Basin-Scale Leakage Risks from Geologic Carbon Sequestration:

Impact on CCS Energy Market Competitiveness

DOE Award DE-FE0000749

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U.S. Department of Energy
National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and Building the Infrastructure for CO_2 Storage
August 21-23, 2012

Presentation Outline

- Benefits to CCUS research program
- Project Goals & Objectives
- Technical Status
  - Thrust I – Reservoir-scale simulations of leakage potential with permeability evolution
  - Thrust II – Leakage impact valuation and risk
  - Thrust III – CCS energy market competiveness and best practices for siting
- Accomplishments to Date
- Summary

Benefit to the Program

This research project has developed simulation tools that predict potential leakage rates from CO_2 injection zones. The basin-scale simulation tool is unique because it accounts for potential changes in leakage rates through wells and caprock fractures caused by geochemical reactions. The project has also developed novel analytical tools that use the geospatial simulations of leakage rates to predict the financial consequences of CO_2 and brine leakage interferences with other subsurface activities and resources. Finally, the project has developed an integrated framework to predict how the costs of leakage could impact the competiveness of CCS in the energy market.

This project contributes to the Carbon Storage Program's effort to develop technologies to demonstrate that 99 percent of injected CO_2 remains in the injection zones, and to the development of BPMs for site selection, characterization, site operation, and closure practices.

Project Overview: Goals and Objectives

- Thrust I: Predict leakage from CO_2 injection zones with precision and low computational effort
  - Develop computationally efficient geochemical models to predict permeability evolution of leakage pathways (PEL model)
  - Incorporate PEL model into the basin-scale simulation tool ELSA
  - Demonstrate ELSA-PEL for CO_2 injection into the Mount Simon sandstone in Ottawa County, MI
- Thrust II: Quantify financial consequences of leakage including costs from interferences with subsurface resources
  - Evaluate and map subsurface resources
  - Develop framework for costing impact to different stakeholders
  - Develop model to predict geospatial risk/probability of incurring leakage costs/damages
- Cont. ..

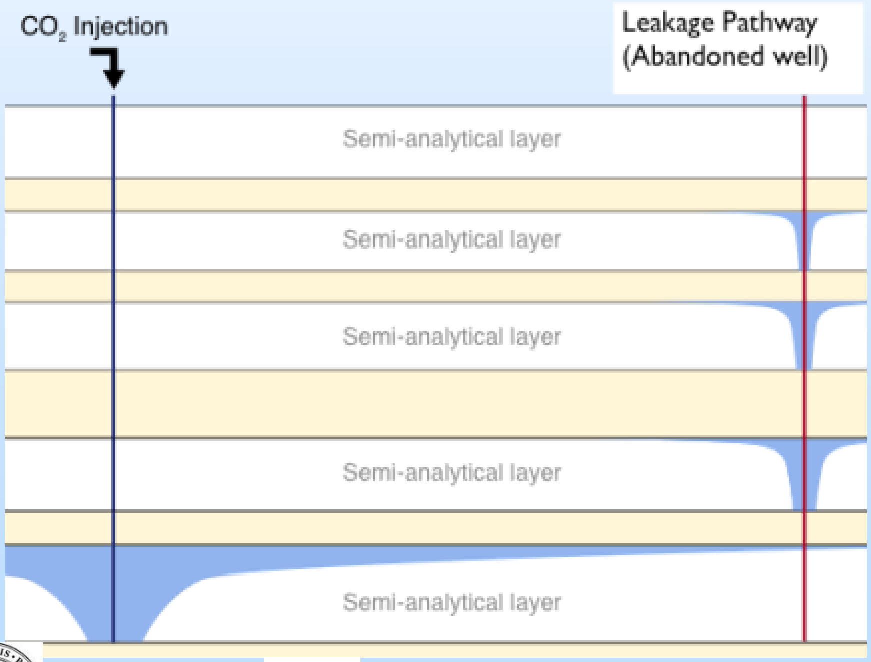
Project Overview (cont.): Goals and Objectives

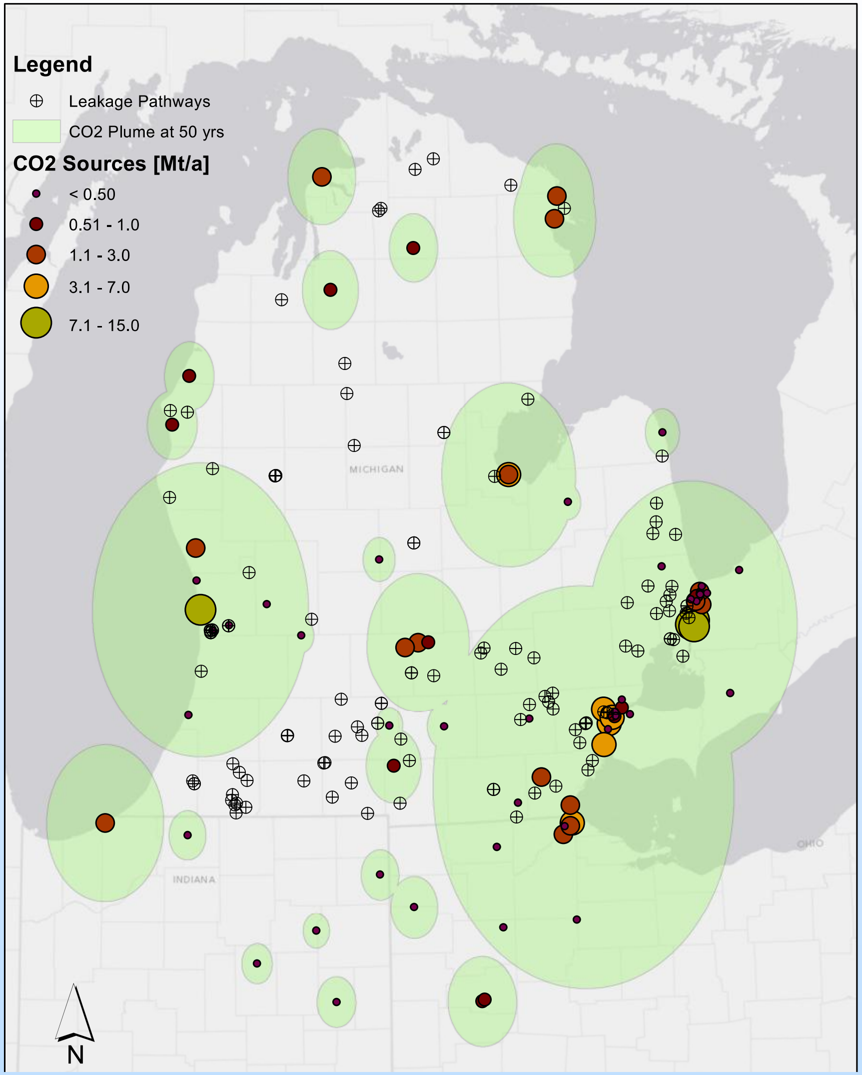
- Thrust III: Examine the competitiveness of CCS in the energy market and quantify the impact of leakage on this market competitiveness
  - Develop costing model for CCS that incorporates cost of leakage
  - Incorporate CCS with leakage into the energy market model MARKAL
  - Evaluate economic mechanisms to increase CCS penetration of the energy market

Basin-Scale Leakage Risk Modeling

Novel aspects of this work:

- Determining the potential for geochemically-driven permeability evolution of leakage pathways
- Predicting leakage interferences with valuable subsurface resources

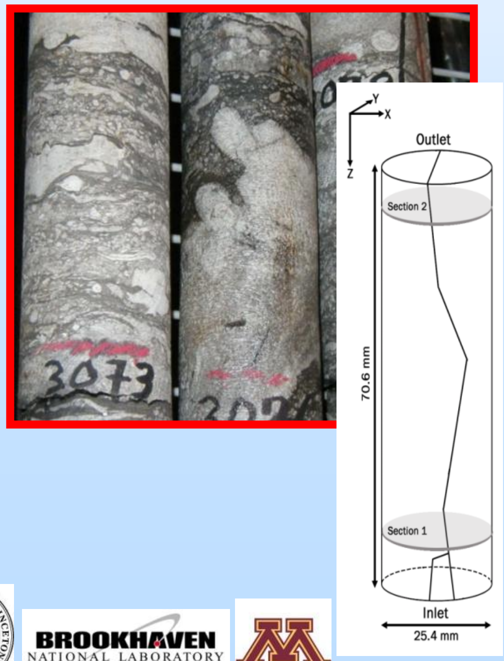




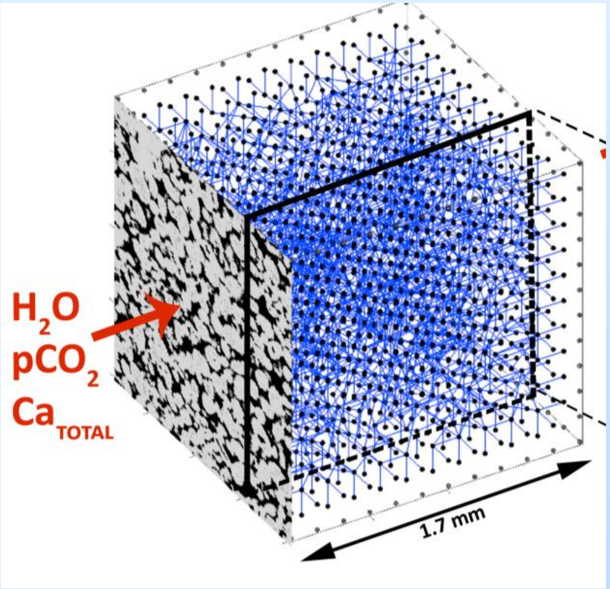
ELSA simulations of 50-yr CO_2 plumes
For CO2 injected under major emitters

What are the conditions that will lead to enhanced or degraded sealing along reactive leakage pathways?

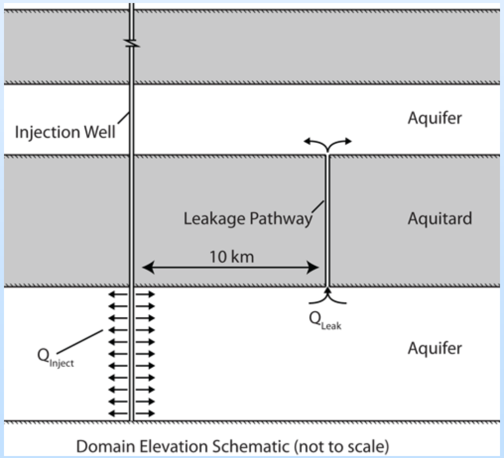
1. Core-scale observations of fractures altered by CO_2-acidified brine



2. Pore-network model of permeability evolution

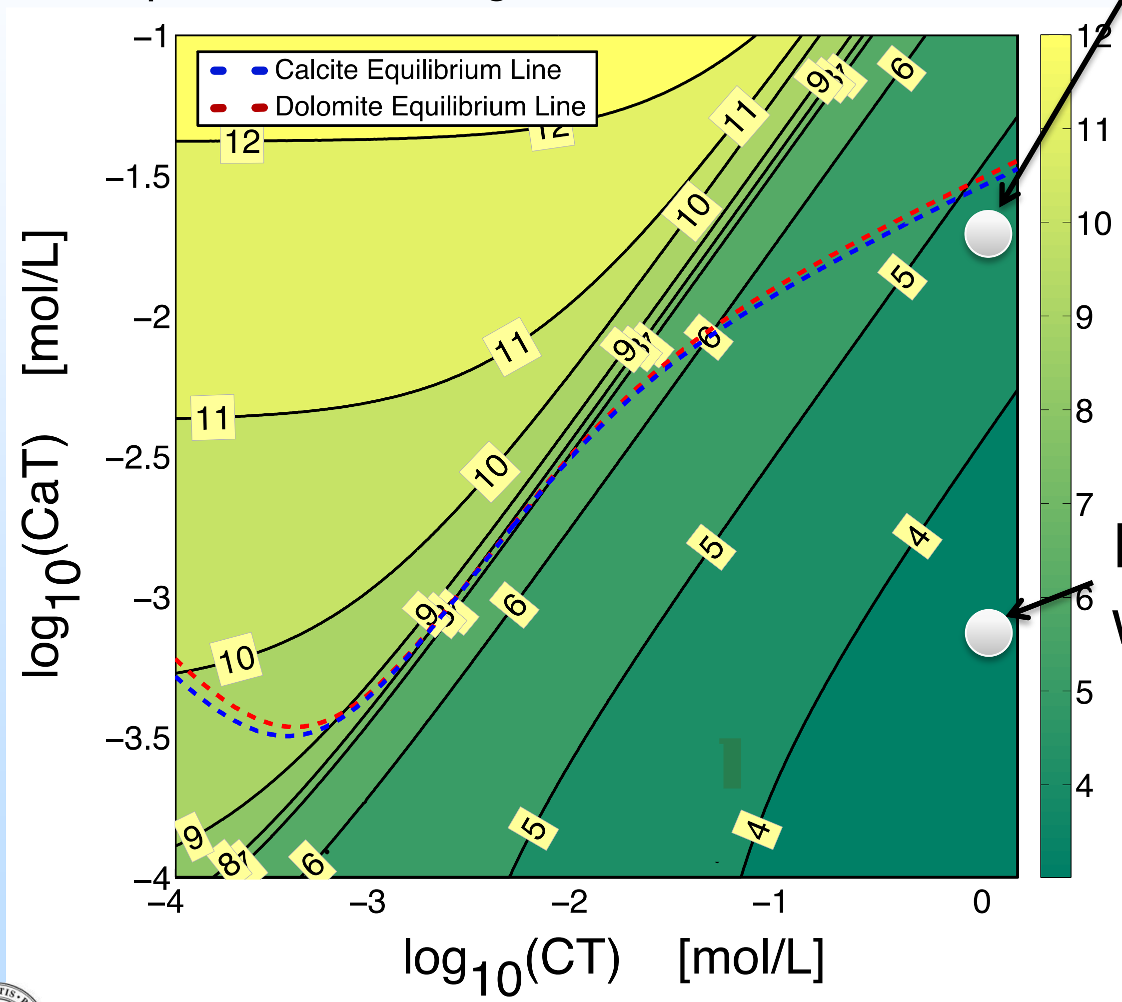


3. Basin-scale leakage model w/ permeability evolution

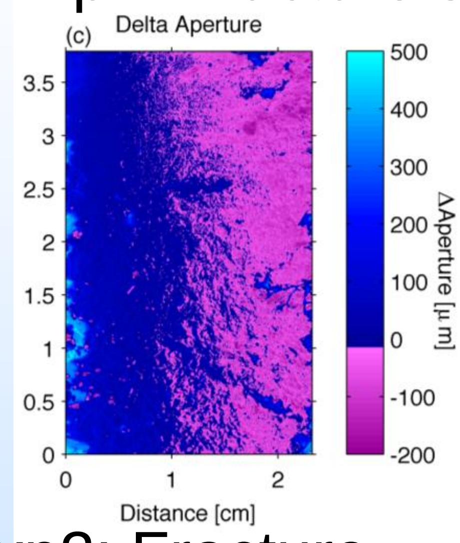


Experiments show potentially important geochemical alterations of caprocks

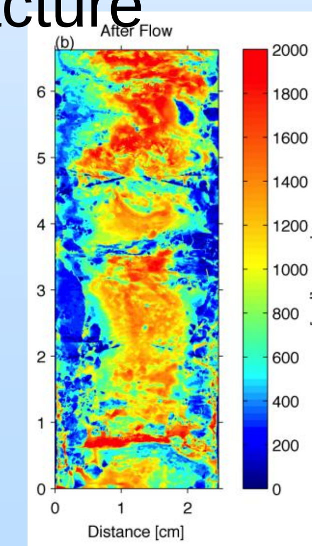
pH Contour – MgT = 30% of CaT



Exp1: Fracture sealing

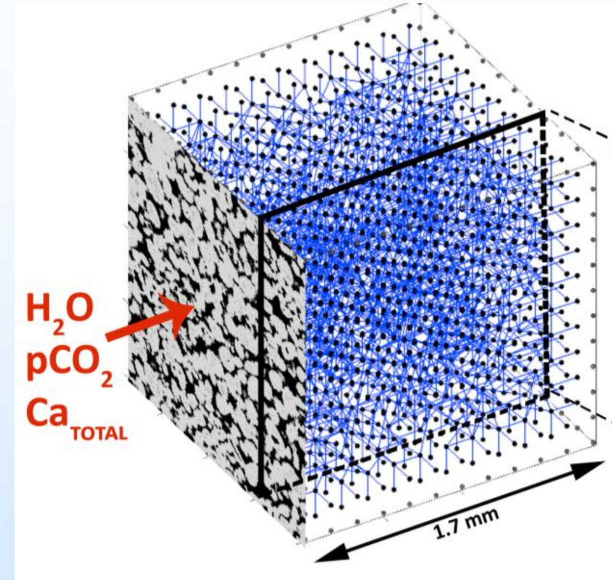


Exp2: Fracture widening

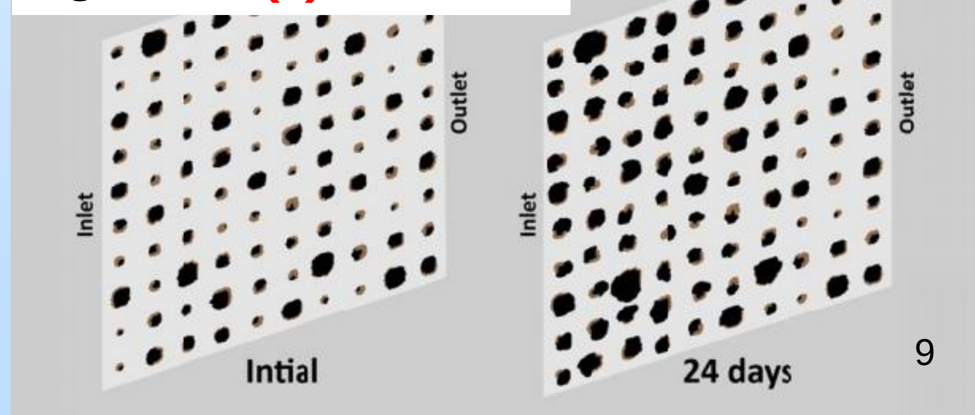


Understand the relationship between permeability evolution and geochemical processes

- Developed pore-network model to explore vast geochemical parameter space
- *Finding*: Predominant impact of calcite dissolution
- *Finding*: Precipitation is slow and results from implausible mixing conditions

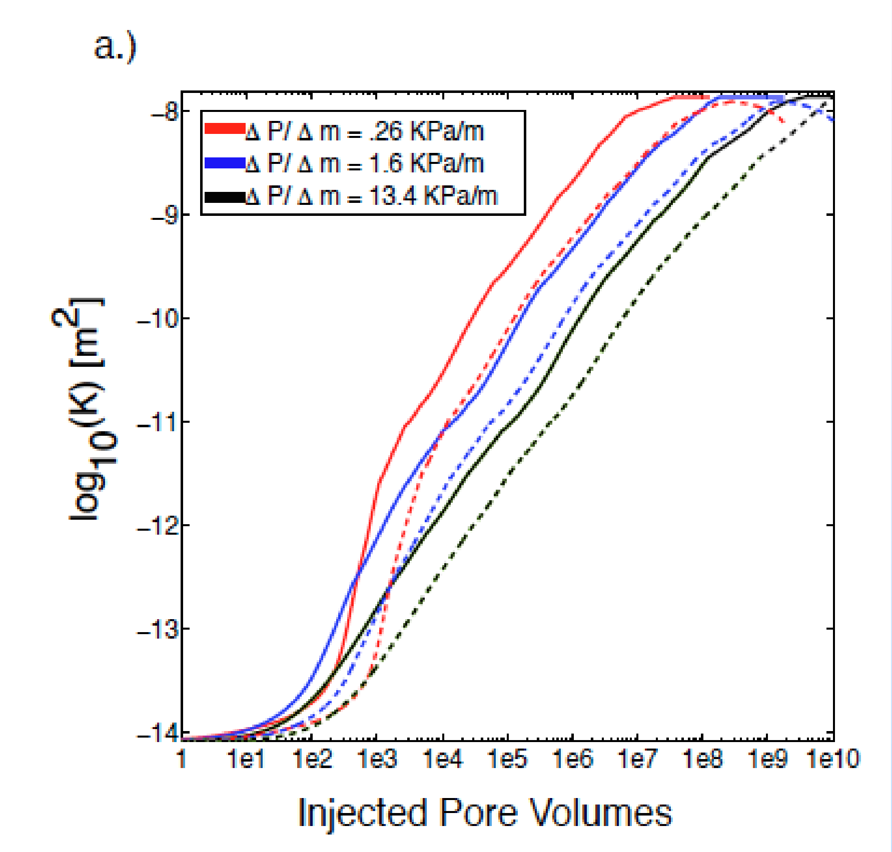


$$Q \sim K(t)\ dP/dl$$



Flow and geochemical conditions complicate predictions of permeability evolution

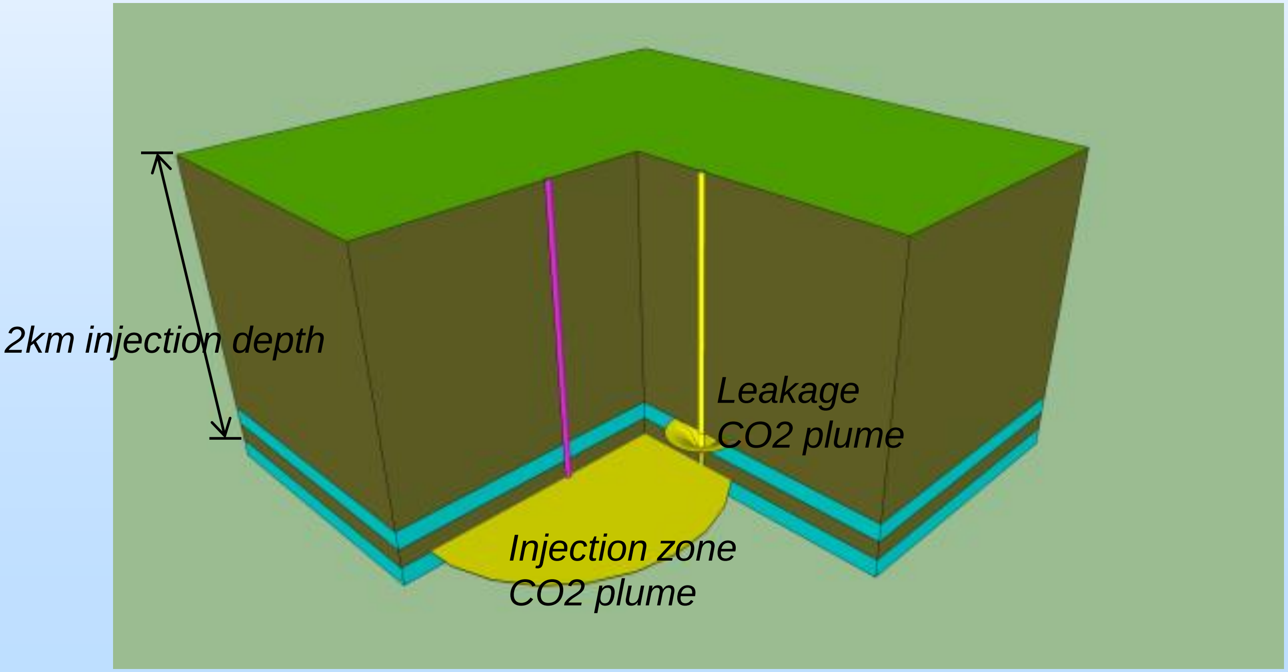
- Simulated evolution of pore networks with different:
  - Mineral composition & spatial distribution
  - Pressure gradient, pH, [Ca] & total carbon
- *Finding*: Simulations produce families of curves that can be used to up-scale permeability evolution



Up-scale geochemically driven permeability evolution for basin-scale simulations

Work in progress:

- Develop kinetic treatment of calcite dissolution within caprock leakage pathways
- Show how permeability evolution impacts leakage predictions for different injection scenarios in Ottawa County



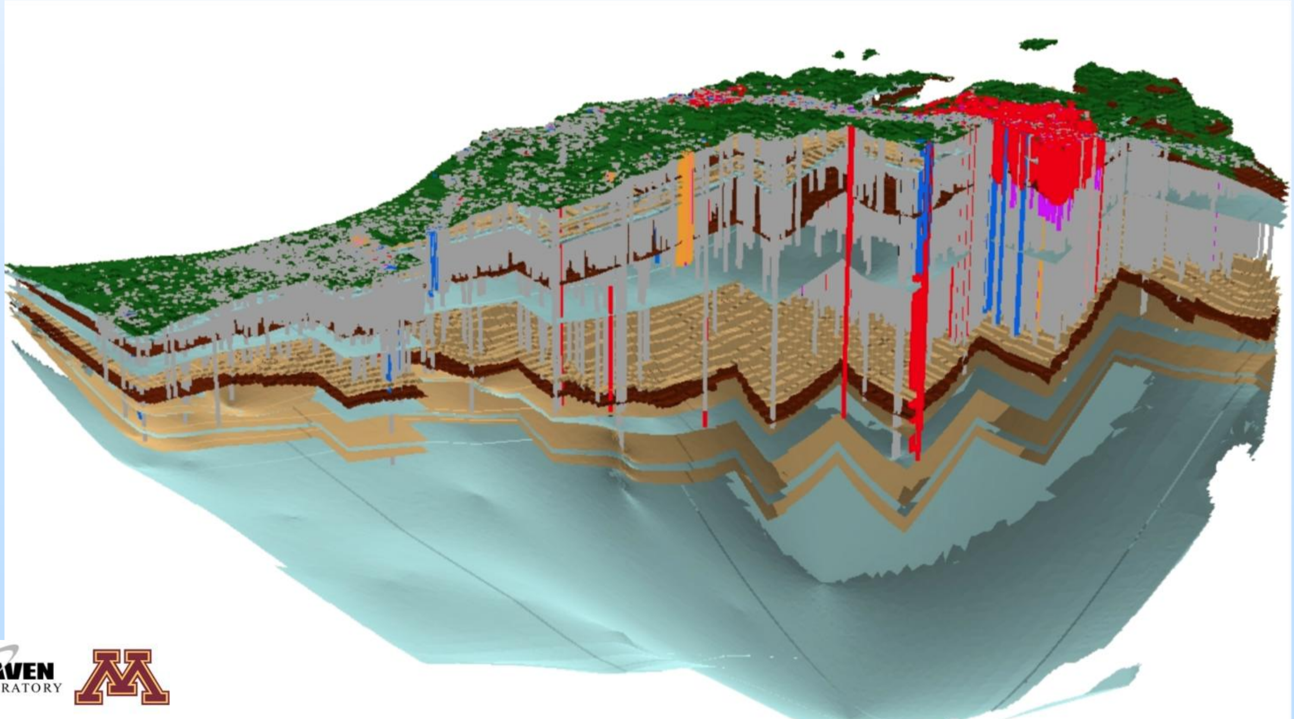
3D Basin-Scale Modeling of CO_2 and Brine Leakage

Leakage Impact Valuation (LIV) methodology

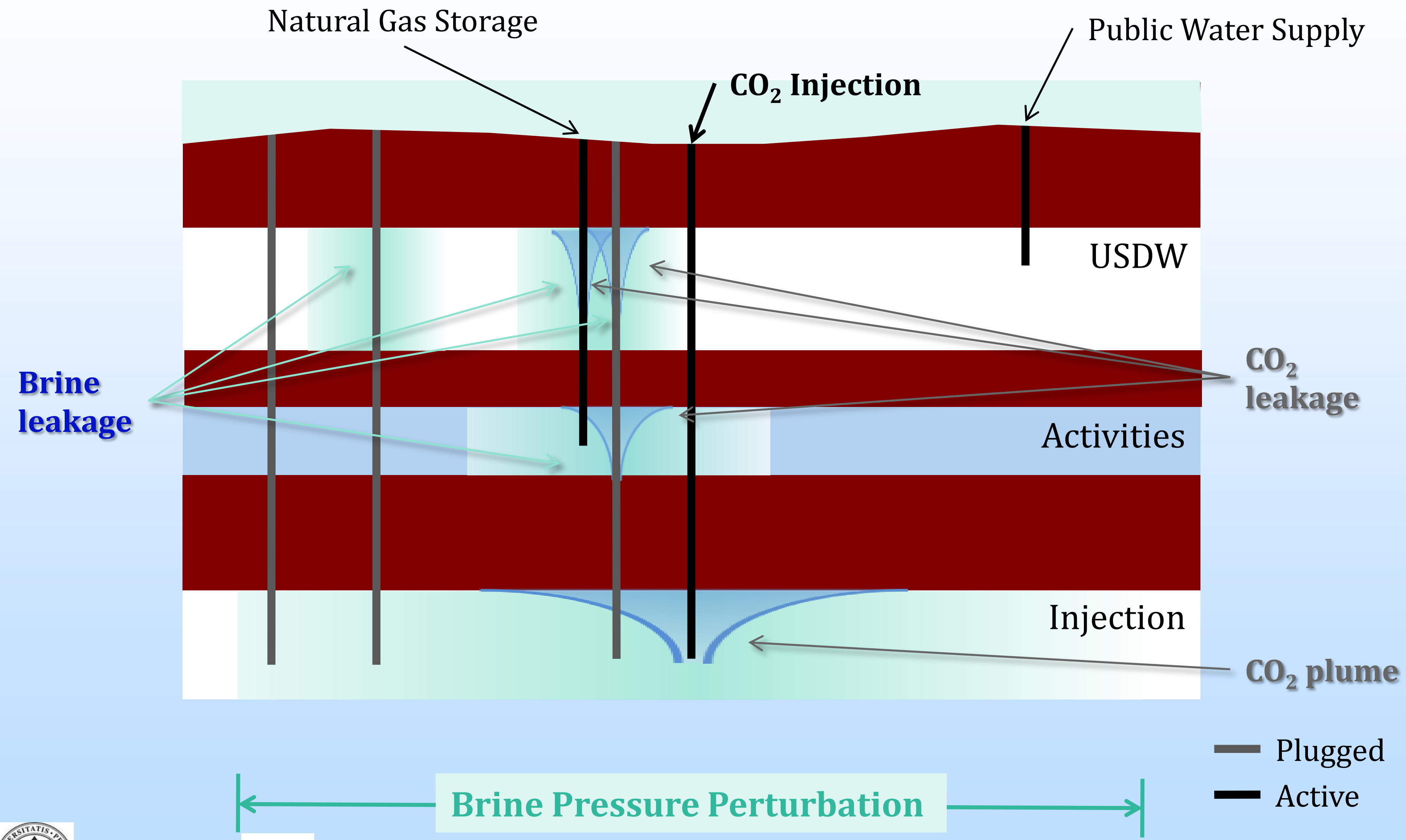
- Identification of major stakeholders
- Financial consequences of leakage

RISCS: Risk Interference of Subsurface CO_2 Storage

- Risk of interference with valuable subsurface resources
- 3D Monetized Leakage Risk Analysis

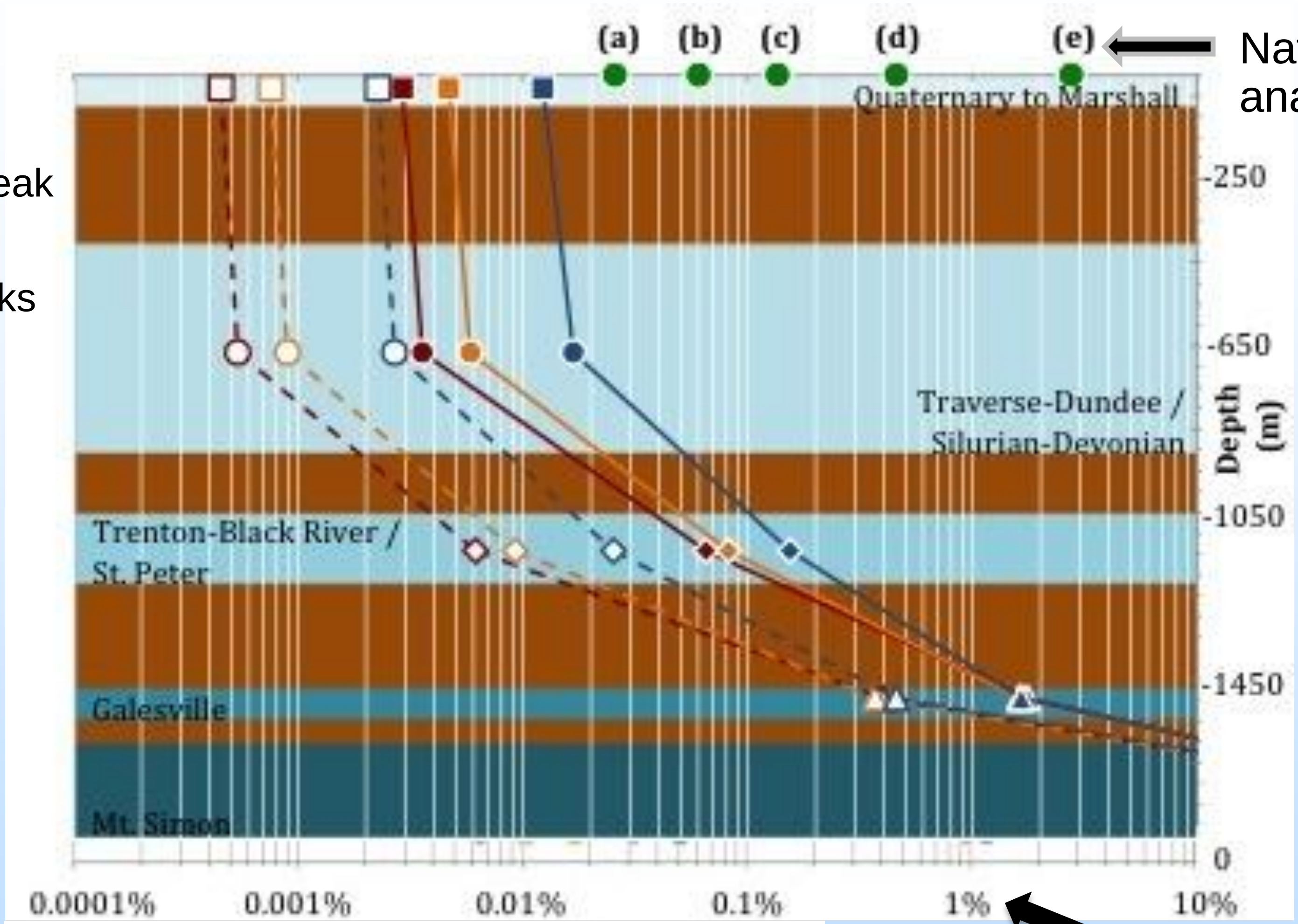


Leakage Interference



Predicted CO_2 leakage into overlying aquifers

Solid
– all wells leak
Dashed
– 1 well leaks



CO_2 leakage after 30 years of injection

Natural leakage analogs (a-e)

Carbon Storage program's goal: <1% CO_2 leaks from injection zone

Leakage Impact Valuation

TYPE OF COST	LEAKAGE SCENARIO																			
	Leakage					Interference: Subsurface Activity					Interference: Groundwater					Migration to Surface				
Diagnostic Monitoring	GO		WU	CP	SO	GO	AO	WU	CP	SO	GO	AO	WU	CP	SO	GO	AO	WU	CP	SO
	GR			CR		GR	AR		CR		GR	AR	WR	CR		GR	AR	WR	CR	E/HR
Containment Activities	GO	AO	WU		SO	GO	AO	WU		SO	GO	AO	WU		SO	GO	AO	WU		SO
	GR		WR			GR	AR	WR			GR	AR	WR			GR	AR	WR		E/HR
Damages	GO	AO				GO	AO				GO	AO	WU			GO	AO	WU	CP	SO
	GR	AR				GR	AR				GR	AR	WR			GR	AR	WR	CR	E/HR
Subsurface Remediation	GO				SO	GO	AO			SO	GO		WU		SO	GO		WU		SO
	GR		WR			GR	AR	WR			GR		WR			GR		WR		ER
Climate Program Compensation	GO			CP		GO			CP		GO			CP		GO			CP	
				CR					CR					CR					CR	

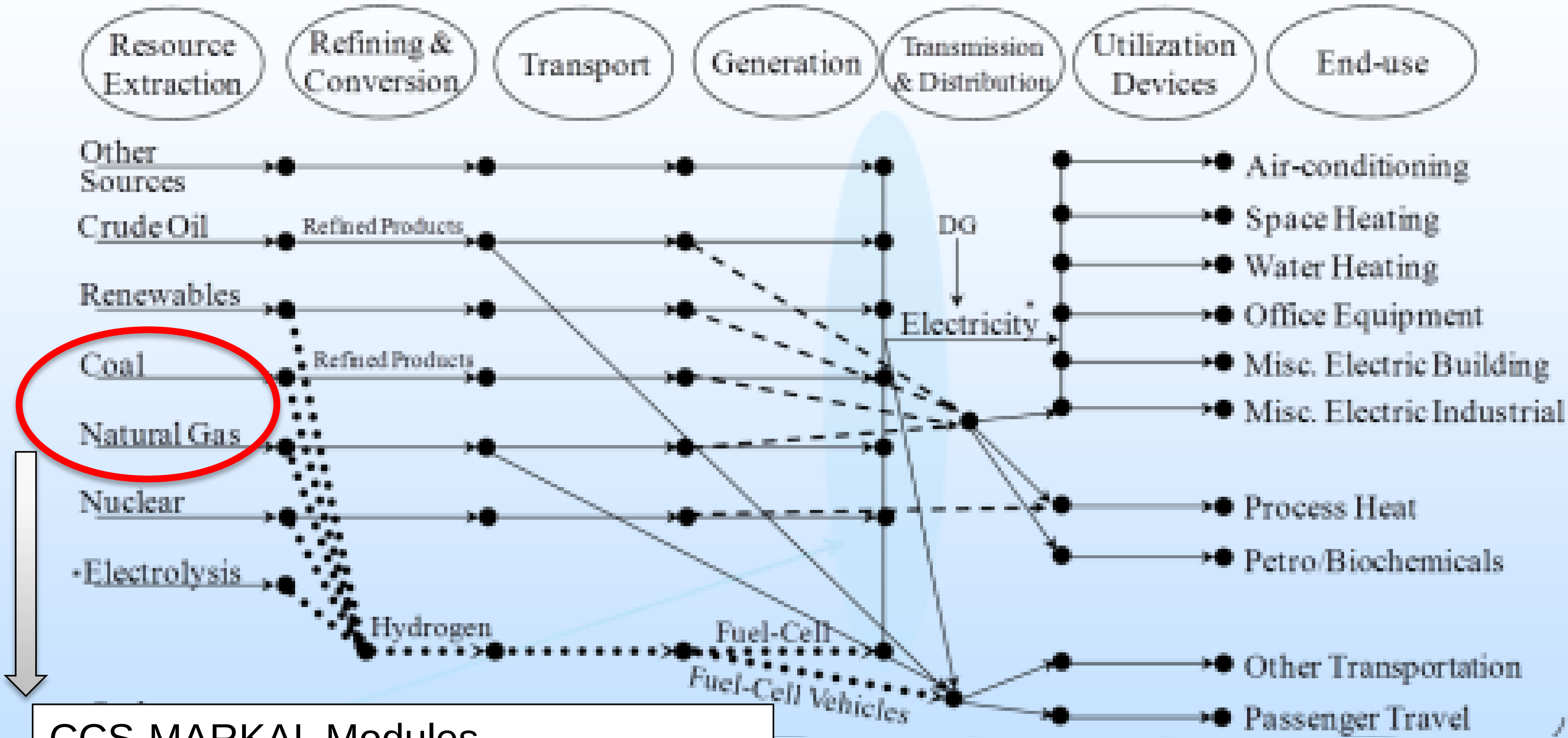
Total Estimated Costs $M (*Natural Gas Storage)	**Low**	**High**	**Low***	**High***	**Low**	**High**	**Low**	**High**
	2.7	97.2	4.9	113.8	38.5	124.3	2.8	129.1

GO	Injection Operator	**AO**	Activity Operator	**WU**	Groundwater User	**CP**	CO2 Producer	**SO**	Surface Owner
GR	Injection Regulator	**AR**	Activity Regulator	**WR**	Groundwater Regulator	**CR**	Climate Regulator	**E/HR**	Environmental/Health Regulator

Financial Consequences of Leakage -- Findings

- Costly even if it causes no subsurface damage, triggers no legal action, and needs no environmental remediation
- Major cost drivers are the obligation to remedy the leak and the potential for the GS operation to incur business interruption costs
- The normalized cost of leakage is very likely to have marginal impact on the total cost of CCS
- Widespread deployment of CCS decreases the financial consequences of leakage

Evaluating Penetration of CCS into U.S. Energy Market Using MARKAL

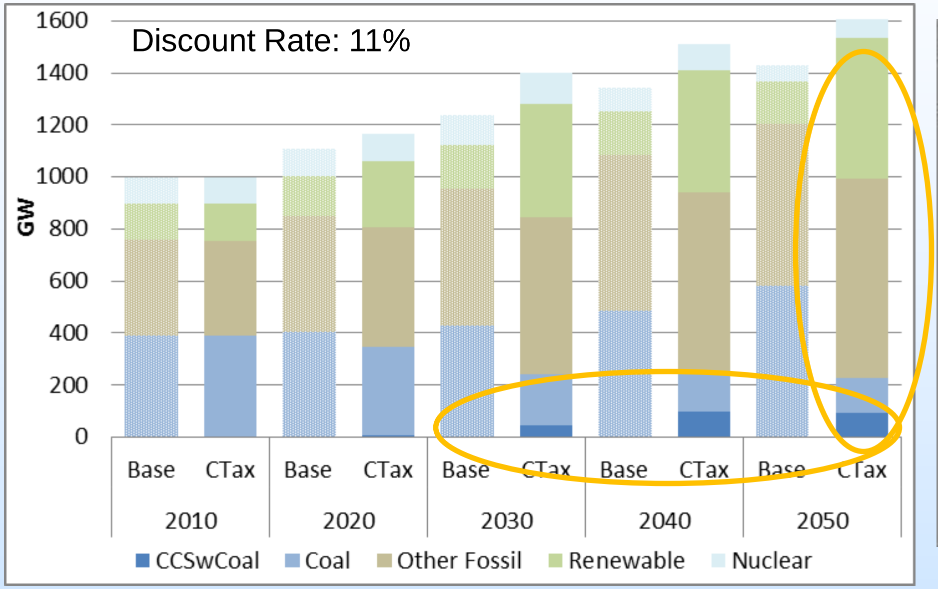


CCS-MARKAL Modules

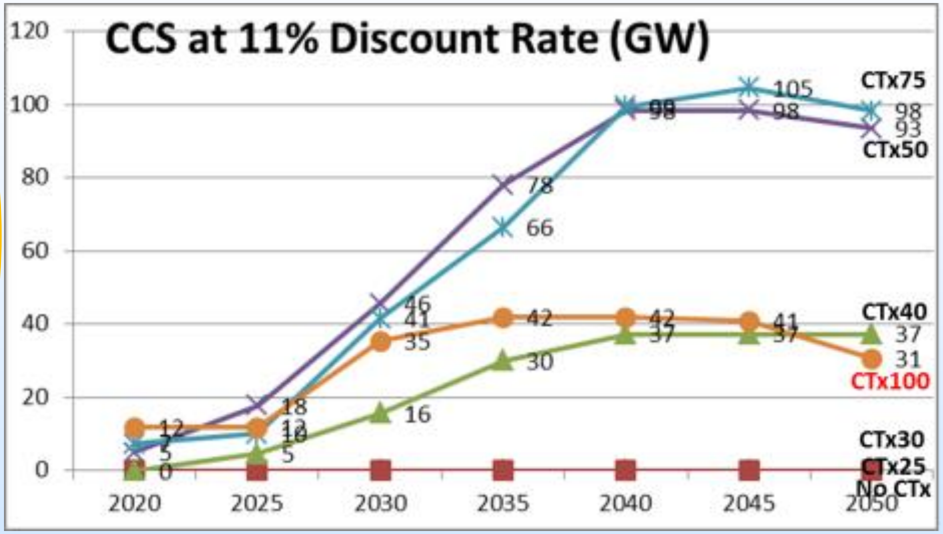
- Costs of capture, transport, injection
- GHG emissions reduction
- Financial consequences of leakage

Energy Market Competitiveness of CCS

Electricity Market: Base Case vs. CO_2 Tax $50



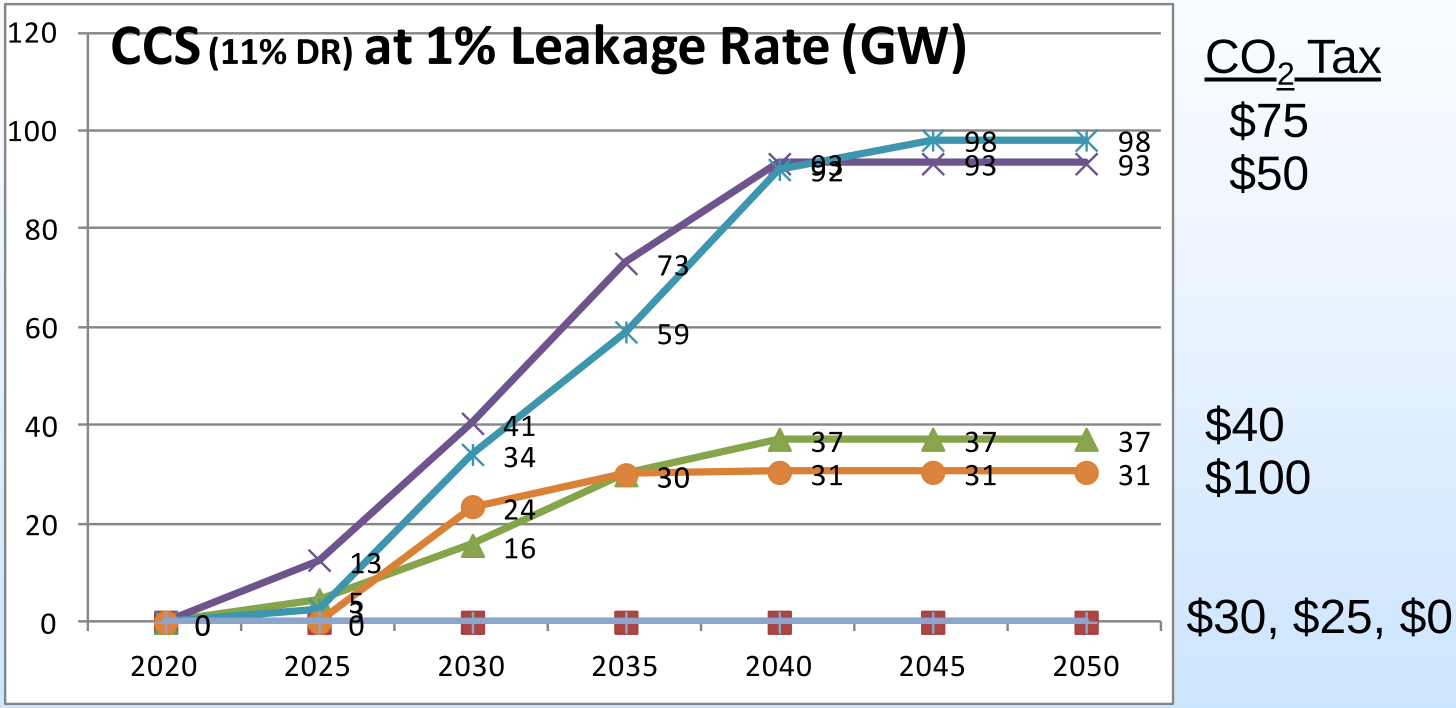
CO_2 Tax Scenarios in the U.S. Energy Market



- Coal deployment decreases in CO_2 tax case, but coal with CCS increases.
- Natural gas and renewables capture more market share

- CCS needs financial incentives to achieve significant market share
- MARKAL points to an optimal carbon tax ($50-70) supporting CCS penetration
- At $100 CO_2 Tax – CCS faces stiff market competition from other energy sources

Impact of Leakage on CCS Competitiveness in the Energy Market



- Cost of 1% leakage rate per year has minimal impact on CCS penetration into the energy market
- Therefore, market forces will not drive the selection of sites with the lowest leakage risk
  - ➢ Need for Site Selection BPM’s coupled with regulatory oversight

Accomplishments to Date – pg1

- Developed an integrated 3D GIS model of the Michigan sedimentary basin underlying the lower peninsula of Michigan, including hydrostratigraphic units and their geologic properties, and more than 400,000 oil, gas and water wells.
- Comprehensively reviewed legal scholarship, legal precedent, and regulations regarding civil and administrative damages for subsurface property in the Michigan Basin, including a comparative analysis of the degree of relevance to CO_2 injection for storage.
- Measured fracture evolution in carbonate caprocks from the Michigan Basin due to simulated leakage of CO_2-acidified brine.
- Developed a reactive transport pore network model to simulate permeability evolution of leakage pathways and used the model to examine the role of geochemical and mineralogical impacts on caprock integrity.
- Developed and demonstrated the Leakage Impact Valuation (LIV) model which estimates the financial consequences of leakage by comprehensively accounting for financial consequences to impacted stakeholders and interferences of leaked CO_2 and brine with other subsurface resources.
- Cont.

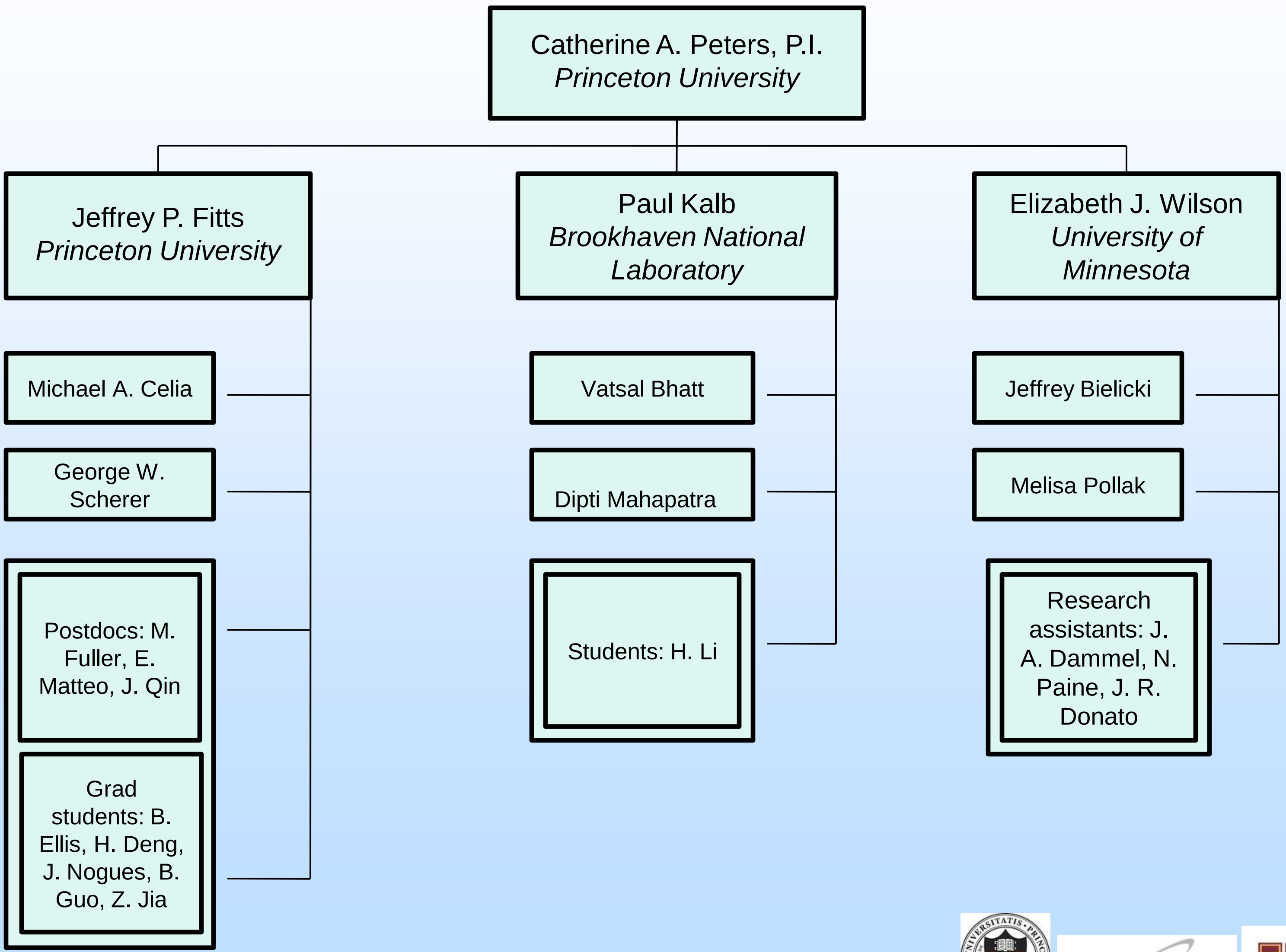
Accomplishments to Date – pg2

- Developed RISCS, a risk interference model for the Michigan Sedimentary Basin, to determine the risks of carbon storage projects with respect to multiple subsurface uses.
- Developed an "economic and policy drivers module", which calculates the cost of CCS and the potential costs incurred by CO_2/brine leakage for a particular geologic setting, injection scenario, and CO_2 leakage scenario.
- Demonstrated ELSA, RISCS and the EPDM for a hypothetical injection into the Mt. Simon formation underlying Ottawa County Michigan and determined scenarios for subsequent leakage of CO_2 and brine into overlying formations.
- Used MARKAL to simulate and project the energy market competitiveness of CCS compared to other energy technologies, and examined the sensitivity to discount rates and carbon tax, and the effect of leakage on this market competitiveness.

Summary: Key Findings & Lessons Learned

- Carbonate caprock fractures have the potential to erode rapidly, but whether this jeopardizes sealing integrity depends on a complex array of mineralogical, geochemical, geomechanical, and hydrologic factors.
  - Given current uncertainties, carbonate formations should be “the caprock of last resort”
- Leakage may be costly even if it causes no subsurface damage, triggers no legal action, and needs no environmental remediation because of remediation and business interruption costs
  - However, the financial consequences of leakage are relatively small when averaged over the life of an injection project.
- There is an optimal carbon tax to maximize CCS market penetration, above which other energy technologies outcompete CCS
  - Regardless, CCS needs financial incentives to achieve significant market share

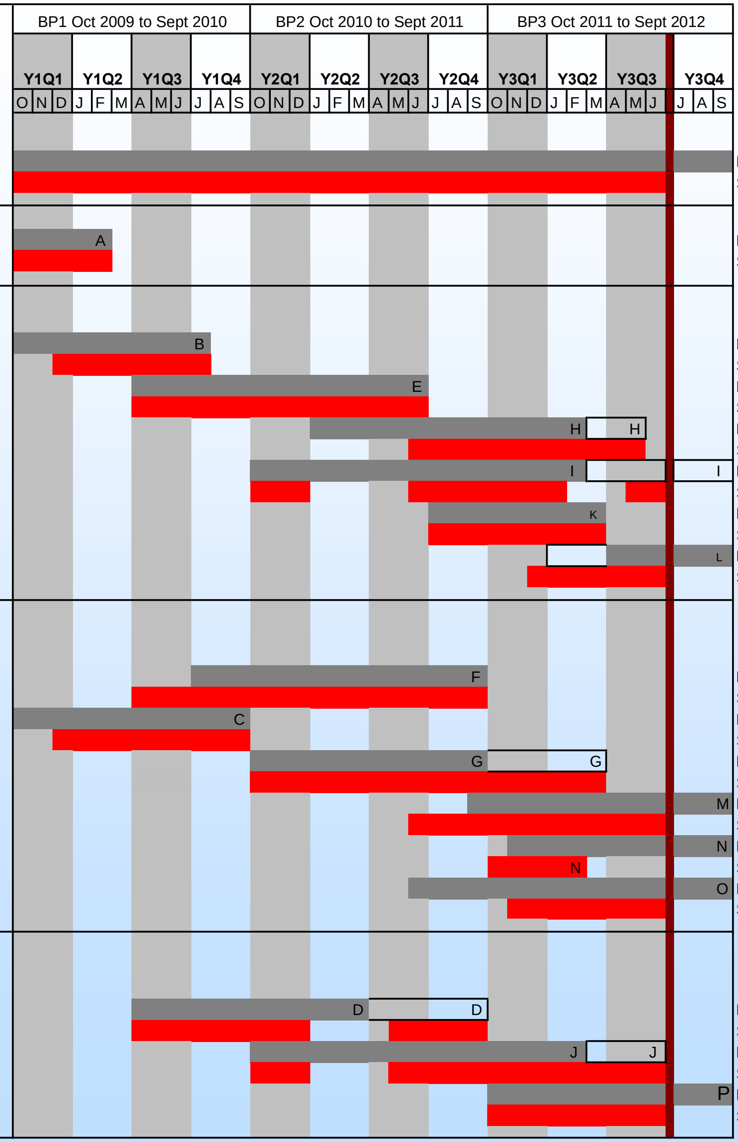
Organization Chart



Gantt Chart

SCHEDULE/MILESTONE STATUS

	PI	
Task 1 -- Project management, planning and reporting	Peters	
Planned		Planned: Oct 2009 to Sept 2012
Actual to date		Status: In progress
Task 2 -- Demonstration Site Selection	Peters/Fitts	
Planned		Planned: Oct 2009 to Feb 2010
Actual		Status: Completed. Findings reported in Y1Q2.
Task 3 -- Geochemical modeling and basin-scale leakage risk modeling		
Subtask 3.1 -- From demonstration site, obtain data …	Fitts	Planned: Oct 2009 to July 2010
Actual		Status: Completed. Findings reported in Y1Q4.
Subtask 3.2 -- Perform geochemical modeling …	Fitts/Scherer	Planned: Apr 2010 to Jun 2011
Actual		Status: Completed. Findings reported in Y2Q3
Subtask 3.3 -- Extract simplified mathematical rules …	Fitts	Planned: Jan 2011 to May 2012
Actual to date		Status: Completed. Findings reported in Y3Q3
Subtask 3.4 -- Develop extended capabilities of Elsa …	Peters/Celia	Planned: Oct 2010 to Jun 2012
Actual to date		Status: In progress. Delayed completion to Y3Q4
Subtask 3.5 – Simulate CO_2 leakage for demonstration site	Peters/Fitts	Planned: July 2011 to Mar 2012
Actual		Status: Completed. Findings reported in Y3Q2.
Subtask 3.6 – Simulate CO_2 leakage for co-injectant SO2	Peters/Fitts	Planned: Dec 2011 to Sept 2012
Actual to date		Status: In progress.
Task 4 -- Bounding risks of CCS projects with respect to multiple subsurface uses, and creating a basin-scale regulatory and liability management framework	Wilson	
Subtask 4.1 -- Gather subsurface data & build GIS model …	Wilson	Planned: Jul 2010 to Sept 2011
Actual		Status: Completed. Findings reported in Y2Q4
Subtask 4.2 -- Review policies, laws, and regulations …	Wilson	Planned: Oct 2009 to Sept 2010
Actual		Status: Completed. Findings reported in Y1Q4.
Subtask 4.3 -- Review civil and administrative damagages …	Wilson	Planned: Oct 2010 to Sept 2011
Actual		Status: Completed. Findings reported in Y3Q2.
Subtask 4.4 -- Examine damage scenarios…	Wilson	Planned: Sept 2011 to Sept 2012
Actual to date		Status: In progress
Subtask 4.5 -- Evalute costs of leakage scenarios …	Wilson	Planned: Nov 2011 to Sept 2012
Actual		Status: Completed. Findings reported in Y3Q2.
Subtask 4.6 -- Coordinate with Markal team …	Wilson	Planned: Jun 2011 to Sept 2012
Actual to date		Status: In progress.
Task 5 -- Evaluate Energy Market Risks and Opportunities of Carbon Sequestration Options with the use of US MARKAL Model	Bhatt	
Subtask 5.1 -- Economic and Policy Drivers Module	Bhatt	Revised plan: Apr 2010 to Sept 2011
Actual		Status: Completed. Findings reported in Y3Q2
Subtask 5.2 -- Define & Calibrate the CCS-MARKAL model	Friley	Planned: Oct 2010 to Feb 2012
Actual to date		Status: Completed. Findings reported in Y3Q3
Subtask 5.3 -- Examine competitiveness of CCS …	Bhatt	Planned: Oct 2011 to Sept 2012
Actual to date		Status: In progress.



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Peer reviewed publications generated from project

- Ellis, B.R.; Bromhal, G.S.; McIntyre, D.L.; Peters, C.A. 2011. “Changes in caprock integrity due to vertical migration of CO_2-enriched brine”, Energy Procedia, 4: 5327-5334, available at http://www.sciencedirect.com/science/journal/18766102.
- Dammel, J., Bielicki, J., Pollak, M., and Wilson, E. (2011). “A Tale of Two Technologies: Hydraulic Fracturing and Geologic Carbon Sequestration.” Environmental Science & Technology, 45(12) pp 5075-5076. available at http://pubs.acs.org/journal/esthag/
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- J. P. Nogues, M. A. Celia, C. A. Peters. “Pore Network Model Development to Study Dissolution and Precipitation of Carbonates”, XIX International Conference on Water Resources CMWR 2012, June 17-22, 2012. available at http://cmwr2012.cee.illinois.edu/SubsurfaceBiogeochemReactiveTrans%28Proceedings%29.html.
- B.R. Ellis, J.P. Fitts, G.S. Bromhal, D.L. McIntyre, R. Tappero, C.A. Peters, 2012. Dissolution-Driven Permeability Reduction of a CO2 Leakage Pathway in a Carbonate Caprock. Environmental Engineering Science. Submitted.