Capture and Geologic Storage of Carbon Dioxide in Deep Saline Formations

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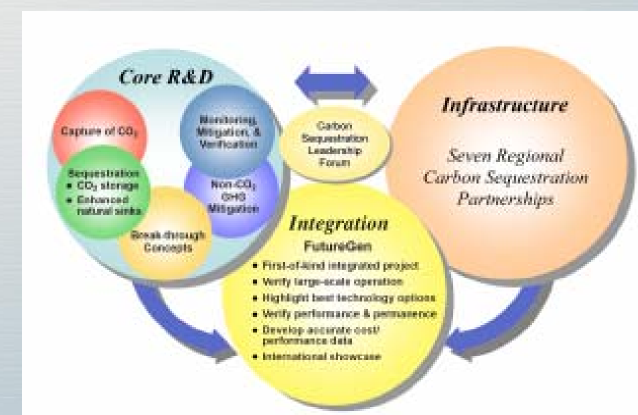
Taiwan CO_2 Sequestration Seminar
July 18, 2006, CTCI Foundation, Taipei, Taiwan

U.S. DOE and Industrial Sequestration Programs and Battelle's Contributions



Battelle CO_2 Program Overview

- **Battelle plays a significant role in all aspects of US CCS Program:**
  - **Mountaineer Plant / AEP Well**
    - First of its kind integrated system at active power plant.
    - Extensive site-specific geologic characterization completed
    - Potential next step is to build a small-scale carbon capture and storage demonstration in Ohio River Valley.
  - **Regional reservoir characterization**
    - Leveraging oil and gas drilling for exploration of CO_2 storage applications.
  - **Midwest Regional Carbon Sequestration Partnership (MRCSP)**
    - Battelle leads the MRCSP in collaboration with a number of organization.
  - **Private projects for power and oil/gas companies**
    - Siting and technical evaluations, i.e. evaluate future power plant locations for sequestration potential.
  - **FutureGen Project**
    - Battelle supports the FutureGen Alliance's work

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Carbon Capture and Storage – A Multiple-Scale Problem

- The Policy and implementation aspects relevant to CO_2 disposal need to be considered at several different scales of evaluation
- These processes/issues range from continental and global scales to basin scale to facility scale and microscopic pore scale

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International Scale

- Understand the scale of the problem
- Identify regions with requirements for CO_2 disposal based on emissions from power plants and oil/gas fields – this is fairly well known
- Identify and categorize potential host formations
- Establish preliminary feasibility
- Combine estimates from several local/regional studies e.g., global capacity estimates, North American Cost curve studies

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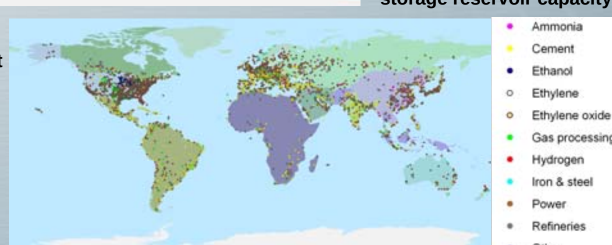
Global CO_2 Storage Capacity
A Very Heterogeneous Natural Resource

- **11,000 $GtCO_2$ of potentially available storage capacity**
- **U.S., Canada and Australia likely have sufficient CO_2 storage capacity for this century**
- **Japan and Korea's ability to continue using fossil fuels likely constrained by relatively small domestic storage reservoir capacity**

- **~8100 Large CO_2 Point Sources**
- **14.9 $GtCO_2$/year**
- **>60% of all global anthropogenic CO_2 emissions**



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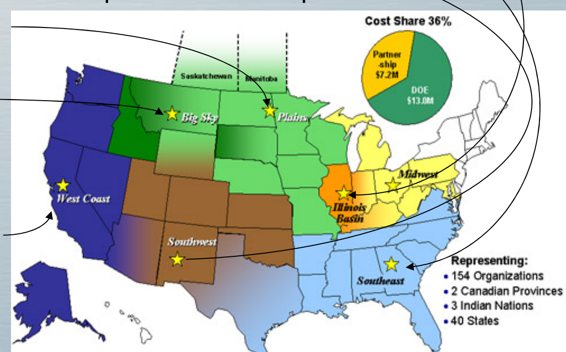
Regional Scale View - Regional Carbon Sequestration Partnerships in the USA

There are seven regional partnerships:

- Geological Carbon Sequestration Options in the **Illinois Basin**
- **Southeast** Regional Carbon Sequestration Partnership
- **Southwest** Regional Partnership for Carbon Sequestration
- **Plains** CO_2 Reduction Partnership
- **Big Sky** Regional Carbon Sequestration Partnership
- **West Coast** Regional Carbon Sequestration Partnership
- **Midwestern** (MRCSP)



See http://www.netl.doe.gov/coal/Carbon%20Sequestration/partnerships/index.htm for more information from NETL on the seven partnerships.

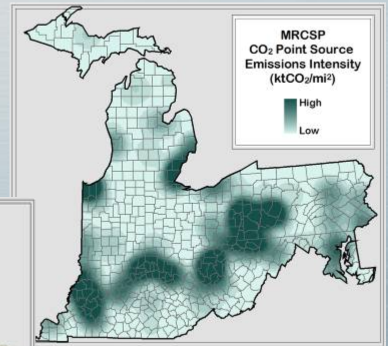
MRCSP partner team is a strategic asset as well as a source of funding

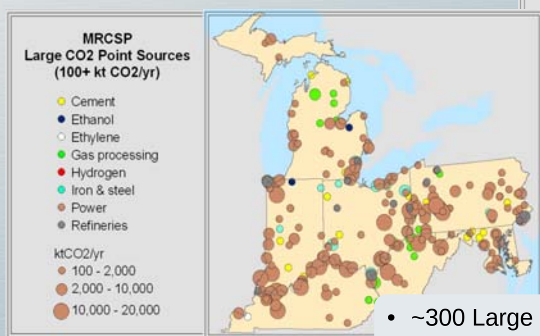
Constellation Energy Group · AEP · Maryland Geological Survey · Stanford University · nrri · Battelle · West Virginia University · bp · Maryland Energy Administration · CONSOL Energy · The Keystone Center · Michigan Basin Core Research Laboratory · Soy Ohio · The Ohio State University · ODNR Geological Survey · Making Ohio Coal the Clean Choice · Pennsylvania Geological Survey · West Virginia Geological Survey · DTE Energy · Cinergy · AJW Inc. · CCX Chicago Climate Exchange · BAARD · Praxair · FirstEnergy · Pacific Northwest National Laboratory · The Ohio Forestry Association · Schlumberger · CEED Center for Energy and Economic Development · B&W · Indiana Geological Survey · Ohio Environmental Council · NETL · American Corn Growers Association · AES Warrior Run · Kentucky Geological Survey University of Kentucky

U.S. Department of Energy/NETL

A Regional View - The MRCSP Region: The Nation's Engine Room

- One in six Americans
- 1/6 of U.S. Economy
- 1/5 of U.S. Electricity Generated
  - ¾ From Coal





- ~300 Large Point Sources (>100,000 tonnes/year)
- ~800 Million tonnes CO_2/year

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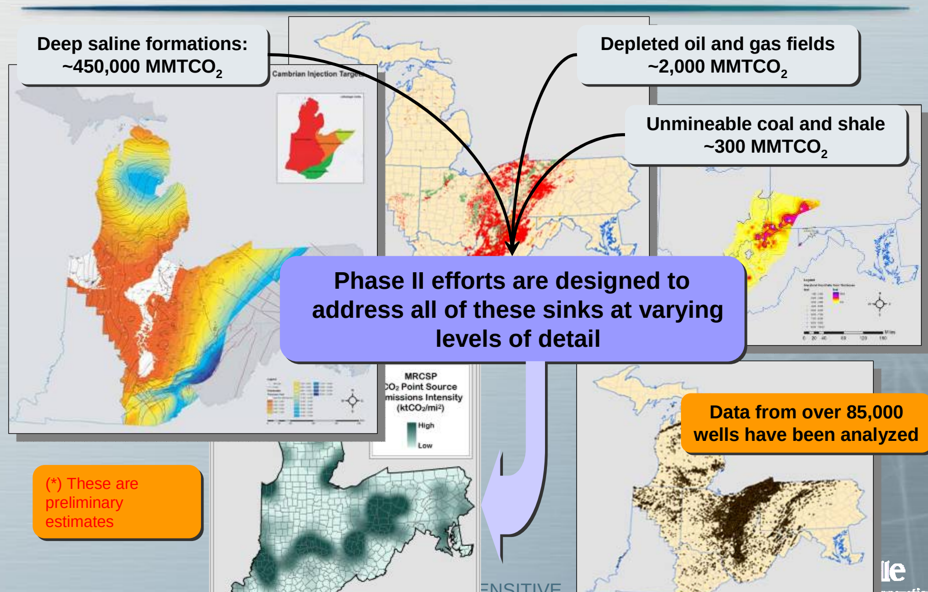
The geological potential of the region is vast and well positioned relative to sources*



(*) These are preliminary estimates

Regional Reservoir Scale

- Evaluation of a single formation for use by multiple injection sites e.g., Mt. Simon Sandstone, RCSP Program mapping efforts
- Regional data on aquifer depth, thickness, permeability, porosity, water levels/pressure, confining layers, tectonics
- Regional geochemistry and mineralogy
- Regional CO_2 emissions vs. capacity
- Economic and regulatory analysis

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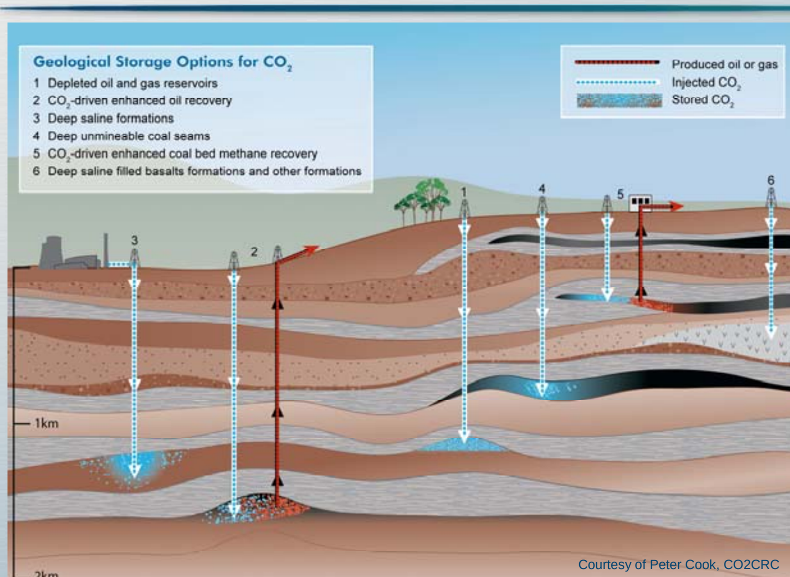
Candidate Geologic CO_2 Storage Formations
Multiple Options



Courtesy of Peter Cook, CO2CRC

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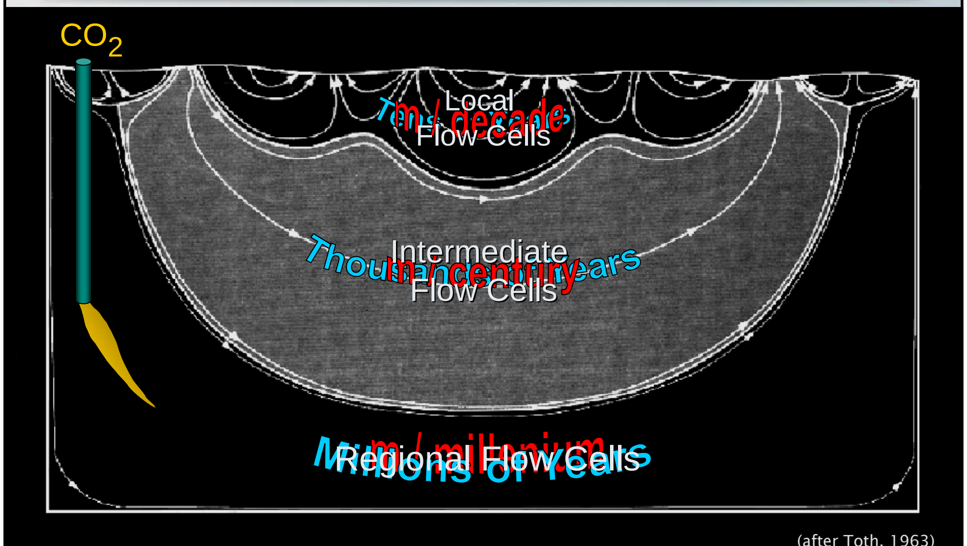
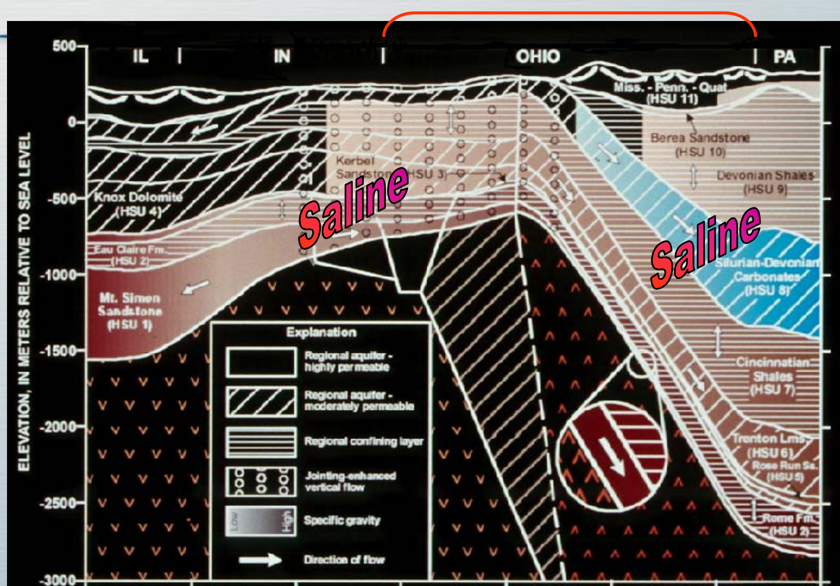
Ground-Water Flow Regimes

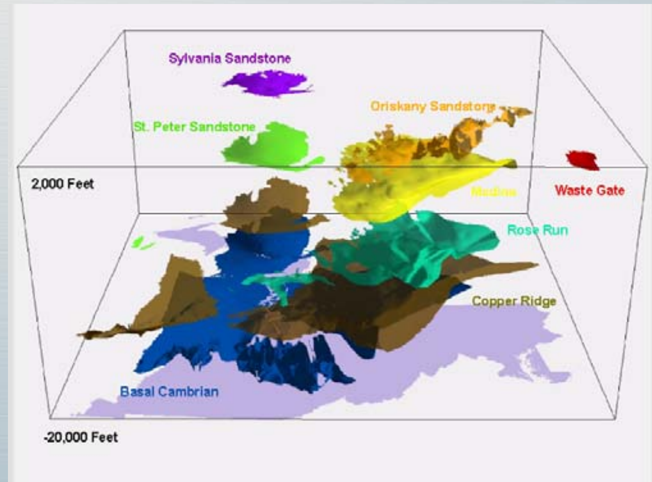


Source: Scott Bair, Ohio State University

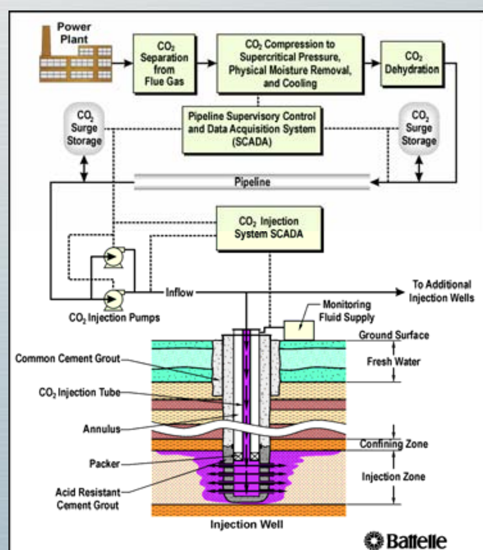
Saline Zones in Deep Aquifers



Regional Scale Challenge – Turn Theoretical Storage Potential into reserves that Can Be Counted when CO_2 Storage Becomes Necessary



Geologic Sequestration System View
Designed to Protect the Environment



FutureGen – Integrated Production and CCS Project

- State-of-the-art, zero-emission power plant
- Use coal to supply power in the future
  - Also to support hydrogen fuel technology
- Battelle assists the FutureGen Industrial Alliance

"Today I am pleased to announce that the United States will sponsor a $1 billion, 10-year demonstration project to create the world's first coal-based, zero-emissions electricity and hydrogen power plant..."

President George W. Bush
February 27, 2003

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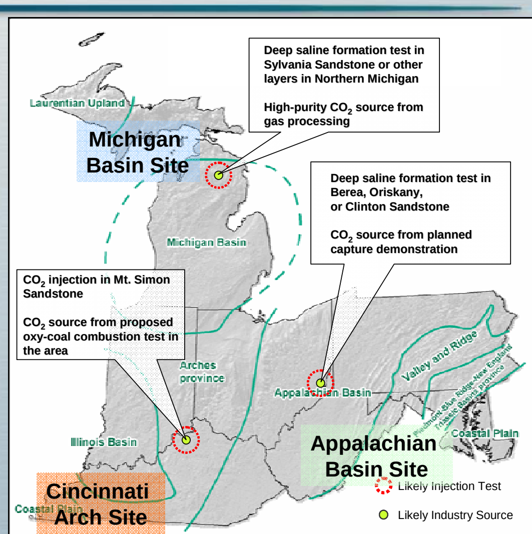
MRCSP Phase II – Demonstration Sites

- Phase II of MRCSP involves field tests of CO_2 storage
- Three main sites are being evaluated
- Site characterization is likely to be completed during 2006
- Sites are located in major geologic structures in MRCSP region and represent regional geologic diversity



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MRCSP Demonstration Site Example: Appalachian Basin

- R.E. Burger Power Plant and Multi-pollutant Control Demonstration

Facility Scale View – Mountaineer Plant, West Virginia, USA

- 1300 MW pulverized coal plant with NOx and SOx control (under construction

Mountaineer/The Ohio River Valley CO_2 Project - A Unique Public Private Collaboration

- **Battelle and PNWD – Phil Jagucki, Joel Sminchak, Bruce Sass, Danielle Meggyesy, *Jim Dooley, Judith Bradbury, Diana Bacon, Prasad Saripalli, Mark Kelley, Mark White, Frank Spane, Ken Humphreys, et al.***
- **DOE/NETL – *Charlie Byrer, Scott Klara, Sean Playcinski, and others***
- **AEP – *Mike Mudd, Dale Heydlauff, Gary Spitznogle, Charlie Powell, Chris Long, John Massey-Norton, Jeri Matheney, Tim Mallan, et al.***
- **Ohio Coal Development Office – *Jackie Bird, Howard Johnson***
- **BP – *Charles Christopher, Gary Kizior, Steve Lamb***
- **Schlumberger – *T.S. Ramakrishnan, Nadja Mueller, and John Tombari et al.***
- **Ohio Geological Survey: *Larry Wickstrom***
- **Regional Geologists: *Tom Wynn, Bill Rike, John Forman, Amy Lang***
- **Stanford's GCEP Program – *Mark Zoback, Amie Lucier***
- ***CO_2 Capture and handling Companies***
- ***Regional Oil and Gas Companies***
- ***CRIEPI (Japan)***
- ***Midwestern Regional Carbon Sequestration Partnership (MRCSP)***

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Site-Specific Characterization
Essential for Safe and Effective Operations

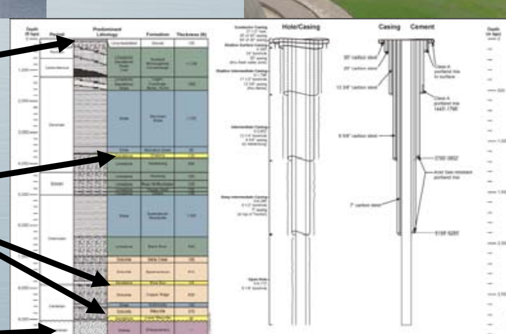
Seismic Survey

Drilling Test Well

Ground level

Possible storage formations > 2,500 ft deep

9,000 feet below the surface



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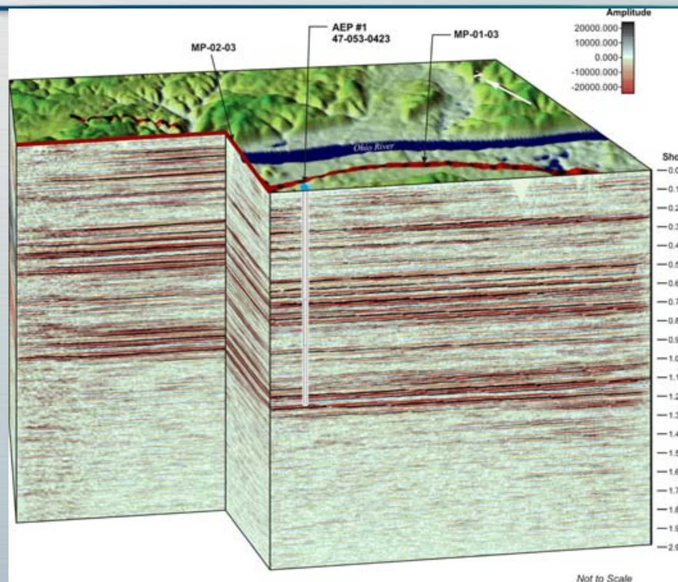
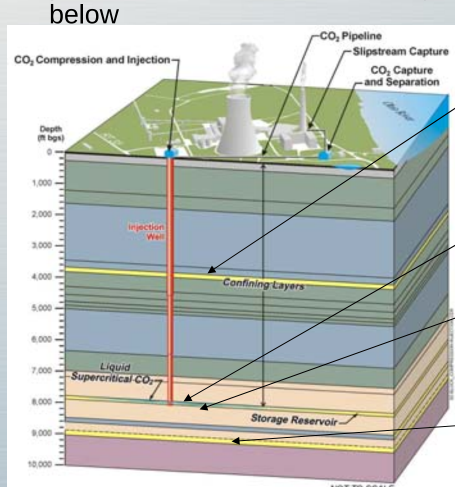
Mountaineer Site - Seismic Survey Demonstrated Impact of Plant Noise and Lack of Faulting



CO_2 Injectivity in the Mountaineer Area

- A number of geologic formations have been evaluated for CO_2 storage potential in the Ohio River Valley region, as shown for Mountaineer site below



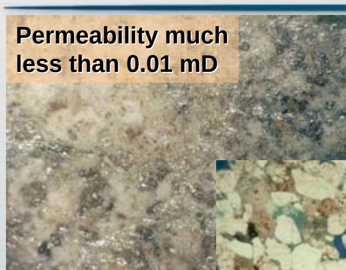
CO_2 injection should also be possible in shallower sandstone and carbonate layers in the region

Rose Run Sandstone (~7800 feet) is a regional candidate zone in Appalachian Basin

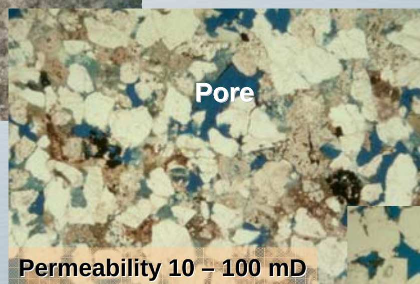
A high permeability zone called the “B zone” within Copper Ridge Dolomite has been identified as a new injection zone in the region

Mount Simon Sandstone/Basal Sand - the most prominent reservoir in most of the Midwest

Sedimentary Rocks
A Microscopic View

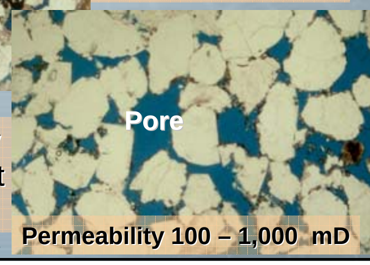


Shale with Extremely Low Permeability Forms Good Caprock



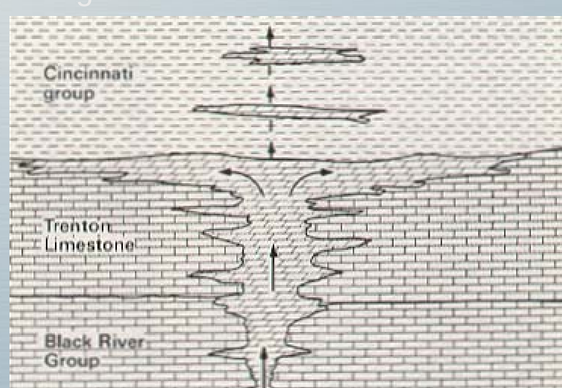
Sandstone with Medium Permeability Forms Good Host Reservoir Medium Cost

Sandstone with High Permeability Forms Excellent Host Reservoir at Low Cost



Oil Production Zone in Trenton Limestone

Coarsely crystalline dolomite formed by mineral replacement of calcite, increase in porosity from dolomitization, and later oil migration.



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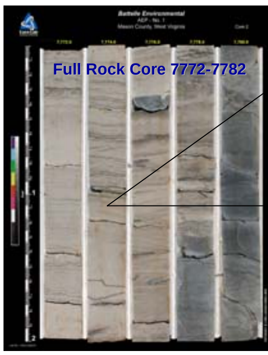
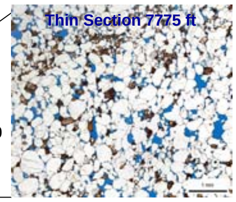
Rose Run Sandstone Core Analysis – Potential Storage Zone

Rose Run Sandstone 7755-7871 ft



Note: fractures shown result of core collection.

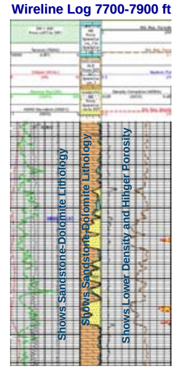
X100



Hydraulic Core Tests 7775 ft

Lithology	= Sandstone
Density	= 2.64 g/mL
Porosity	= 10.4%
Permeability	= 49 mD

Wireline Log 7700-7900 ft



- Bp has recently completed state-of-the-art CO_2 relative permeability analysis on these samples as part of their sponsorship of the project

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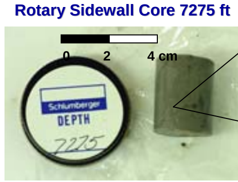
Beekmantown Dolomite – Immediate Overlying Caprock

Beekmantown Dolomite 7210-7755 ft

Rotary Sidewall Core 7275 ft

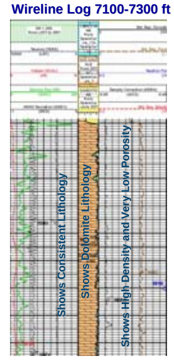


X100

Hydraulic Core Tests 7275 ft

Lithology	= Dolomite
Density	= 2.82 g/mL
Porosity	= 0.38%
Permeability	= <0.001 mD

Wireline Log 7100-7300 ft



- Presence of multiple, thick, low- permeability containment zones has been established in the well and through seismic survey

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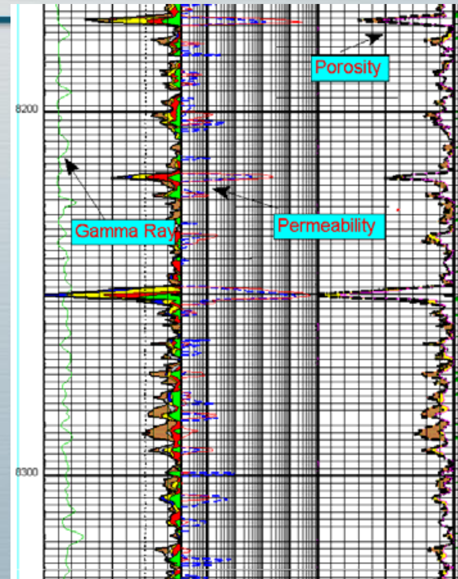
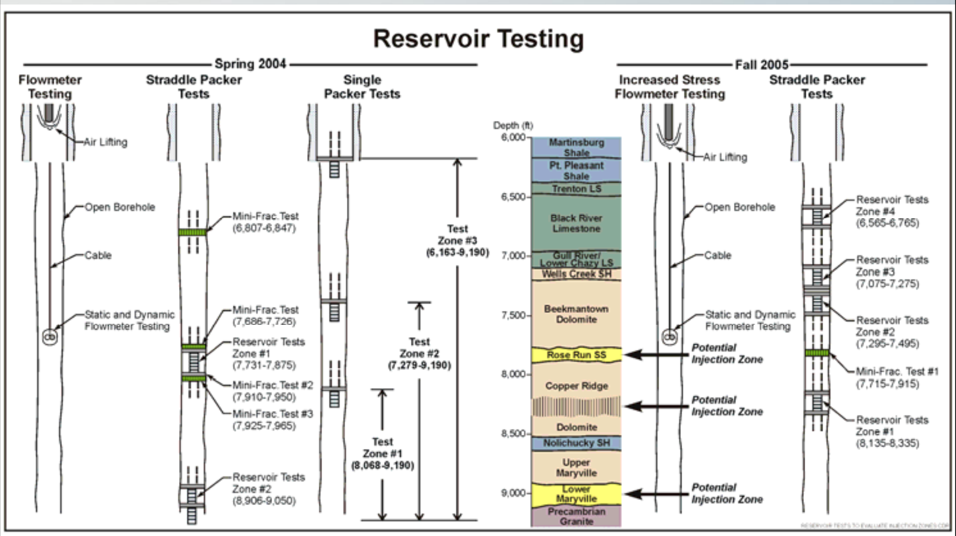
It is Important to Identify New Targets:
e.g., Lower Copper Ridge Dolomite at Mountaineer

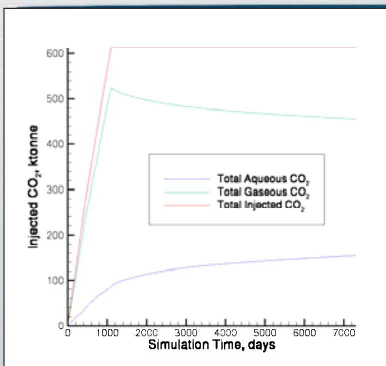
- Rocks under Rose Run dominated by dense dolomite (carbonate) layers
- However, storage potential was observed in part of Copper Ridge Dolomite (B-Zone at 8100-8300 ft depth) based on NMR testing
- This has also been validated through detailed stress tests in AEP well, which show that this zone may even have higher injectivity than the Rose Run
- Similar high permeability zone observed in several wells, including one near Gavin plant. This is promising for regional storage potential

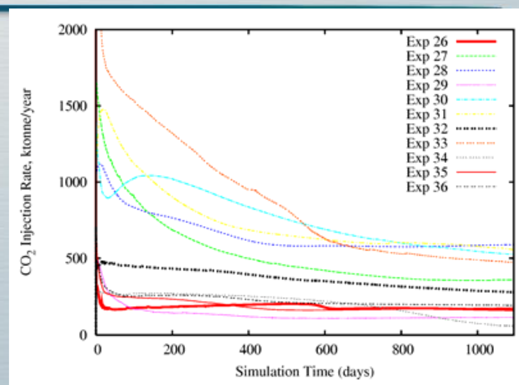


Detailed Reservoir Tests of entire open borehole to Validate Injectivity in Rose Run and Copper Ridge have been Conducted



Rose Run Simulation – Injection Rate Change and Dissolution for Vertical Well





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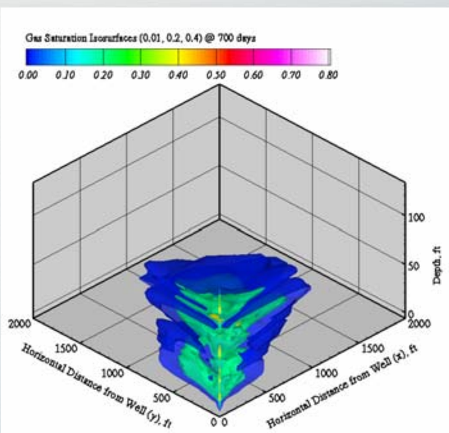
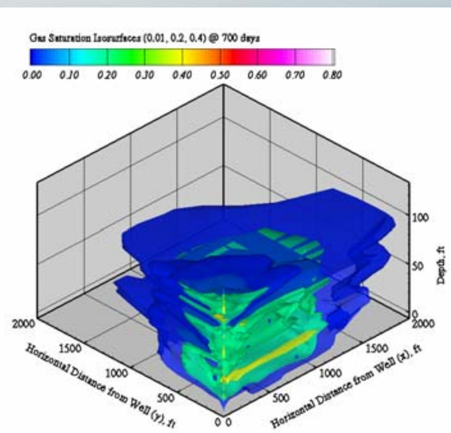
Preliminary Rose Run Vertical and Lateral Well 3-D Simulation

STOMP Subsurface Transport Over Multiple Phases





Vertical Well Configuration for the Rose Run Formation

700 days

Horizontal Well Configuration for the Rose Run Formation

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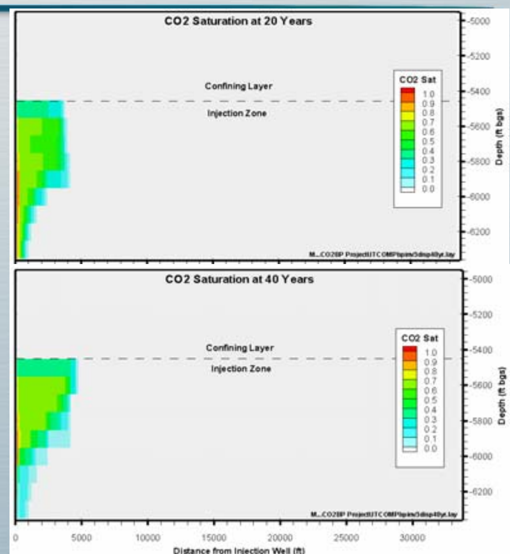
Mt. Simon Sandstone West-Central Indiana Example – High Thickness, Low Permability Case

- CO_2 spreads to about 4,000 ft in 20 years at about 1 million tonnes per year
- There is very little additional spreading after injection stops
- No leakage into confining layers is observed



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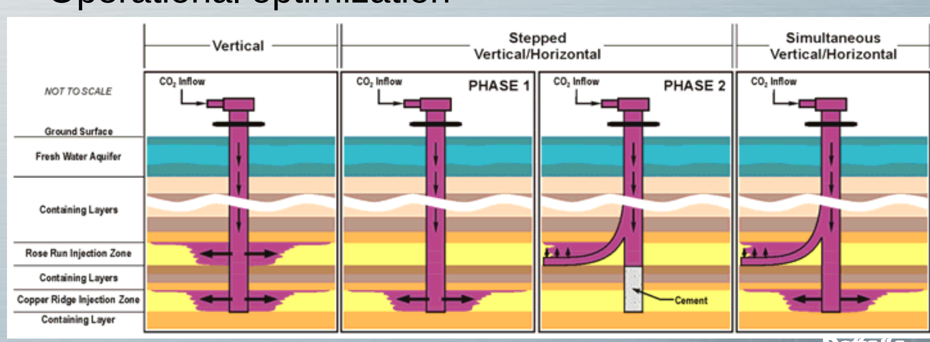
Injection System Optimization

- Multiple injection zones
- Lateral wells
- Reservoir stimulation
- Operational optimization



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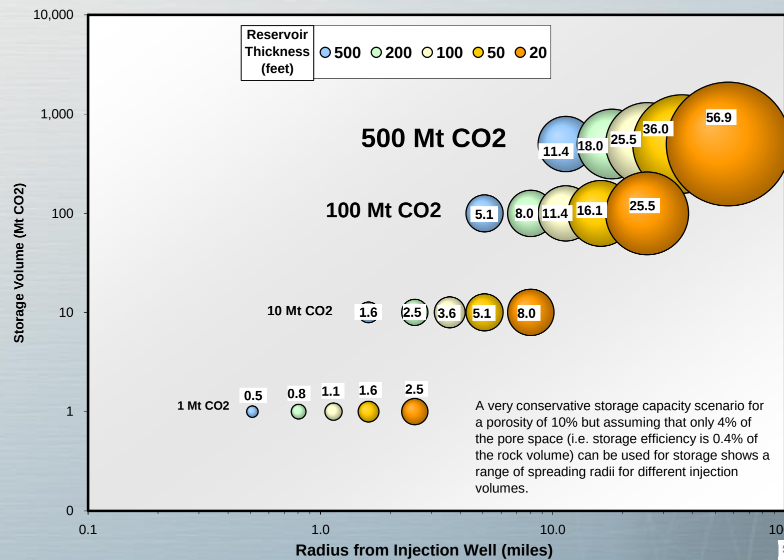
CO_2 Spreading Areas for low Storage Efficiency Assumption and Varying Thickness and Volumes



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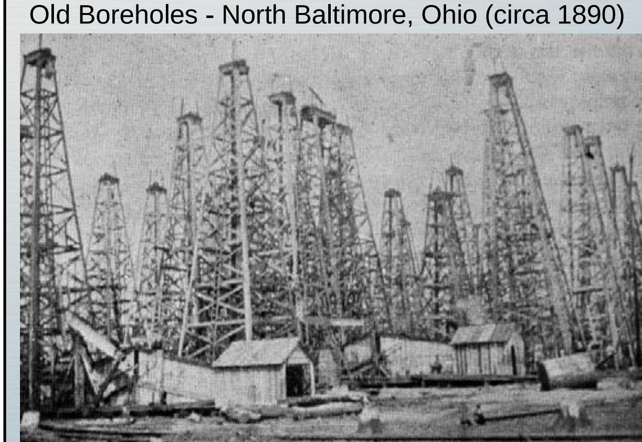
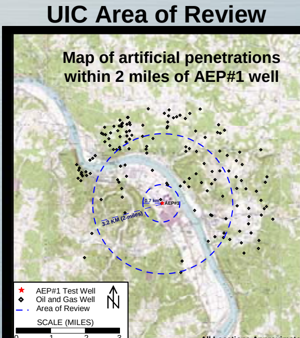
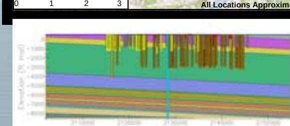
Evaluating Potential Leakage Pathways – No Deep Penetrations Present in the Area

Old Boreholes - North Baltimore, Ohio (circa 1890)



UIC Area of Review





Geologic cross section showing well depths near AEP#1 (in blue).

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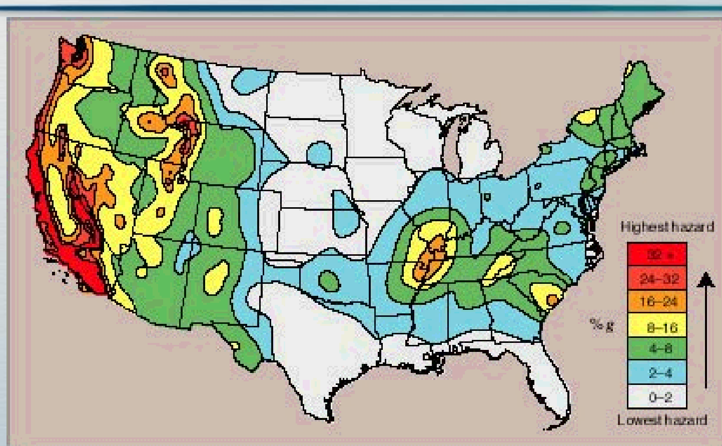
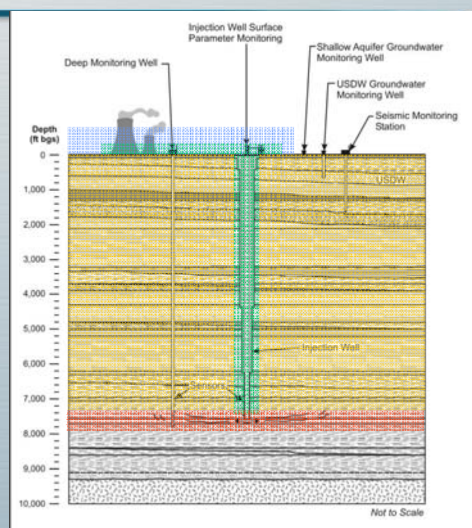
Most of the Midwest is in a Low Seismic Hazard Zone, But Faulting needs to be considered (USGS National Seismic Hazard Mapping Project)



- Seismic and geomechanical assessment will be critical for locating CCS facilities in Taiwan

Monitoring Injected CO_2 - Layered Monitoring Objectives

- •Injection/Capture System
- •Operational Safety
- •Leakage
- •Injected CO2

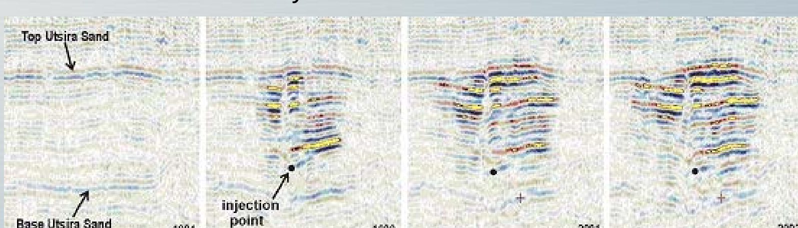


CO_2 Monitoring Systematics

System	Remote	Surface	Observation Well(s)
Injection Pressure	4-D Seismic	Seismograph	Temperature/ Pressure
Flow Rate	Electromagnetic/ Seismic Crosswell	Soil Gas	Flow/ Density
Fluid Composition	Vertical Seismic Profile/Wireline	USDW Aquifer Sampling	Fluid Samples
Well Workovers	Tracers	Downhole Stressmeters	ERT

Example – Seismic Monitoring at Sliepner

- 4-D Seismic- proven technology with demonstrated effectiveness, but reservoir thickness and velocities may limit usefulness.
- X-well seismic/VSP- high velocities in reservoir rocks may make it difficult to detect density contrast.



- Microseismic- high background
  “noise” would require installation of geophones in bedrock wells.
- ERT/EMT (electrical resistance tomography/electrical magnetic tomography) - somewhat experimental, more applicable in an established well-field with numerous monitoring wells in place.

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Stakeholder Outreach (Public Acceptance is Critical for CCS

- Mountaineer Project Example - Numerous meetings by Battelle and AEP personnel to inform key stakeholders about the project
  - Plant managers and employees at and near the power plant
  - Regional and national NGOs (NGO Workshop in January 2004)
  - Local and state officials – mayors, county commissioners, state legislators
  - Federal Officials -senators and congressmen, DOE
  - State PSC, Development Office, Energy Task Force
  - State DEP and EPA officials (EPA Workshop)
  - Numerous scientific meetings and workshops

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CO_2 Capture Overview – MRCSP Phase I Report

Technologies Considered

- Amine Scrubbing
- Alkaline Salt Scrubbing
- Ammonia Scrubbing
- Physical Absorption
- Gas Separation Membrane
- Gas Absorption Membrane
- Physical Adsorption
- Solid Chemical Absorption
- Cryogenic
- Hydrate Formation
- Electrochemical Separation
- Biochemical Separation
- Oxyfuel
- Chemical Looping Combustion

An Amine Capture Plant on a Gas Processing Plant
Photo provided by CONSOL Energy

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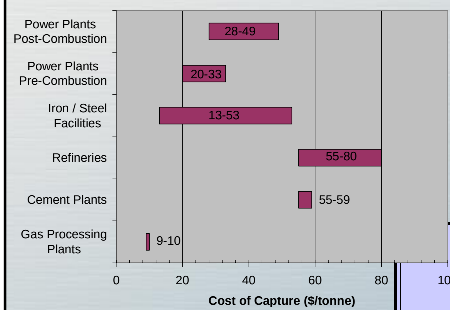
Capture Analysis



Cost of capture is in the range of \$20 to \$50 per tonne of CO_2 for most MRCSP sources

Capture technologies were ranked as:
- **"L" Likely,**
- **"A" Attractive, and**
- **"S" Speculative**

Source Type	Point of Capture	Amine Scrubbing	Ammonia Scrubbing	Physical Absorption	Gas Separation Membrane	Gas Absorption Membrane	Oxyfuel + Drying/Compression	Simple Drying/Compression
Power Plants Post-Combustion	Flue Gas	L	A	--	A	A	A	--
Power Plants Pre-Combustion	Shifted Syngas	--	--	L	A	--	--	--
Iron / Steel Facilities	Blast Furnace Gas (~60-70% of total CO_2)	L	--	L	A	S	--	--
Refineries	Heater/Boiler Flue Gas (~65-85% of total CO_2)	L	S	--	A	S	A	--
Cement Plants	Kiln Flue Gas	L	S	--	S	S	S	--
Gas Processing Plants	Vented CO_2	--	--	--	--	--	--	L

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Take Home Messages
CCS

- Evaluation and implementation of CCS will require assessments at multiple scales
- The overwhelming criteria for siting a CCS-enabled facilities will relate to things like injectivities and total reservoir capacity
- Deep saline formations will be the workhorse for the USA and many other countries.
- While CCS technologies are likely to deploy first in non-power markets first, if CCS is to make a large contribution to addressing climate change it must be effectively integrated with large coal-fired electricity and H_2 production.

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Take Home Messages
CCS

- The cost of capturing CO_2 is **not** the single biggest obstacle standing in the way of CCS deployment.
- No one has ever attempted to determine what it means to store 100% of a large power plant's emissions for 50+ years.
  - How many injector wells will be needed? How close can they be to each other?
  - Can the same wells be used for 50+ years?
  - What measurement, monitoring and verification (MMV) "technology suites" should be used and does the suite vary with time?
  - How long should post injection monitoring last?
  - Who will regulate CO_2 storage on a day-to-day basis? What criteria and metrics will this regulator use?

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Thank you!

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