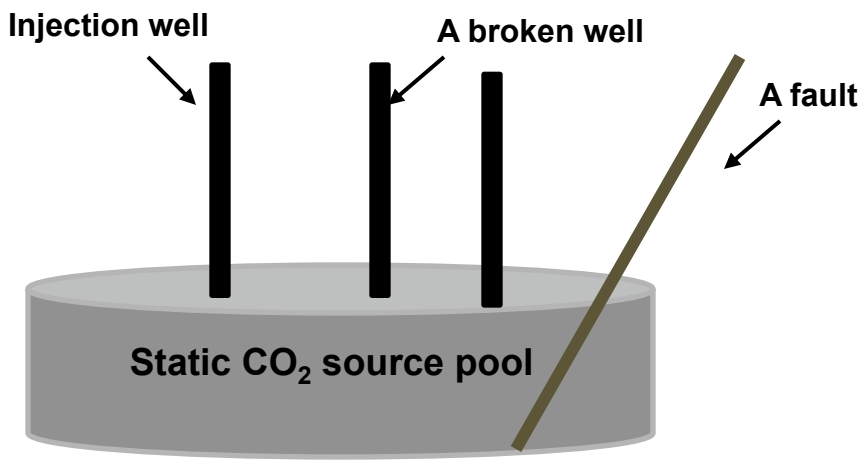


(Juanes et al., 2008)

FUTURE WORK: CO_2 STORAGE IN DEEP SALINE AQUIFER

Formation	Deep saline aquifer	Depleted oil/gas reservoir
Space	A layer of target formation Continuous	Individual reservoir(s) Discrete
Leaking scenarios	Leak when encountering broken wells Leak when encountering faults	Leak through intersecting wells Leak through faults/fractures





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Thanks! Questions?

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