RISK ASSESSMENT FOR CO_2 GEOLOGICAL SEQUESTRATION

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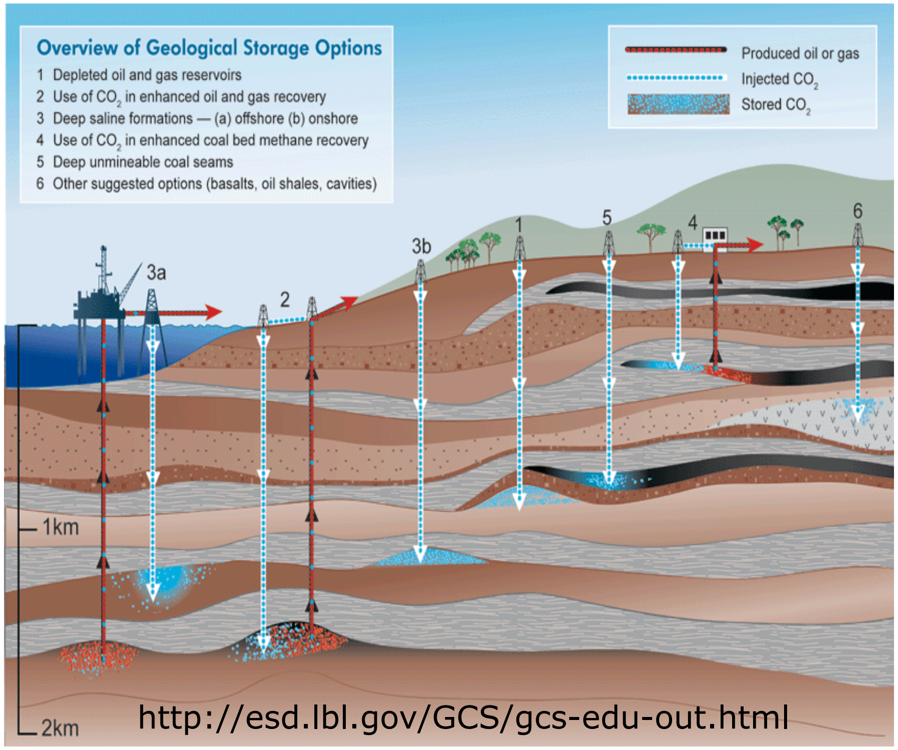
OUTLINE

- Introduction to CO_2 sequestration
- A sequestration simulator
- Risk assessment work
- GPU parallel computing
- Conclusions and future work

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

REVIEW OF SEQUESTRATION MODELING

- Assess the feasibility of CO_2 sequestration
- Models for
  - Pre-injection estimation: capacity evaluation, injection rate, etc
  - Post-injection prediction: evolution of the sequestration system

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Reference	Model	Modeled problems	Formation	Trapping mechanism
Bickle et al., 2007	analytical	Calibration of model to seismic monitoring data from the Sleipner injection site in the North Sea	homogeneous	
Bromhal et., 2005	numerical : PSU-COALCOMP	Storage with enhanced coal-bed methane recovery	homogeneous	sorption
Doughty and Pruess, 2004	Numerical: TOUGH2	Simulated injection at Frio, TX, test site, evaluated effects of numerical artifacts, choice of characteristic curves	Stochastic three-dimensional heterogeneous	Capillary trapping dissolution
Fiett et al., 2007	Numerical CHEARS	Injection into saline aquifer, assessed impact of varying heterogeneity(sand/shale ratio) on migration	Stochastic three-dimensional heterogeneous	Dissolution, capillary trapping
Gaus et al., 2005	Numerical	Considered impact of geochemical reactions induced by CO_2 injection on caprock integrity, based on the Sleipner site	Layered heterogeneity	Dissolution, mineralization

*: G.Schnaar and D. C. Digiulio, Vadose Zone Journal, 2009

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REVIEW OF SEQUESTRATION MODELING (CONT'D)

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Reference	Model	Modeled problems	Formation	Trapping mechanism
Gheraidi et al., 2005	Numerical: TOUGHREACT	Assessed impact of mineral precipitation and dissolution reactions on migration through caprock; sensitivity analysis for initial mineralogy, kinetic parameters, caprock permeability	Layered heterogeneity	Dissolution, mineralization
Izgec et al., 2005	Numerical: STARS	Calibrated model of mineral precipitation and decrease in permeability to data from core experiments; sensitivity analysis for mineralization rate parameters	Homogeneous	Dissolution, mineralization
Jessen et al., 2005	Numerical:ECLIPSE300	Injection with enhanced oil recovery operation, analyzed different operation strategies for maximizing storage	Stochastic heterogeneity	Dissolution, capillary trapping
Juanes et al., 2006	Numerical:ECLIPSE100	Injection into PUNQ-S3 oil production test-case model; sensitivity analyses for hysteresis	Heterogeneous	Dissolution, capillary trapping
Kovscek and Wang, 2005	ECLIPSE300	Geologic sequestration with enhanced oil recovery, evaluation of project design alternatives	Stochastic heterogeneity	Dissolution, capillary trapping
Knauss et al.,2005	Numerical: CRUNCH	One-dimensional radial injection into Frio formation, TX; evaluated impact of co-contaminants in injected CO_2 stream	Heterogeneous	Mineralization, dissolution

*: G.Schnaar and D. C. Digiulio, Vadose Zone Journal, 2009

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REVIEW OF SEQUESTRATION MODELING (CONT'D)

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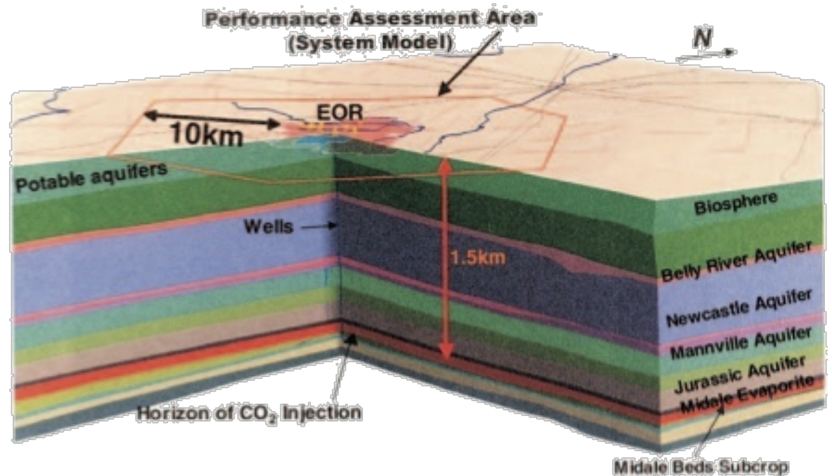
Reference	Model	Modeled problems	Formation	Trapping mechanism
Lagneau et al., 2005	Numerical: Hytec	One- and two-dimensional simulation of evolution of fixed circular zone of high dissolved-CO_2 water	Homogeneous	Dissolution, mineralization
Leonenko and Keith, 2008	Numerical: CMG IMEX	Assessed efficiency of brine circulation at accelerating dissolution of CO_2	Homogeneous	Dissolution
LeNeveu, 2008	Semianalytical: CQUESTRA	Semianalytical solutions for assessment of leakage through abandoned well bores and fractures; applied to data from Weyburn basin, Saskathewan	Layered heterogeneity	Dissolution, mineralization, capillary trapping
Lindeberg, 1997	Numerical: ECLIPSE100	Injection in formation similar to North Sea; sensitivity analysis for permeability; assessed leakage through penetration; migration under non-flat caprock	Homogeneous, layered heterogeneity cases	Dissolution
Nordbotten et al., 2004, 2005a, 2005b, 2006a, 2006b	Analytical	Analytical solutions for CO_2 leakage through abandoned wells	Homogeneous	
Oldenburg et al., 2001	Numerical: TOUGH2	Injection into formation based on Rio Vista gas field in California for sequestration and enhanced natural gas recovery	Homogeneous	

*: G.Schnaar and D. C. Digiulio, Vadose Zone Journal, 2009

CQUESTRA

- **IEA GHG Weyburn CO_2 Monitoring & Storage Project**



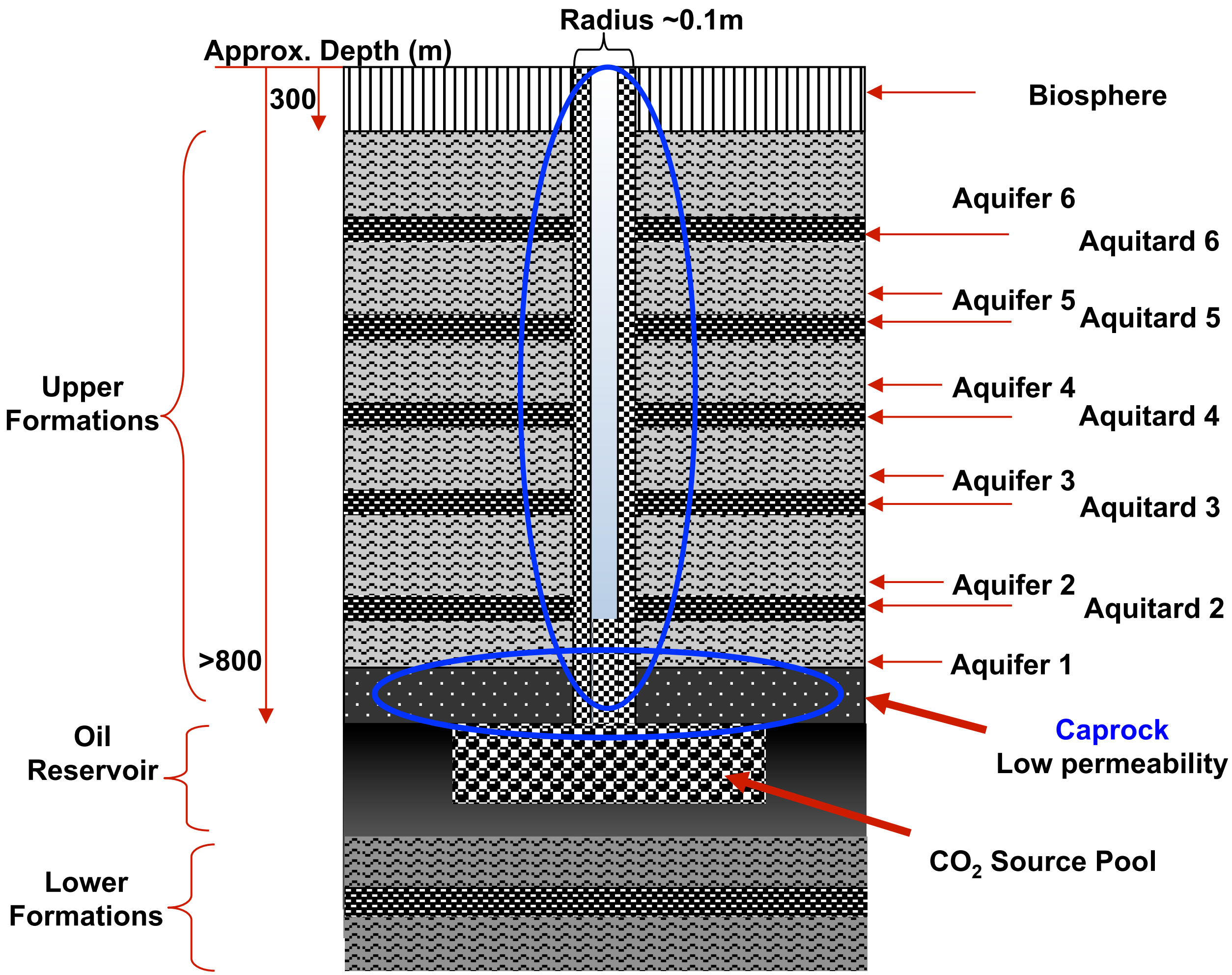
Figures from Whittaker et al., 2004

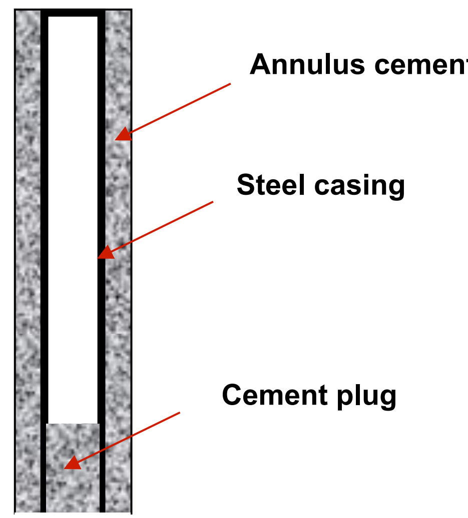
- **Address the migration and fate of CO_2 by quantifying**
  - **The leakage rate of CO_2 to the biosphere**
  - **The spatial extent of CO_2 plumes underground**
- **Starts from the end of EOR phase**

REVIEW OF RISK ASSESSMENT WORK

- **What is the risk associated with sequestration?**
- **Models are used for quantitative risk analysis to predict CO_2 movement in response to varying conditions or scenarios**
  - **Walton et al., 2005, used probabilistic risk assessment to understand and evaluate the performance of CO_2 geological sequestration.**
  - **Raza et al., 2009, performed uncertainty analysis using Monte Carlo simulation for capacity estimates and leakage potential for a saline aquifer.**

PHYSICAL SYSTEM





Simplified geological structure

PROCESS DESCRIPTION

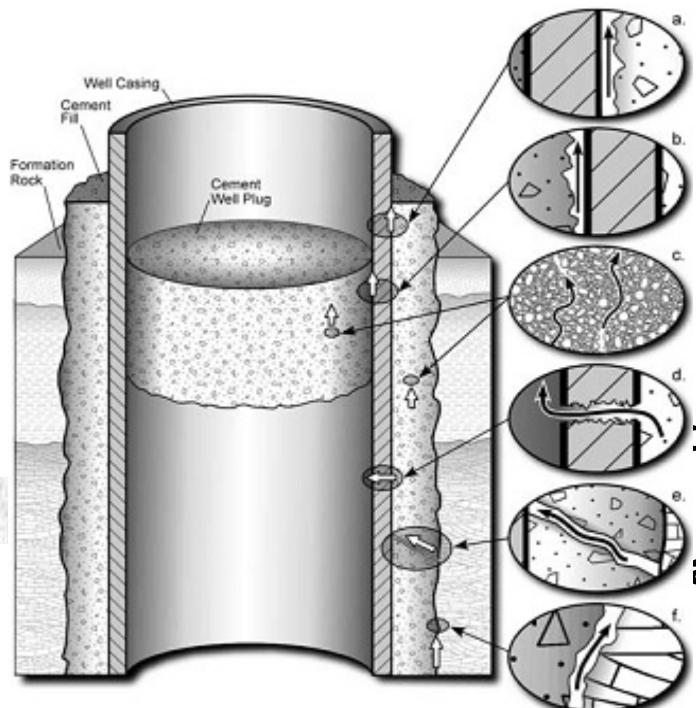
- **Viability of a sequestration system:**

Leakage

Failed seals of wellbore

vs .

Sequestration



ding formations

apping

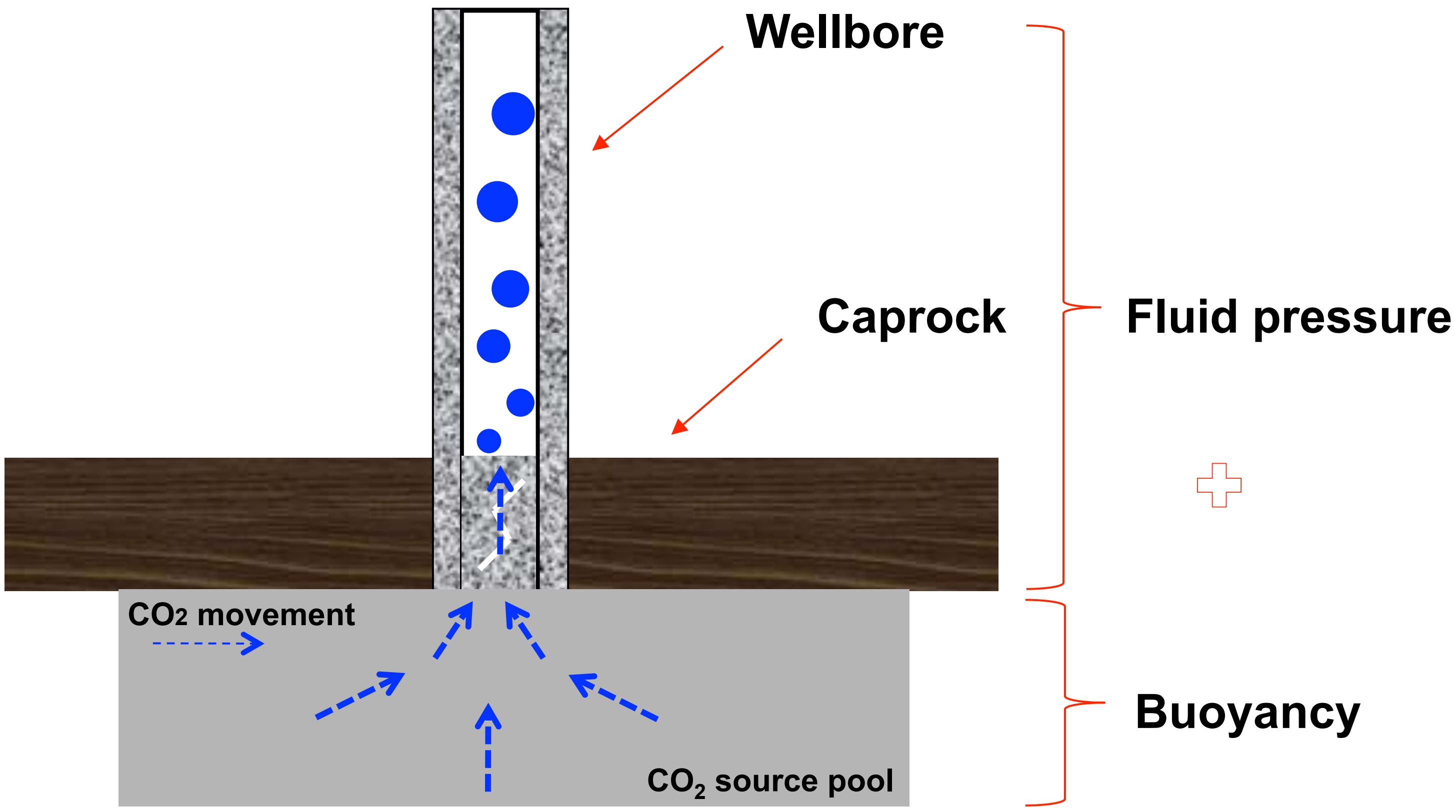
Celia et al., 2004

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

M: CO_2 mass
Fi: inflow rate = 0
Fo: outflow rate = leakage-sequestration

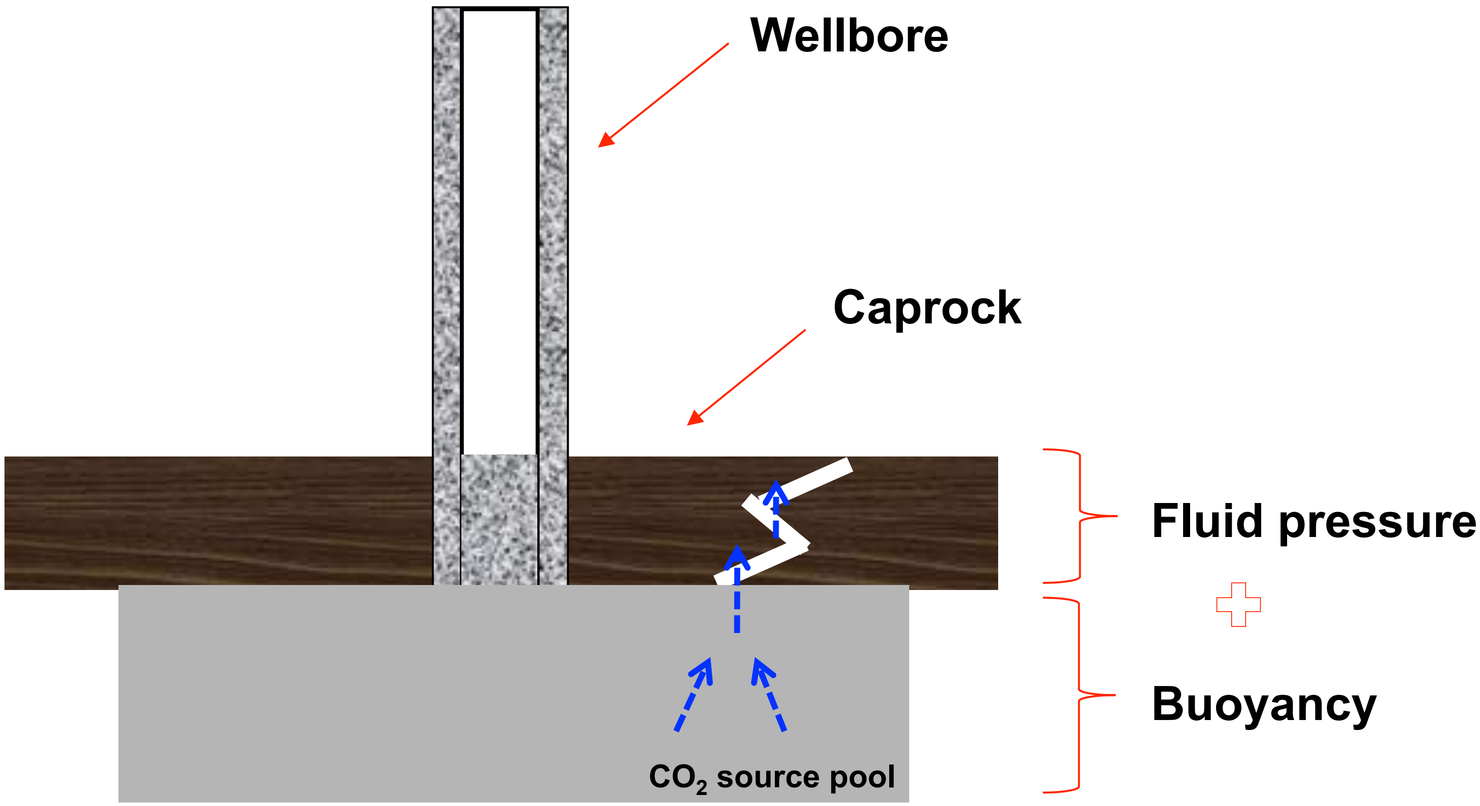
LEAKAGE THROUGH WELLBORE

- **Non-penetrating well equation**



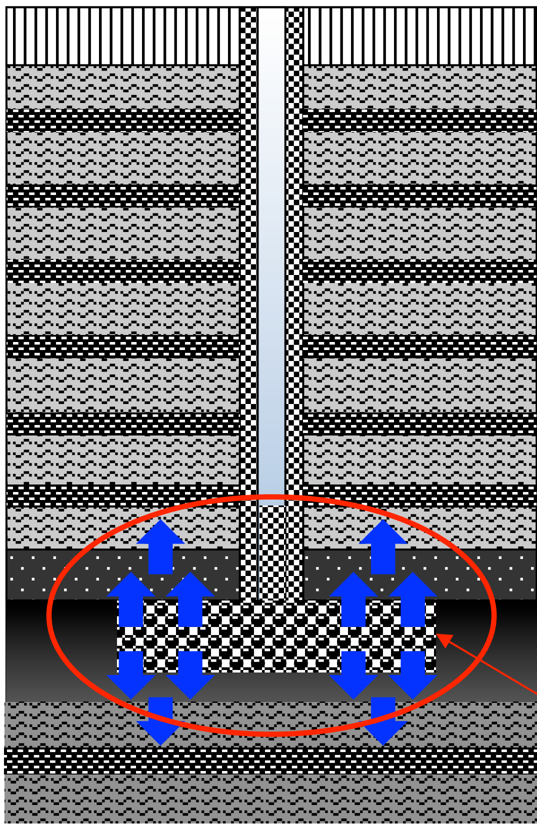
MOVEMENT THROUGH CAPROCK

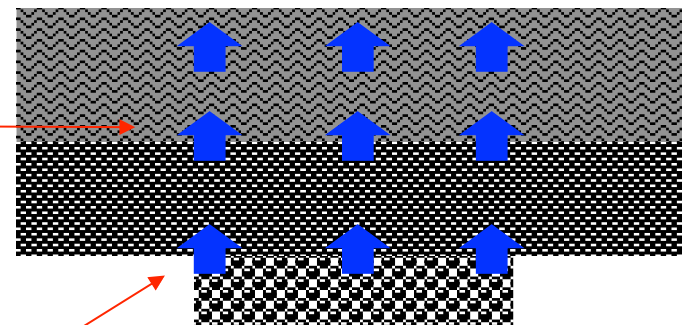
- Equation for drainage in tunnels



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

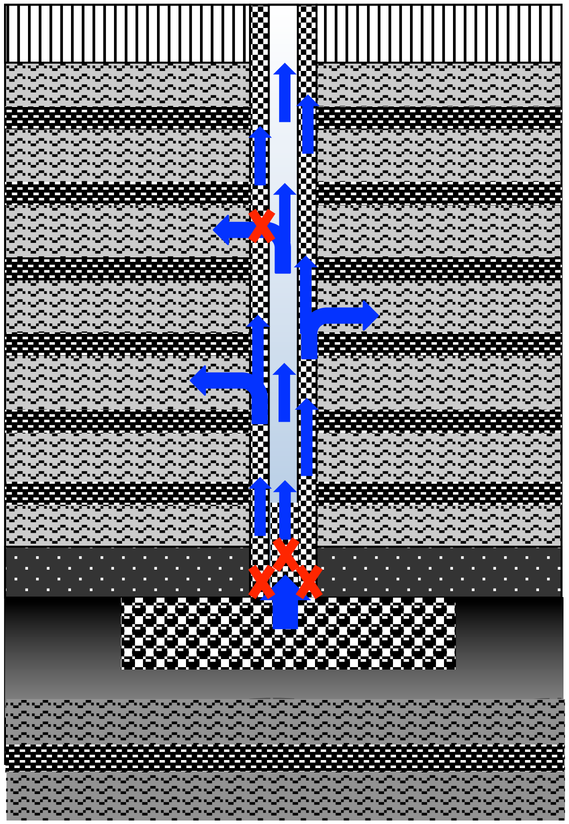
    - Aquifer with advection, dispersion and reaction
    - Aquitard with diffusion and reaction

    ➔ Apply solution for temperature profile

    ➔ Get CO_2 concentration in the formation

    ➔ Obtain steady state flux at the wall of the wellbore

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



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

OVERALL MASS BALANCE

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

$$M = M_0 \exp(-\beta t) - \frac{F_D}{\beta}[1-\exp(-\beta t)] - \frac{2\alpha \exp(-\beta t)}{\sqrt{\pi\beta}} \int_0^{\sqrt{\beta t}} \exp(\lambda^2)\,d\lambda$$

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

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

Depends on the failure times of wellbore components

M_0 is the initial mass of the CO_2 source pool; F_D is the flow rate by diffusion from pool; λ is the first order rate constant for mineralization; N_w is the number of wellbores intercepting the pool; N_F is the number of fractures in the caprock; ρ_w is the density of water; ρ_s is the density of the CO_2 phase; K_s is the hydraulic conductivity of the reservoir; K_F is the hydraulic conductivity of the fracture; φ_s is the average head gradient; φ_F is the head gradient at the fracture; ε_s is the porosity of the reservoir; S_s is the fractional saturation of CO_2 in source pool; r_b is the radius of wellbore; h0 is the initial height of the source pool; w_F is the width of the fracture; A_s is the area of the source pool; C_o is the solubility of CO_2 ; D is the free diffusion coefficient; and τ is the tortuosity factor.

MODEL PARAMETERS

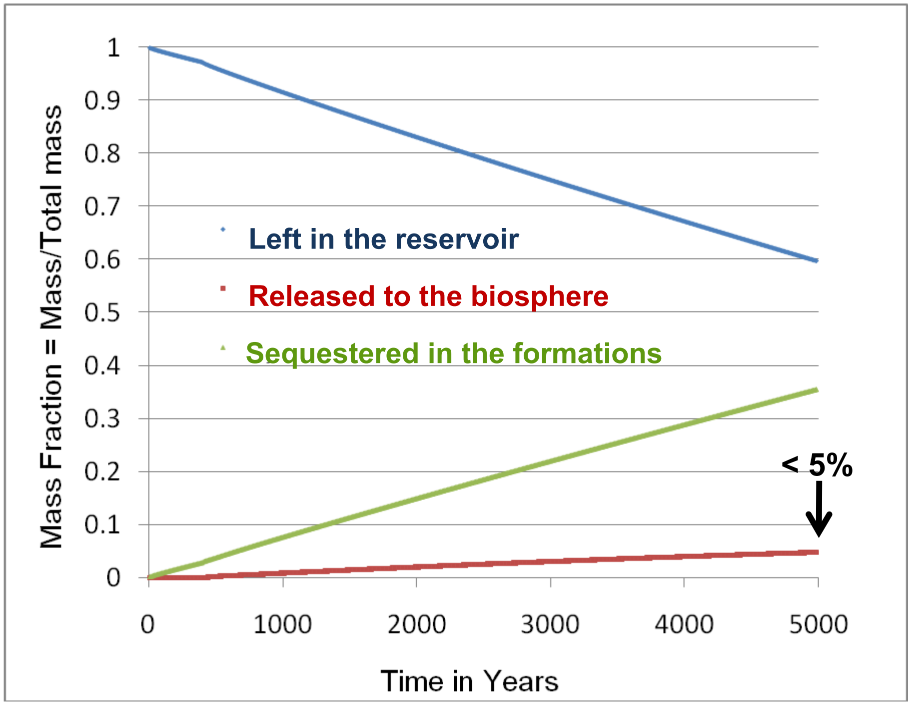
- **Parameters:**
  - Main independent parameters

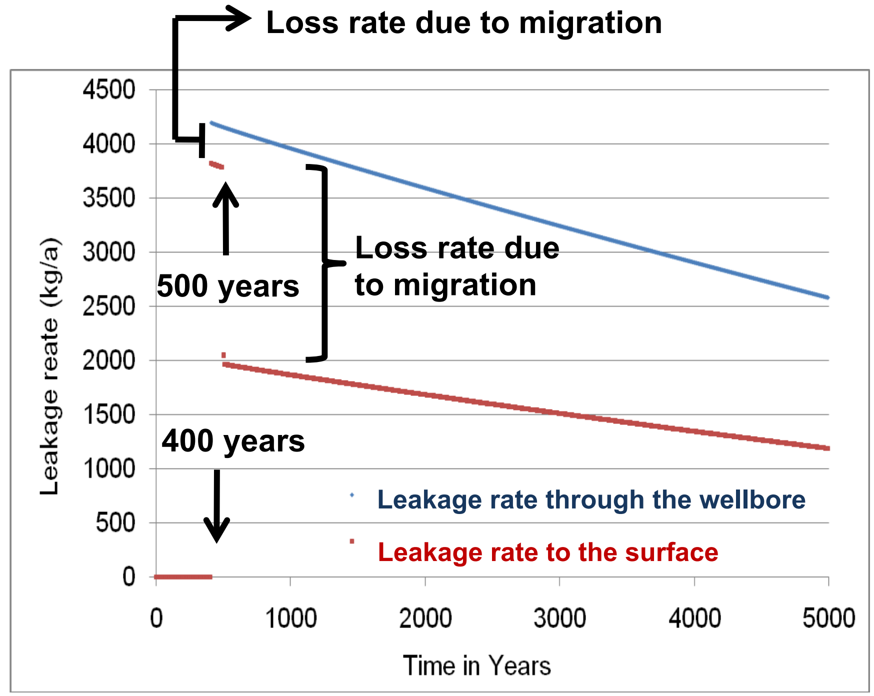
Formation	Brine water	CO_2 phase	Wellbore
•Depth •Thickness •Permeability •Porosity •Tortuosity •Mineralization rate •…	•Salinity •Pressure •Surface tension of the free phase •Temperature gradient •Darcy velocity •Capillary pressure in reservoir •Dispersion coefficients •…	•Mass •Composition •Thermo-property •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.

RESULTS FOR ONE SET OF PARAMETERS





CO_2 mass fractions vs. time

CO_2 leakage rate (kg/a) vs. time

RISK ASSESSMENT

- **Probabilistic risk assessment** provides risk distribution due to the uncertainty

Input:
Randomly Sampled from probability distribution function of independent parameters

Monte Carlo simulation →

Output:
Statistical Analysis

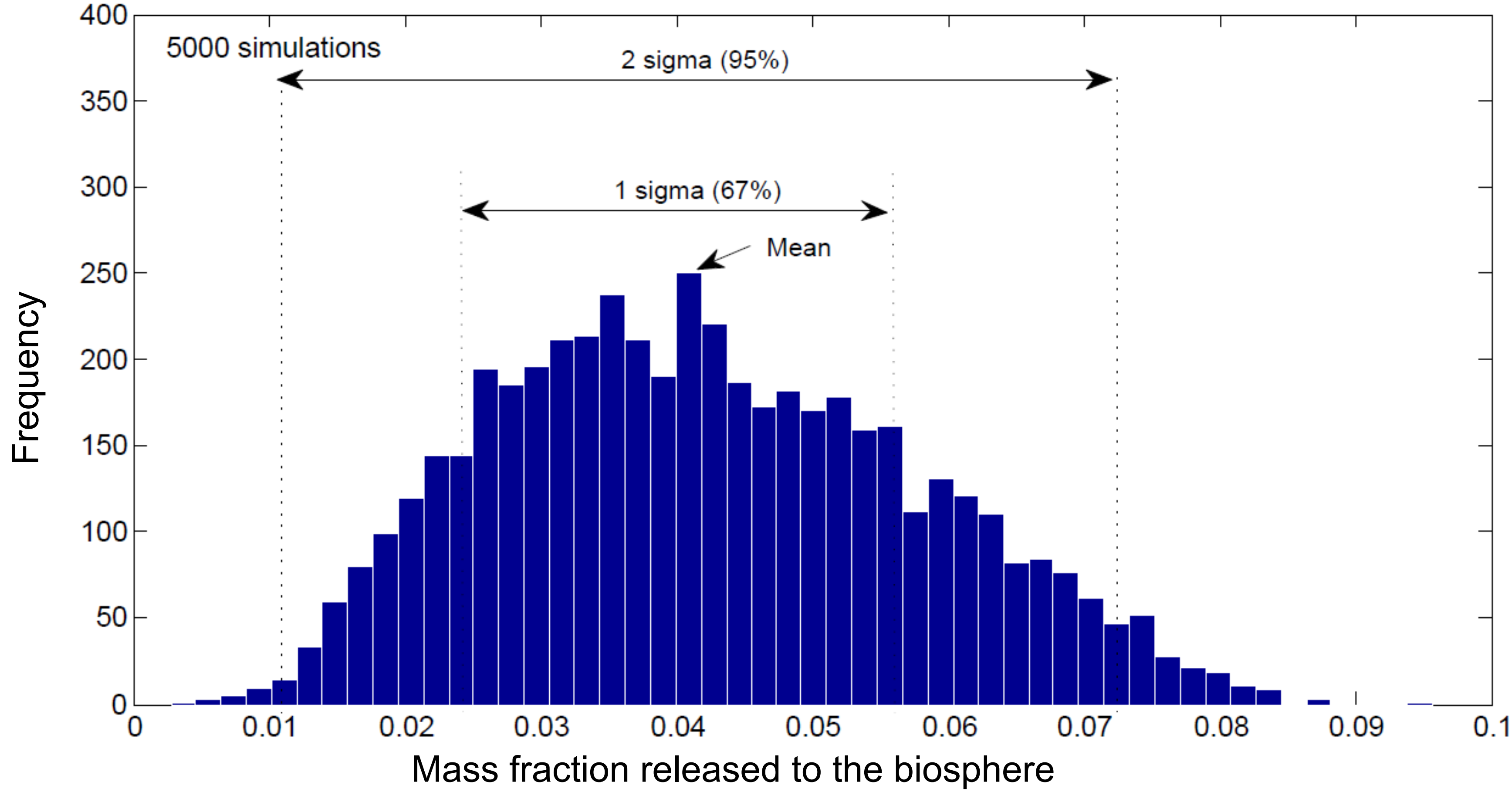
MONTE CARLO SIMULATION

Generated inputs with independent parameters							
sample #	x1	x2	x3	x4	x5	…	xn
	Permeability	Porosity	Leakage time	Darcy Velocity	Fracture #'s	…	
1							
2							
…							
5000							

Simulator

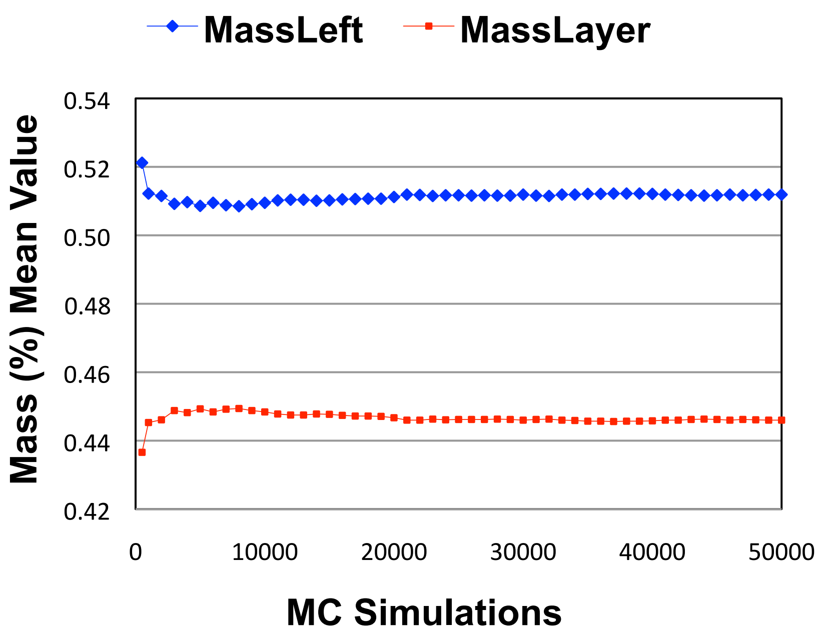
Model Outputs				
y1	y2	y3	…	ym
Mass left	Mass released	Leakage rate		
1				
2				
…				
5000				

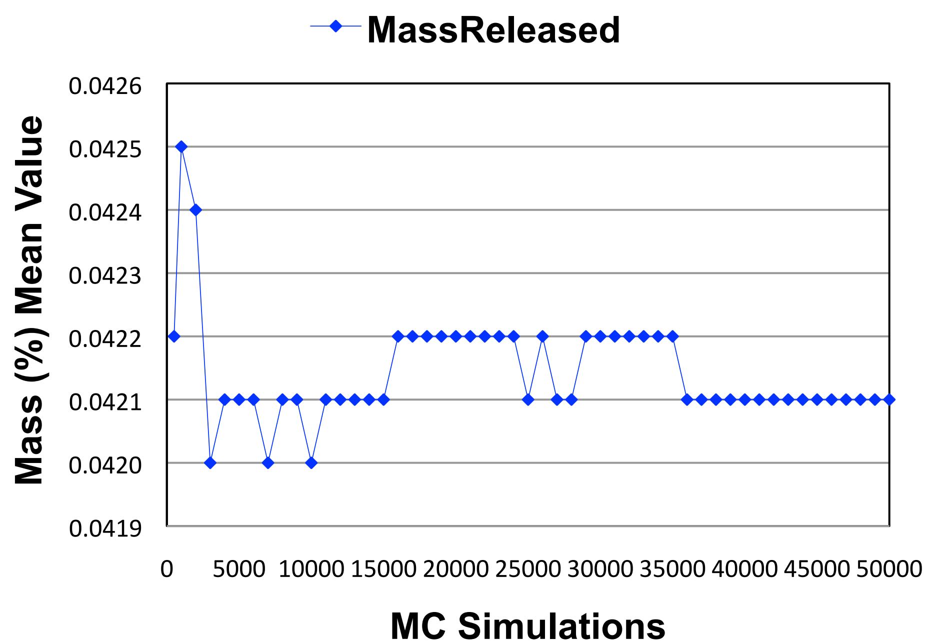
RESULTS FOR MONTE CARLO SIMULATION



Frequency histogram showing fraction released to the biosphere at 5000 years

CONVERGENCE OF MONTE CARLO SIMULATION



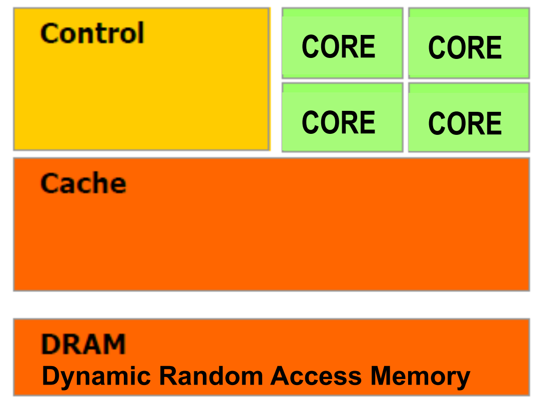


Mean value of mass fractions vs. numbers of simulations

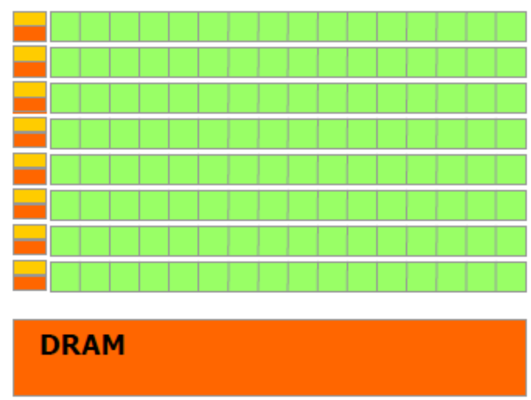
GPU PARALLEL COMPUTING

- Multi-core and many-core

CPU



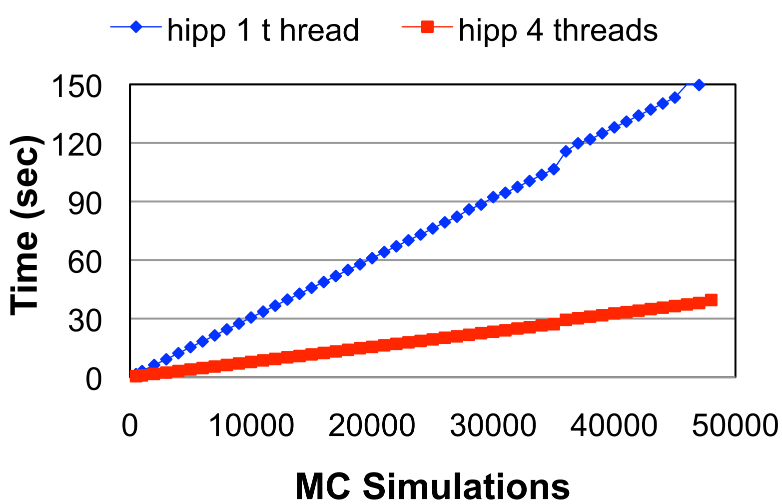
GPU



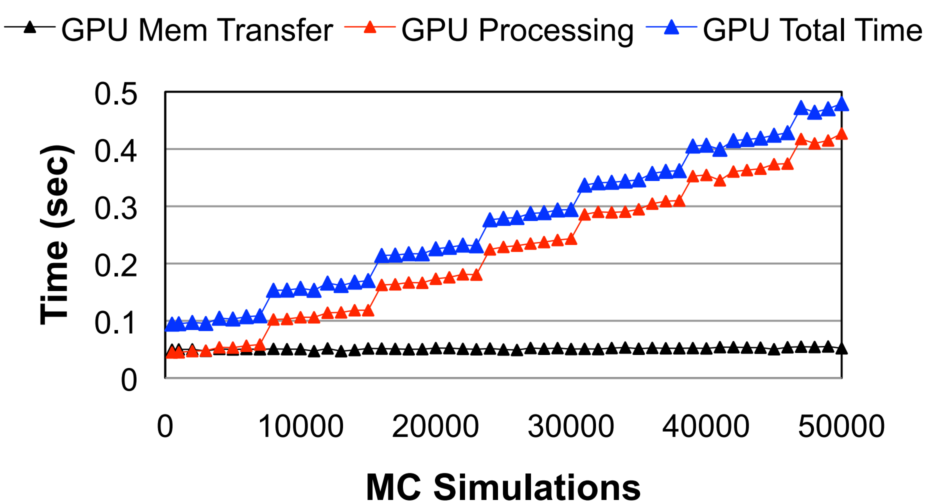
http://www.nvidia.com/object/GPU_Computing.html

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

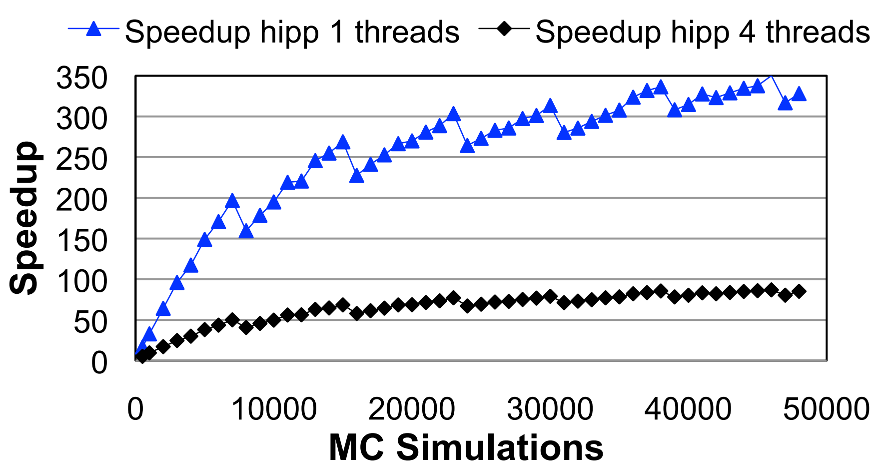
GPU SPEEDUPS



Intel Core2 Quad @ 2.83 GHz



Tesla C1060 series GPUs, 240 Processors



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CONCLUSIONS AND FUTURE WORK

- 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
  - 350 times speedups
- Future work
  - Conduct extensive scenario analysis
  - Identify parameters/failure scenarios using derivative-free optimization algorithms

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