Characterizing and Selecting Appropriate Sites for Geologic Storage of CO_2:

Key Issues and Information Needs

Jens T. Birkholzer, LBNL

EPA Geologic Sequestration Technical Workshop, July 10-11, 2007

Outline

- Introduction
- Key Attributes of a Good Storage Site
- Geological Storage Options and How These Affect Site Characterization and Permitting
- Workflow, Information Needs, and Information Sources
- How Much is Enough?

➢ Which Information Would I Want To See If I Was To Permit a Site?

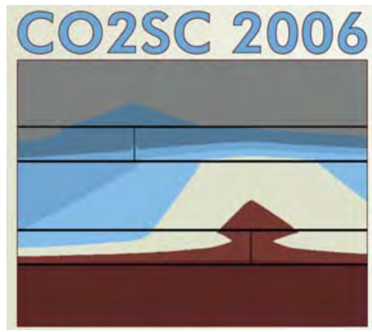
CO2SC 2006

International Symposium on Site Characterization for CO_2 Geological Storage

LBNL, March 20-23, 2006

Sponsored by EPA

- About 80 Contributions
- 26 International Papers
- 11 Countries
- 47 Oral Presentations
- 28 Poster Presentations
- More than 150 Participants



Organizing Committee: J. Birkholzer, C.-F. Tsang, S. Benson (LBNL), A. Karimjee, B. Kobelski (EPA)

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Topics and Sessions

The CO2SC Symposium addressed various aspects associated with selection and characterization of potential sites for the geological storage of CO_2

- General Framework
- Characterization Methods and Technology
- Regional and Project Case Studies
- Characterization of Leakage Pathways
- Fundamental Processes
- Screening and Ranking Tools
- Regulatory and Social Issues
- Panel Discussion **(Benson, Bachu, Finley, Molz, Orr, Tombari)**

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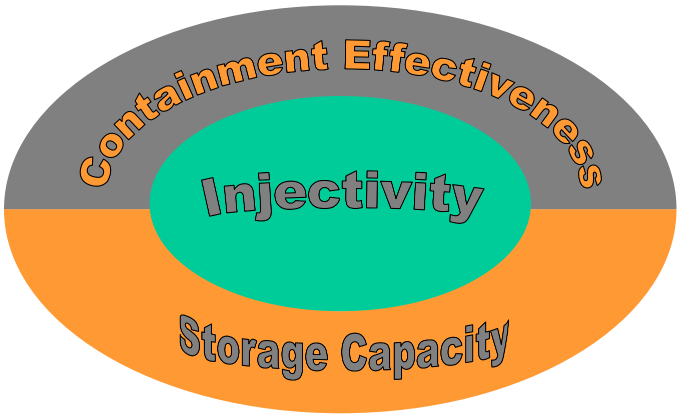
Key Attributes of a Storage Site



Benson, CO2SC 2006

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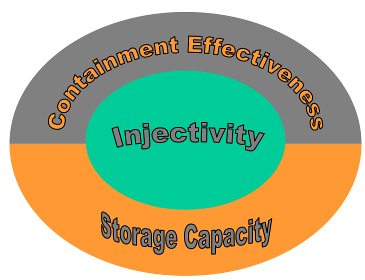
Injectivity

- Adequate permeability and thickness
- Injectivity can be improved
  - Injection strategy (e.g., number of wells, injection length)
  - Stimulation (hydrofracturing)
- Permeability possibly affected by CO_2-rock-water interactions



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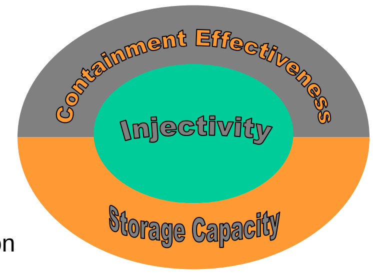
Storage Capacity

- Adequate accessible pore volume
  - Unit thickness and extent
  - Effective porosity, compressibility
  - Heterogeneity
  - CO_2 pore occupancy
  - Extent of CO_2 plume (short term focus on separate phase)
- Sufficient depth for storage at supercritical conditions
- Brine displacement without harm to environment



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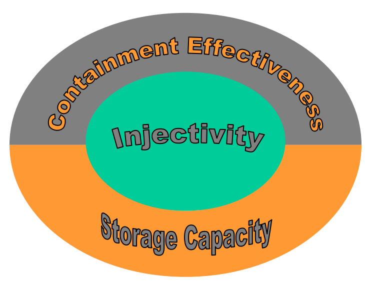
Containment

- Seal Properties
  - Capillary barrier
  - Permeability barrier
  - Pressure barrier
- Continuous and thick
- Geographically extensive
- Geomechanically stable
- Geochemically stable
- Absence of continuous and conductive faults
- Abandoned or leaking wells accounted for
- (Secondary or multiple seals)



➡ **Probably most difficult to characterize**

➡ **Most relevant to regulators**

Vulnerability Assessment

- Leakage Attenuation Potential
  - Possible leakage scenarios and conditions
  - Shallow seals
  - Buffer aquifers
- Impact of CO_2 Leakage at Land Surface
  - Topography
  - Wind, climate
  - Land use, population
  - Surface water
  - Vegetation
- Impact of CO_2 Leakage and Brine Migration on Groundwater
  - Groundwater use (USDW?)
  - Water chemistry and aquifer mineralogy
  - Confined or unconfined
  - Regional-scale hydrogeology

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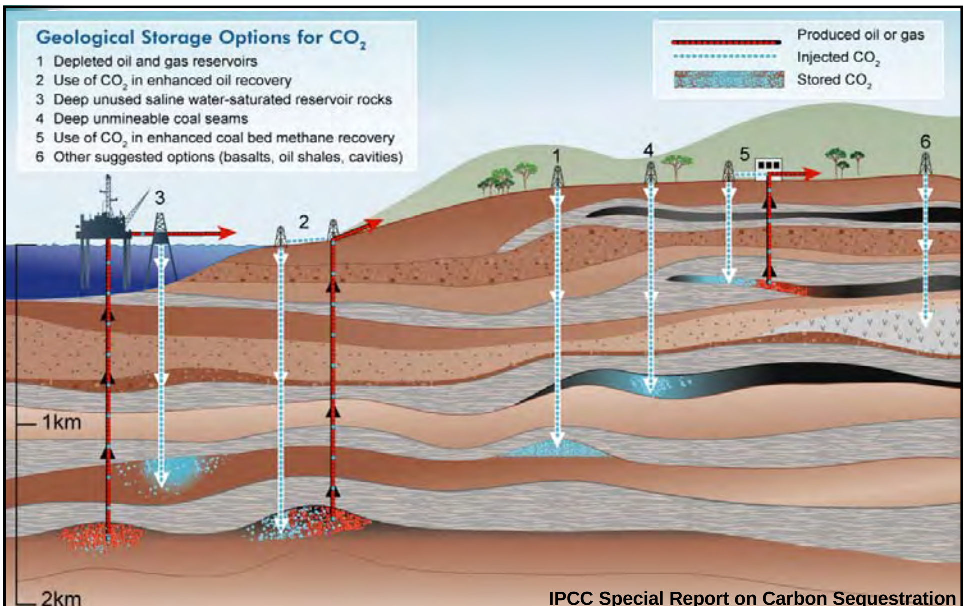
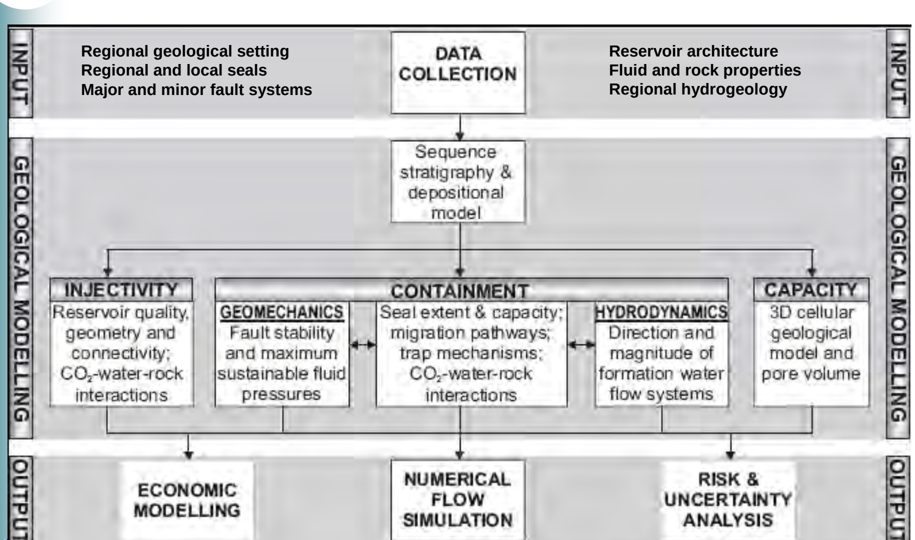


Different storage options have different characteristics, and different characterization needs

Site Characterization Needs to be Specific to Storage Type

- Depleted oil and gas fields
  - \+ Injectivity and capacity well established
  - \+ Proven capacity to hold hydrocarbons
  - \+ Generally well characterized
  - – Sites not necessarily available when and where needed
  - ➢ **Key containment concern: Leakage through wells (knowledge of abandoned wells, well integrity)**
- Deep saline formations
  - \+ Largest storage capacity
  - \+ Usually no competing resource issues because of high salinity
  - – Uncertainty about injectivity and capacity estimates
  - – Containment difficult to characterize and demonstrate (seal adequacy over ~ 100 km^2 or so)
  - – Usually limited information available, often new wells, geophysics, etc. required
  - ➢ **Key containment concern: Leakage through faults and fractures (fault detection, fault characteristics, seal integrity with time)**

Site Characterization Workflow



Gibson-Poole et al., CO2SC 2006

Monitoring Plan and Remediation Plan

Information and Data Sources

Key Attribute	Key Information	Characterization Method/Data Source
Injectivity	Permeability and thickness; Connectivity; Chemical reaction with minerals	Core analysis and testing; Well-logs (existing or new wells); 2D or 3D seismic; Production history; Laboratory experiments on cores; In-situ stress and pressure measurements; Hydro-fracture analysis; Leak-off tests Supported by simulation models
Storage Capacity	Thickness and accessible porosity; Reservoir structure, compartmentalization and heterogeneity; plume size; residual trapping	Core analysis and testing; Well-logs (existing or new wells); 2D or 3D seismic; Structural maps; Laboratory experiments on cores; Water chemistry (age); Fill-spill analysis Supported by simulation models
Containment Efficiency	Seal characteristics; Fault location and properties; Geomechanical properties; Chemical reaction with minerals; Well locations and integrity	Core analysis and testing; Well-logs (existing or new wells); 2D or 3D seismic; Structural maps; Fault seal analysis; Laboratory experiments on cores; Water chemistry (age); In-situ stress and pressure measurements; Failure analysis; Well location maps and completion records; Well location verification; Aerial surveys Supported by simulation models

- Mostly conventional methods used in hydrogeology, oil and gas
- Additional data needs for vulnerability assessments

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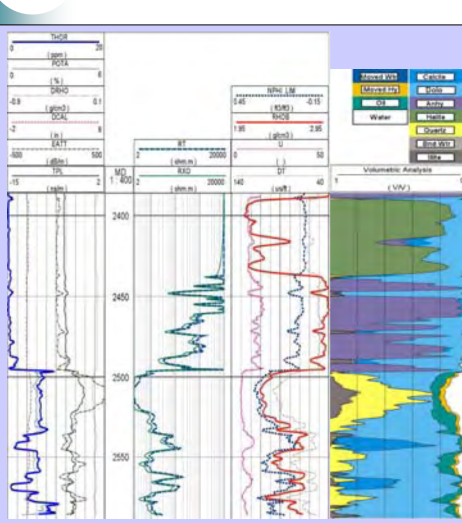
Examples: Borehole Data



Neutron, Density, GR → Porosity *(Primary & Secondary)*, Lithology, Clay Content

Resistivity → Fluid Saturations

Accurate mineralogy with Spectrocospy

Geomechanical Properties with Sonic Logs, Dipole Logs

Stress Direction with Multiarm Calipers

Borehole images

Pressure, temperature data, tilt, etc.

>> Calibrated with core data

Jammes et al., CO2SC 2006

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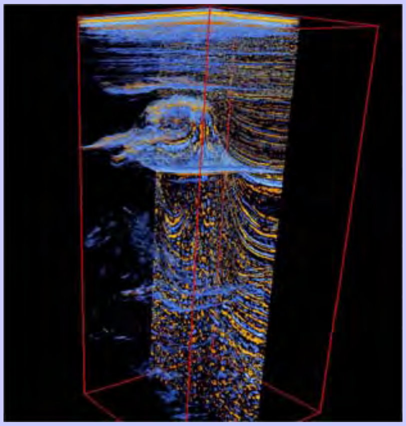
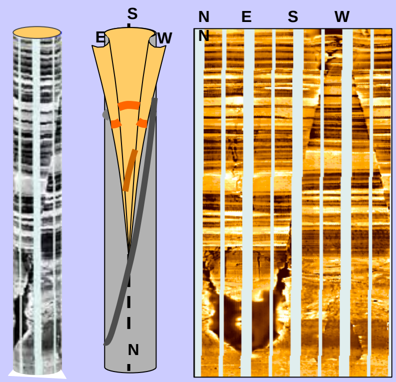
Examples: Fault Detection



3D Seismic



Core Analysis, Borehole Imaging

Jammes et al., CO2SC 2006

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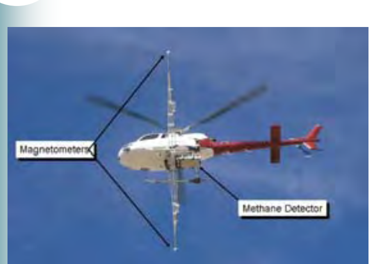
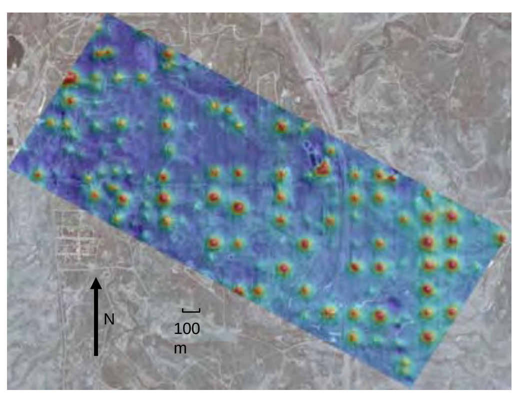
Examples: Airborne Surveys



Well Detection



Veloski and Hammack, CO2SC 2006

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Model Support

Injectivity, Capacity, Containment

- Multi-phase simulation of CO_2 migration (migration pathways, injectivity and capacity estimates)
- Modeling of leakage scenarios (leakage rates)
- Geochemical simulation (geochemical trapping, caprock integrity)
- Geomechanical simulation (hydro-fracturing, caprock integrity)

Vulnerability Assessment

- Regional-scale simulation of brine displacement
- Reactive transport modeling of CO_2 intrusion in USDW
- Atmospheric dispersion models
- Models predicting land surface deformation

➢ Powerful simulation tools exist; concern is rather data availability and model validation

How Much Is Enough?

- Resources will be scarce at full deployment of CCS (experts, regulators, budget, data, schedule)
- Which data are must-have versus nice-to-have for permitting a site (type and amount of data)?
- We know what can be done; it is difficult, however, to work out what is not necessary
- Pilot projects and early large-scale projects can help determine minimum set of information (do more than necessary, as a basis for prioritizing next time)
- Pilots must not become de facto standards, or unduly raise expectations
- Regulators expect “complete”, but not overwhelming information

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If I Was a Regulator And Had to Permit a Deep Saline Project*…

Which Information Would I Want to See?

*Assume there are no leaking or potentially leaking wells

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General Guidelines

- Protect human health and the environment
- Ensure that decisions are cost-effective
  - ➢ Have reasonable expectations regarding site characterization requirements
  - ➢ Allow for flexibility in evaluation and permitting
  - ➢ View site characterization, monitoring plan, and remediation plan as a package (e.g., containment concerns balanced by enhanced monitoring plan)

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Basic Expectations

- Geological model with regional and local geologic structure from depth to surface
  - Based on: regional geological assessments with structural maps and cross-sections, existing wells, 2D seismic
- Detailed evaluation of the main seal(s), with focus on petrophysics, tectonics, long-term integrity
  - Based on: existing and new wells, ideally 3D seismic, core analysis, fault seal analysis
- Evaluation of target reservoir and demonstration of sufficient injectivity (pressure buildup) and capacity
  - Based on: existing and new wells, seismic, core analysis
- Prediction of plume migration during injection and relaxation phase
  - Based on: reservoir properties, multi-phase simulation accounting for buoyancy

Basic Expectations (cont.)

- Discussion of brine displacement and migration
  - Based on: Hydrogeological evaluation
- Discussion of possible leakage scenarios and paths
  - Guides level of monitoring activities
- Discussion of environmental assets near storage site
  - Guides level of monitoring activities
- Monitoring and remediation plans
  - "Less than optimal" sites or sites not well characterized can benefit from sound monitoring and remediation plans

Additional Expectations

- Geomechanical study of seal integrity
  - Should be done if: injection pressure close to critical, seismic activity, presence of faults, no secondary seals
  - Based on: failure analysis, fault reactivation analysis, geomechanical models
- Geochemical study of seal integrity
  - Should be done if: thin reactive caprock, no secondary seals
  - Based on: Laboratory experiments, geochemical models
- Impact assessment for credible leakage scenarios (prediction of rates and impact on environment)
  - Should be done if: limited geological information, sparse data, no secondary seals, uncertainty about properties of detected faults
  - Based on: hydrodynamic models for CO_2 migration, impact assessment (geochemical modeling of USDWs, atmospheric dispersion models)

Additional Expectations (cont.)

- Prediction of brine displacement and migration
  - Should be done if: valid concern about impact of brine displacement on basin-scale hydrogeology
  - Based on: regional-scale models
- Evaluation of geochemical changes in target reservoir
  - Should be done if: valid concern that mobilized hazardous matter can escape from reservoir (e.g., with leaking CO_2 or displaced brine)
  - Based on: laboratory experiments, geochemical models

Main Conclusions

- A carefully selected and characterized site can be safe (i.e.; it meets acceptable levels of risk)
- Solid geologic model is key starting point for evaluating a storage site
- Sophisticated suite of measurements methods and simulation tools is available for site characterization
- Regulators face important task in deciding about the must-have versus the nice-to-have site information
- One key concern is large-scale characterization of seals for saline formations
- Possibility of some leakage should be assumed at any site; monitoring and remediation plan should be in place

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Backup Slides

Site Characterization – When?

- Would characterization of a site occur only prior to CO_2 injection, or should it continue (and be refined) throughout the injection phase, and during later monitoring and verification stages?
- Should we define three phases of site characterization?
  - pre-injection
  - injection
  - post injection
- Alternatively, should "site characterization" be the pre-injection phase and is the injection/post injection phase a "site verification" phase?

Cook, CO2SC 2006

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Site Characterization – When?

- Staged approach (learning by doing) would have important ramifications for permitting[1]:
  - approval would be based on not too extensive characterization and documentation
  - monitoring CO_2 movement would provide important information on site characteristics[2]
  - monitoring during injection and post injection phases would verify site suitability
  - remediation plans need to be in place if things go wrong

[1]Lindeberg, Can the Risk for CO2 Escape from Geological Storage be Quantified?, Review Lecture, GHGT-8

[2]Doughty, Site Characterization for CO2 Geological Storage and Vice Versa – The Frio Site as a Case Study, CO2SC 2006

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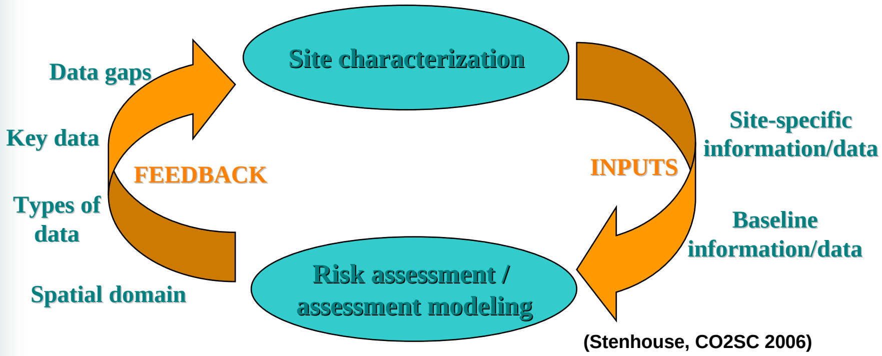
Site Characterization and Risk Assessment



(Stenhouse, CO2SC 2006)

- Risk Assessment (RA) expresses risk formally as the product of consequence of a FEP times its probability
- Will site characterization ever provide level of detail needed to conduct a formal risk assessment, particularly when it comes to low-probability and high-risk events?

EPA Sponsored Research at LBNL

- Large Releases of CO2 (2005 – 2006)
  - To evaluate the possibilities and consequences of large releases from a CO2 storage reservoir
- CO2 Geological Storage and Groundwater (just started)
  - To evaluate geochemical impact of CO2 leakage into USDW's (Task A)
  - To evaluate impact of CO2 storage on large-scale groundwater systems (Task B)
  - Co-funded by NETL

- Research projects address key technical gaps relevant for regulators

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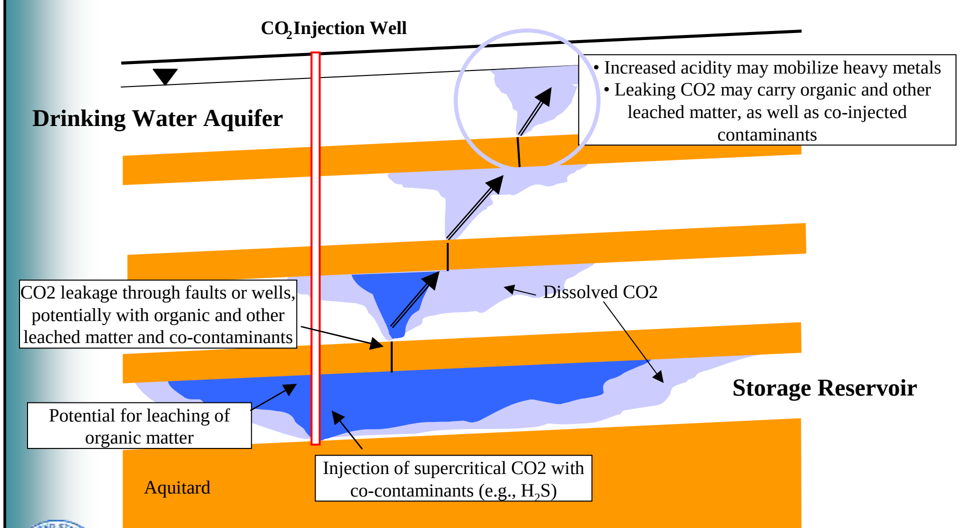
Large Releases of CO2

- Survey of natural and industrial analogs of CO2 releases to identify the relevant features, events and processes (FEPs) involved[1]
- Development of potential release scenarios for risk assessment[2]
- Simulations of hydrological and geomechanical processes that could initiate CO2 release and promote its acceleration[3]
- Literature survey to identify potential co-contaminants in CO2 captured from current and future coal-burning power plants[4]

[1]Lewicki et al., Environmental Geology, in press
[2]Birkholzer et al., GHGT-8
[3]Rutqvist et al., GHGT-8
[4]Apps, LBNL-59731

Groundwater Quality Concerns



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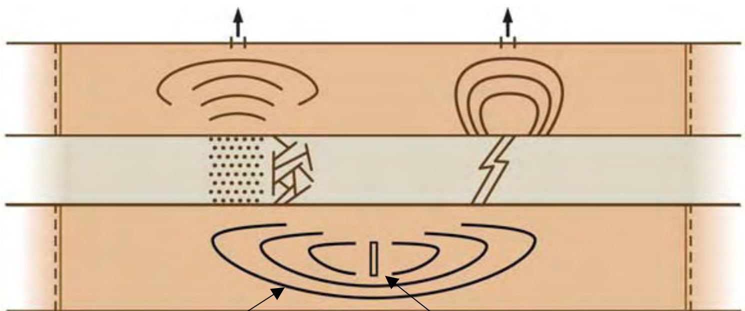
Regional Groundwater Systems

Need understanding of displaced water movements; in particular, those into USDW's

Need to evaluate the effects on: groundwater table, discharge and recharge zones and rates, and properties and characteristics of USDW's



Need understanding of increase and extent of water pressure buildup, both in the storage formation and shallower aquifers separated by aquitards

Amounts of CO2 to be injected underground will be very large

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Site Characterization Definition

The collection, analysis and interpretation of data and the application of knowledge to judge, with a degree of confidence, if an identified site will store a specific quantity of CO_2 for a defined period of time and meet all health, safety, environmental requirements."

Cook, CO2SC 2006

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CO2SC Panel Discussion

- Solid geologic model is key starting point
- Comprehensive suite of measurement methods and simulation tools is available
- Avoid specifying particular technologies in regulation
  - Different needs, varying effectiveness, allow for innovation
- Pilots and early large-scale projects are important base of experience (learning by doing)
- One key concern is large-scale characterization of seals for saline formations
  - How to detect ALL faults
  - How to derive fault PROPERTIES
- Possibility of some leakage should be assumed at any site; monitoring and remediation plan should be in place

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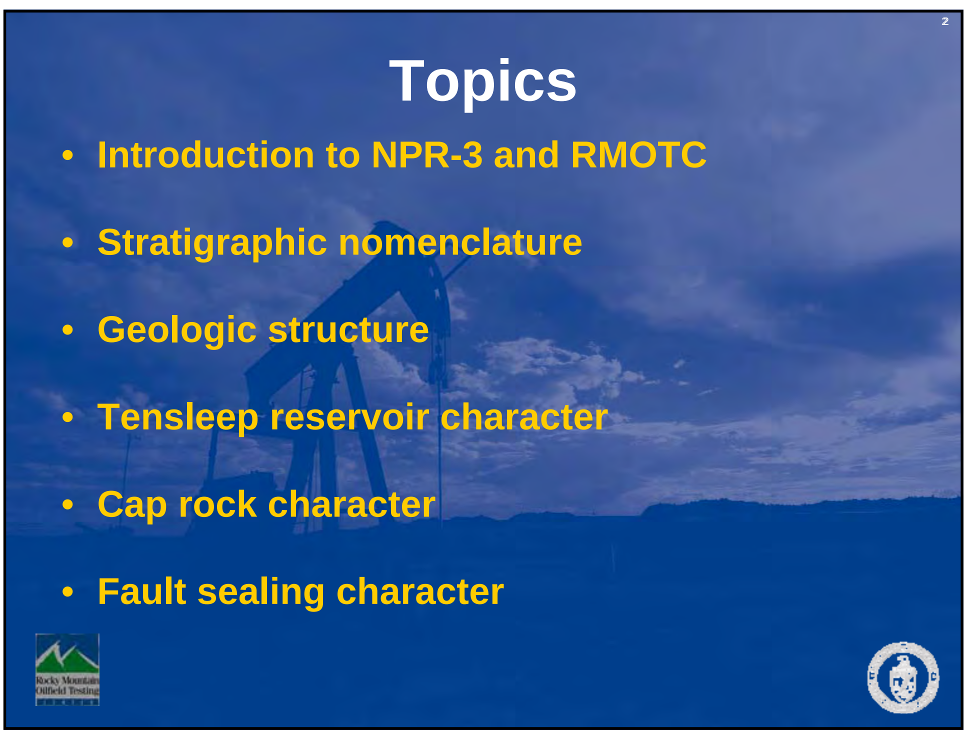
ROCKY MOUNTAIN
OILFIELD TESTING
CENTER
EPA Geologic Sequestration Technical Workshop:
Part I: Geological Considerations
July 10 and 11, 2007; Grand Hyatt, Washington, DC

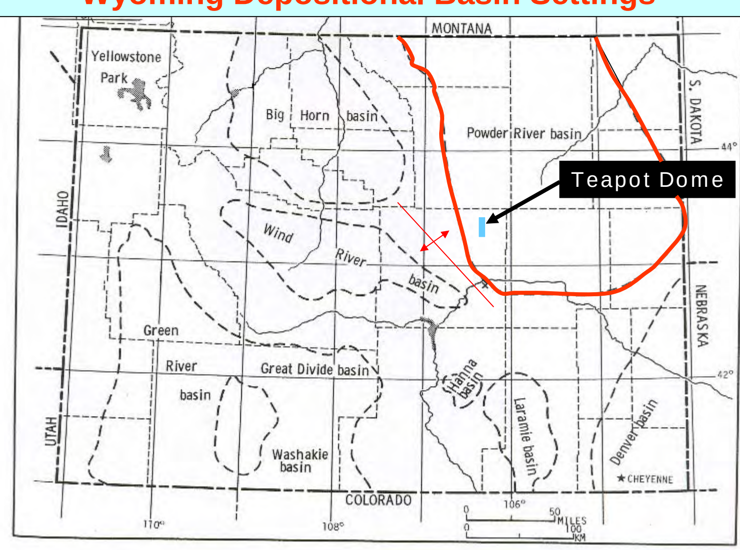

2
Topics
• Introduction to NPR-3 and RMOTC
• Stratigraphic nomenclature
• Geologic structure
• Tensleep reservoir character
• Cap rock character
• Fault sealing character

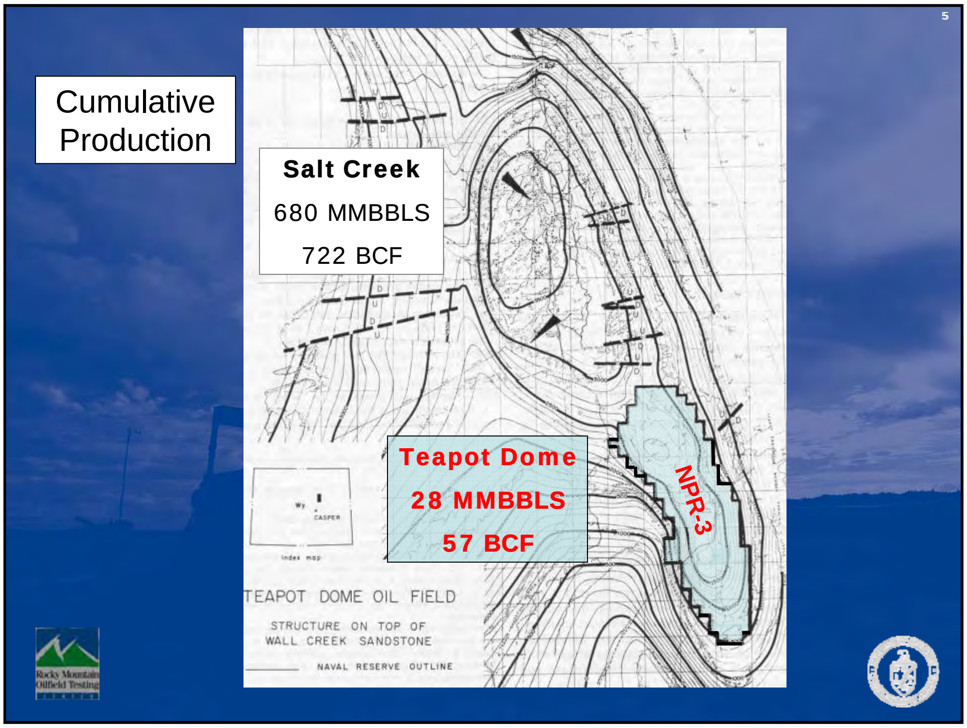
3

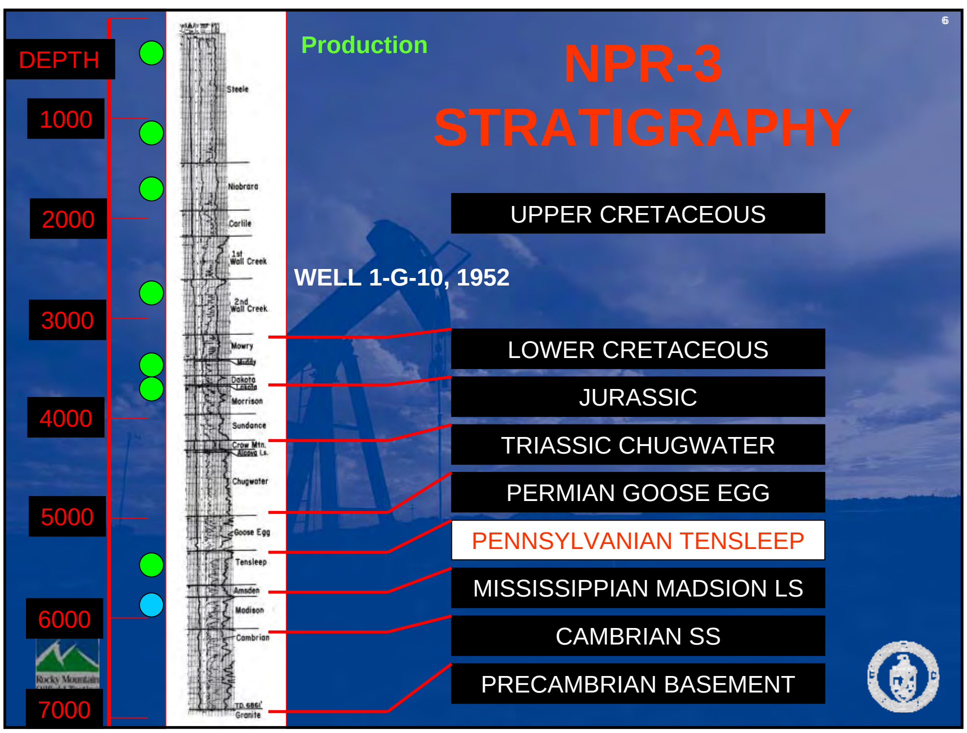
Naval Petroleum Reserve No. 3

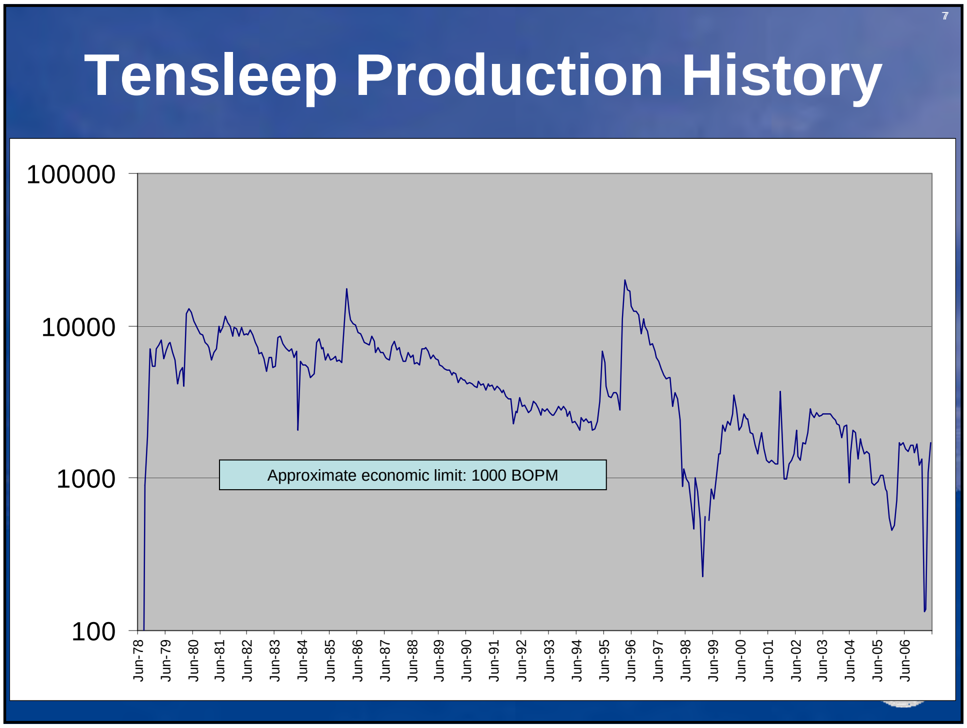
4

Wyoming Depositional Basin Settings




5
Cumulative Production
Salt Creek
680 MMBBLS
722 BCF
Teapot Dome
28 MMBBLS
57 BCF
NPR-3
TEAPOT DOME OIL FIELD
STRUCTURE ON TOP OF
WALL CREEK SANDSTONE
NAVAL RESERVE OUTLINE


6
DEPTH
1000
2000
3000
4000
5000
6000
7000
Production
NPR-3
STRATIGRAPHY
UPPER CRETACEOUS
WELL 1-G-10, 1952
LOWER CRETACEOUS
JURASSIC
TRIASSIC CHUGWATER
PERMIAN GOOSE EGG
PENNSYLVANIAN TENSLEEP
MISSISSIPPIAN MADSION LS
CAMBRIAN SS
PRECAMBRIAN BASEMENT
Steele
Niobrara
Carlile
1st Wall Creek
2nd Wall Creek
Mowry
Dakota
Morrison
Sundance
Crow Mtn.
Chugwater
Goose Egg
Tensleep
Amsden
Madison
Cambrian
Granite


7
Tensleep Production History
100000
10000
1000
100
Approximate economic limit: 1000 BOPM
Jun-78
Jun-79
Jun-80
Jun-81
Jun-82
Jun-83
Jun-84
Jun-85
Jun-86
Jun-87
Jun-88
Jun-89
Jun-90
Jun-91
Jun-92
Jun-93
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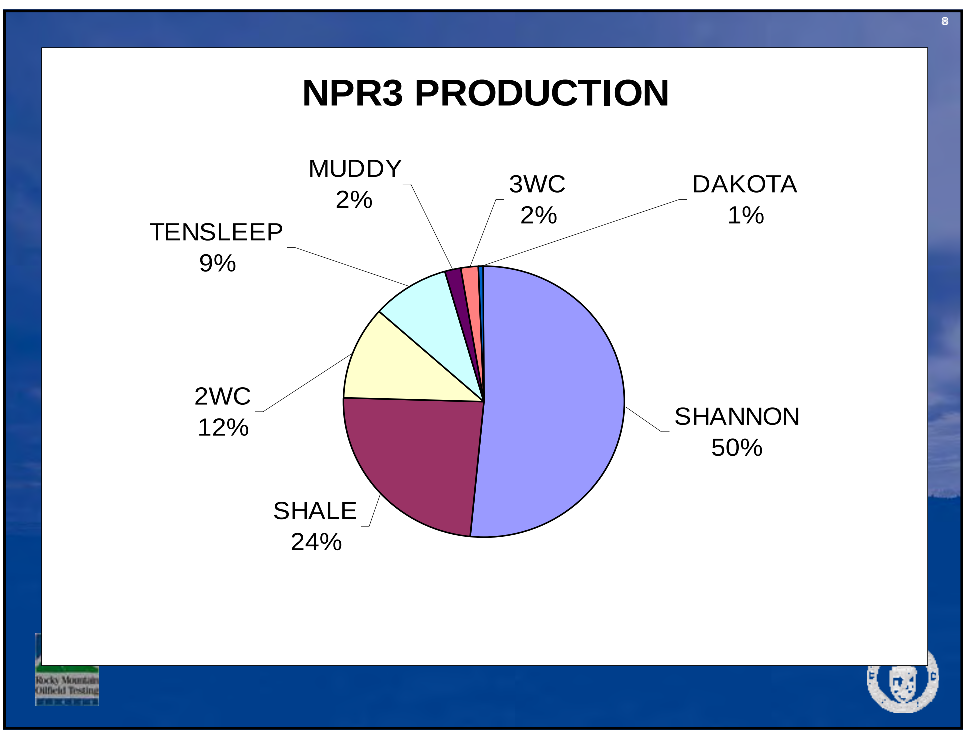
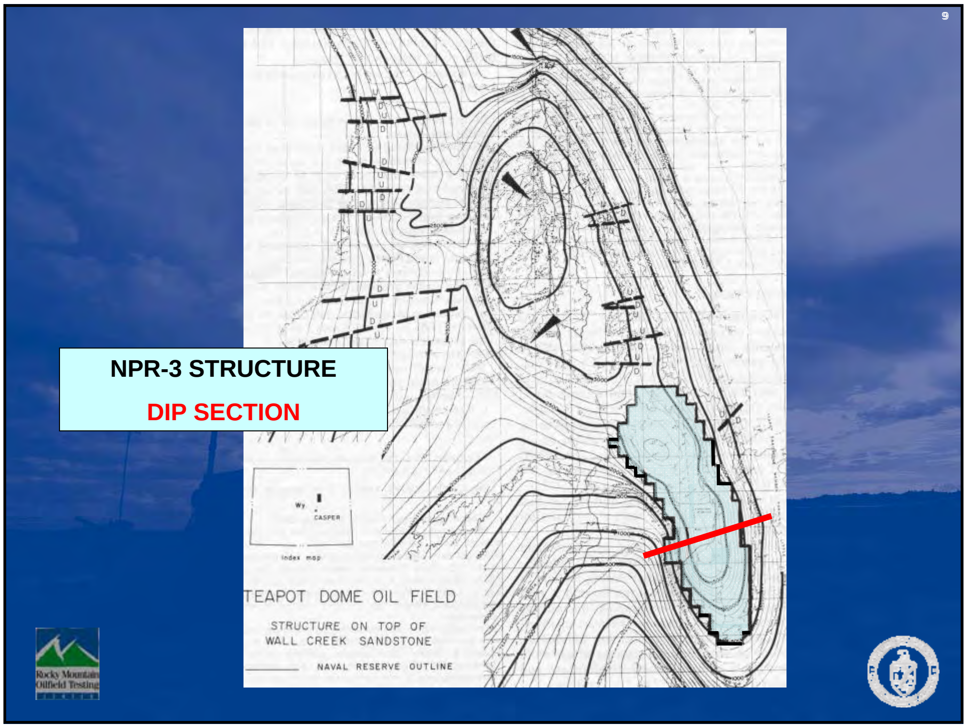
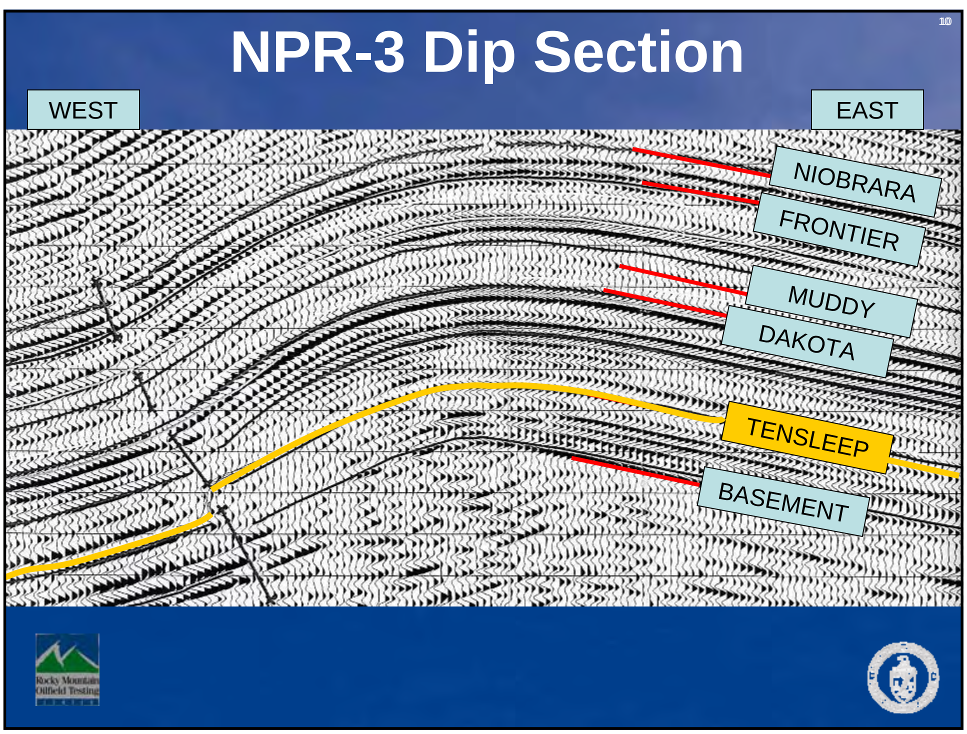
Jun-04
Jun-05
Jun-06


8
NPR3 PRODUCTION
MUDDY
2%
3WC
2%
DAKOTA
1%
TENSLEEP
9%
2WC
12%
SHANNON
50%
SHALE
24%

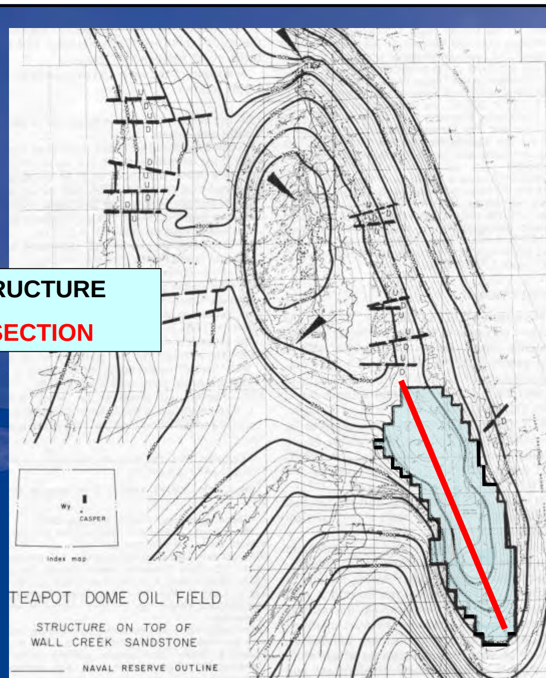

9
NPR-3 STRUCTURE
DIP SECTION
Wy.
CASPER
index map
TEAPOT DOME OIL FIELD
STRUCTURE ON TOP OF
WALL CREEK SANDSTONE
NAVAL RESERVE OUTLINE
Rocky Mountain
Oilfield Testing


10
NPR-3 Dip Section
WEST
EAST
NIOBRARA
FRONTIER
MUDDY
DAKOTA
TENSLEEP
BASEMENT
Rocky Mountain
Oilfield Testing

11

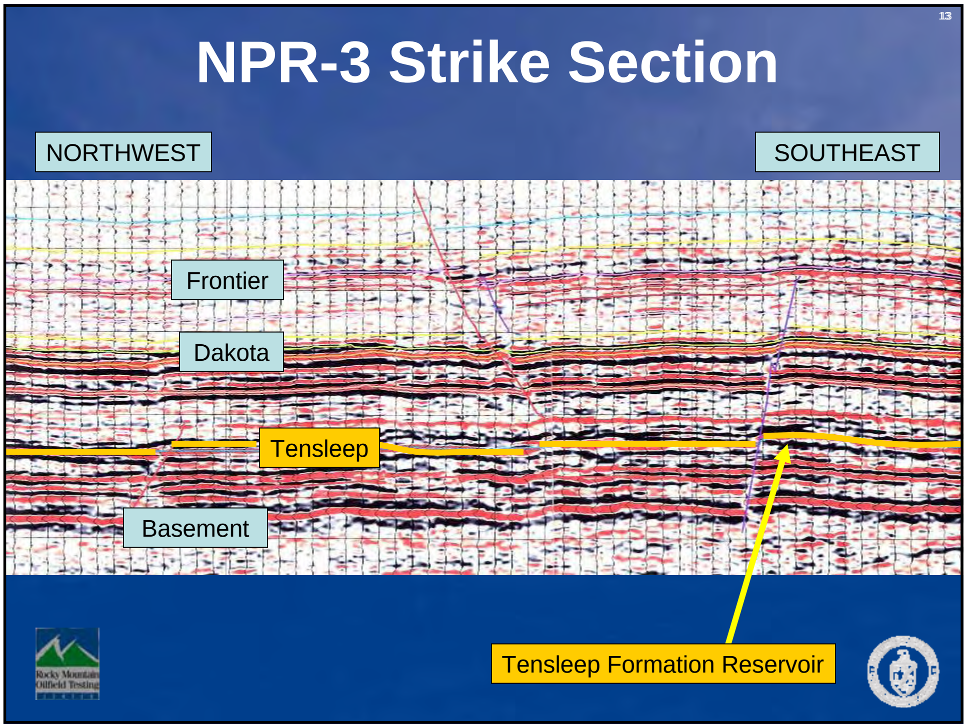
Tensleep Structure at NPR-3

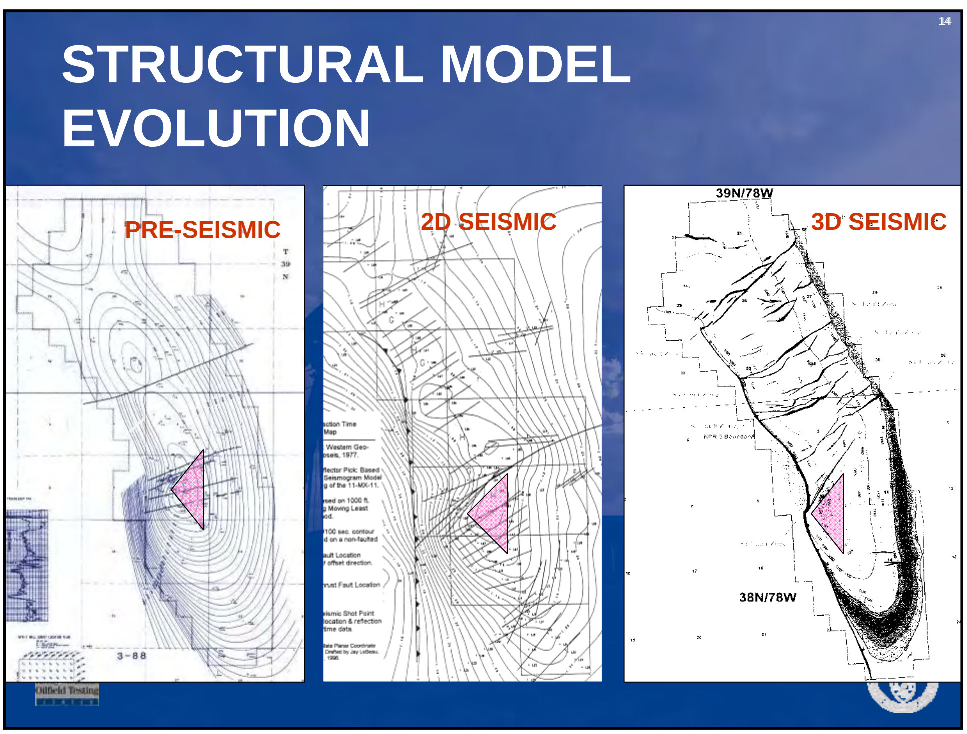
12



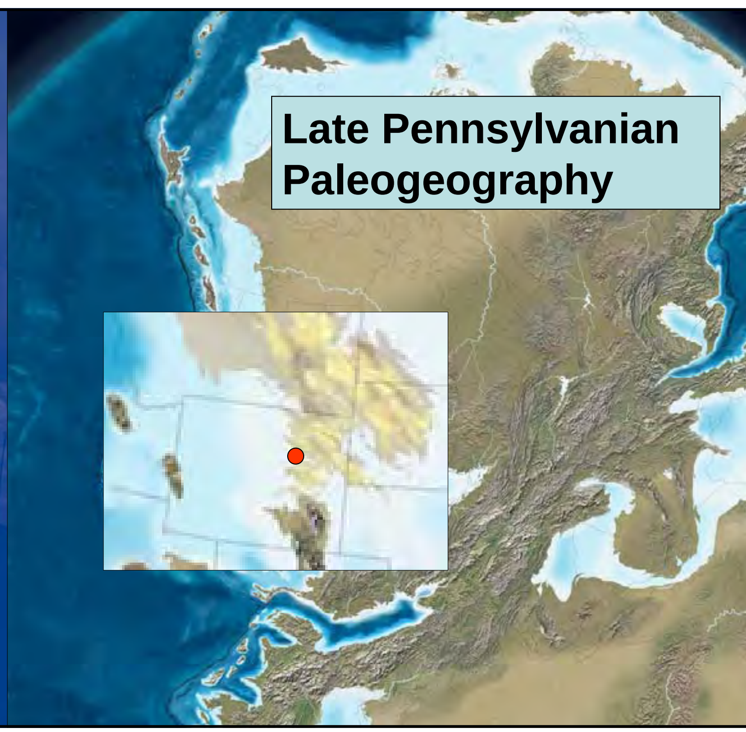
NPR-3 STRUCTURE

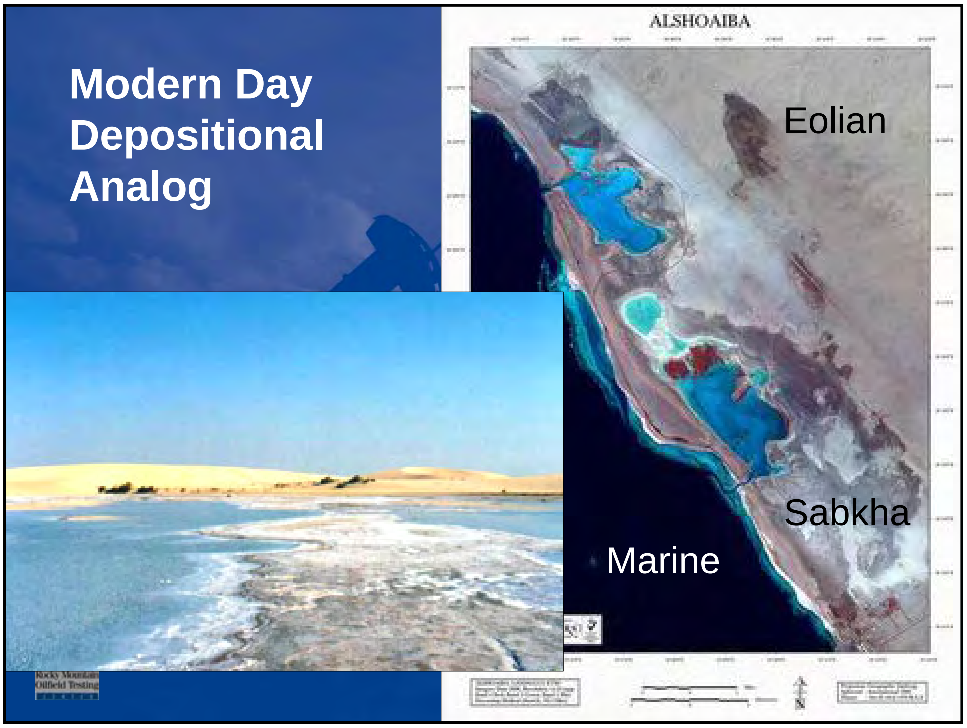
STRIKE SECTION

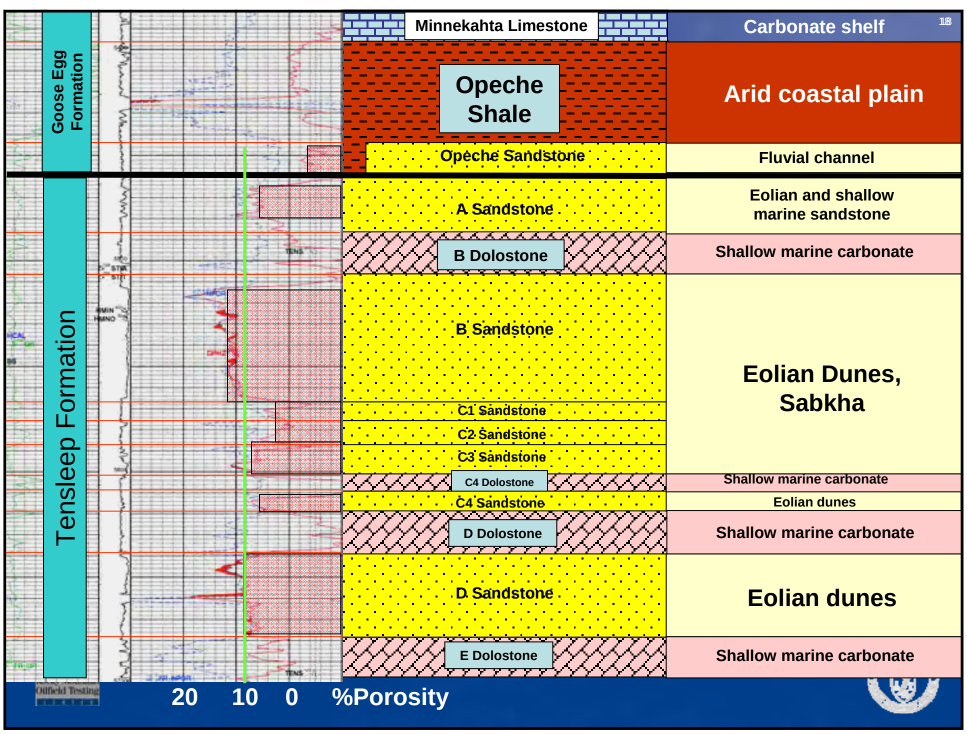

13
NPR-3 Strike Section
NORTHWEST
SOUTHEAST
Frontier
Dakota
Tensleep
Basement
Tensleep Formation Reservoir
Rocky Mountain Oilfield Testing


14
STRUCTURAL MODEL EVOLUTION
PRE-SEISMIC
2D SEISMIC
3D SEISMIC
39N/78W
38N/78W

TENSLEEP DEPOSITIONAL ENVIRONMENTS

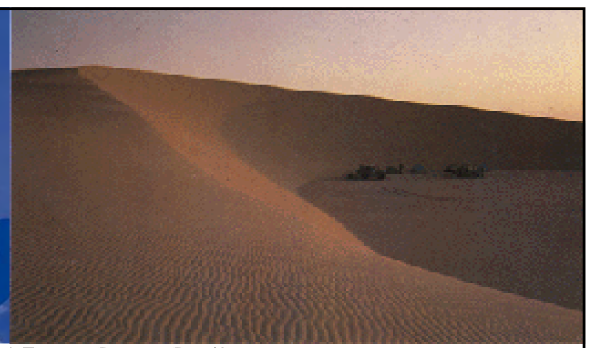



Modern Day Depositional Analog
ALSHOAIBA
Eolian
Sabkha
Marine

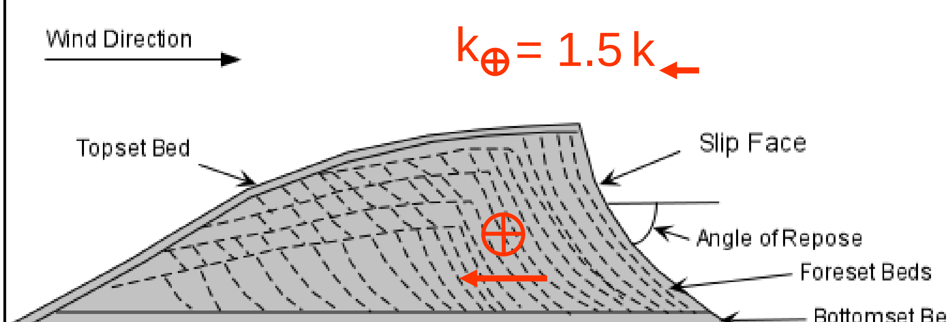

18
Goose Egg Formation
Tensleep Formation
Minnekahta Limestone
Carbonate shelf
Opeche Shale
Arid coastal plain
Opeche Sandstone
Fluvial channel
A Sandstone
Eolian and shallow marine sandstone
B Dolostone
Shallow marine carbonate
B Sandstone
Eolian Dunes, Sabkha
C1 Sandstone
C2 Sandstone
C3 Sandstone
C4 Dolostone
Shallow marine carbonate
C4 Sandstone
Eolian dunes
D Dolostone
Shallow marine carbonate
D Sandstone
Eolian dunes
E Dolostone
Shallow marine carbonate
20
10
0
%Porosity

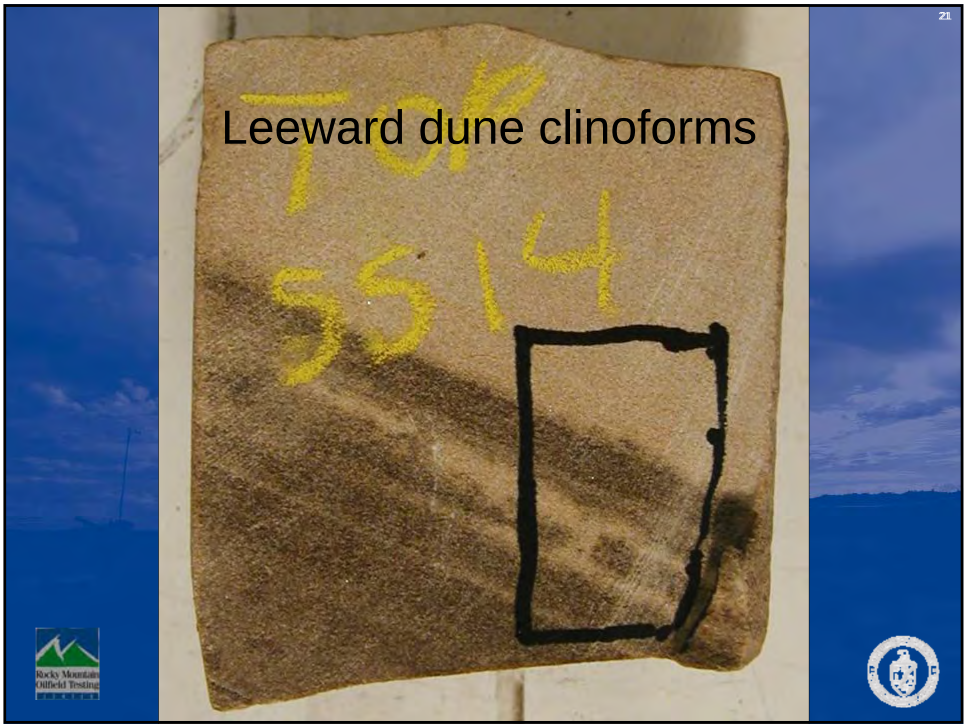
Horizontal Permeability Heterogeneities, Eolian Dune Facies, Tensleep Sandstone Formation

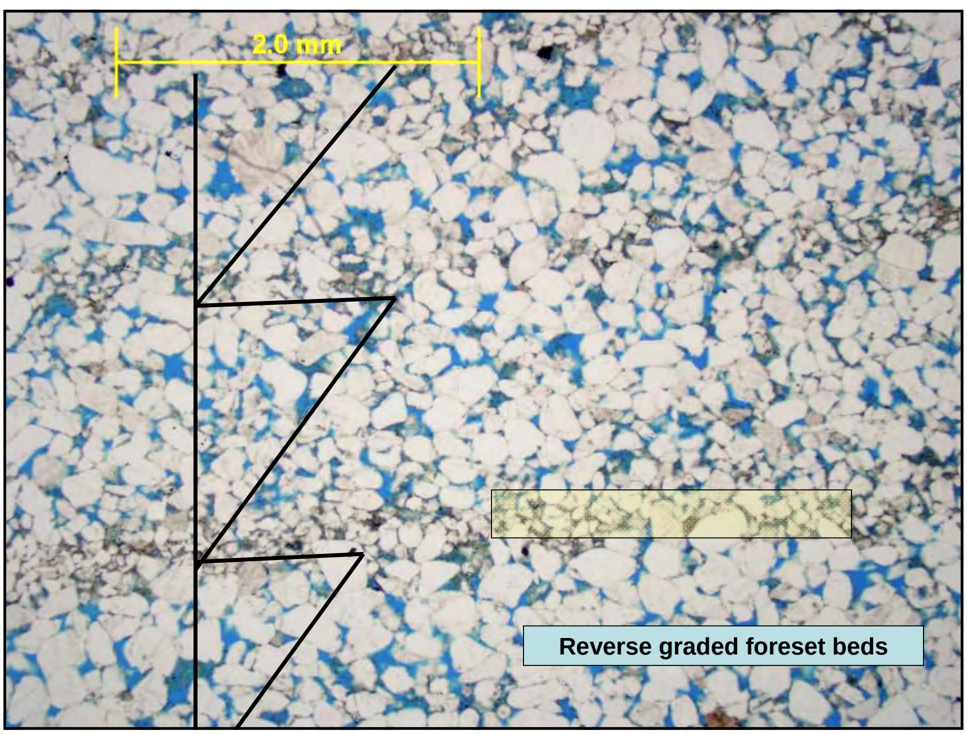
EOLIAN DUNES

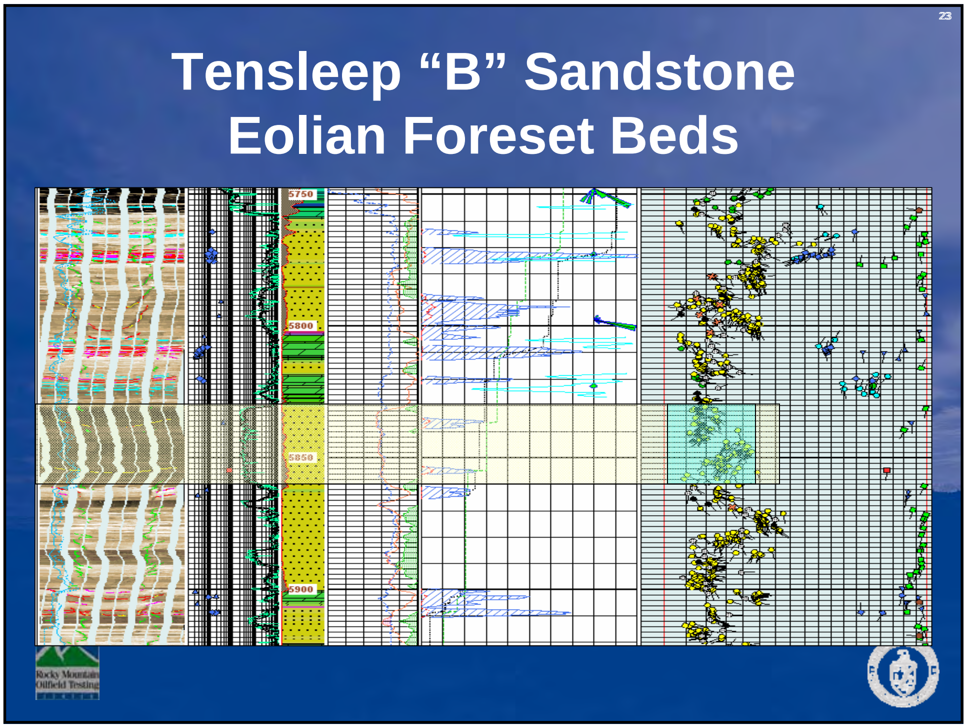


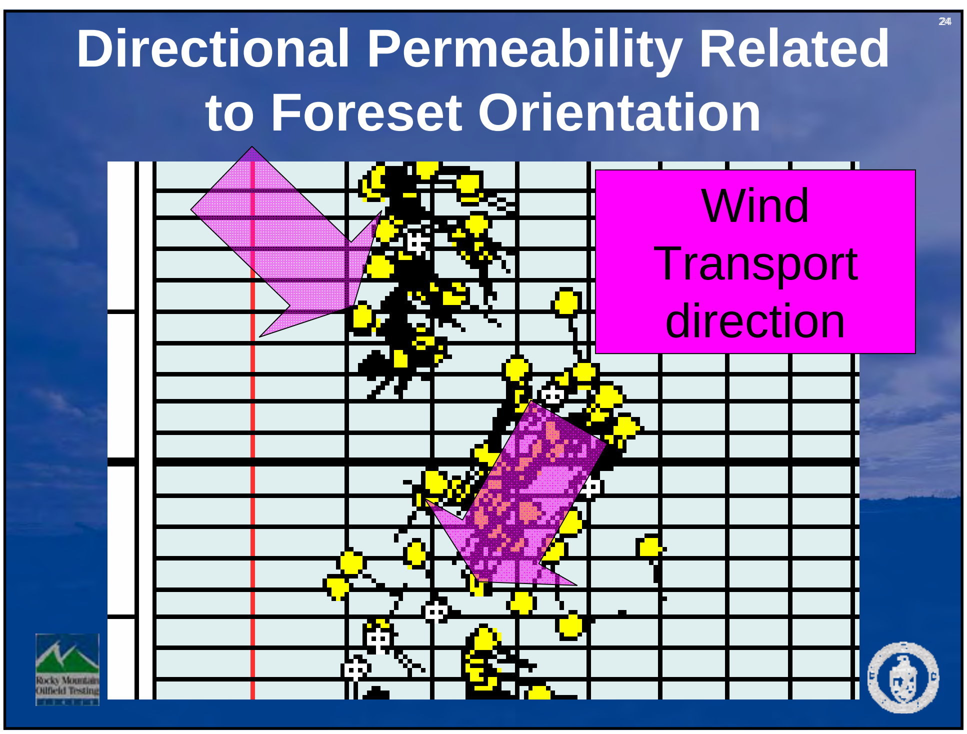
Sand Dune Cross Section




21
Leeward dune clinoforms
TOP
5514
Rocky Mountain Oilfield Testing

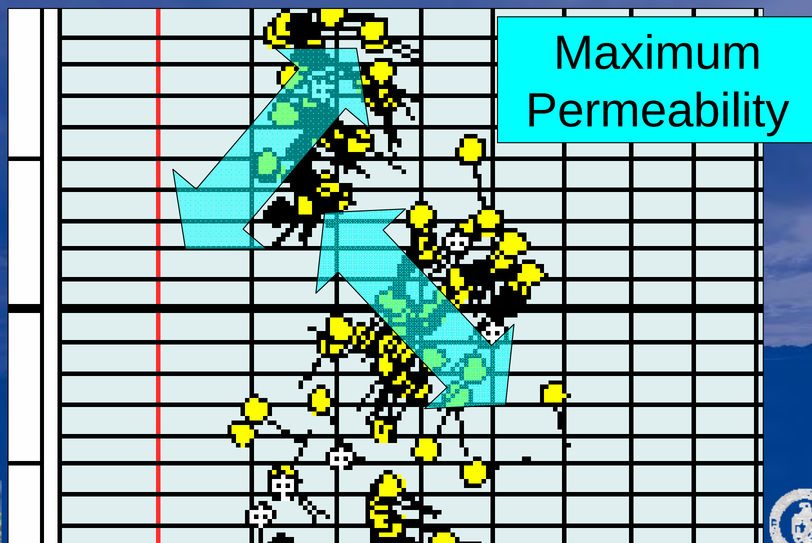

2.0 mm
Reverse graded foreset beds


23
Tensleep "B" Sandstone
Eolian Foreset Beds
5750
5800
5850
5900


24
Directional Permeability Related
to Foreset Orientation
Wind
Transport
direction

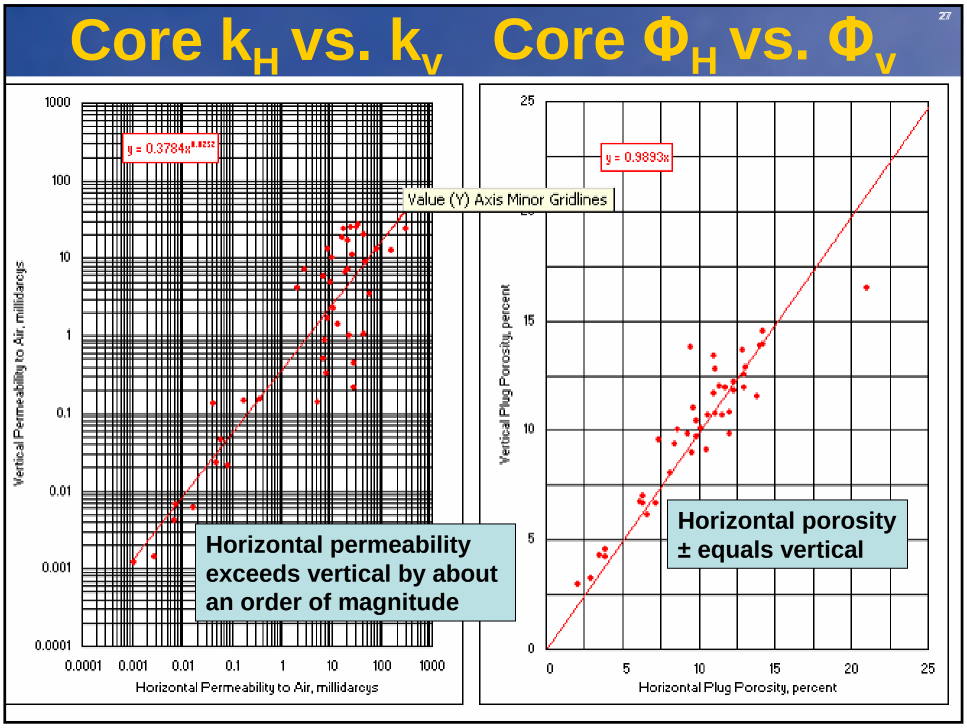
25

Directional Permeability Related to Foreset Bed Orientation

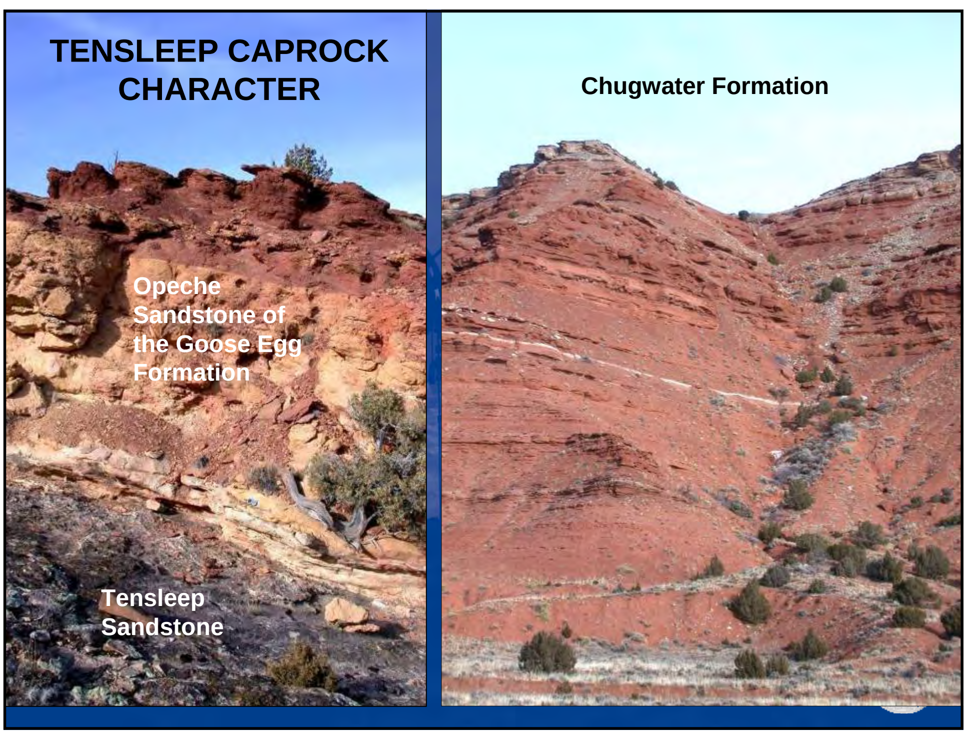


26

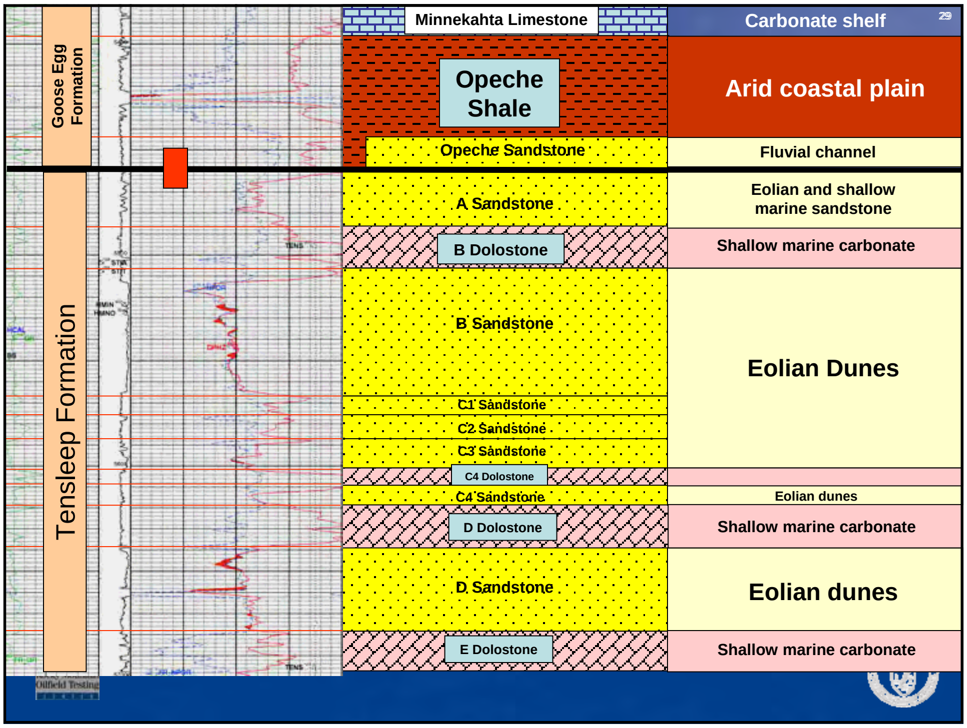
Vertical Permeability Heterogeneities, Tensleep Sandstone Formation

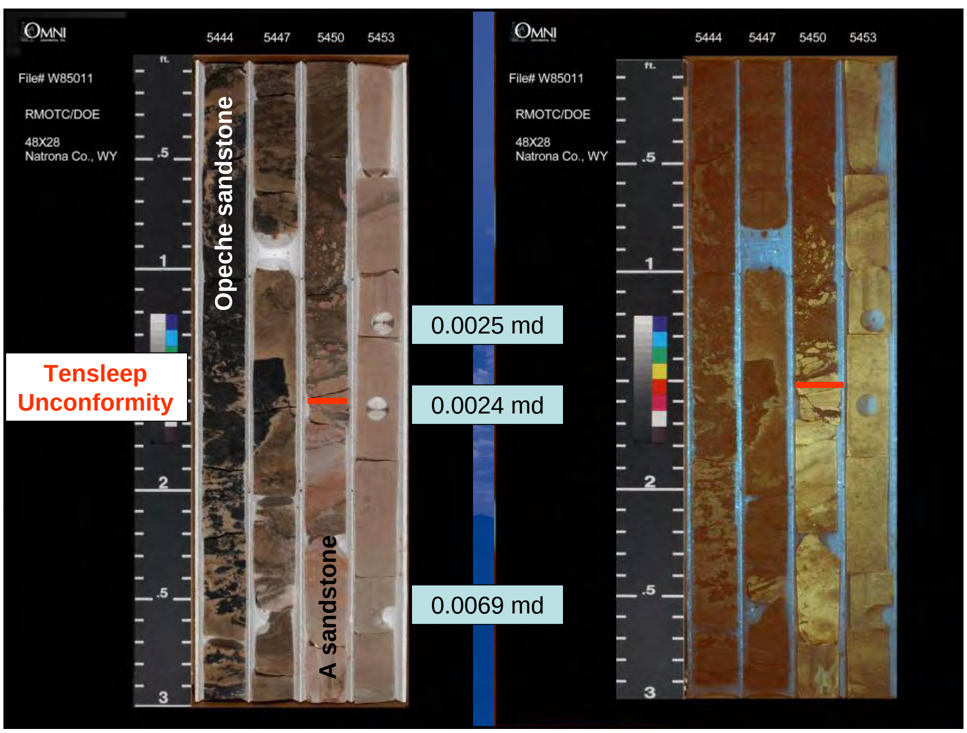


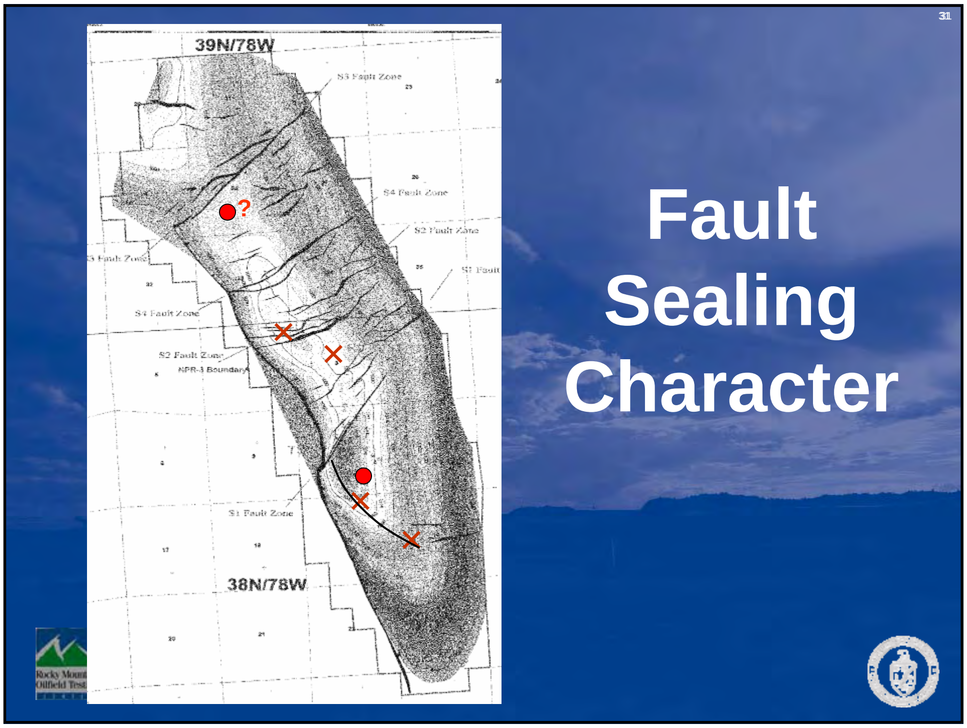
27
Core k_H vs. k_V
Core Φ_H vs. Φ_V
y = 0.3784x
Value (Y) Axis Minor Gridlines
1000
100
10
1
0.1
0.01
0.001
0.0001
Vertical Permeability to Air, millidarcys
0.0001 0.001 0.01 0.1 1 10 100 1000
Horizontal Permeability to Air, millidarcys
Horizontal permeability exceeds vertical by about an order of magnitude
y = 0.9893x
25
15
10
5
0
Vertical Plug Porosity, percent
0 5 10 15 20 25
Horizontal Plug Porosity, percent
Horizontal porosity ± equals vertical

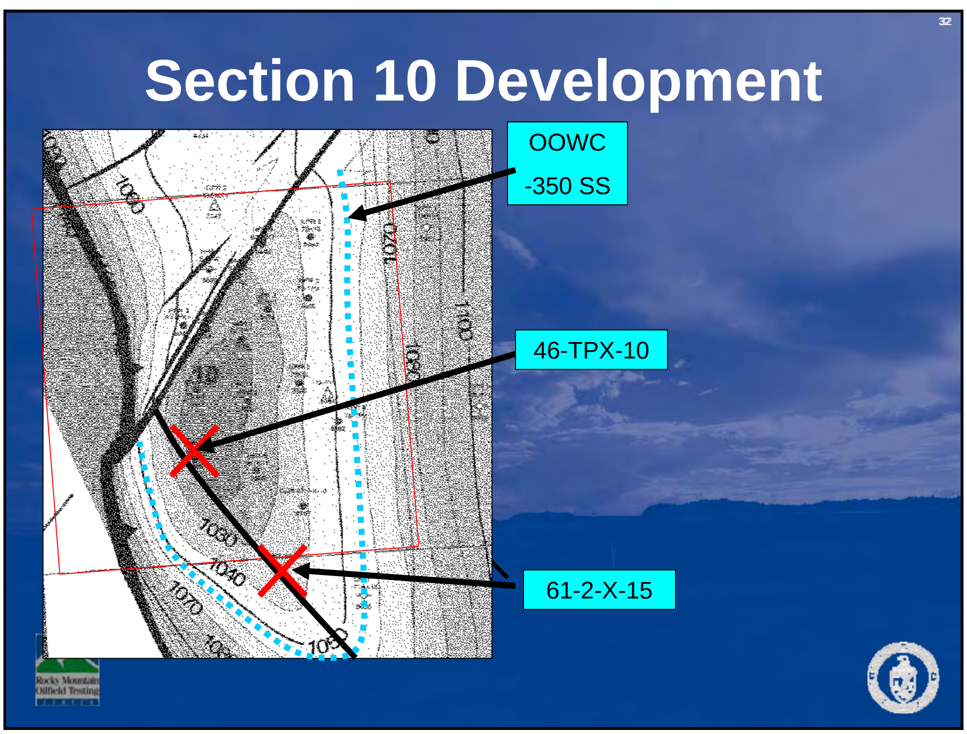


TENSLEEP CAPROCK CHARACTER
Opeche Sandstone of the Goose Egg Formation
Tensleep Sandstone
Chugwater Formation


Goose Egg Formation
Tensleep Formation
Minnekahta Limestone
Carbonate shelf
Opeche Shale
Arid coastal plain
Opeche Sandstone
Fluvial channel
A Sandstone
Eolian and shallow marine sandstone
B Dolostone
Shallow marine carbonate
B Sandstone
Eolian Dunes
C1 Sandstone
C2 Sandstone
C3 Sandstone
C4 Dolostone
C4 Sandstone
Eolian dunes
D Dolostone
Shallow marine carbonate
D Sandstone
Eolian dunes
E Dolostone
Shallow marine carbonate


OMNI
File# W85011
RMOTC/DOE
48X28
Natrona Co., WY
5444
5447
5450
5453
Opeche sandstone
A sandstone
Tensleep Unconformity
0.0025 md
0.0024 md
0.0069 md

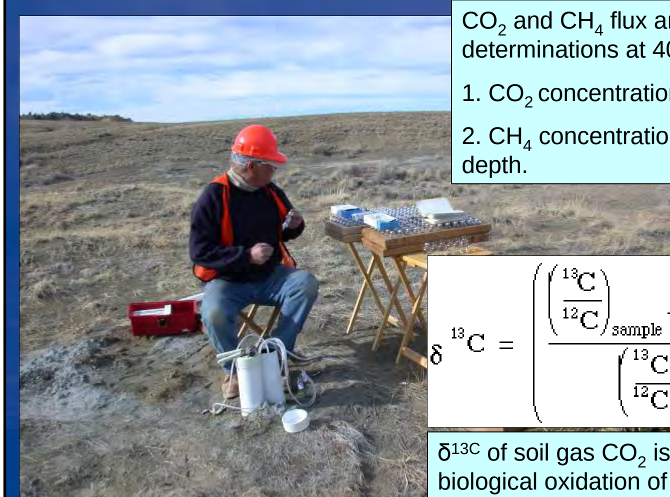

31
Fault Sealing Character
39N/78W
S3 Fault Zone
S4 Fault Zone
S2 Fault Zone
NPR-3 Boundary
S1 Fault Zone
38N/78W


32
Section 10 Development
OOWC
-350 SS
46-TPX-10
61-2-X-15
1030
1040
1070

Fault Evaluations

- Soil Gas Flux (Ron Klusman, Colorado School of Mines)
- Carbonate fracture filling character (Sean Brennan, USGS)
- Geomechanical fault studies (Laura Chiaramonte, Stanford U.)
- Surface geologic mapping
- Trenches

Ron Klusman, CSM



CO_2 and CH_4 flux and concentration determinations at 40 stations:

1. CO_2 concentration increases with depth,
2. CH_4 concentration decreases with depth.

$$\delta^{13}C = \left(\frac{\left(\frac{^{13}C}{^{12}C}\right)_{sample} - \left(\frac{^{13}C}{^{12}C}\right)_{standard}}{\left(\frac{^{13}C}{^{12}C}\right)_{standard}} \right) * 1000$$

δ^{13C} of soil gas CO_2 is sourced from biological oxidation of organic matter.

Reference: Klusman, 2006

Sean Brennan, USGS

Timing of hydrocarbon emplacement and calcite lined fractures:

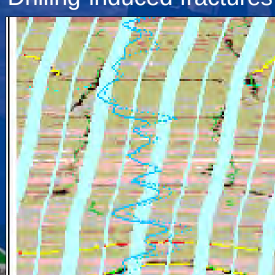
1. Fractures formed 10-12 Ma, followed by emplacement of hydrocarbons,
2. Calcite formed at greater temperatures and depths than present, 600-1500 m.
3. No connection to CO_2 seq. reservoirs.

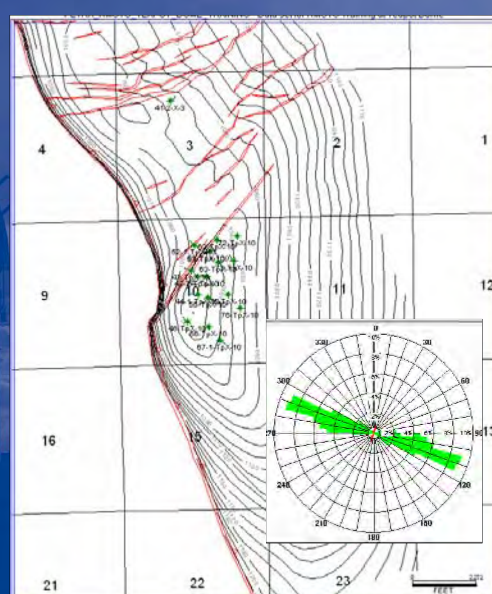
Reference: Brennan, 2006

Laura Chiaramonte, Stanford U.

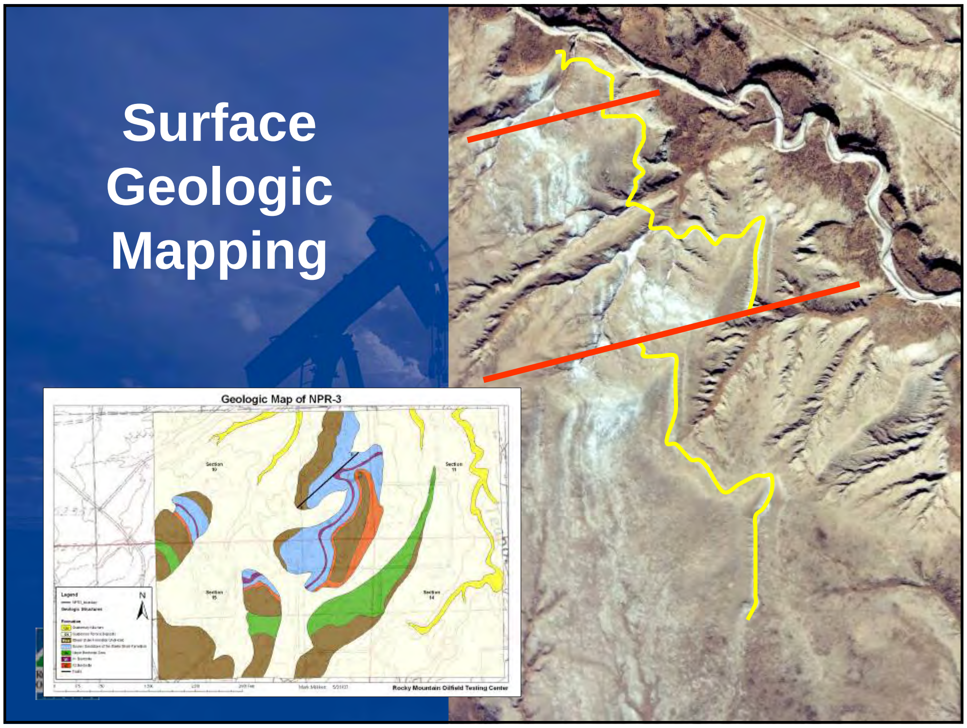
Geomechanical studies of in-situ stress orientations predicting fault reactivation through increased reservoir pressure.

Drilling-induced fractures





Reference: Chiaramonte, 2006


Surface Geologic Mapping
Geologic Map of NPR-3
Rocky Mountain Oilfield Testing Center

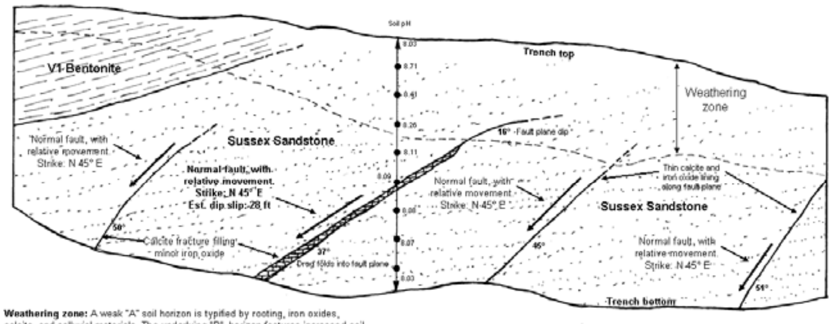

38
Trenches

NPR-3 GEOLOGY TRENCH 87-10E

Mark Milliken (RMOTC) and Ron Klusman (Colorado School of Mines), May 2007

Note: This trench is located about 20 ft NE and parallel to trench 87-10W.

Trench bearing: N 35° W



Weathering zone: A weak "A" soil horizon is typified by rooting, iron oxides, calcite, and colluvial materials. The underlying "B" horizon features increased soil pH values. The B horizon is typified by calcite precipitation along older root paths due to illuviation. Soil pH values are courtesy of Ron Klusman.

Sussex Sandstone Member of the Steele Shale Formation (Upper Cretaceous): Tan to dark brown in color. Generally unconsolidated thin-bedded marine sandstone interbedded with silty shale. Includes occasional well-cemented sandstone zones.

Calcite fracture filling: Secondary calcite, white to buff color, abundant well developed crystalline facets. Thickness ranges from 0.1 in. to 4 inches and may include multiple emplacement events.

V1 Bentonite: Oxidized bentonite, yellowish orange in color. The lowest in a series of at least nine bentonite beds above the Sussex Sandstone. The base of V1 is about 23 ft above the resistant Sussex Sandstone outcrop. Based on the fault plane geometry in this trench and 87-10W, the estimated dip slip is 28 ft S.

Scale

Horizontal = Vertical

One foot

One meter

Location
NPR-3
SE/4 SE/4 Sec. 10
T. 38 N., R. 78 W.
Natrona Co., WY
43.27369558 -106.19379242

40

Origin of calcite fault/fracture filling

41

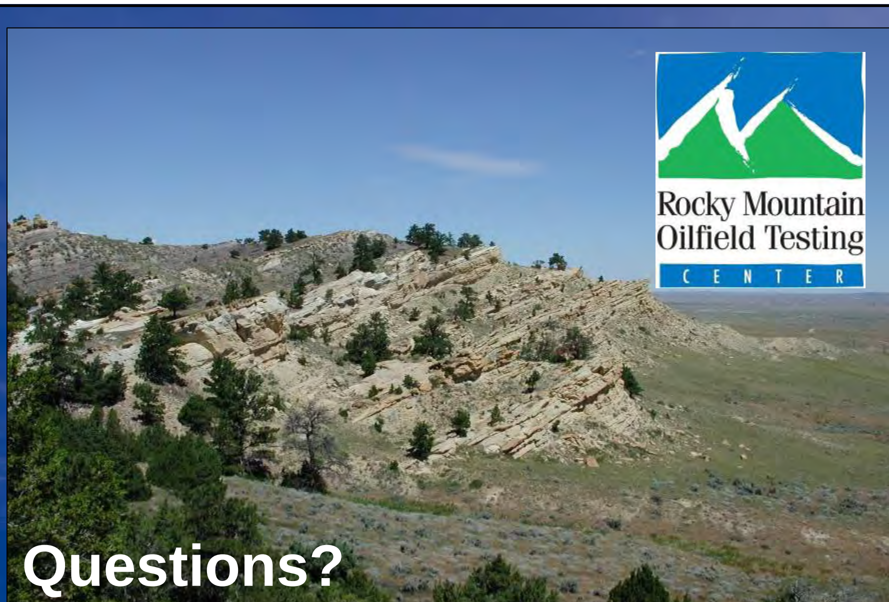
Selected References

Brennan, Sean, K. Dennen, and R. Burruss, 2006, Timing and hydrocarbon emplacement in ozokerite and calcite lined fractures, Teapot Dome, WY; USGS Open file report 2006-1214, 23 p.

Chiaramonte, Laura, M. Zoback, J. Friedmann, and V. Stamp, 2006, Geomechanical site characterization to constrain CO_2 injection Feasibility: Teapot Dome EOR pilot: Proceedings, CO_2SC Symposium 2006, Lawrence Berkeley National Laboratory, Berkeley, California, March 20-22, 2006, 3 p.

Klusman, Ronald, 2006, Detailed compositional analysis of gas seepage at the National Carbon Storage Test Site, Teapot Dome, WY, USA: Applied Geochemistry, 21 (2006), p. 1498-1521.

42



An Assessment of Geological Carbon Sequestration Options in the Illinois Basin

Subsurface Geological Considerations in Carbon Sequestration

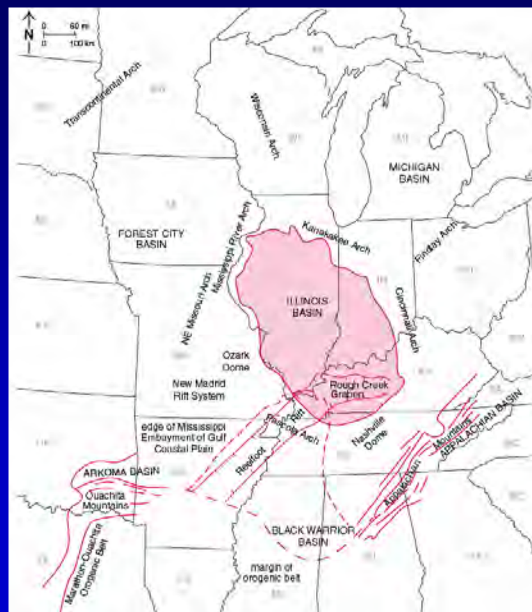
Robert J. Finley
July 10, 2007
EPA Technical Workshop

Midwest Geological Sequestration Consortium
www.sequestration.org

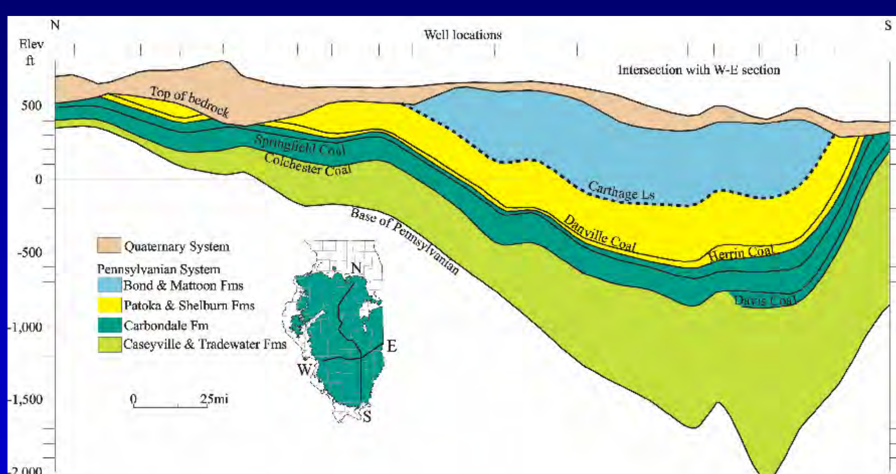
Acknowledgements

- This work is being supported by the U.S. Department of Energy, Office of Fossil Energy, as part of the Regional Sequestration Partnerships Program, and by the Illinois Office of Coal Development (DCEO) through the Illinois Clean Coal Institute, under the Midwest Geological Sequestration Consortium (MGSC)
- The MGSC is a collaboration led by the geological surveys of Illinois, Indiana, and Kentucky

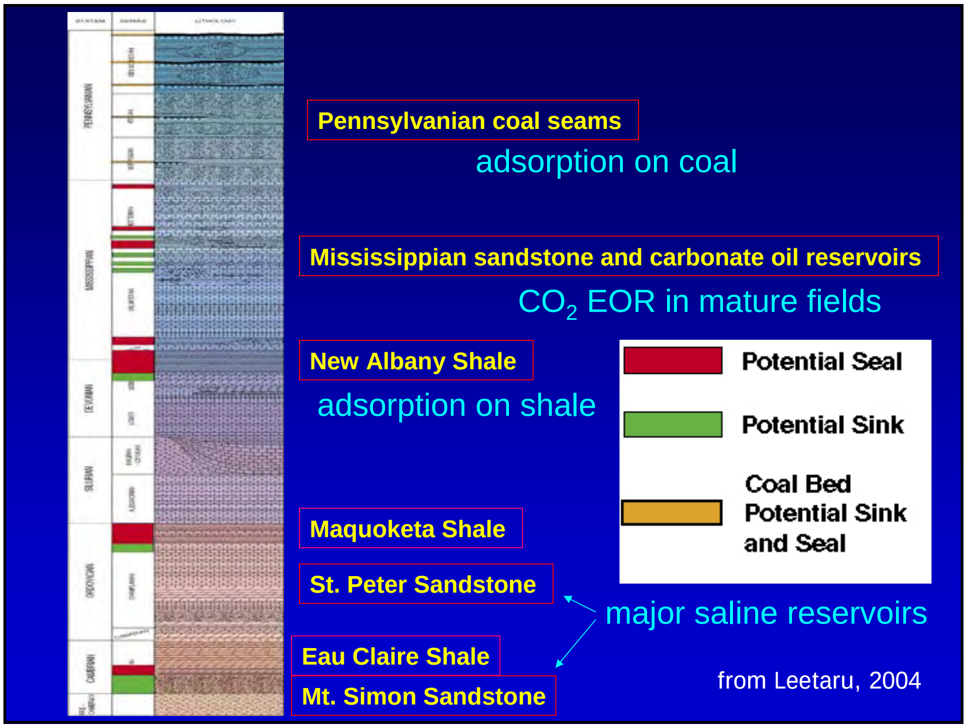
Illinois Basin



N-S Cross Section of Coal-bearing Strata in Illinois



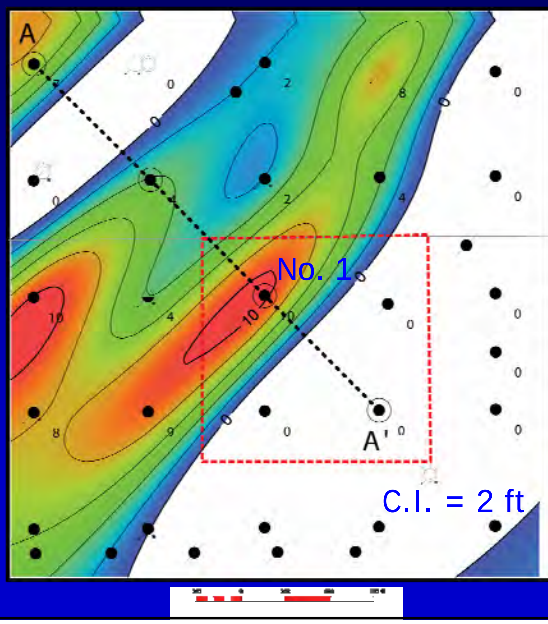
By Christopher Korose, Jamie McBeth, and Colin Treworgy, ISGS



Inject/Soak/Produce (“Huff ‘n Puff”) Field Test, Loudon Field, Fayette Co., Illinois

- Use single oil producing well to alternate CO_2 injection and oil production
- CO_2 injected as a gas (immiscible)
- Quantify in-situ PVT properties of CO_2 and reservoir oil (laboratory)
- Optimize injected volume and soak time via compositional reservoir simulation (VIP)
- Carry out environmental monitoring
- 43 tons CO_2 injected week of March 19, 2007

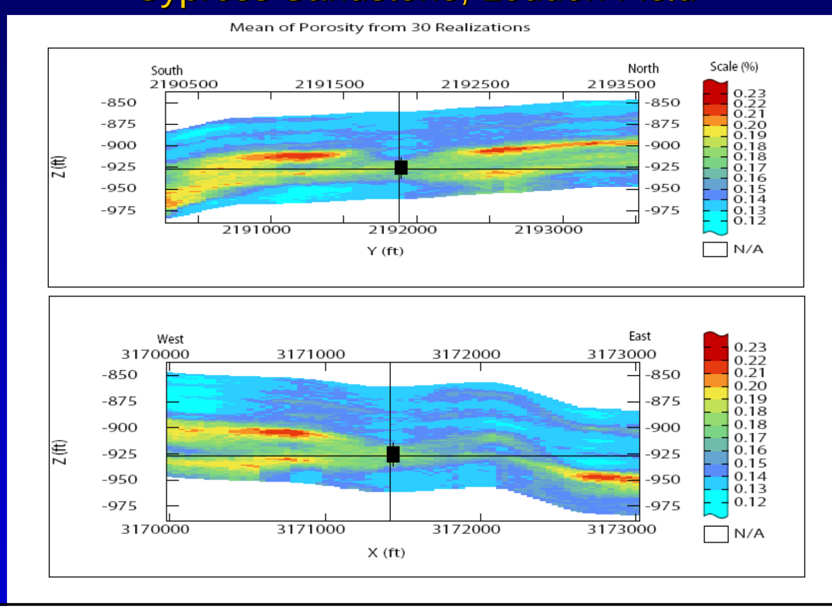
Owens Lease, Cypress A9 Zone



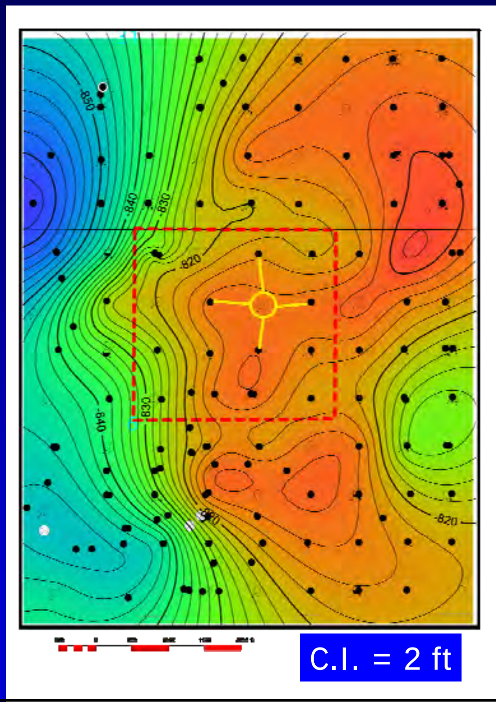
- Stacked, northeast trending linear sand ridges
- Owens No. 1 and four surrounding wells monitored

Porosity Model for Huff 'n Puff Test Site

Cypress Sandstone, Loudon Field



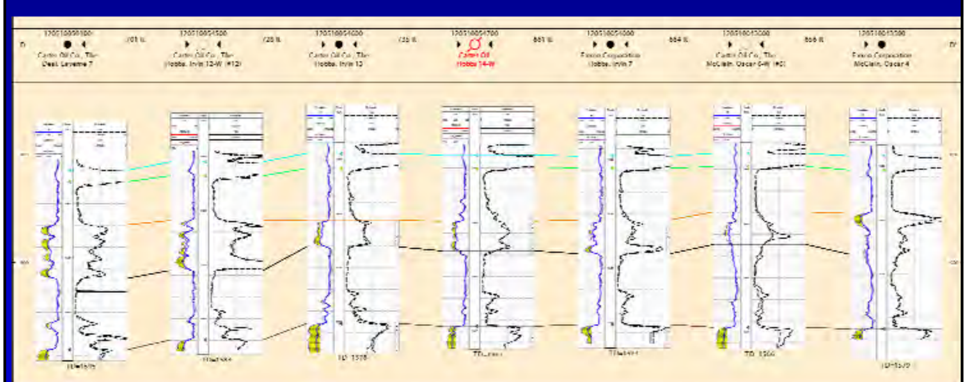
Immiscible Pattern Flood
Hobbs Lease, Loudon Field



- 160 acre lease with a water injector and four surrounding producers
- Injector will be converted to CO_2
- About 2,500 tons to be injected starting in July 07

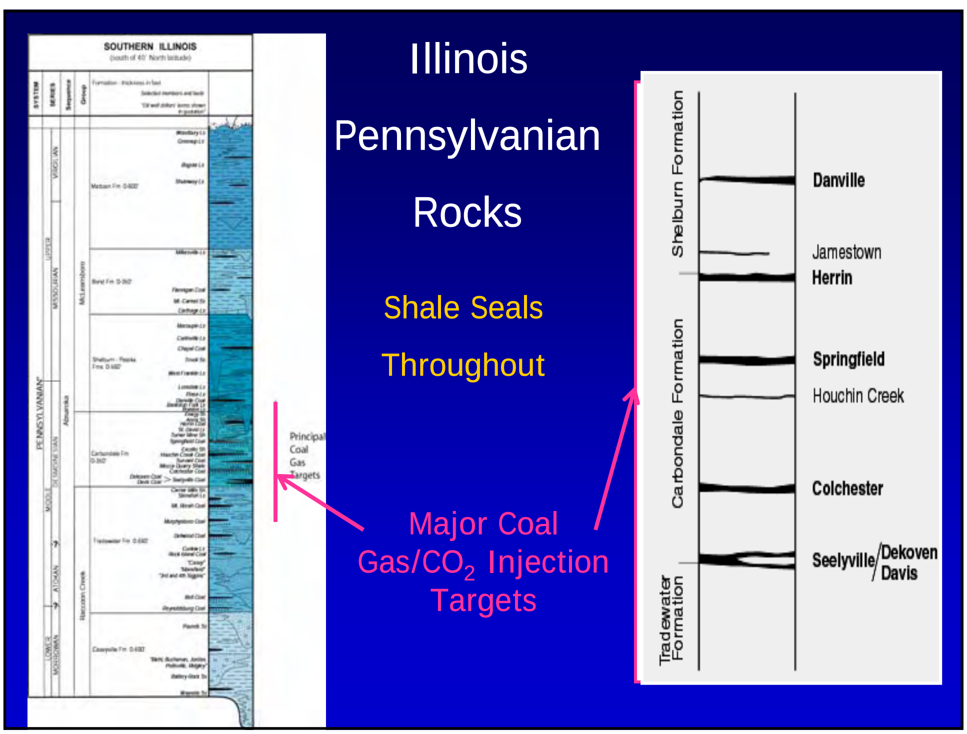
Hobbs Lease Shows Good Lateral Continuity at Cypress Level

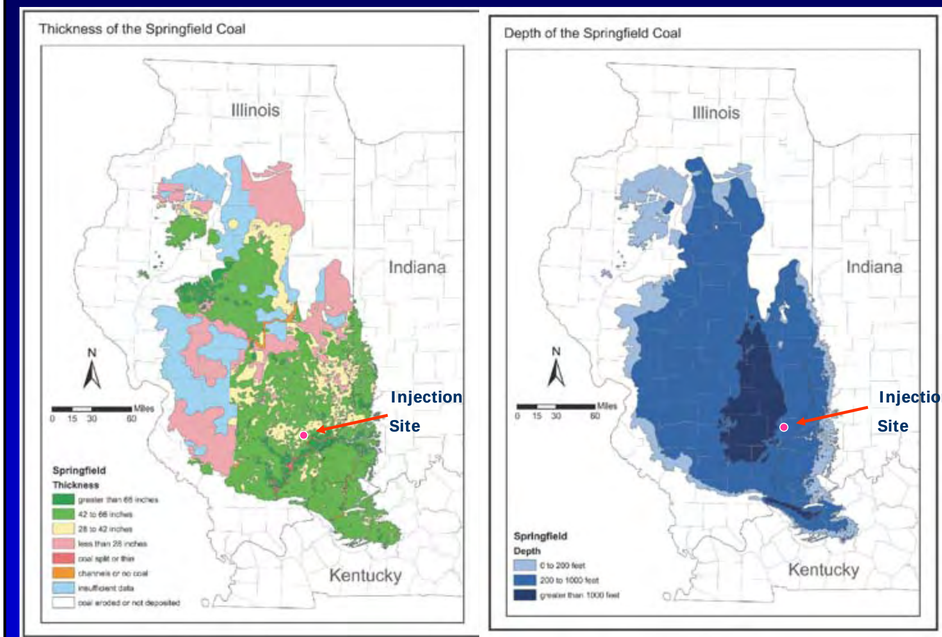
- Hobbs 14-W injector will be converted
- Lower zone will be isolated with bridge plug



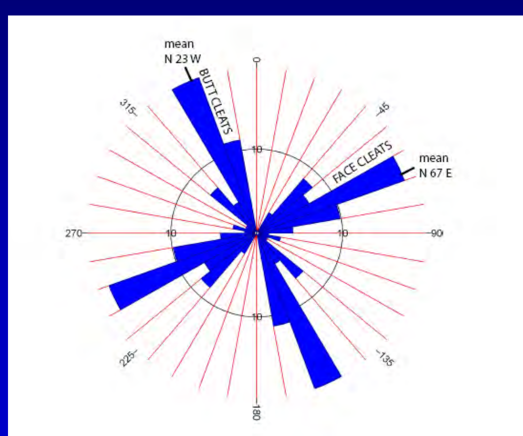
Coal Seam Injection Site
Wabash County, Illinois

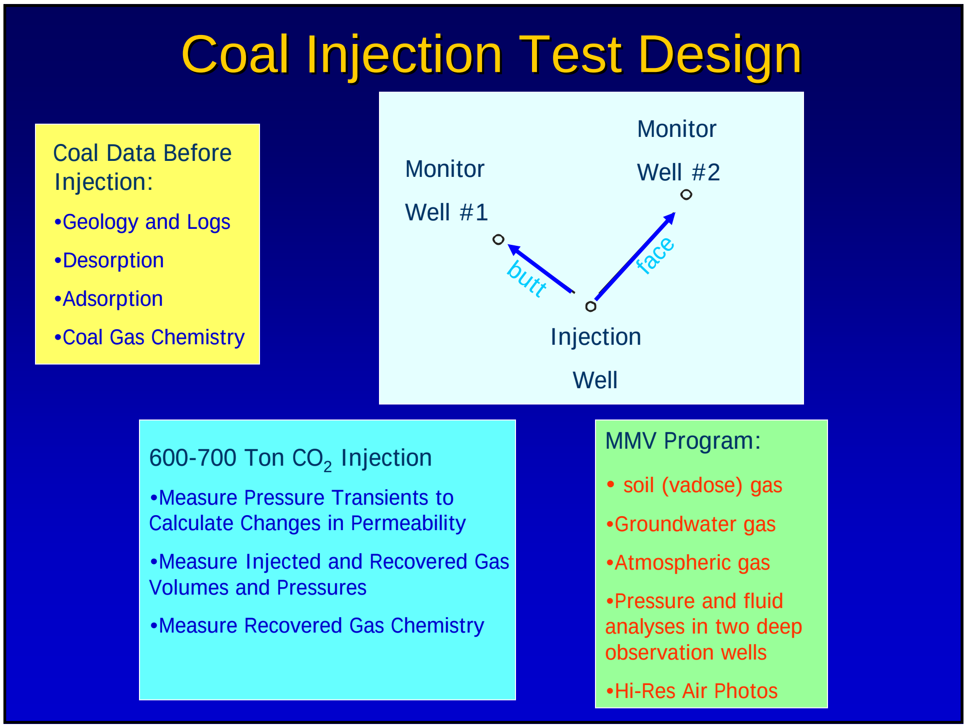
- Springfield Coal
  - > 6 feet thick
  - ~ 920 feet deep
- COMET modeling used to define
  - 3 wells, spacing ~150 feet (orthogonal), to be drilled, cored, and DST in early July 2007
- Surface injection specifications:
  - Injection volume- up to 700 tons CO_2
  - Injection duration- 20 to 30 days

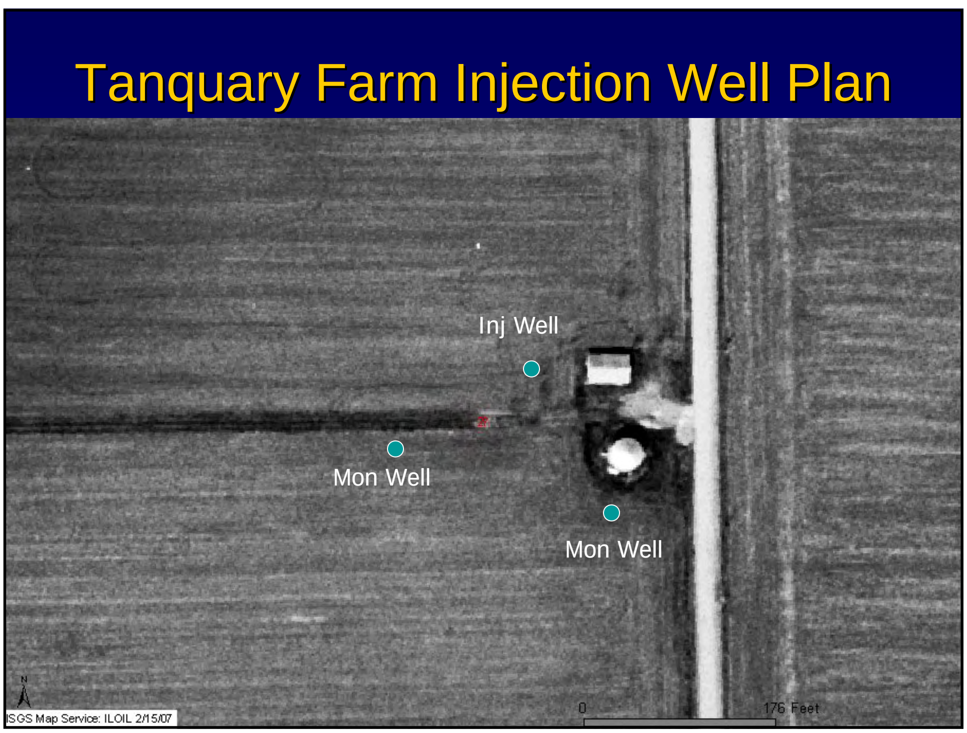




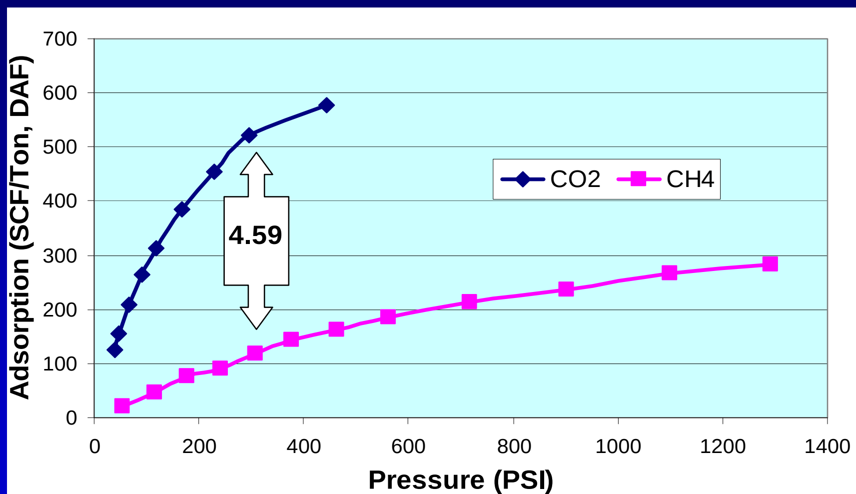
Springfield Coal Cleat Orientations at Wabash Mine, 6 miles SE




Coal Injection Test Design
Coal Data Before Injection:
•Geology and Logs
•Desorption
•Adsorption
•Coal Gas Chemistry
Monitor Well #1
Monitor Well #2
butt
face
Injection Well
600-700 Ton CO_2 Injection
•Measure Pressure Transients to Calculate Changes in Permeability
•Measure Injected and Recovered Gas Volumes and Pressures
•Measure Recovered Gas Chemistry
MMV Program:
• soil (vadose) gas
•Groundwater gas
•Atmospheric gas
•Pressure and fluid analyses in two deep observation wells
•Hi-Res Air Photos


Tanquary Farm Injection Well Plan
Inj Well
Mon Well
Mon Well
N
ISGS Map Service: ILOIL 2/15/07
0
176 Feet

Indiana coal –high volatile bituminous rank



Example of CO_2 and CH_4 adsorption isotherm

COMET Modeling Study to Determine Well Spacing for ECBM Pilot

Well spacing criteria:

- quantifiable response at observation/production wells:
  - within 30 days
  - pressure: 1.0 psi; gas saturation: 10%
- observation wells oriented orthogonal to CO_2 injector
  - observation wells equidistant from injector
  - relatively close spacing to ensure response
- cleat orientation:
  - Face = x direction
  - Butt = y direction

Pilot:

- 1 injector, 2 observation/production wells

COMET Modeling Study to Determine Well Spacing for ECBM Pilot

Reservoir model:

- Area: ~ 21 acres
- Grid: single layer (Herrin coal, 4.0’), hybrid grid
- Infinite flow boundary at outer edge of model.
- Wells:
  - 16 observation/production with 150’ and 300’ spacing
  - observation/production wells oriented along x and y axis and 45° diagonal

Reservoir Parameters:

- Most likely values obtained from DST, core data from recently tested area wells, and regional data
- Data is extracted from raw COMET output using a data parsing program written at ISGS for graphic presentation and continuous data analysis

COMET Modeling Study to Determine Well Spacing for ECBM Pilot

Variables in study:

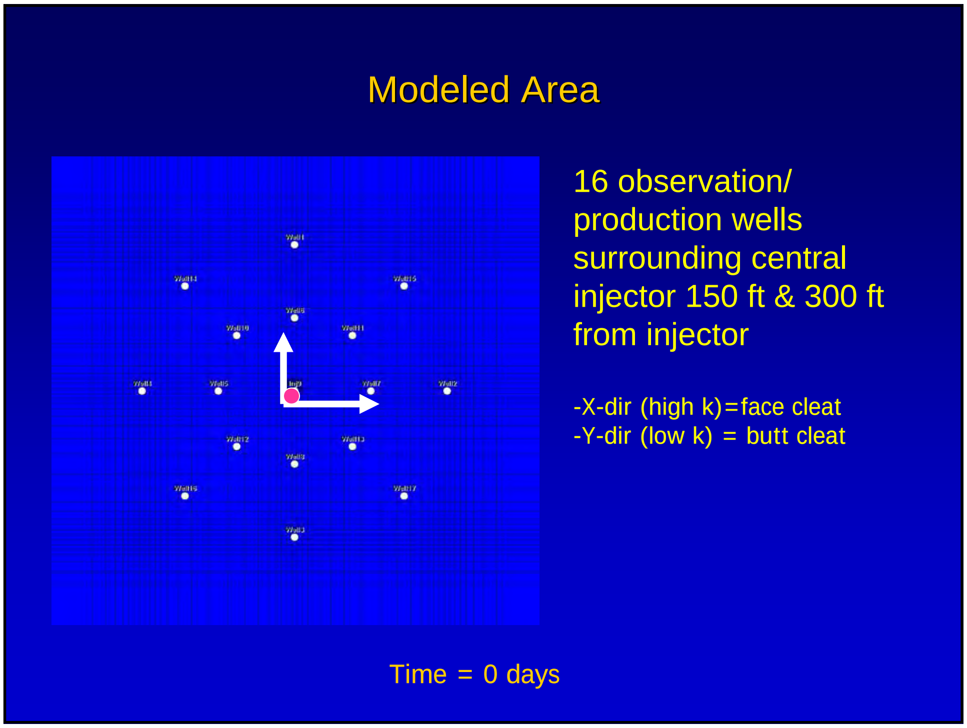
matrix & pore compressibility, cleat spacing, initial gas concentration, stress dependent permeability, porosity, skin, matrix swelling, CH_4 & CO_2 sorption time, differential permeability (K_x/K_y) = {2-8}, CH_4 Langmuir constants, and relative permeability.

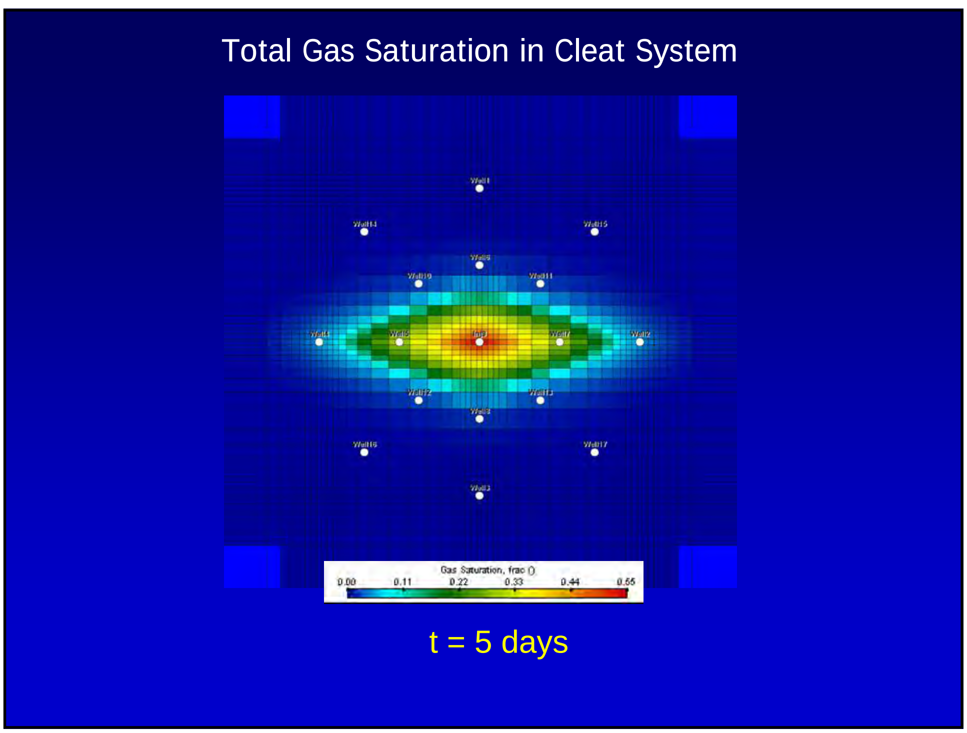
Tested 36 scenarios revolving around our most likely values

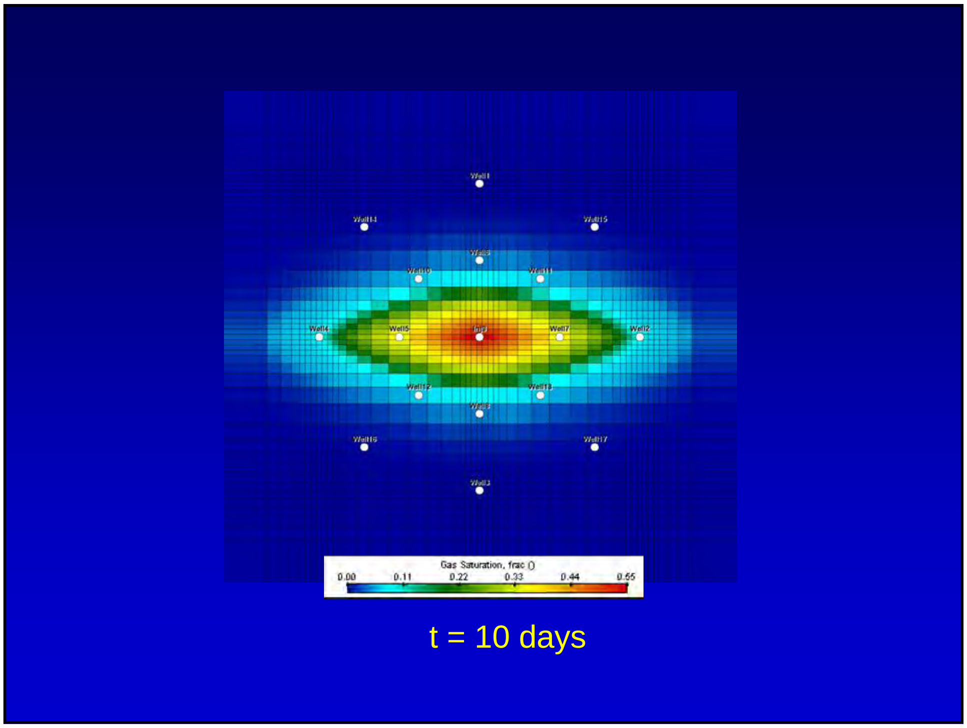
Total gas saturation recorded for:

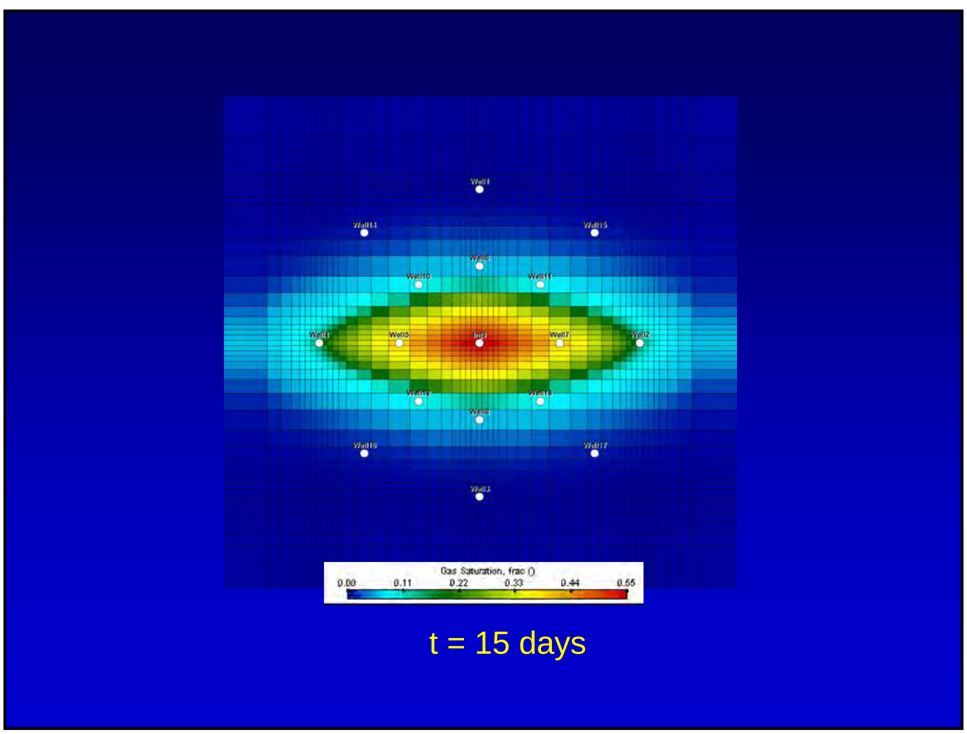
- 150’ wells: x, y, 45 degree diagonal
- 300’ wells: x, y, 45 degree diagonal

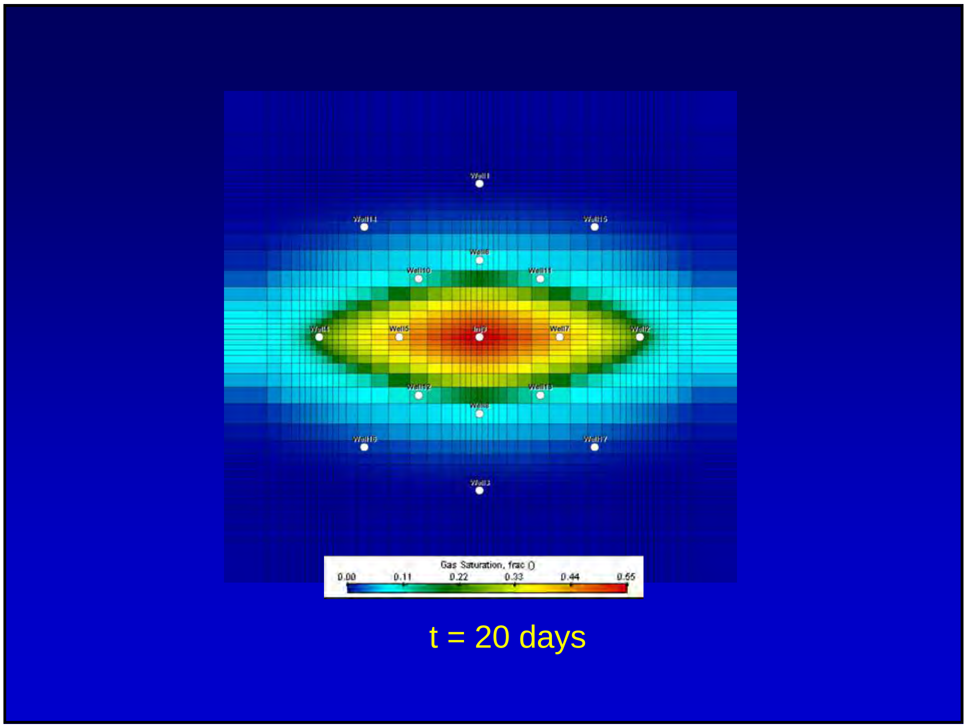
Breakthrough was defined at total gas saturation equal to 1, 10, and 25%.

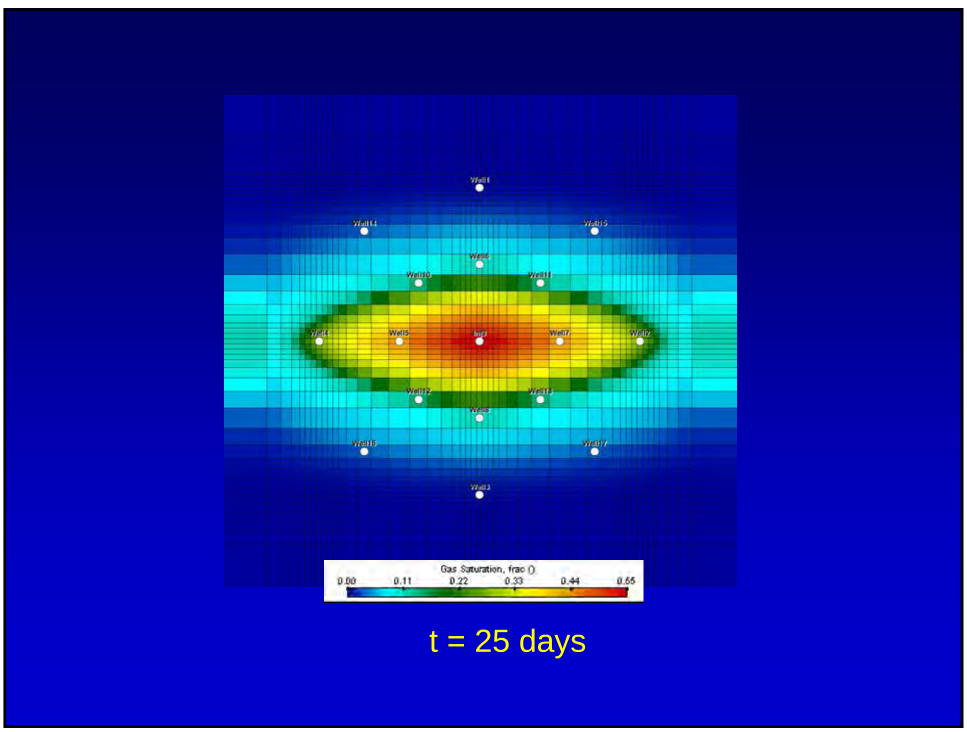

Modeled Area
16 observation/ production wells surrounding central injector 150 ft & 300 ft from injector
-X-dir (high k)=face cleat
-Y-dir (low k) = butt cleat
Time = 0 days

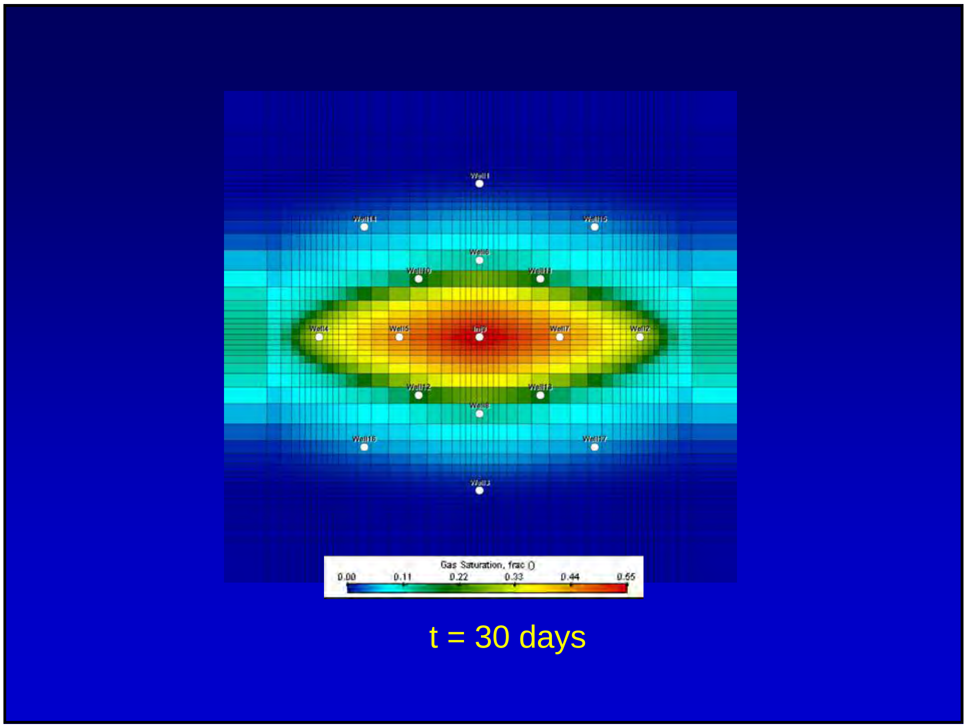

Total Gas Saturation in Cleat System
Gas Saturation, frac ()
0.00
0.11
0.22
0.33
0.44
0.55
t = 5 days

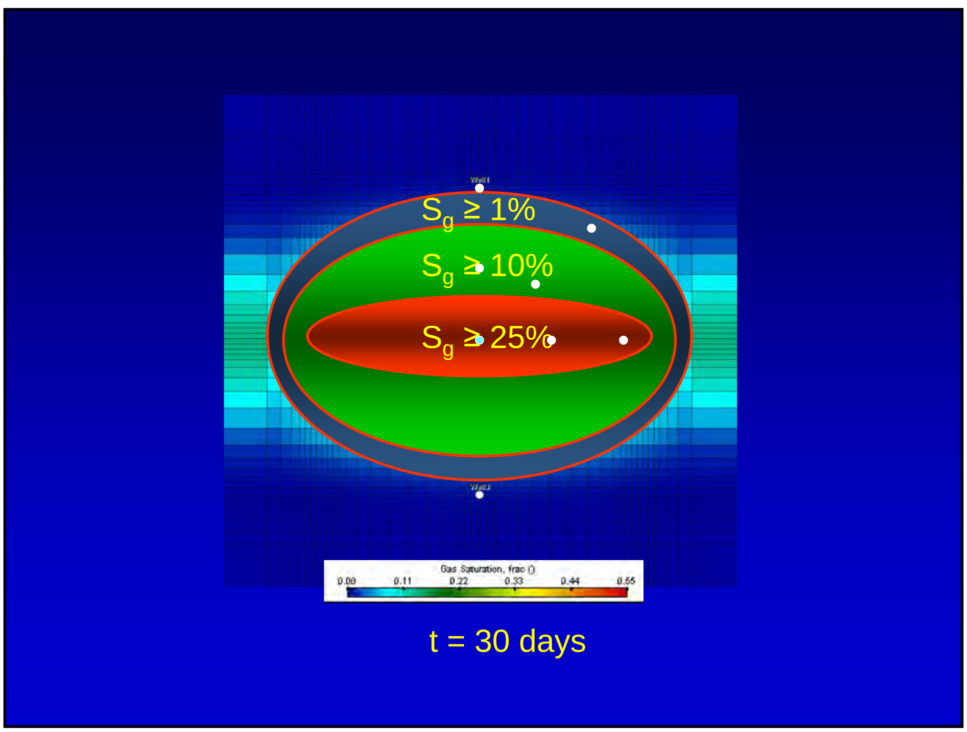

Gas Saturation, frac ()
0.00 0.11 0.22 0.33 0.44 0.55
t = 10 days


Gas Saturation, frac ()
0.00 0.11 0.22 0.33 0.44 0.55
t = 15 days


Gas Saturation, frac ()
0.00 0.11 0.22 0.33 0.44 0.55
t = 20 days


Gas Saturation, frac ()
0.00 0.11 0.22 0.33 0.44 0.55
t = 25 days


Gas Saturation, frac ()
0.00
0.11
0.22
0.33
0.44
0.55
t = 30 days


S_g ≥ 1%
S_g ≥ 10%
S_g ≥ 25%
Gas Saturation, frac ()
0.00
0.11
0.22
0.33
0.44
0.55
t = 30 days

ECBM Pilot Conclusions:

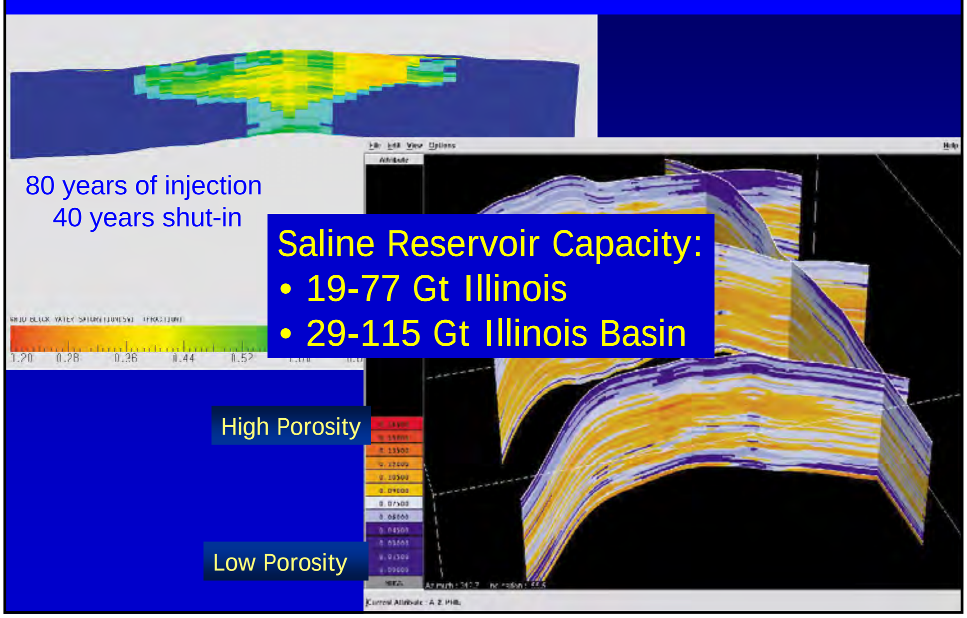
Percent of 36 simulations in which breakthrough occurs

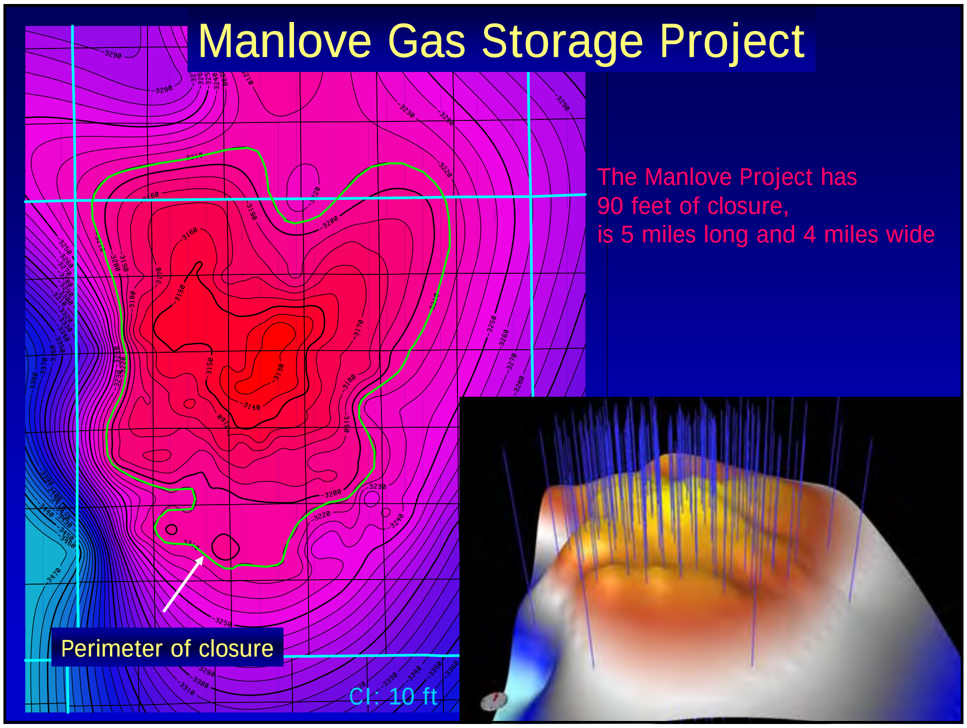
		Sg = 1%	Sg = 10%	Sg = 25%
	X-dir:	100	100	97
150' wells	Y-dir	100	100	84
	Diag:	100	100	97
	X-dir:	100	100	22
300' wells	Y-dir	0	0	0
	Diag:	3	0	0

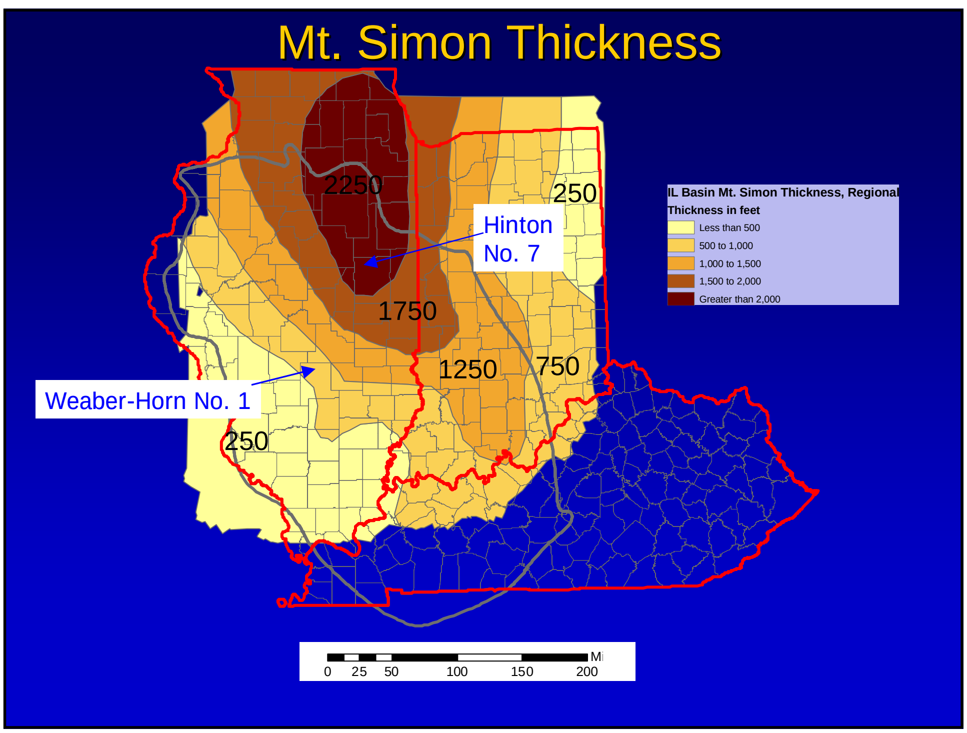
(X-dir = high perm, Y-dir = low perm, Diag = intermediate)

- **150’ wells: In the lowest permeability direction (pessimistic case) breakthrough at Sg = 25% occurs 84% of cases.**
- **300’ wells: breakthrough only significant in high permeability direction.**
- **Indicates appropriate spacing of about 150 feet.**

Mt. Simon Sandstone

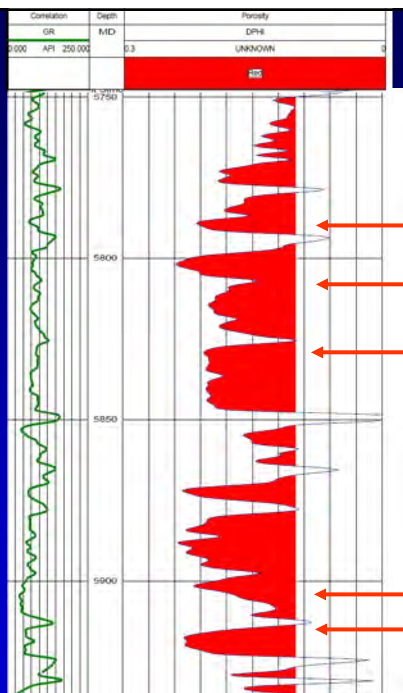



Manlove Gas Storage Project
The Manlove Project has
90 feet of closure,
is 5 miles long and 4 miles wide
Perimeter of closure
CI: 10 ft


Mt. Simon Thickness
2250
250
Hinton
No. 7
1750
1250
750
Weaber-Horn No. 1
250
IL Basin Mt. Simon Thickness, Regional
Thickness in feet
Less than 500
500 to 1,000
1,000 to 1,500
1,500 to 2,000
Greater than 2,000
Mi
0 25 50 100 150 200

Mt. Simon Sandstone Reservoir

- Mt. Simon Sandstone is used for natural gas storage in Champaign County, IL at 4,000 to 4,200 ft
- Mt. Simon core has been recovered from a few deep exploration wells, such as this sample from near Salem, IL at 8,467 drilled in 1966



Core Analysis Hinton No. 7

5789 ft, 54 mD, 21.1 Ø

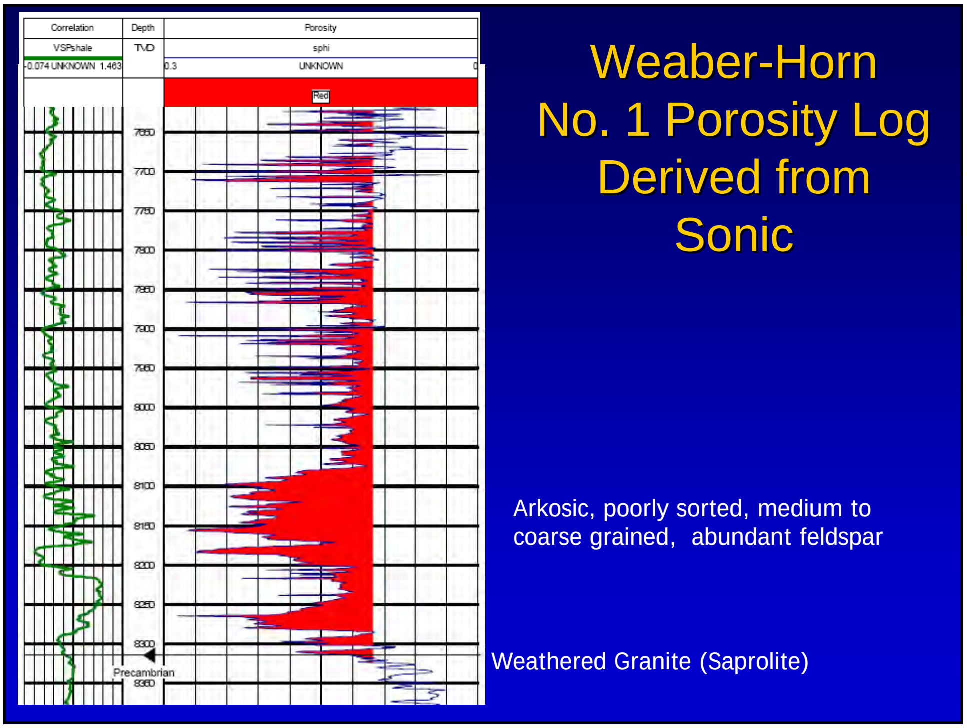
5815 ft, 617 mD, 20.8 Ø

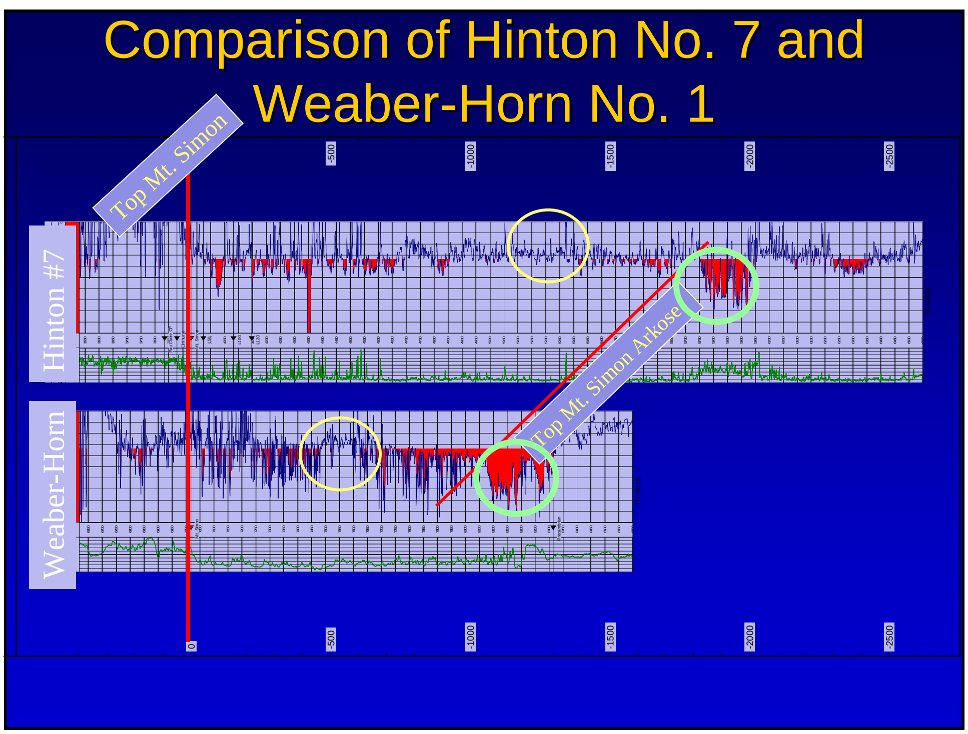
5836 ft, 1300 mD, 23.1 Ø

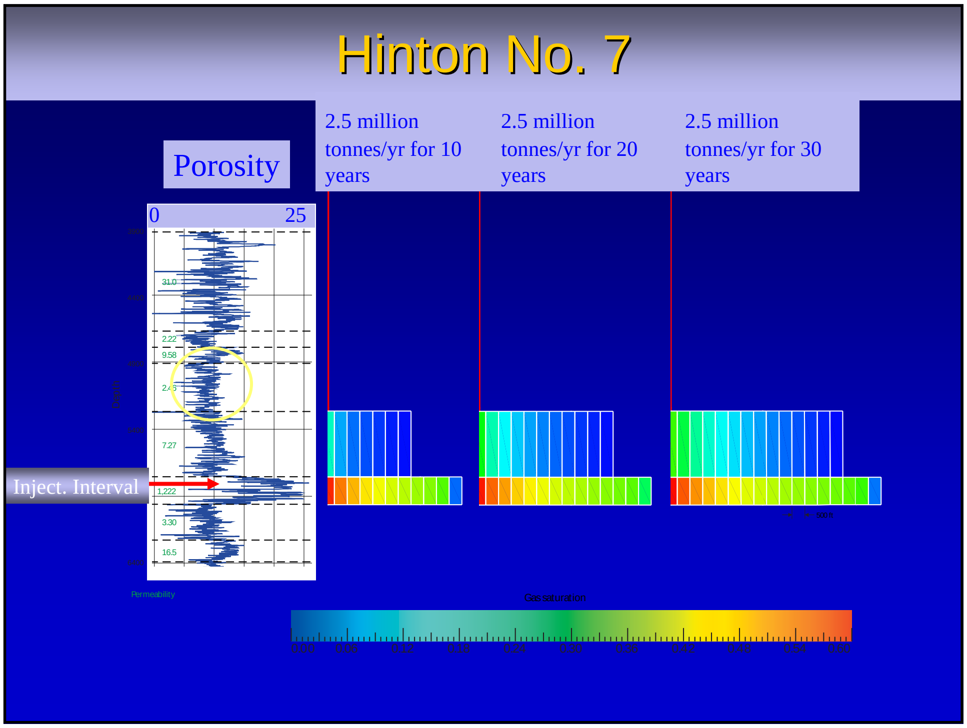
Rocks can contain up to 20% Potassium Feldspar. Leached grains throughout sample

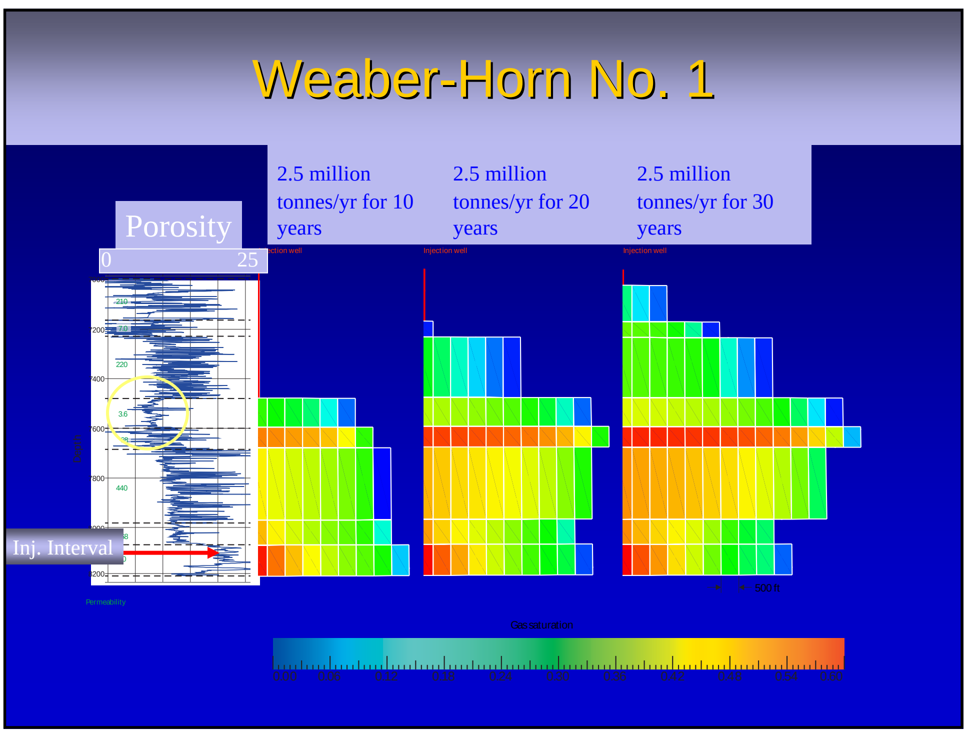
5904 503 mD, 19.1 Ø

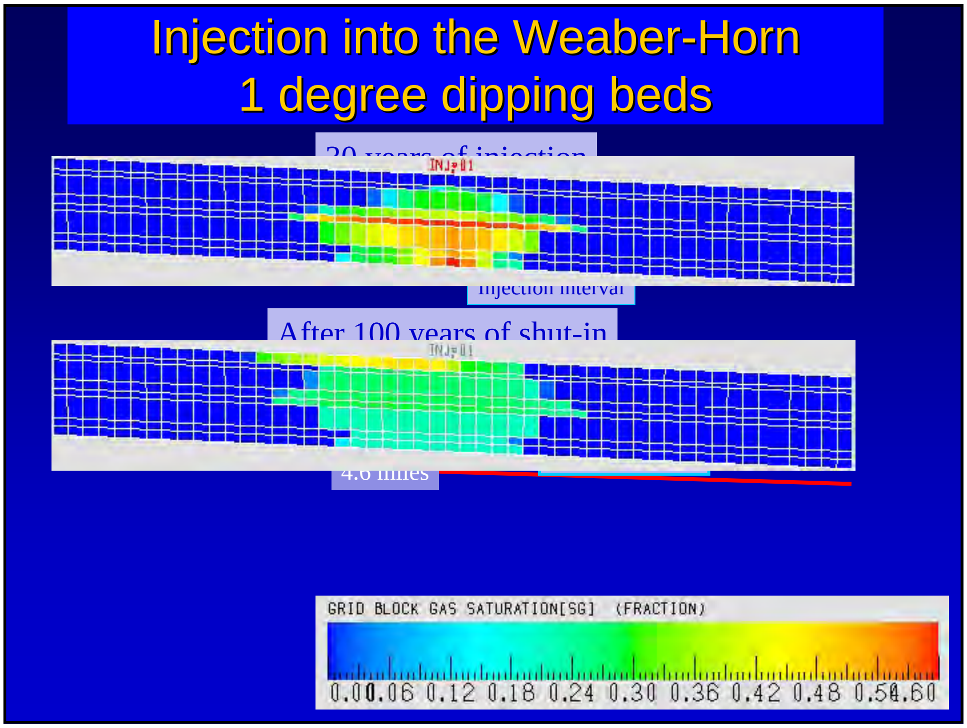
5916 ft, 9.08 mD, 20.3 Ø

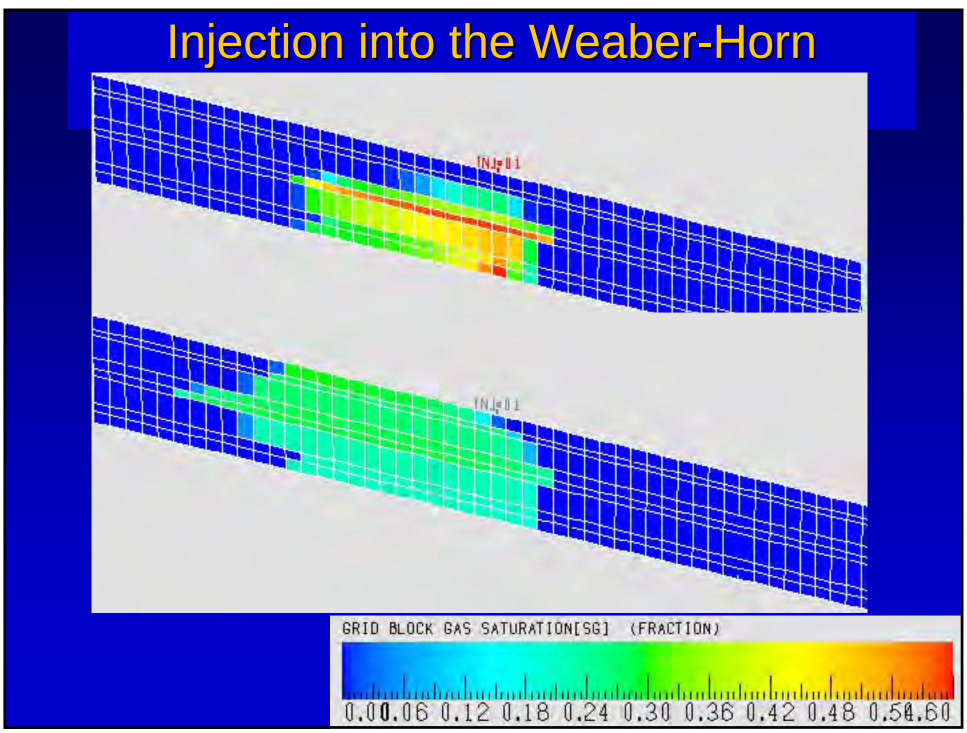

Weaber-Horn
No. 1 Porosity Log
Derived from
Sonic
Correlation
Depth
Porosity
VSPshale
TVD
sphi
UNKNOWN
Red
Precambrian
Arkosic, poorly sorted, medium to coarse grained, abundant feldspar
Weathered Granite (Saprolite)

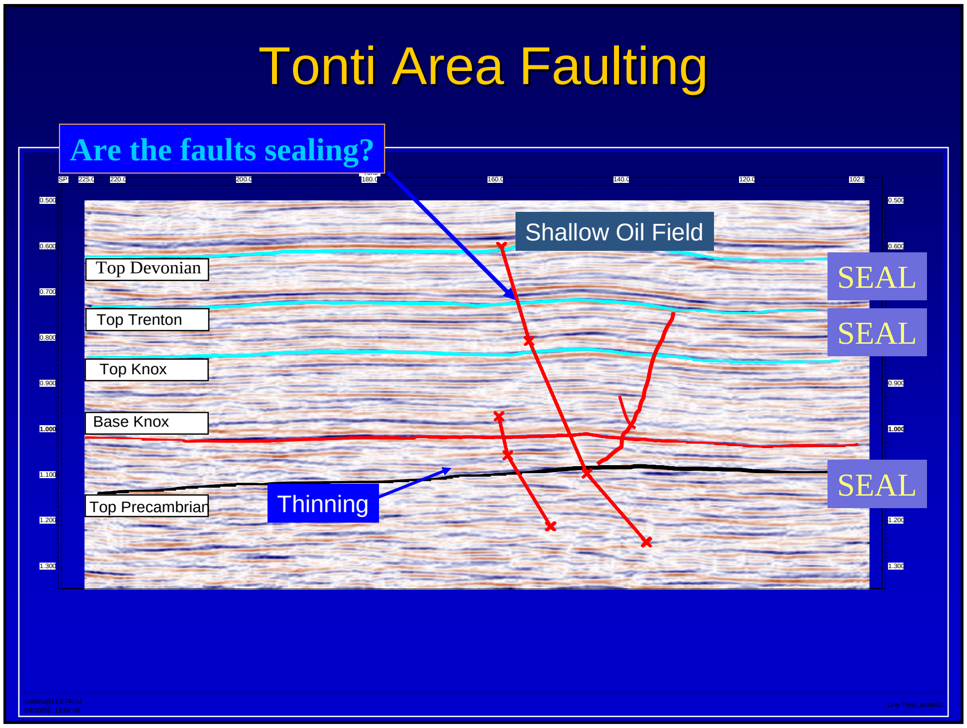

Comparison of Hinton No. 7 and Weaber-Horn No. 1
Top Mt. Simon
Hinton #7
Weaber-Horn
Top Mt. Simon Arkose
0
-500
-1000
-1500
-2000
-2500

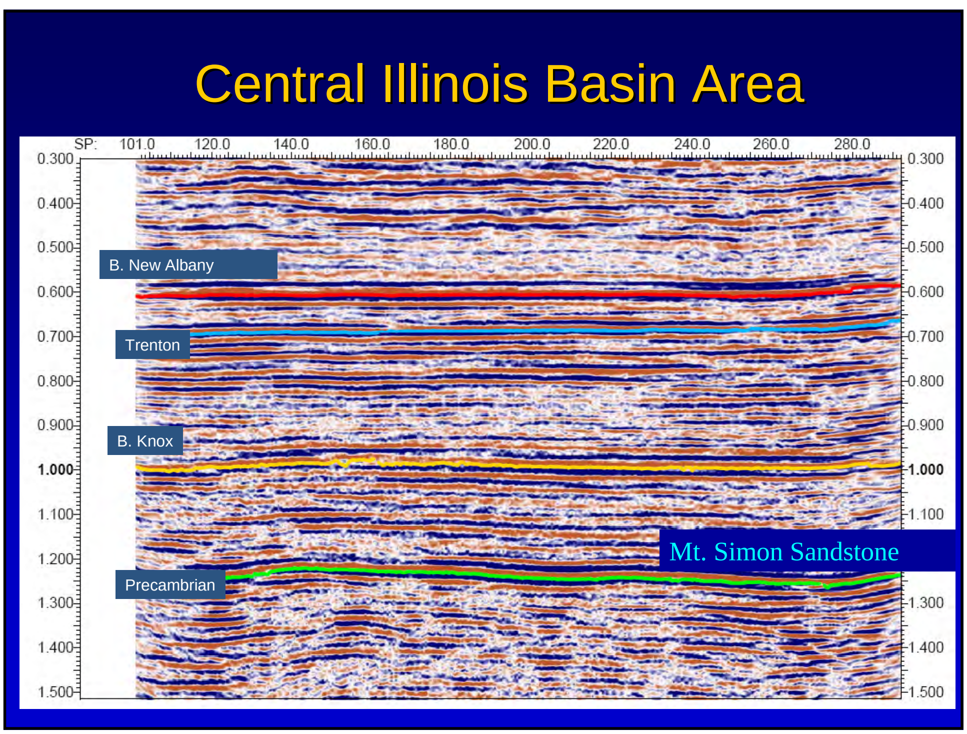

Hinton No. 7
Porosity
0
25
2.5 million tonnes/yr for 10 years
2.5 million tonnes/yr for 20 years
2.5 million tonnes/yr for 30 years
Inject. Interval

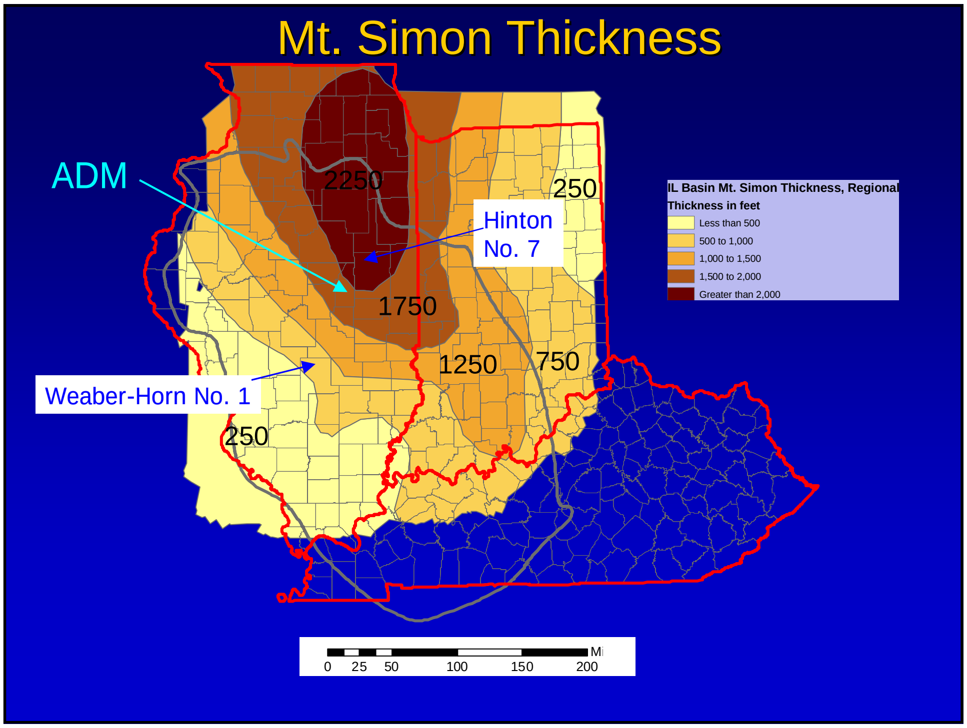

Weaber-Horn No. 1
Porosity
0
25
2.5 million tonnes/yr for 10 years
2.5 million tonnes/yr for 20 years
2.5 million tonnes/yr for 30 years
Inj. Interval

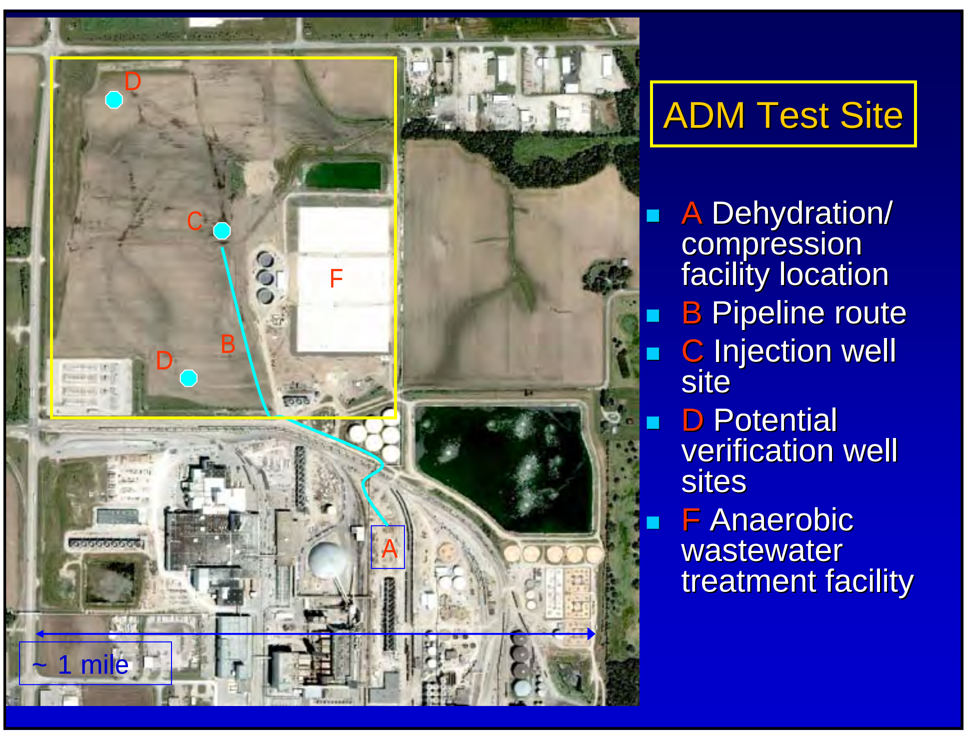

Injection into the Weaber-Horn
1 degree dipping beds
After 100 years of shut-in
GRID BLOCK GAS SATURATION[SG] (FRACTION)
0.00 0.06 0.12 0.18 0.24 0.30 0.36 0.42 0.48 0.54 0.60


Injection into the Weaber-Horn
GRID BLOCK GAS SATURATION[SG] (FRACTION)
0.00 0.06 0.12 0.18 0.24 0.30 0.36 0.42 0.48 0.54 0.60


Tonti Area Faulting
Are the faults sealing?
Shallow Oil Field
Top Devonian
Top Trenton
Top Knox
Base Knox
Top Precambrian
Thinning
SEAL
SEAL
SEAL

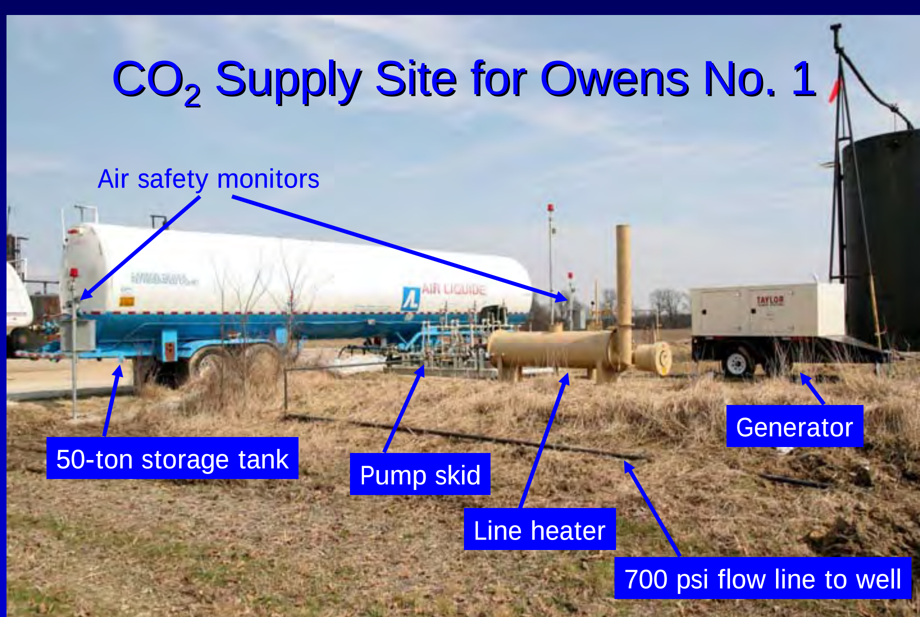

Central Illinois Basin Area
SP: 101.0 120.0 140.0 160.0 180.0 200.0 220.0 240.0 260.0 280.0
0.300 0.400 0.500 0.600 0.700 0.800 0.900 1.000 1.100 1.200 1.300 1.400 1.500
B. New Albany
Trenton
B. Knox
Mt. Simon Sandstone
Precambrian


Mt. Simon Thickness
ADM
2250
250
Hinton
No. 7
1750
1250
750
Weaber-Horn No. 1
250
IL Basin Mt. Simon Thickness, Regional
Thickness in feet
Less than 500
500 to 1,000
1,000 to 1,500
1,500 to 2,000
Greater than 2,000
0 25 50 100 150 200
Mi

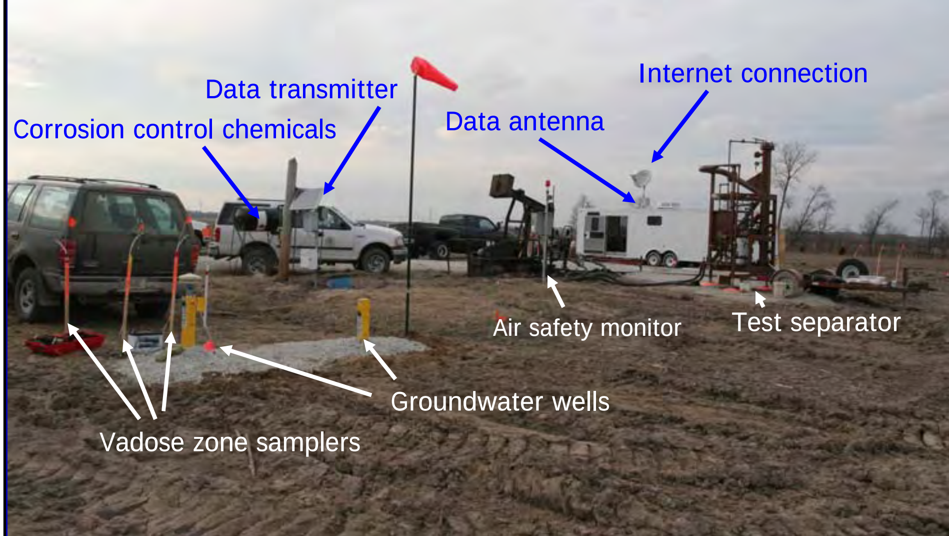

ADM Test Site
A Dehydration/ compression facility location
B Pipeline route
C Injection well site
D Potential verification well sites
F Anaerobic wastewater treatment facility
D
C
F
B
D
A
~ 1 mile

Monitoring, Mitigation and Verification

- Develop integrated geochemical/geomechanical model to guide MMV program using extensive data collection from injection well and initial geophysical surveys for site characterization
- Utilize Phase II techniques for testing ambient air, soil vadose zone, groundwater, and observation of vegetation
- Two verification wells to enhance geophysical observations of plume boundaries, confirm those boundaries by subsurface sampling, and sample formations above the primary seal
- Continue MMV for 2-3 years after I million tons injected



Owens No. 1 Well Site



Midwest Geological
Sequestration Consortium
www.sequestration.org

Potential for Near-term CCS Deployment in the USA: EPA Area of Review Workshop

JJ Dooley, CL Davidson, and RT Dahowski

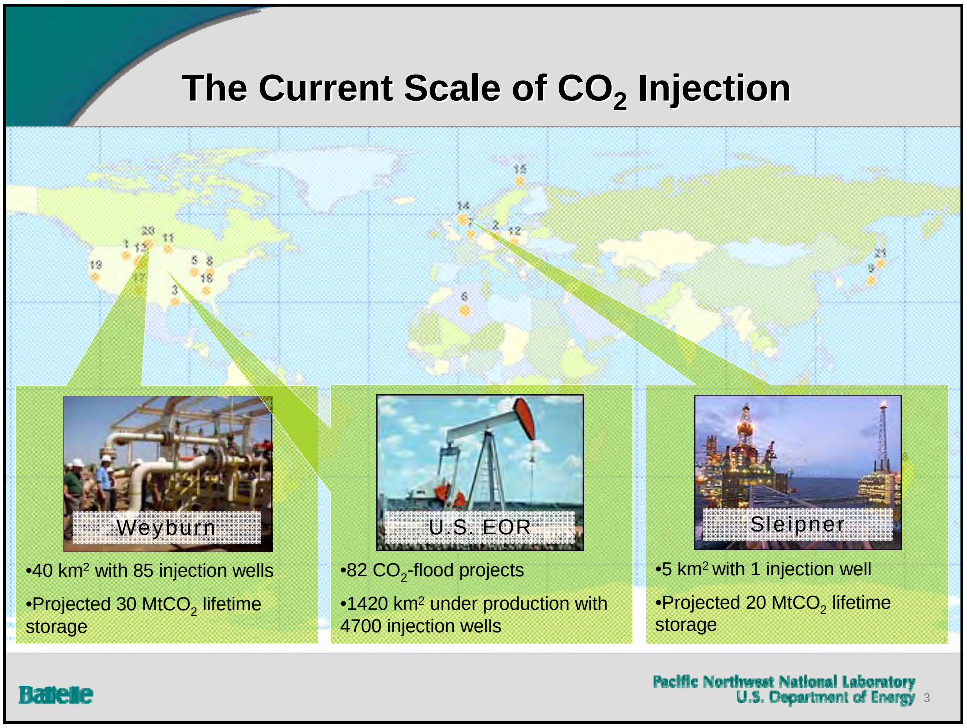
Joint Global Change Research Institute
Pacific Northwest National Laboratory
Battelle

July 10, 2007

PNNL-SA-56061

Key Points

- The deployment of carbon dioxide capture and storage technologies will be driven by efforts to explicitly regulate greenhouse gas emissions.
- The CCS technical literature is clear on a couple of key points:
  - The potential deployment of CCS could be very large.
  - The large scale deployment of CCS will require the presence of a significant disincentive on the free venting of greenhouse gas emissions (e.g., >$25/ton$CO_2$).
  - The majority of CCS deployment and deep geologic CO_2 storage will occur in the second half of this century.
- This is often misinterpreted as implying that CCS deployment – and perhaps significant deployment -- will not take place for many years to come.


The Current Scale of CO_2 Injection
Weyburn
•40 km^2 with 85 injection wells
•Projected 30 MtCO_2 lifetime storage
U.S. EOR
•82 CO_2-flood projects
•1420 km^2 under production with 4700 injection wells
Sleipner
•5 km^2 with 1 injection well
•Projected 20 MtCO_2 lifetime storage
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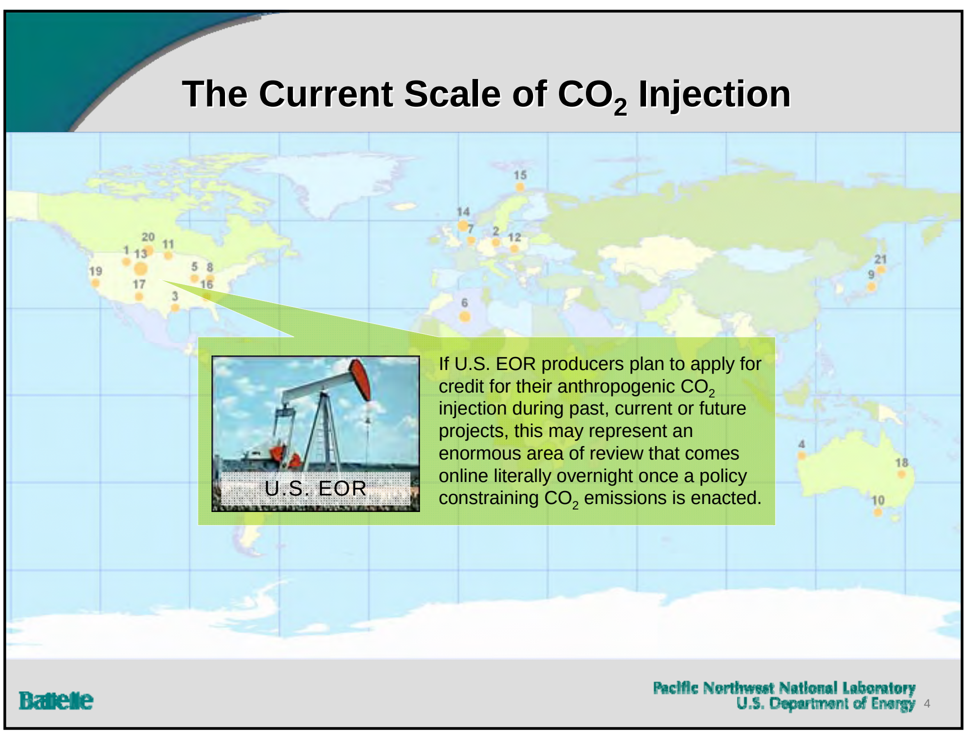
The Current Scale of CO_2 Injection
U.S. EOR
If U.S. EOR producers plan to apply for credit for their anthropogenic CO_2 injection during past, current or future projects, this may represent an enormous area of review that comes online literally overnight once a policy constraining CO_2 emissions is enacted.
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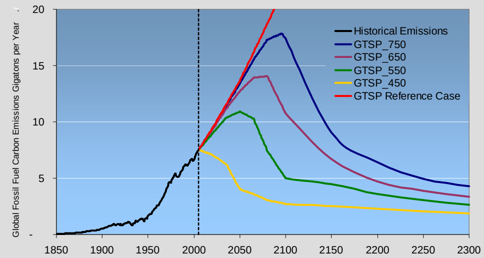
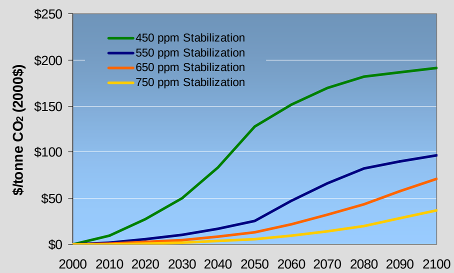
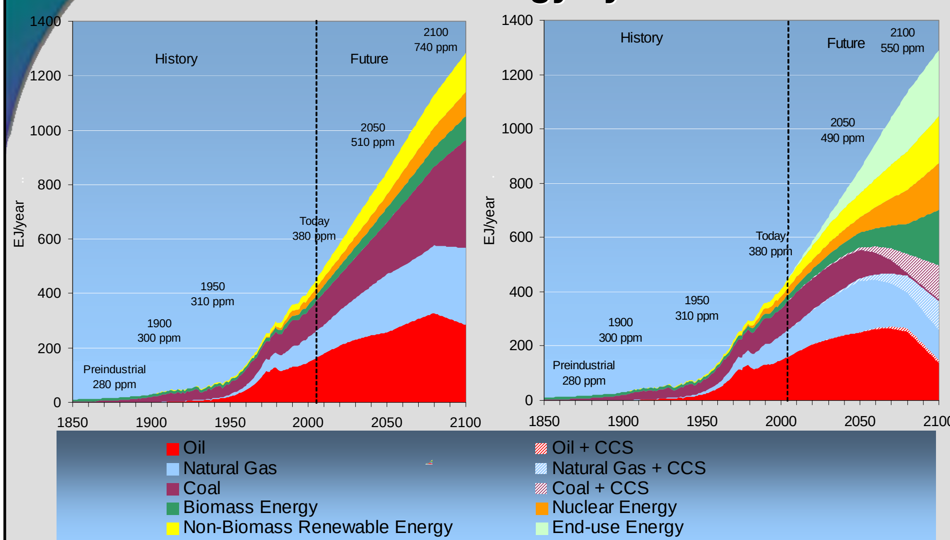
Climate change is a long-term strategic problem with implications for today

- Stabilizing atmospheric concentrations of greenhouse gases and not their annual emissions levels should be the overarching strategic goal of climate policy.
- This tells us that a fixed and finite amount of CO_2 can be released to the atmosphere over the course of this century.
  - We all share a planetary greenhouse gas emissions budget.
  - Every ton of emissions released to the atmosphere reduces the budget left for future generations.
  - As we move forward in time and this planetary emissions budget is drawn down, the remaining allowable emissions will become more valuable.
  - Emissions permit prices should steadily rise with time.





Stabilization of CO_2 concentrations means fundamental change to the global energy system



CCS Deployment Across the US Economy: *Large CO_2 Storage Resource and Large Potential Demand for CO_2 Storage*

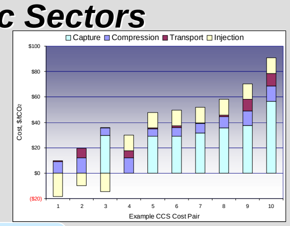
3,900+ $GtCO_2$ Capacity within 230 Candidate Geologic CO_2 Storage Reservoirs

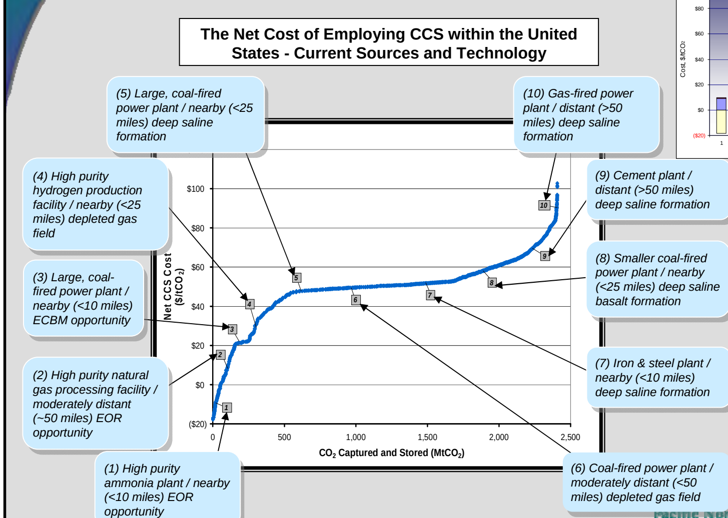
- 2,730 $GtCO_2$ in deep saline formations (DSF) with perhaps close to another 900 $GtCO_2$ in offshore DSFs
- 240 Gt CO_2 in on-shore saline filled basalt formations
- 35 $GtCO_2$ in depleted gas fields
- 30 $GtCO_2$ in deep unmineable coal seams with potential for enhanced coalbed methane (ECBM) recovery
- 12 $GtCO_2$ in depleted oil fields with potential for enhanced oil recovery (EOR)

1,715 Large Sources (100+ $ktCO_2$/yr) with Total Annual Emissions = 2.9 $GtCO_2$

- 1,053 electric power plants
- 259 natural gas processing facilities
- 126 petroleum refineries
- 44 iron & steel foundries
- 105 cement kilns
- 38 ethylene plants
- 30 hydrogen production
- 19 ammonia refineries
- 34 ethanol production plants
- 7 ethylene oxide plants

CCS Deployment Across the US Economy: *Differentiated CCS Adoption Across Economic Sectors*





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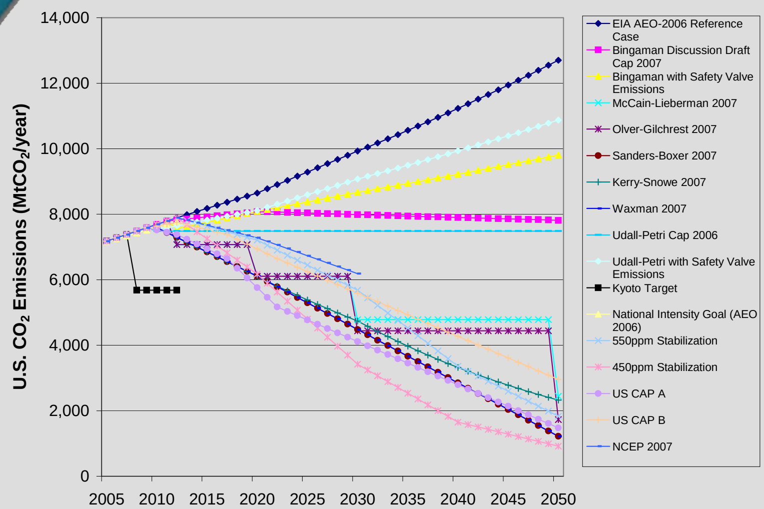
WRI Analysis of Economy-wide Climate Bills in 110th Congress (2005-2050)



Projections from: John Larsen. "Global Warming Legislation in the 110th Congress: How do emissions reduction bills currently before Congress compare?" World Resources Institute. February 1, 2007. http://www.wri.org/climate/topic_content.cfm?cid=4265

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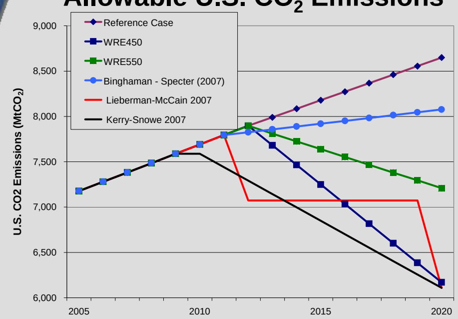
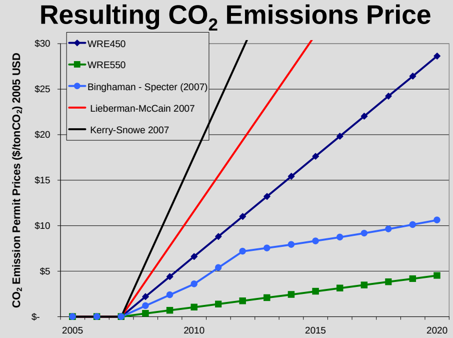
Selected Legislative Proposals to Address US CO_2 Emissions 2005-2020

Allowable U.S. CO_2 Emissions



Resulting CO_2 Emissions Price



CO_2 emissions permit price based upon projections taken from: Sergey Paltsev, John M. Reilly, Henry D. Jacoby, Angelo C. Gurgel, Gilbert E. Metcalf, Andrei P. Sokolov and Jennifer F. Holak Assessment of U.S. Cap-and-Trade Proposals. MIT Joint Program on the Science and Policy of Global Change. Report No. 146. April 2007. http://web.mit.edu/globalchange/www/MITJPSPGC_Rpt146.pdf

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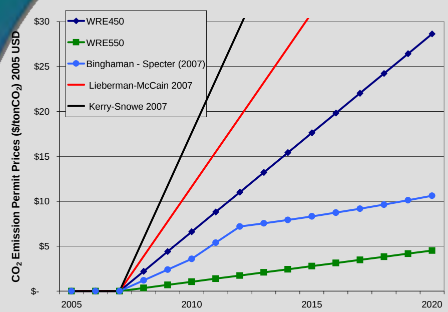
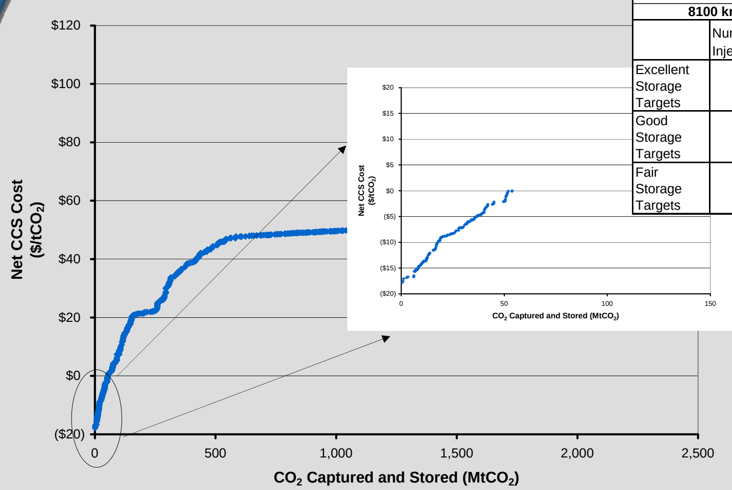
Selected Legislative Proposals to Address US CO_2 Emissions 2005-2020



	Date CO_2 permit price first exceeds \$0/tonCO_2	Date CO_2 permit priceprice first exceeds \$5/tonCO_2	Date CO_2 permit price price first exceeds \$10/tonCO_2	Date CO_2 permit priceprice first exceeds \$15/tonCO_2
WRE450	2008	2009	2012	2014
WRE550	2008	2020		
Binghaman	2008	2011	2019	
Lieberman-McCain 2007	2008	2009	2010	2011
Kerry-Snowe 2007	2008	2008	2010	2010

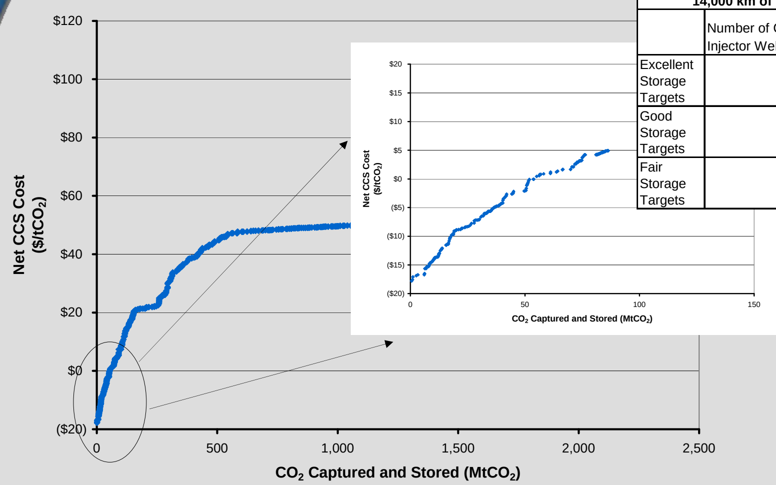
Potentially 54 MtCO_2/year being stored at +130 sites for less than \$0/tonCO_2

CO_2 Permit Price < \$0/tonCO_2		
54 MtCO_2 / year being stored		
8100 km of trunk pipelins		
	Number of CO_2 Injector Wells	Area of Review (km^2)
Excellent Storage Targets	143	1,209
Good Storage Targets	176	2,044
Fair Storage Targets	309	5,026



Potentially 86 $MtCO_2$/year being stored at +190 sites for less than $5/tonCO_2$

CO2 Permit Price < $5/tonCO2		
86 MtCO2 / year being stored		
14,000 km of trunk pipelines		
	Number of CO_2 Injector Wells	Area of Review (km^2)
Excellent Storage Targets	219	1,925
Good Storage Targets	272	3,255
Fair Storage Targets	484	8,004



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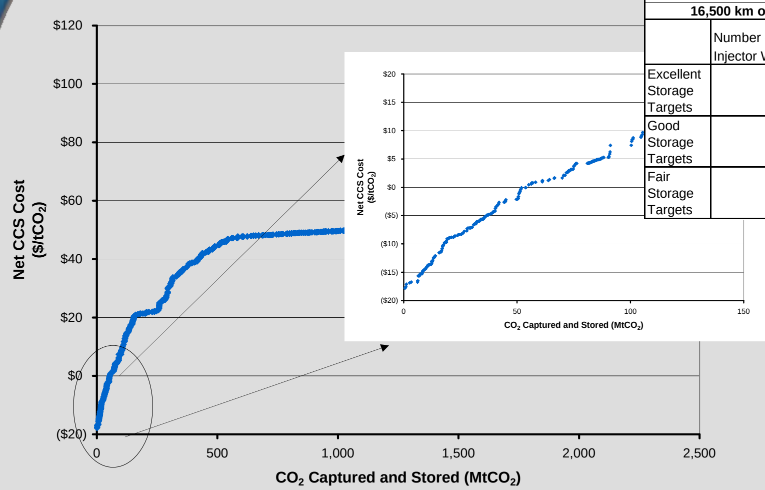
Potentially 105 $MtCO_2$/year being stored at ~216 sites for less than $10/tonCO_2$

CO2 Permit Price < $10/tonCO2		
105 MtCO2 / year being stored		
16,500 km of trunk pipelines		
	Number of CO_2 Injector Wells	Area of Review (km^2)
Excellent Storage Targets	255	2,351
Good Storage Targets	321	3,974
Fair Storage Targets	582	9,772



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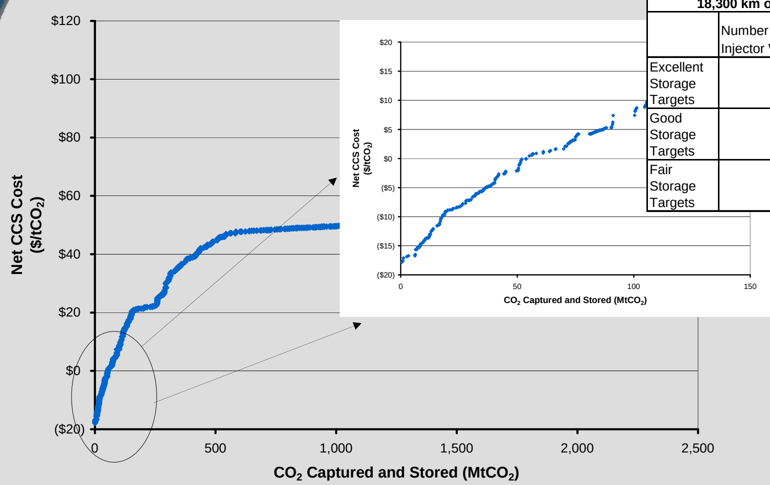
Potentially 130 $MtCO_2$/year being stored at ~240 sites for less than $15/tonCO_2$

CO₂ Permit Price < $15/tonCO₂		
130 $MtCO_2$ / year being stored		
18,300 km of trunk pipelines		
	Number of CO_2 Injector Wells	Area of Review (km^2)
Excellent Storage Targets	290	2,911
Good Storage Targets	378	4,920
Fair Storage Targets	705	12,099



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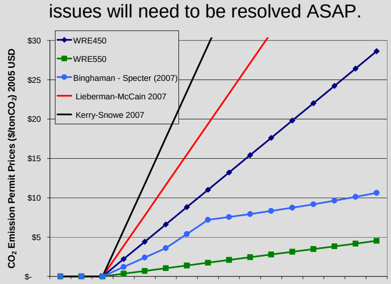
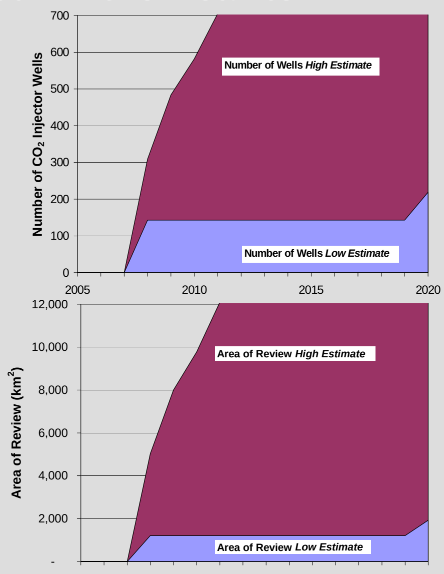
Significant CCS Deployment Could Occur in the Near-term

While there is still a great deal of uncertainty about the precise nature of future US climate policy, there should be little doubt that a number of critical CCS issues will need to be resolved ASAP.





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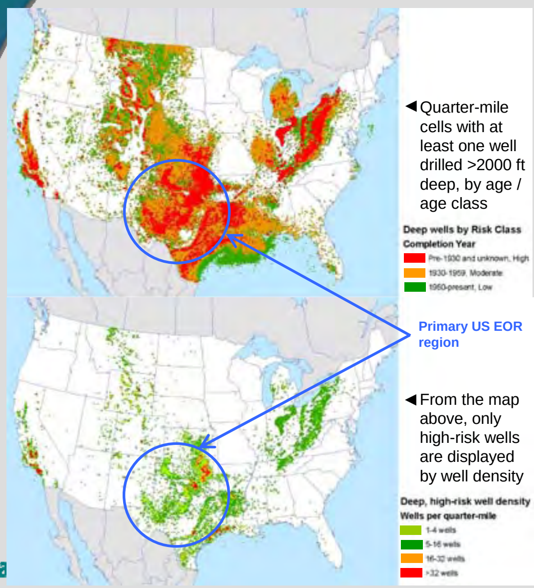
Area of Review: Existing Wells

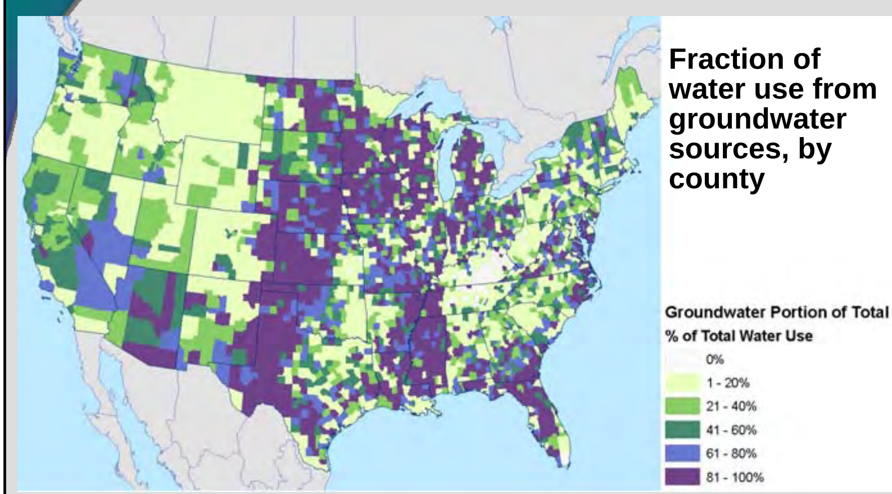


The areas of the U.S. with the largest current EOR production are also perforated with deep wells, many of which may have been drilled prior to 1930.

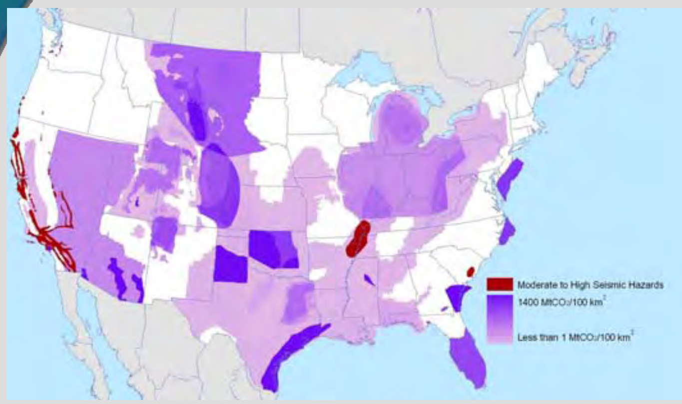
This may represent a significant concern in the area of review for many CCS projects.

Mitigation of risks and the cost associated with mitigating these risks associated with lost / unknown wells, or wells that have been improperly plugged and abandoned will likely be higher in highly developed areas than in other regions of the country.

Area of Review: Protecting Valuable Groundwater Resources

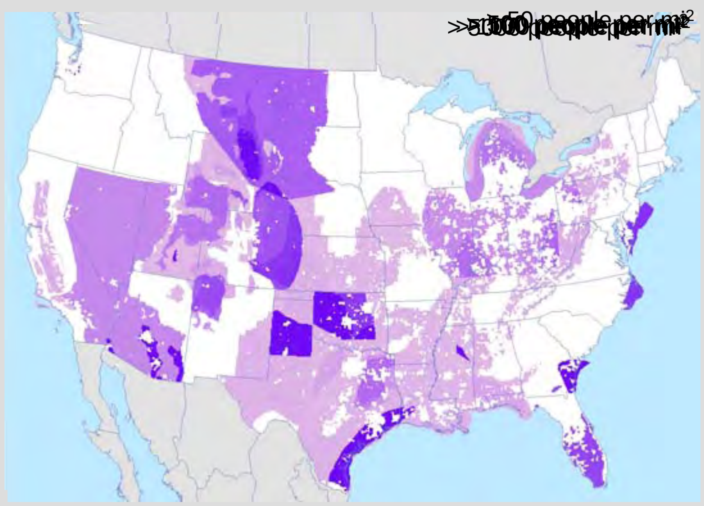


Area of Review: Potential Risks from Seismic Activity



Potential geologic CO_2 storage formations overlain across areas of Moderate to High Risk of damage from seismic events

Area of Review: Population Density Near Potential Geologic CO_2 Storage Formations



Summary Points

- The significant CCS deployment could occur in short-term.
- Within a few years of the enactment of explicit greenhouse gas regulations, the deployment of CCS systems within the U.S. could result in
  - The operation of hundreds of dedicated CO_2 injector wells
  - Cumulative CO_2 injection areas of reviews that are thousands if not tens of thousands of kilometers
- There are a number of issues that will need to be addressed – perhaps in a short amount of time – to enable the safe, effective and economic deployment of CCS technologies within the U.S.

The Methodology for Determining the Use of a Fixed Radius Area of Review or Zone of Endangering Influence When Conducting an Area of Review Analysis for Underground Injection Control Operations

By

S. Stephen Platt, EPA Region 3
UIC National Expert

David Rectenwald, EPA Region 3
UIC Inspector

Are the SDWA and UIC Regulations Clear on the Protection of Underground Sources of Drinking Water

And if they are,

what are those protection standards, anyway?

Protection Standards

- Section 144.12
- Section 1421(b)(1)(A)-(D)
- Section 1425
- **Common Theme**: Prevent Underground Injection Which Endangers Drinking Water Sources

Section 144.12 of the UIC Regulations

- (a) “No owner or operator shall construct, operate…any injection activity in a manner that allows the movement of fluid containing any contaminant into an underground source of drinking water…”, and
- (a) “The applicant shall have the burden of showing that the requirements of this paragraph are met.”

Section 1421(b)(1)(A)-(D)

- (b)(1) “Regulations for State Programs shall contain minimum requirements to prevent underground injection which endangers drinking water sources.”

- (B) “Shall require that the applicant for a permit satisfy the State that underground injection will not endanger drinking water sources.”

Section 1425

- “State Program must meet the requirements of Section 1421(b)(1)(A)-(D).”
- “No injection should be authorized that endangers drinking water sources.”
- “Represent an effective program to prevent injection which endangers drinking water sources.”
- “Ensures that a State program demonstrates an equivalent degree of protection.”

Program's Mandate is Clear

- **PROTECT UNDERGROUND SOURCES OF DRINKING WATER!**

What is the Purpose of an Area of Review Analysis?

- **During injection, significant pressure buildup can occur in the injection zone.**
- **Fluid migration can occur through unplugged/abandoned wells, faults, fractures, etc.**
- **The Area of Review is conducted to prevent injection and formation fluid migration out of the injection zone and into underground sources of drinking water (USDW).**

EPA Region 3 Area of Review Process

- Burden of proof clearly on applicant.
- Permit application may contain one-quarter mile fixed radius or zone of endangering influence calculation submission.
- Geologic and operational information must be submitted (even for fixed radius).
- Region verifies through calculation acceptability of either submission.

EPA Region 3 Area of Review Process (cont.)

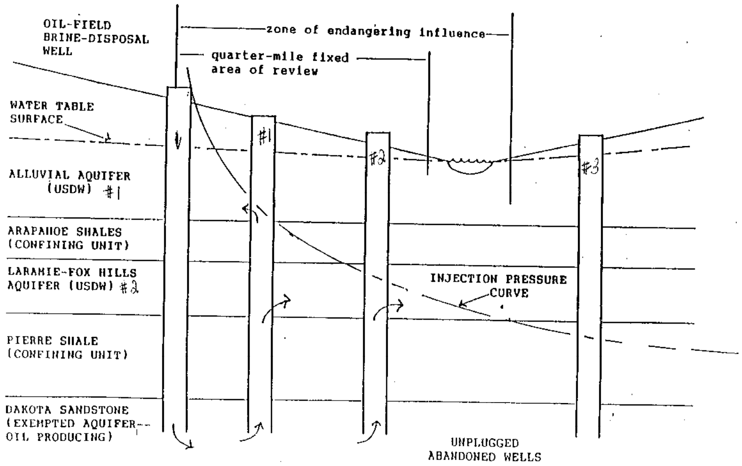
- One-quarter mile fixed radius extended if calculation confirms it should be larger.
- Less than one-quarter mile permitted if confirmed through calculation.
- Region conducts field survey to identify presence of unplugged/abandoned wells.
- If operational parameters change, area of review reevaluated.

Fixed Radius Area of Review
vs.
Zone of Endangering Influence

- Can an **operator** choose either one?
- Yes
- Can a **regulator** accept either one?
- Depends

AREA OF REVIEW

Here is how the zone of endangering influence can extend past the quarter-mile fixed area of review. The zone of endangering influence is the region where injection pressures may force fluid out of the intended injection reservoir into a USDW.



When Might the Use of a ZEI Calculation Prove Advantageous ?

- Development of a new field or expansion of an old field where,

  * Extensive oil and gas development has occurred in the past,

  * The potential for abandoned/unplugged wells is likely,

  * The existence of faults or fractures is likely.

  * Data is available and reliable.

What must you know to conduct a ZEI Calculation?

- ***Reservoir Pressure** ***Injection Rate**
- Length of Injection Fluid Viscosity
- ***Specific Gravity** ***Permeability**
- Reservoir Thickness Formation Compressibility
- Porosity Surface Elevation
- Injection Zone Depth ***Base of Lowermost USDW**

- ***Most Critical Parameters**

- **Radial Flow Calculation Typically Used**
- **Modified Theis Equation (Sec. 146.6)**
- **The assumption that conditions within the injection zone are similar throughout.**
- **Is this assumption necessary for CO_2 injection?**

So, if a fixed radius or ZEI calculation both provide uncertainty, what's left for an operator or regulator to do?

MONITORING

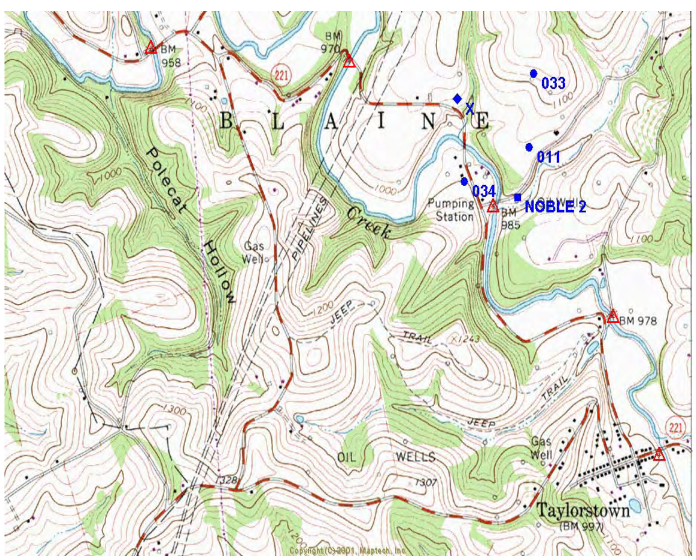
Historical Perspective Pennsylvania Direct Implementation

- Oil discovered in Pennsylvania in 1859.
- Long history of drilling and abandonment.
- Poor public record.
- Estimates of 10,000 abandoned/unplugged wells.
- Began direct implementation June 1984.

UIC Class II Enhanced Recovery Permit

Taylorstown, PA

- Field originally drilled in early 1900s,
- Poor well records,
- Concern over abandoned wells raised by public,
- Permit remand,
- Region incorporates fluid monitoring to prevent endangerment.



Monitoring at Taylorstown

- Injection into Gordon Sandstone at depths averaging 2500 feet,
- Average thickness of Gordon is 11 feet,
- Average porosity is 19 percent,
- Average permeability is 100 millidarcies,
- Lowermost USDW at depth of 500 feet,

Monitoring at Taylorstown (cont.)

- Monitoring wells were located between the injection wells and possible abandoned well locations,
- Injection began prior to production,
- Monitoring fluid level provided continuous record of formation response,
- ZEI calculation conducted to estimate fluid level response,
- After 9 months, several monitoring wells exhibit fluid levels above USDW.

PARAMETER	011	033	034
Initial Pressure	100 psi	100 psi	100 psi
Injection Rate	590 STB/D	255.6 STB/D	731.5 STB/D
Viscosity	1	1	1
Specific gravity	1	1	1
Formation volume factor	1	1	1
Permeability	100 md	100 md	100 md
Reservoir thickness	12 ft	12 ft	12 ft
Compressibility	.0000032 psi -1	.0000032 psi -1	.0000032 psi -1
Porosity	.19	.19	.19
Distance to Monitoring Well	745 ft	1834 ft	701 ft
Calculated Reservoir Pressure at Monitoring Well	346 psi	180 psi	411 psi

Table 1. ZEI Calculation for Nobel 2 Monitoring Well, Taylorstown, PA Project

The results of the ZEI calculation show

- Calculation after 286 days of injection,
- Pressure influence from the 3 injection wells at monitoring well Nobel 2 totaled 937 psi.,
- This pressure equates to a fluid column of 2158 feet,

Results of ZEI Calculation (cont.)

- Top of Gordon Sand was at a depth of 2330 feet at the monitoring well,
- Resulting calculated fluid level was 178 feet below land surface,
- The observed fluid level was 125 feet below land surface,
- Reasonable agreement provides confidence for prediction at other project locations.

Well Number	Distance to Hypothetical Monitoring Well	Calculated Reservoir Pressure at Hypothetical Monitoring Well (X)
011	1320 ft	306 psi
033	1320 ft	189 psi
034	1320 ft	356 psi
Total		851 psi

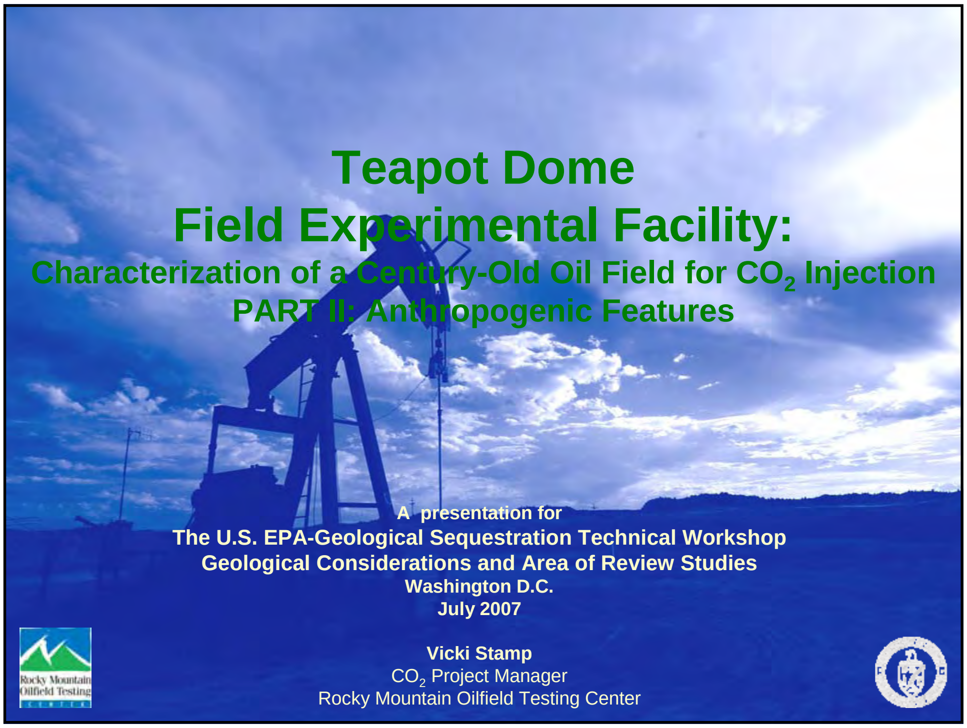
Table 2. Hypothetical Calculation of Pressure Influence at One-Quarter Mile

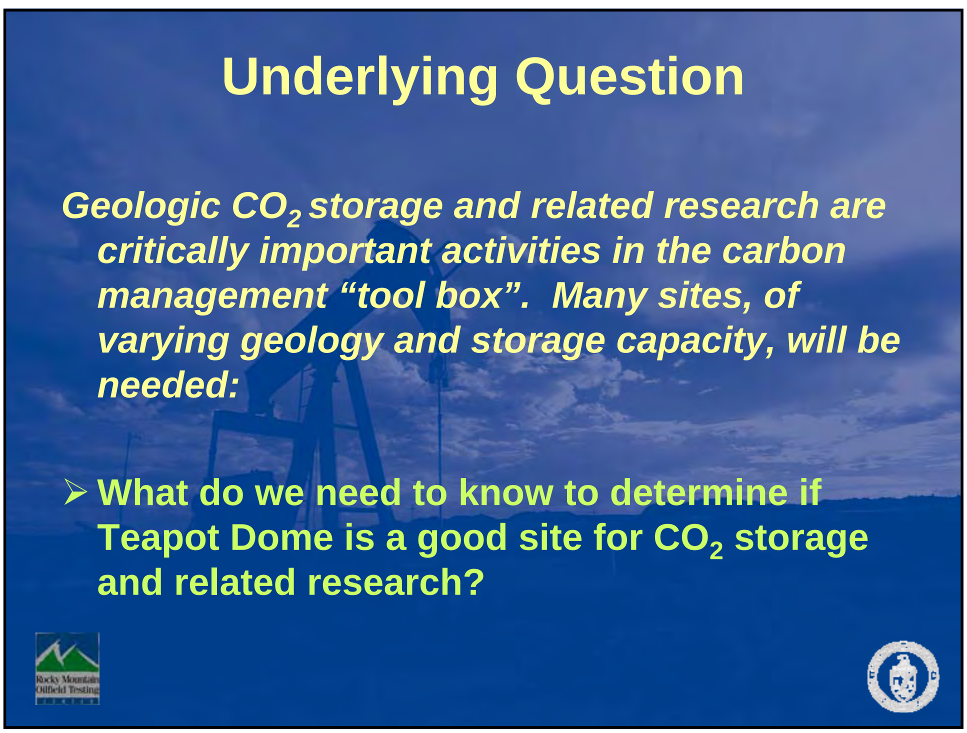
Result of ZEI Calculation at One-Quarter Mile

- Hypothetical well X at one-quarter mile,
- Total pressure of 851 psi would equate to fluid column of 1963 feet,
- Fluid level 400 feet below land surface,
- After 286 days of injection, fluid would be into USDW if abandoned well existed at this location.

Conclusions

- Non-Endangerment standard must be met,
- Fixed radius AOR may not be adequate,
- ZEI calculation should be performed,
- Adopt the KISS Principle
- Monitoring may be the only way to ensure protection of USDWs if potential pathways for fluid migration exist.



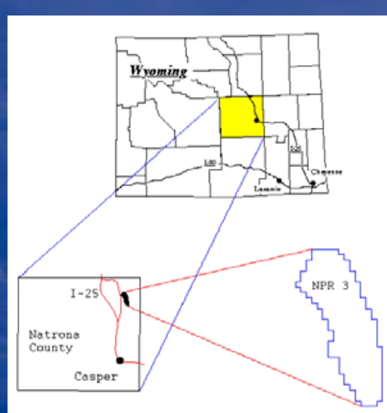


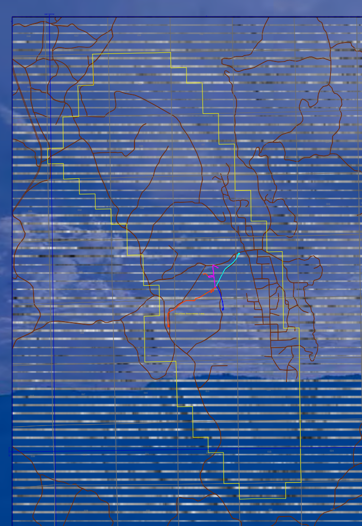
Teapot Dome Field Experimental Facility: Characterization of a Century-Old Oil Field for CO2 Injection PART II: Anthropogenic Features

Goals of presentation

- Program history:
  - Site characteristics, capabilities and activities
- Questions identified
- Results and current status
- Key areas for continuing research and technology development
- Identify challenges, remaining questions, data needs
- Project / site opportunities

Teapot Dome Location





The field occupies roughly 10,000 acres, 35 miles north of Casper WY.

Elevation data courtesy of Geological Data Services

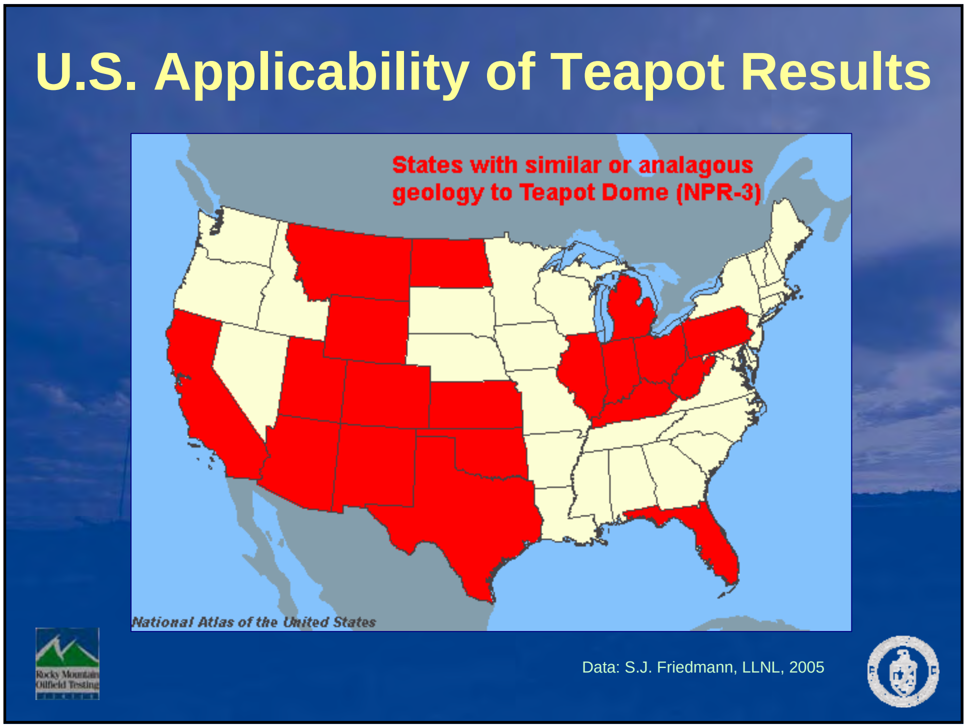
Existing infrastructure

~600 active wells, ~1300 wells total, drilling and workover rigs, equipment & field staff

Photo courtesy S. Cooper, Sandia NL

Why Teapot Dome?

- **Field-scale U.S. site possible**
- **Integrate Salt Creek: direct industry and Program benefit**
- **Side-by-side, field-scale comparison, same reservoirs**
- **Unique scientific opportunity**
- **Complement other U.S. pilot projects**
- **Expand on pilots, provide opportunities absent on commercial oil and gas properties**
- **100% USG owned and operated, testing focus:**
  - **full access, rich public database available**
- **Consistent commitment to public outreach, tech transfer, transparency**
- **Anadarko support, other industrial partners**
  - **MOA, CO_2 supply, MMV, research and science collaboration**
- **Strong foundation for successful long-term program, *if site is suitable.***


U.S. Applicability of Teapot Results
States with similar or analagous geology to Teapot Dome (NPR-3)
National Atlas of the United States
Data: S.J. Friedmann, LLNL, 2005
Rocky Mountain Oilfield Testing


Teapot Dome CO_2 Project Partners
Scientific and engineering testing, deployment, and technology transfer
Rocky Mountain Oilfield Testing CENTER
Anadarko Petroleum Corporation
UNIVERSITY OF WYOMING
GCEP
NETL
USGS
SCHOOL OF MINES 1874 COLORADO
LELAND STANFORD JUNIOR UNIVERSITY ORGANIZED 1891
Sandia National Laboratories
Los Alamos NATIONAL LABORATORY
BERKELEY LAB
PEI PRINCETON ENVIRONMENTAL INSTITUTE
MANCHESTER
The University of Manchester
Carbon Mitigation Initiative
TEXAS A&M PETROLEUM ENGINEERING
iReservoir.com e-solution for global energy
McCutcheon ENERGY COMPANY Applied Earth Sciences

Where to start?
What do we need to know?

Goals: Identify small early project(s) at manageable scale and cost, fully characterize, develop experience and build on early success:

- Gross Site Screening: What zones might be suitable?
  - Depth, pressure, reservoir character, applicability / relevance, capacity
  - High-grade candidates with EOR potential or saline aquifers
- What zones do we rule out?
  - Shallow (low P), poor seal, too many (old) well penetrations: high risk, high cost
- Compare zone / site geologic and reservoir characteristics, develop short list of possible candidates:
  - Faults, fracturing: how to evaluate?
- Preliminary risk assessment: Site and zone-specific
  - Wells, predicted impacts of injection (modeling)
  - Predict fault sealing behavior
  - Databases, data needs
  - Begin baseline assessments
  - Geologic model, dynamic reservoir models
- What is the appropriate AoR? What other features should be included?
  - What is the proposed scale of the project?

Site characterization components

Teapot Dome

- Regional geology
- Reservoir geology
- ***Reservoir histories screening, models***
- Soils, aquifers, ***reservoir fluids***
- Petrology, petrophysics, ***geomechanics,*** seismic interp. (CSM, UW, LBL, ***TA&M***, UH, BYU, ***Stanford, WVU***)
- ***CO_2-specific baseline assessments: CSM, U of Manchester, NETL***

Anthropogenic data outline

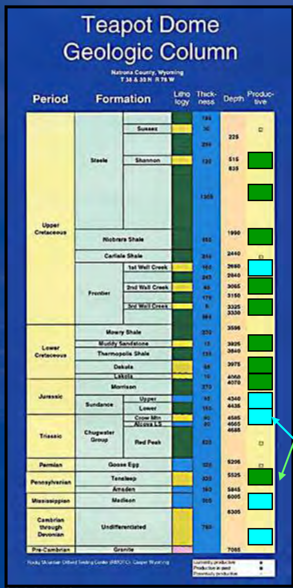
- Reservoir screening and history
- Fluid characteristics
- Proposed project descriptions
- Geomechanics and reservoir modeling (Wadleigh, Stanford, LLNL)
  - Preliminary and comprehensive leakage risk assessments
- Baseline assessments / MMV testing:
  - Soil gases, gas flux (CSM), baseline and monitoring
  - Noble gas baseline (U of Manchester), tracer monitoring
  - Magnetometry and atmospheric gases: well locating, baseline gas concentrations (NETL, Fugro, Apogee)
  - Microhole VSP (LBL, NETL)
- Area of Review considerations
  - Wells histories, infrastructure
  - CO_2 injection operations

Reservoir Screening and History

Work Completed:

- ***Reservoir screening winners: Tensleep, Crow Mtn.***
- Historical data consolidation and review
- Conceptual project design
- EOR assessment and preliminary design
- Preliminary modeling of target zone
- Fine grid modeling of pilot and CO_2 movement
- Preliminary leakage risk assessment
- *Geomechanical modeling coupled with reservoir flow model (in progress)*

NPR-3 Reservoir Summary



9 Producing (oil-bearing) intervals:

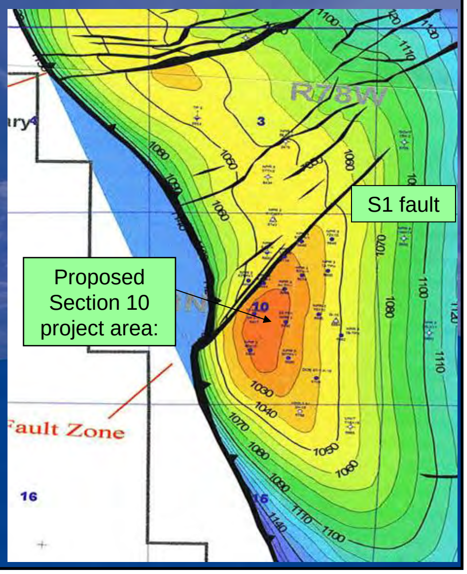
- Depths 500'-5500' (Shannon to Tensleep)
- Good range of oil/rock chemistry and petrophysics

Additional 5-6 water-bearing intervals:

- Fresh and saline, 3000-8000'
- Range of dep. environments, clastic (Ss) & carbonate
- Crow Mtn. Class II disposal zone (4500')
- Madison underlies field

Tensleep Reservoir

- Summary:
  - Well control: few penetrations, modern
  - Small, viable EOR target
  - P = 2350 psi, 32 API
  - Depth 5500', 8% porosity, 80 md, h = 50'
  - Risk assessment, caprock
  - Regional impact
  - Research, MMV relevance



Reservoir Characterization and Modeling High-level task list - Full field

- Digitize logs from “deep wells”
- Import wells and logs into GeoGraphix system
- Continuing to map surfaces and faults at NPR-3.
- Complete full 3D integrated seismic interpretation of multiple key horizons and faults
- Seismic depth conversion to match well data
- Special geoscience analysis
- Build 3D geocellular model
- Run dynamic flow simulation, perform history match and tune model for fit (Tnslp)
- Continue loading production history and completions data into production mgmt system
- Implement real-time production data capture and surveillance
- Load (historic) drilling data into system to enable improved drilling operations, planning and design
- Implement new strategies and policies for cleaning up the existing databases, and maintaining well files as new data is added

Green: completed; Yellow: in progress; White: planned

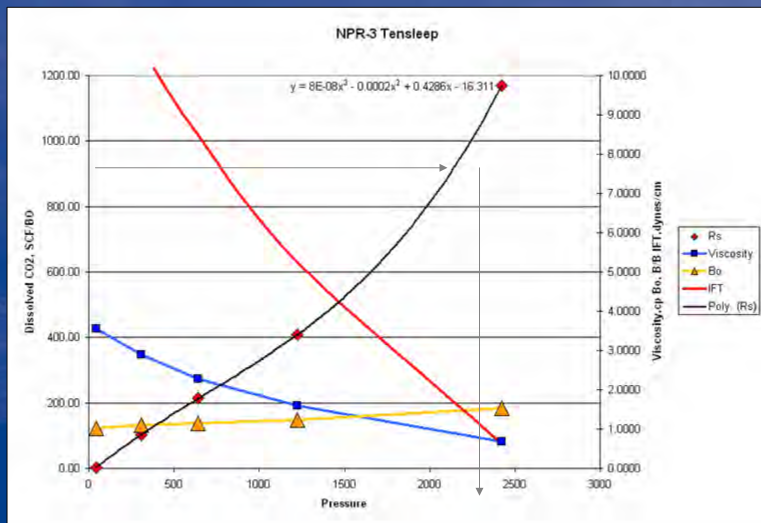
Tensleep EOR / storage demonstration

Compelling state and regional drivers to study EOR and storage in the Tensleep at Teapot Dome:

- 2/3 of Wyoming production comes from Tensleep or equivalent
- Rangely CO_2 EOR in the Weber (Tensleep equiv.)
- Significant volumes in Colorado & Utah
- Analogs throughout U.S. & internationally

Tensleep fm, Alcova Canyon, WY

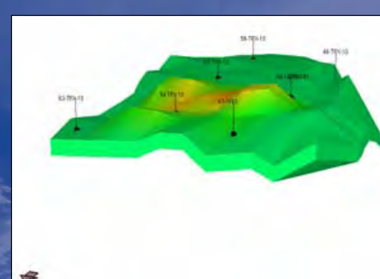
Fluid Testing Quantifies Tensleep EOR Potential



Oil expands by 25%, viscosity reduces by 66%, IFT cut 90%

NPR-3 Gravity-Stable Miscible CO_2

- **Cost-effective testing of gravity-stable operation in Tensleep fm**
  - High relief structure
  - Significant fracturing, faulting
  - Active aquifer
  - Available wellbores for both operation and monitoring
- **Fluid analyzed and test design simulated**
  - Lab fluid tests were used to generate equation of state inputs for simulation tuning
  - Simulation at field scale and proposed test scale



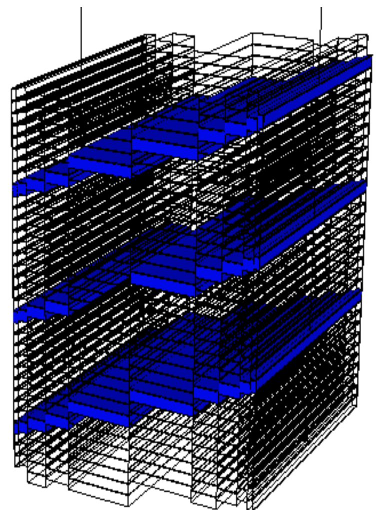
Tensleep Section 10 project area

•Results support proceeding with injection

The reservoir is thick and heterogeneous:

Perfect for gravity-stable CO_2 flooding

Formation is like a 5-story building



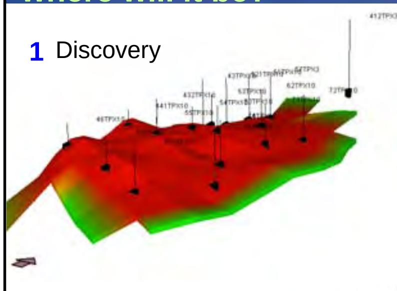
Fine-gridded simulation study 50’x50’x60’

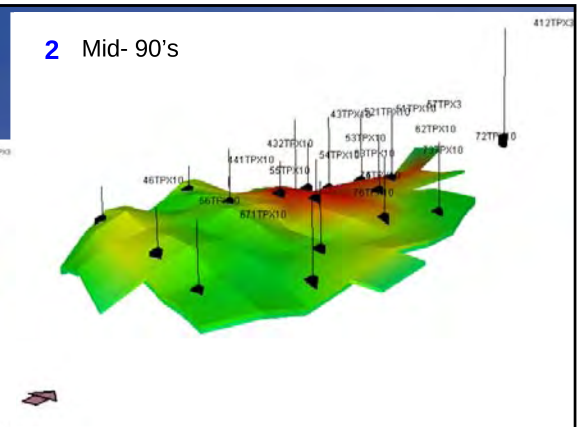
Courtesy: Wadleigh 2005

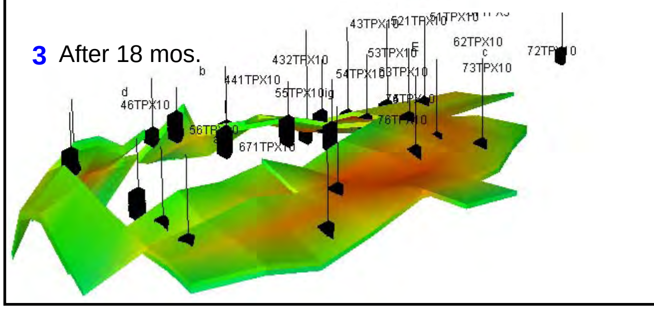
Tensleep EOR Simulation

- **Commercial simulator**
  - Computer Modeling Group (CMG)
  - Compositional simulator (GEM)
  - Modeled as dual porosity, dual permeability
- **Model includes**
  - History matching of field-scale model
  - EOS inputs from laboratory oil-CO_2 testing
  - Fracture system characterized with support from Sandia National Laboratories and Texas A&M
  - Fine gridded model of large enough test area to contain impact of short-term test injection

Scoping Model:
Where was the oil, and where will it be?







Clockwise from upper left:

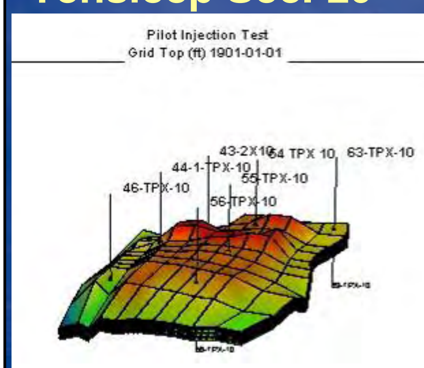
Fig. 1: oil saturation (red) at discovery

Fig. 2: in 1990

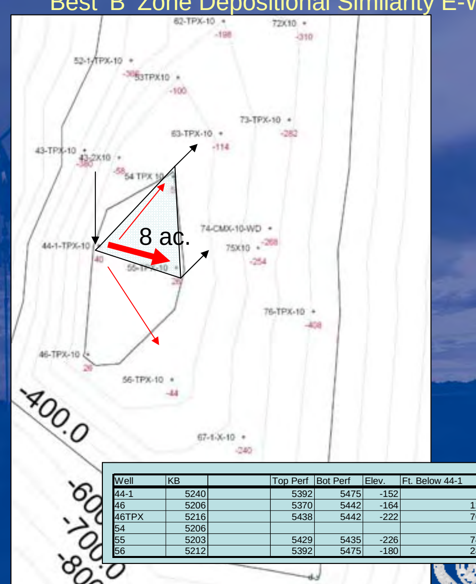
Fig. 3: after 18 months of CO_2

Wadleigh, 2005

Finer grid blocks: Views of Test Area, Tensleep Sec. 10



44-1-TPX-10 CO_2 Test Injection Well, Best 'B' Zone Depositional Similarity E-W



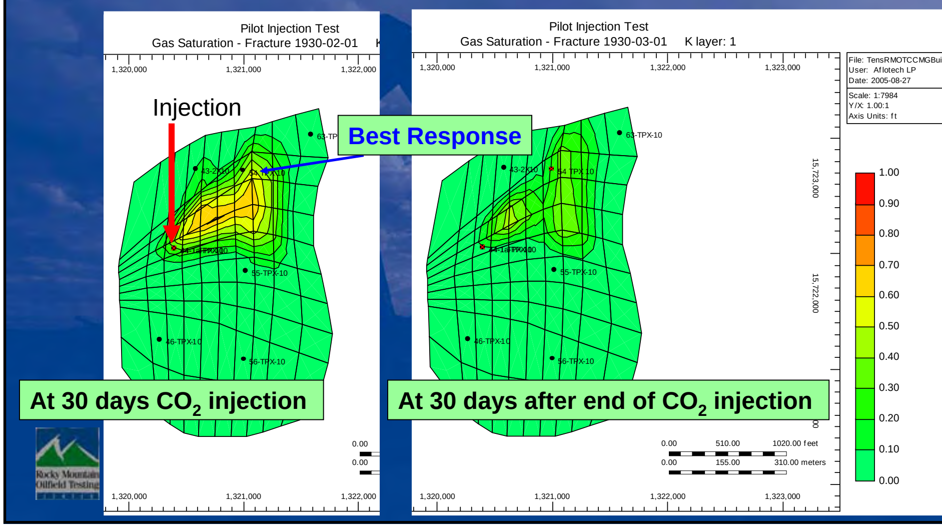
Well	KB		Top Perf	Bot Perf	Elev.	Ft. Below 44-1
44-1	5240		5392	5475	-152	
46	5206		5370	5442	-164	12
46TPX	5216		5438	5442	-222	70
54	5206					
55	5203		5429	5435	-226	74
56	5212		5392	5475	-180	28

Rocky Mountain Oilfield Testing

Wadleigh, 2005

30-Day CO_2 Test Injection: Gas Saturation in Top Layer Fractures

Good CO_2 solubility and transport



Section 10 EOR / Storage Project: Area of Review?

Pilot:

- *Model area contains almost all projected impacts; model will be tuned based on pilot results, monitoring data.*
- *CO_2 volume is very small, minimizes risk.*
- *Few existing wells projected to be affected.*
- *Will evaluate casing /cement integrity of project area wells prior to start-up, and w/o as needed. Injection well will be recompleted.*
- *Interventions, if needed, may include shutting in wells, suspending injection, etc.*
- *MMV will be included.*
- ***Routine oil and gas operation***
- ***Expansion of pilot contingent on results.***

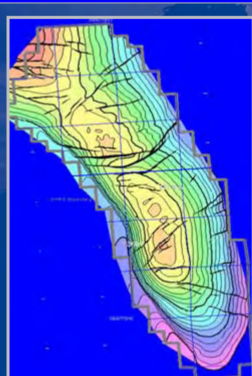
Proposed CO_2 Transport Operations

- Trucked for early experiments (Section 10 Tensleep pilot, Crow Mtn. test)
- Pipeline proposed if long-term project is viable
- SWEA in progress; includes pipeline options and both Section 10 projects

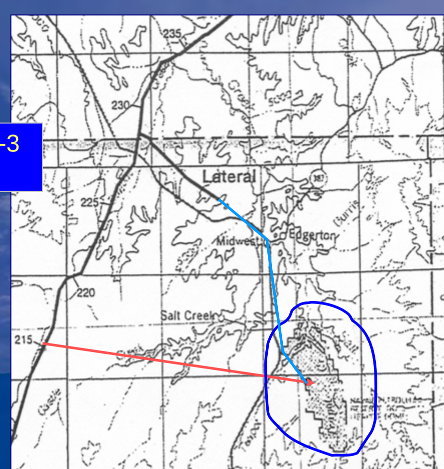
Anadarko / Salt Creek CO_2 Pipeline

- **Location of the pipeline**
- **Proximity to NPR-3**

Distance from main line to central NPR-3 location ~15 mi or less.



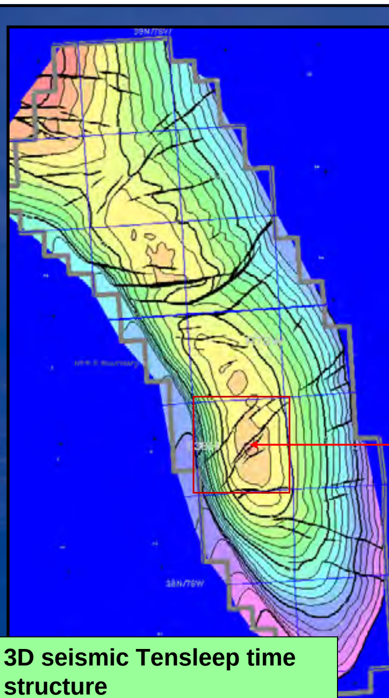
Teapot Dome (NPR-3)



Saline Aquifer Storage Test

- Crow Mountain Ss
- 3 existing Class II disposal wells
- Co-locate with Tensleep project (Sec.10)
- Water analysis, permeability, caprock
- Several surrounding wells available for monitoring
- Research focus:
  - MMV tool sensitivity and detection limits, comparison, integration
  - Predict and quantify multiple storage mechanisms

Tensleep Structure and Section 10 topography



3D seismic Tensleep time structure

Sec. 10 wells, Tensleep and Crow Mtn.

Baseline assessments, partner research

(partial list)

- **CSM- Klusman**:
  - Soil gas and gas flux, baseline and monitoring phases
- **CSM- Hurley**:
  - LIDAR mapping of Tensleep outcrop
- **LLNL- Friedmann**:
  - Fault seal / leakage risk assessment
- **Stanford U / GCEP- Zoback, Chiaramonte:**
  - field geomechanical model, prediction of fault and fracture behavior, integrate flow model
- **Princeton U / PEI- Scherer:**
  - CO2-cement interactions
- **U of Manchester- Ballantine**:
  - Noble gases as tracers
- **USGS- Burruss**:
  - Reservoir compartmentalization and seepage assessment
- **NETL / LANL / LBNL- Long, Majer**:
  - Microdrilling and VSP monitoring applications
- **U of Houston- Marfurt / Sullivan**:
  - 3D seismic data, curvature and attribute analysis for detailed fracture and fault understanding
- **BYU- McBride:**
  - Shallow high-resolution 2D seismic

BASELINE CHARACTERIZATION: Soil Gas / Gas Flux

- **PI: Dr. Ronald Klusman, Colorado School of Mines**
- **Goal: Establish baseline soil gas composition and gas flux field-wide, prior to CO_2 injection.**
- **Yr 1: surface and shallow soil gas and gas flux sampling and analysis. Report completed.**
- **Yr 2: 10- meter deep holes prepared and instrumented. C-13/C-12 ratio, CH_4 and CO_2, C-14 content of CO_2. Report completed.**
- ***Yr 3: Section 10 area grid completed. Analysis underway.***
- ***Plan: Monitoring during injection.***

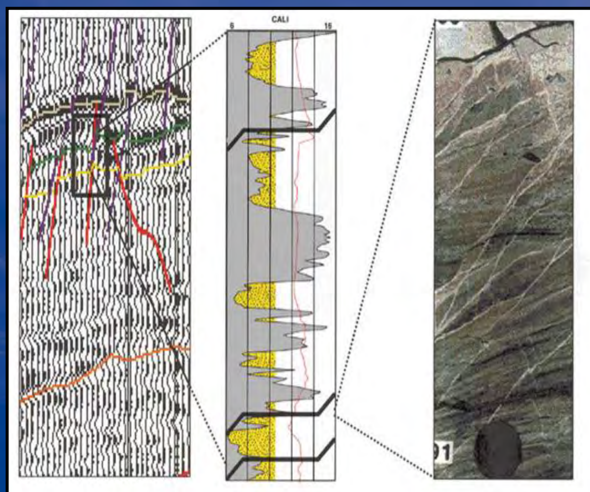
Below: Aluminum collar (1 meter square), gas flux chamber and infrared CO_2 monitor.

Above left: Dr. Klusman extracts a 1 meter soil gas sample.

Above right: Plexiglas chamber placed over collar prior to sampling.

Bottom right: Chamber is covered with plastic tarp prior to sampling; sample is withdrawn for analysis of methane content.

Fault Seal Risk Assessment



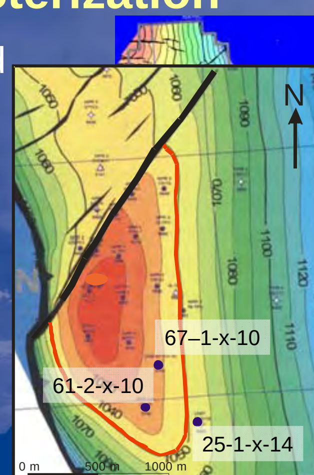
Leakage risk occurs at all scales; accurate characterization requires multiple data sets and detailed analysis.

Friedmann, 2004

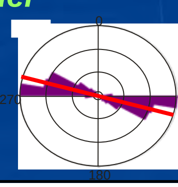
Seismic, well log (esp. FMI), core, and production data (e.g. flow rates, pressure variations) are key to accurate risking of fault seal.

Geomechanical Characterization

- Stanford University: M. Zoback and L. Chiaramonte
- Determine stress tensor
- S1 fault characterization
- Tensile fracture analysis from FMIs
- **~17 Mpa of excess pressure required to cause fault slippage**
- ***Good news for pilot and future of storage.***
- ***Incorporate into GEM model***



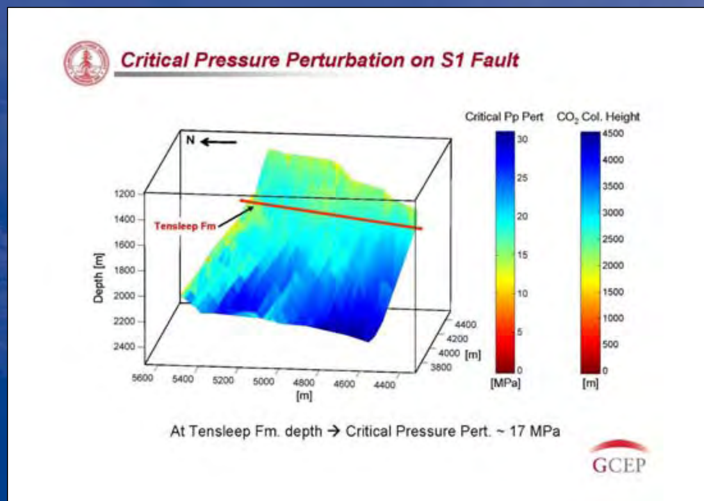
Well 67-1-X-10
(Milliken & Koepsel, 2002)



GCEP

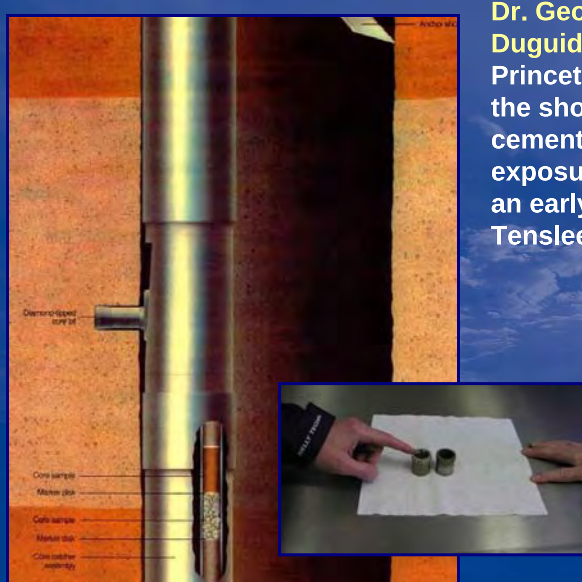
Stanford Findings: S1 Fault

Critical Pressure Perturbation ~17 MPa



From Chiaramonte, Zoback, et al., AGU Annual Meeting, 2006. Session T12A, Paper T12A-07

Wellbore / Cement Integrity



Dr. George Scherer, Andrew Duguid
Princeton U (CMI) investigated the short-and long-term state of cements and casing after exposure to CO_2. The work was an early study in Sec. 10 Tensleep.

Princeton Environmental Institute

Univ. of Manchester: Noble Gas Tracers

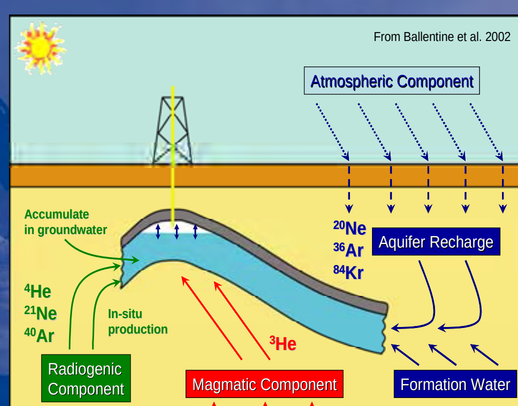
- **PI: Dr. Christopher Ballantine; PhD student Sarah Mackintosh**
- Teapot baseline and Salt Creek EOR data gathered
- Lab work and PhD research in progress
  - Initial analytical results encouraging
  - Improve understanding of :
    - Fluid interactions within the sequestration system
    - Fluid losses from the system
    - Physical and chemical sources and sinks of CO_2

U of M research team sampling at Teapot with Ron Klusman, CSM, May 2005.

Phase 2 research proposal submitted in June 2007.

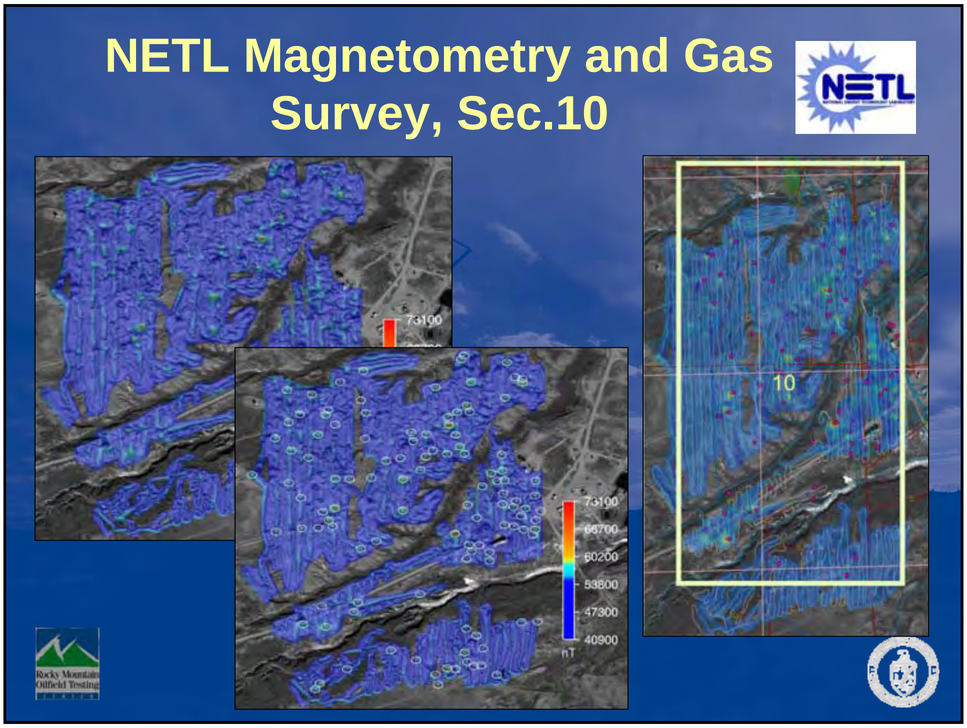
Noble Gases in a Nutshell

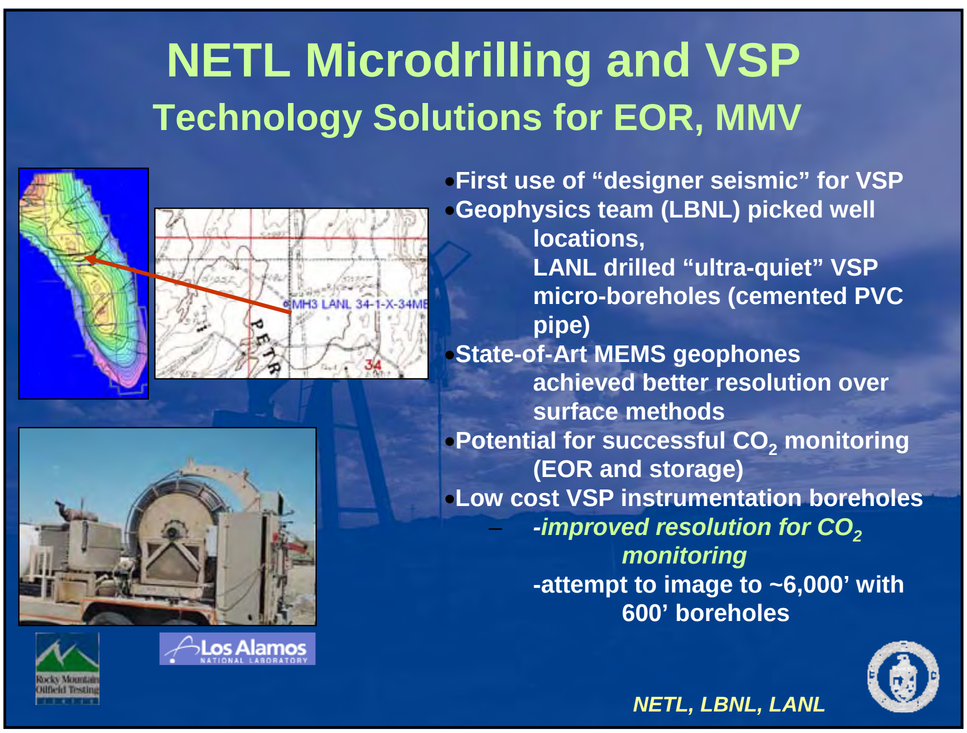
- **He, Ne, Ar, Kr, Xe**
- **Three Sources:**
  - **Groundwater (air)**
  - **Crust (Radiogenic)**
  - **Mantle**
- **Isotopically Distinct**
  - **Resolvable**



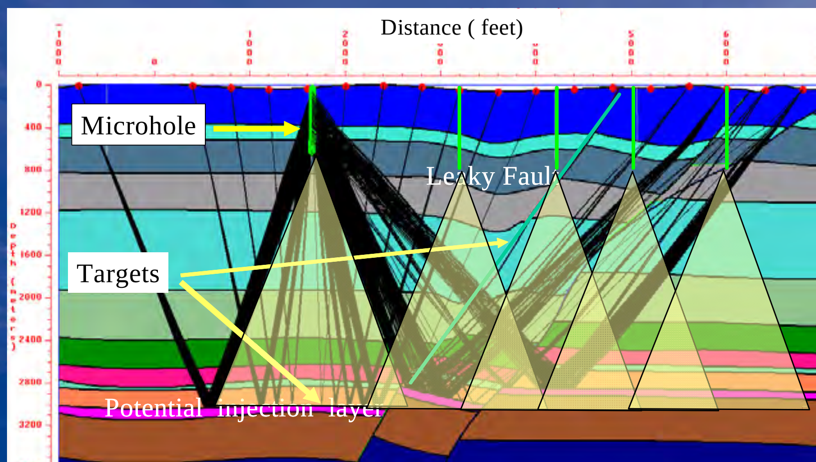
- **Quantify interaction/origin of fluids sourced from these different regions**

S. Mackintosh, U of M


NETL Magnetometry and Gas Survey, Sec.10
73100
66700
60200
53800
47300
40900
nT
10


NETL Microdrilling and VSP
Technology Solutions for EOR, MMV
•First use of "designer seismic" for VSP
•Geophysics team (LBNL) picked well locations,
LANL drilled "ultra-quiet" VSP micro-boreholes (cemented PVC pipe)
•State-of-Art MEMS geophones achieved better resolution over surface methods
•Potential for successful CO_2 monitoring (EOR and storage)
•Low cost VSP instrumentation boreholes
– -improved resolution for CO_2 monitoring
-attempt to image to ~6,000' with 600' boreholes
MH3 LANL 34-1-X-34ME
34
Los Alamos NATIONAL LABORATORY
NETL, LBNL, LANL

Basis of Imaging Work at RMOTC: Establish Potential of Deep VSP Using Microholes



Courtesy E. Majer, LBNL (2006)

Research Focus

- Site characterization
  - Tensleep EOR potential
- Storage permanence
- Public safety of storage
- Adequacy and cost-effectiveness of monitoring tools
- Confidence in design and MMV capabilities:
  - Scientific, public

Anthropogenic data covered

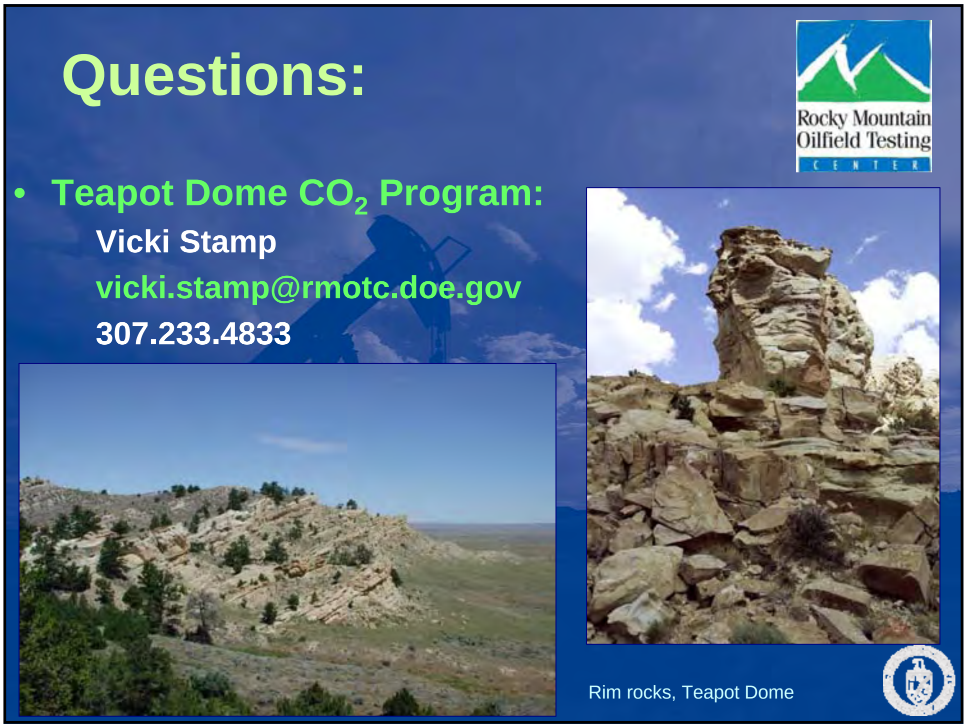
- Reservoir screening and history
- Fluid characteristics (RMOTC)
- Proposed project descriptions
- Geomechanics and reservoir modeling (Wadleigh, Stanford, LLNL)
  - Preliminary and comprehensive leakage risk assessments
- Baseline assessments / MMV testing:
  - Soil gases, gas flux (CSM), baseline and monitoring
  - Noble gas baseline (U of Manchester), tracer monitoring
  - Magnetometry and atmospheric gases: well locating, baseline gas concentrations (NETL, Fugro, Apogee)
  - Microhole VSP (LBL, NETL)
- Area of Review considerations
  - Wells, infrastructure
  - CO_2 injection operations

Conclusion

Characterization results to-date indicate Teapot Dome is a good project site for collaborative research on key geoscience and operations questions for CO_2 storage and monitoring.

Major areas proposed for future work:

- **EOR / oil field storage**
- **Saline aquifer storage**
- **Monitoring (MMV) tool sensitivity, development, comparison and integration**
- **Long-term testing related to storage safety and wellbore integrity**


Questions:
Rocky Mountain Oilfield Testing CENTER
• Teapot Dome CO_2 Program:
Vicki Stamp
vicki.stamp@rmotc.doe.gov
307.233.4833
Rim rocks, Teapot Dome

The effect of CO_2 sequestration on wells in the area of influence

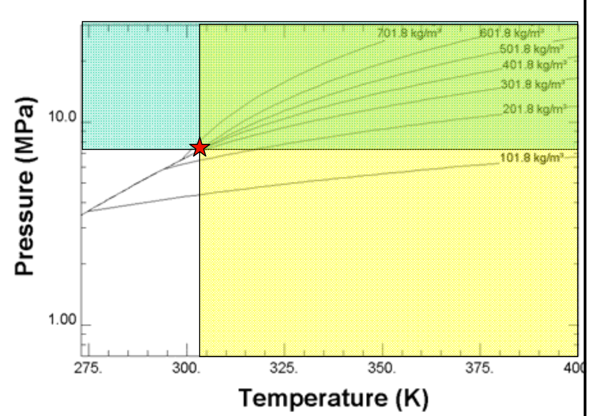
US EPA Geosequestration Workshop

Andrew Duguid
July 11, 2007

Schlumberger

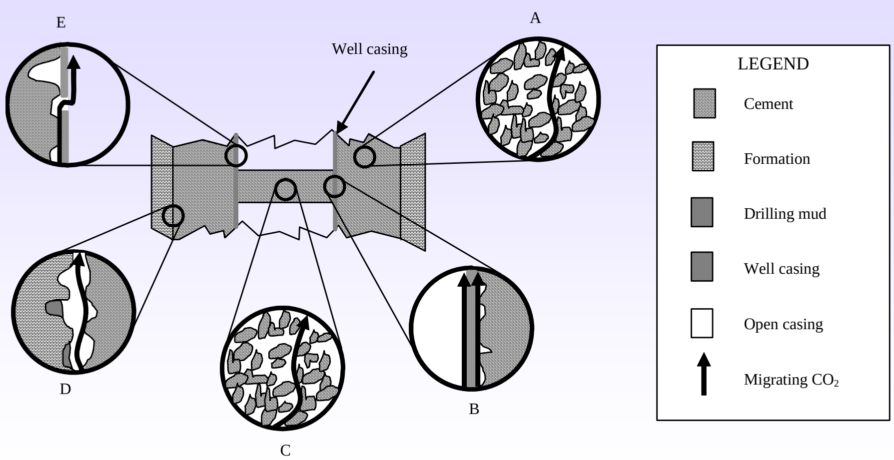
CO_2 properties

- CO_2 Critical point
  - 304.13 K and 7.3773 MPa 467.6 kg/m^3 28.838 μPa-s
- Water (pure)
  - 998.56 kg/m^3 780.56 μPa-s
- Oil
  - 900 kg/m^3 90 μPa-s
- Methane
  - 52.438 kg/m^3 12.855 μPa-s



References NIST REFPROP V8.0; Bromhal et al

Avenues for leakage



Cement degradation reactions

- CO_2 dissociation

  $CO_2 + H_2O \leftrightarrow H_2CO_3^* \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-}$

- Cement dissolution

  $Ca(OH)_2(s) + 2H^+ + CO_3^{2-} \longrightarrow CaCO_3(s) + 2H_2O$

  $Ca_3Si_2O_7H{\bullet}4H_2O(s) + 2H^+ + CO_3^{2-} \longrightarrow CaCO_3(s) + SiO_xOH_x(s)$

  $Ca(OH)_2(s) + H^+ + HCO_3^- \longrightarrow CaCO_3(s) + 2H_2O$

  $Ca_3Si_2O_7H{\bullet}4H_2O(s) + H^+ + HCO_3^- \longrightarrow CaCO_3(s) + SiO_xOH_x(s)$

- Calcium carbonate dissolution

  $CO_2 + H_2O + CaCO_3(s) \leftrightarrow Ca^{2+} + 2HCO_3^-$

  $2H^+ + CaCO_3(s) \leftrightarrow CO_2 + Ca^{2+} + H_2O$

How do the properties of CO_2 influence wells in the AoR

5

- The low density of CO_2 means that there needs be a natural barrier to flow above the storage formation
  - CO_2 will tend to pool at the top of the sequestration formation
  - CO_2 will always want to leak through and vertical features (wells or faults) that may be open pathways for flow
  - The critical interfaces for leakage will be the interfaces between the cement and formation and cement and casing at the top of the storage formation
- Even if a well has proved to have good zonal isolation for oil or brine the low viscosity and density may allow CO_2 to travel through pathways not available to the other fluids

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What types of cement/additives are appropriate for corrective action on abandoned wells?

6

- Cements for remediation and construction of new wells can still be portland based.
- CO_2 resistant portland cements have been used and are currently available.
  - Some CO_2 resistant cements work by reducing the amount of calcium hydroxide (CH) and increasing the amount of calcium silica hydrate (C-S-H). CSH is more resistant to CO_2 attach than CH. Additives such as pozzolans provide additional silicon to create C-S-H.
  - Additives such as bentonite which require a large increase in the water-to-cement (W/C) ratio should be avoided. High W/C can lead to accelerated cement degradation

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Should fields with large numbers of active or abandoned wells generally be considered unsuitable for CO_2 geosequestration?

- Large numbers of penetrations will raise the likelihood that a leaky well will exist in the vicinity of the sequestration formation.
- This is a risk that will be encountered and must be dealt with
- A long as each of the wells are properly evaluated, remediated and monitored then the field could be a candidate.
- Even wells that do not pierce the storage formation may act as conduits for leakage if the cap rock is compromised – The buoyant nature of CO_2 will always allow for vertical migration if a pathway exists

How does the corrosive nature of CO_2 impact wells in the AoR?

- Portland-based cements are subject to degradation due to carbonic acid exposure
  - Based on laboratory experiments under diffusion control (static conditions) it will take between 10^4 and 10^6 years for total degradation of 25 mm of Class H well cement
  - Based on laboratory experiments under reaction control (flowing conditions) it will take between ½ and 50 years to totally degrade 25 mm of Class H well cement
  - *Unless there is a pathway for carbonic acid to flow through or across the cement sheath in a well degradation should be slow*
- Steel casings are also subject to corrosion due to exposure to low pH and brines.

Reactions in cement at the interface

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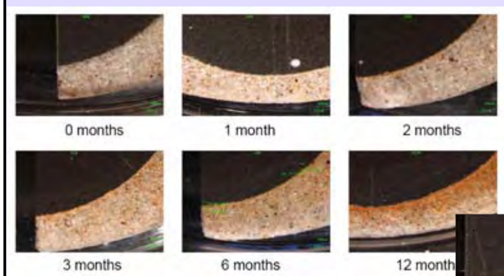
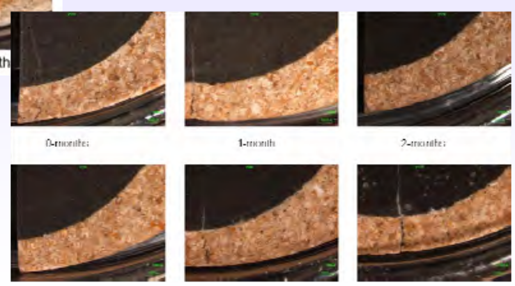
Sandstone-cement at pH 3 and 20°C



Limestone-cement at pH 5 and 20°C



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Are any additional corrective actions needed for "properly" constructed and abandoned wells to address the corrosive nature of CO_2?

10

- Assuming that a well has sufficient zonal isolation – CO_2 and carbonic acid will not have pathways for flow – the cement in the wells should last a sufficient amount of time
  - No additional corrective action should be needed for wells with good initial integrity (zonal isolation)
- The high pH of cement means that if there is no pathway for CO_2 or brine to reach a steel casing then the steel should be protected from degradation

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Limitations on injection size or pressure satisfy corrective action requirements

- "Director may limit injection pressure so that pressure in the injection zone does not exceed hydrostatic pressure at the site of any improperly completed or abandoned well within the AoR. This limitation could satisfy the corrective action requirement or be part of a compliance schedule until required corrective action has been taken." [40 CFR 144.55]
- Once the volume of CO_2 is greater than that which can dissolve into the formation fluid an injection pressure less than hydrostatic pressure of will have limited influence on leakage potential
  - The difference in density between the formation fluid and CO_2 will mean that pressure drive is not a necessary condition for leakage – So a limitation on size and pressure will only affect how many wells are encountered and not the likelihood of leakage from a specific well

Are existing UIC Program requirements for corrective action sufficient?

- *"…well permits shall identify the location of all known wells within the injection well's area of review which penetrate the injection zone…" [40 cfr 144.55]*
  - This does not address any search for unknown wells. In the case of old oil fields it maybe necessary to require documentation in the permit that a search was conducted for old "lost" wells
- *For such wells which are improperly sealed, completed, or abandoned, the applicant shall also submit a plan consisting of such steps or modifications as are necessary to prevent movement of fluid into underground sources of drinking water (''corrective action''). [40 cfr 144.55]*

Are existing UIC Program requirements for corrective action sufficient?

13

- *In determining the adequacy of corrective action proposed by the applicant under 40 CFR 144.55 and in determining the additional steps needed to prevent fluid movement into underground sources of drinking water, the following criteria and factors shall be considered by the Director:*
  - *(a) Nature and volume of injected fluid;*
  - *(b) Nature of native fluids or by-products of injection;*
  - *(c) Potentially affected population;*
  - *(d) Geology;*
  - *(e) Hydrology;*
  - *(f) History of the injection operation;*
  - *(g) Completion and plugging records;*
  - *(h) Abandonment procedures in effect at the time the well was abandoned;*
  - *(i) Hydraulic connections with undergroundsources of drinking water. [40 CFR 146.07]*
- Again the corrective action plan should include plans to search for “lost” wells.
- Because of the buoyant nature of CO_2 all potential connections to USDWs should be specifically considered, not just direct pathways between the storage formation and the USDWs
- Because of the density difference CO_2 is more likely to reach USDWs than other “heavier” fluids so a monitoring plan maybe need to be part of the corrective action plan

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Summary

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- The density and viscosity of CO_2 are very different from most fluids currently being injected into UIC injection wells
  - Leakage does not need to be pressure driven
- Abandoned and existing wells are subject to degradation by exposure to carbonic acid
  - The rate of degradation is dependant on the flow regime of the carbonic acid
- Existing regulations need to be more specific. The properties of CO_2 are not similar to the properties of fluids that are typically injected and the regulations should reflect the differences

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"The role of Existing Wells in Projecting Performance Standards for Engineered Saline Reservoirs"

Ian J. Duncan

Washington DC July 11th 2007

Bureau of Economic Geology
Jackson School of Geosciences
The University of Texas at Austin

BUREAU OF ECONOMIC GEOLOGY

- Established in 1909
- Oldest research unit of The University of Texas at Austin
- Geological Survey of Texas

Gulf Coast Carbon Center

Gulf Coast Carbon Center (GCCC)

Gulf Coast Carbon Center

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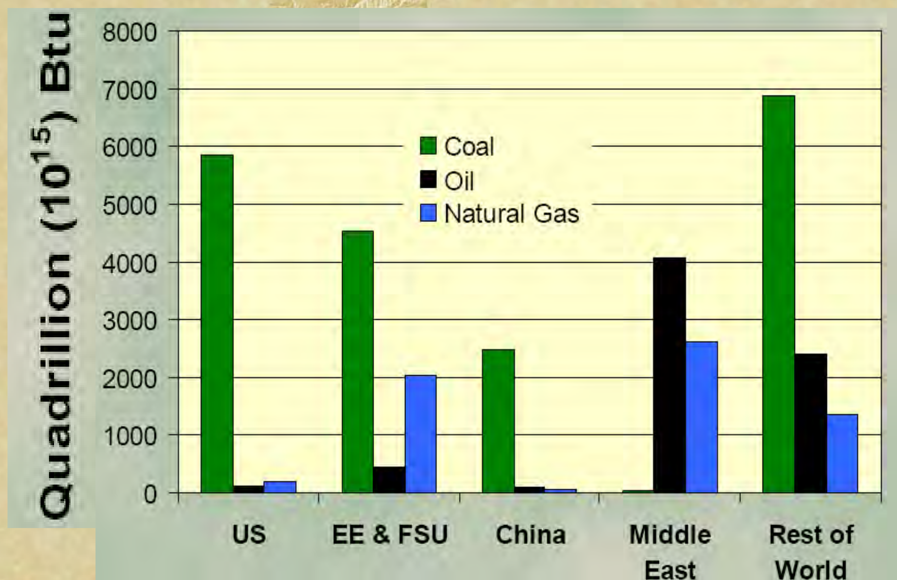
NRG



Elements for Permitting Framework

- **Regional Focus needed as well as AOR**
- **Performance based not Command- and-Control**
- **Learning by Doing**
- **MMV** (Monitoring, Mitigation, Verification)

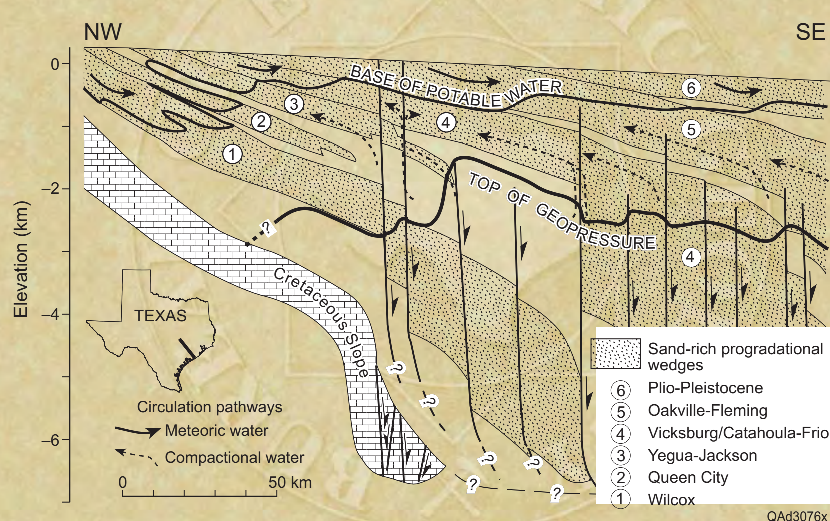
Region of Influence Issues

(1) Area of elevated pressure

(2) Area of mobile – CO_2

(3) Area brine set in motion in response to injection

Gulf Coast Characteristics



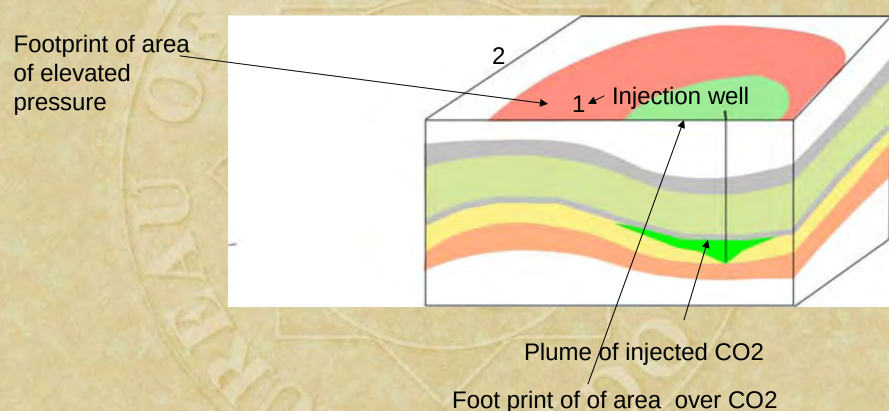
Source: Galloway (1982) and Galloway et al. (1982)

Region of Influence Issues

Potential Problems within Region of influence

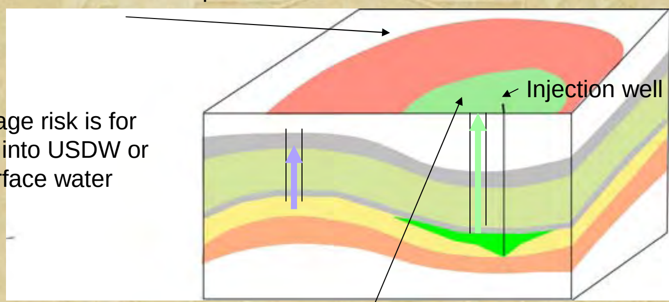
- reservoir and seal quality
- distribution and character of existing wells
- nature of faults (seals or conduits?)

Region of Influence



Risk is different in different parts of the Region of Influence, and changes with time

Footprint of area of elevated pressure



Leakage risk is for brine into USDW or to surface water

Foot print of of area over CO2

Leakage risk is for
CO2 into the atmosphere,
also possibility for damage to biosphere,
to USDW or surface water

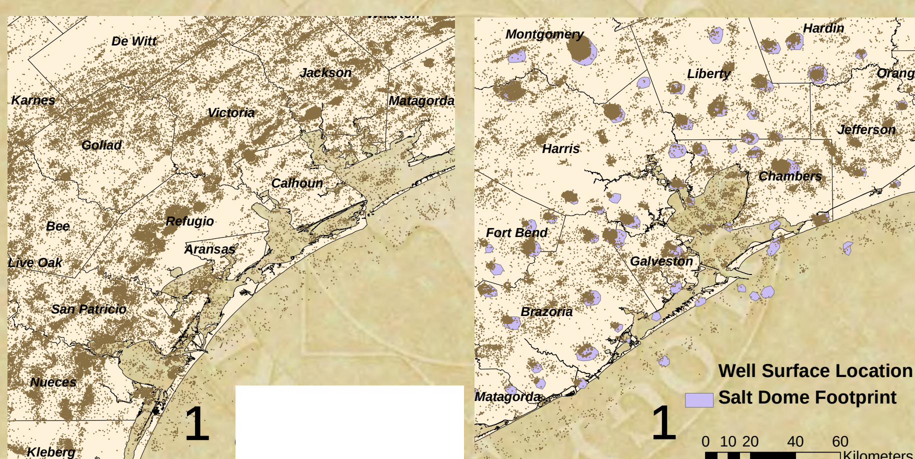
Region of Influence Issues

- Region of influence probably larger than we think
- Approach to Permitting should have regional component
- Nicot and Duncan (2007) suggest hierarchical permitting with "General Permits" on regional scale

Regional Evaluation
Wells

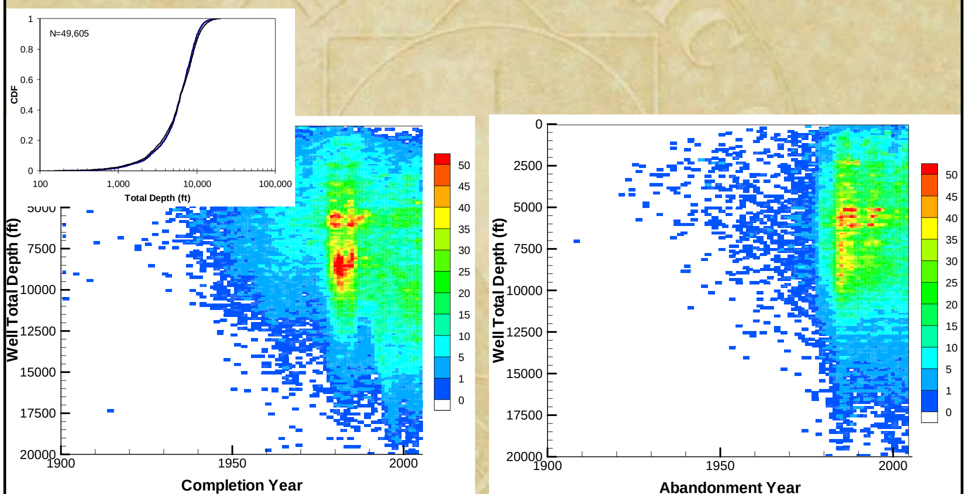
- Inventory – assessment of volumes below most and oldest well penetrations.
- Field tests for performance of wells
  - Frio site: test of a single retrofit well
  - SWCARB test of 35 years of injection at SACROC – surface and aquifer
  - SECARB – above-zone monitoring as a test of well performance

Tx GC Well Areal Distribution



Source: RRC

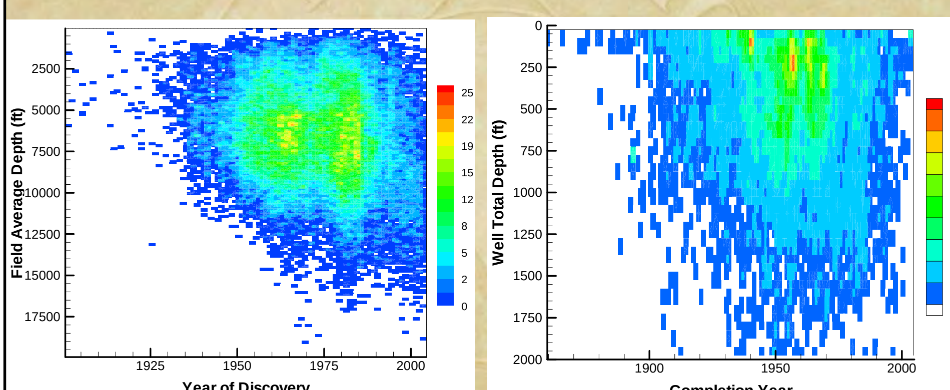
Tx GC Well Depth Distribution



Include all wells : production, injection, utility, exploration, wildcat…

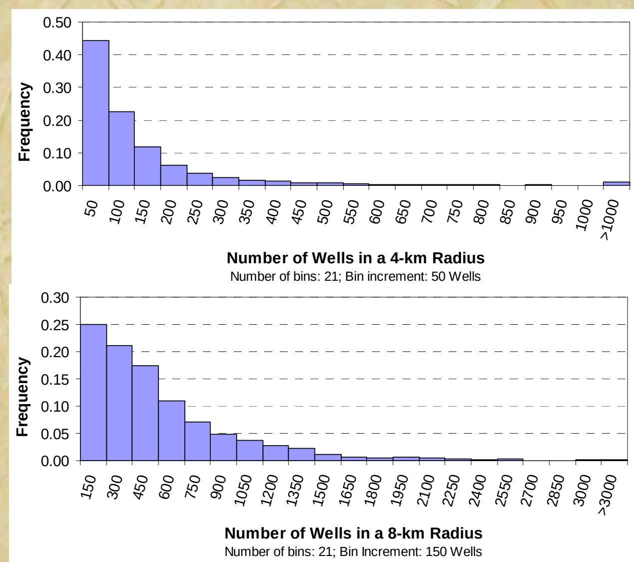
Source: RRC

Tx GC Field Depth Distribution



Source: RRC -TWDB

Well Density

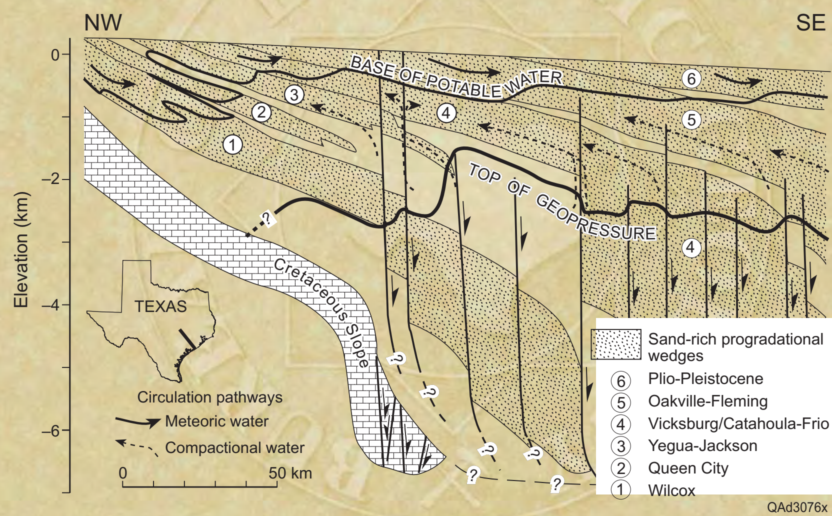


Regional Evaluation

Reservoir Structure/ Seals

- Inventory – assessment of volumes below most and oldest well penetrations.
- Field tests for performance of wells
  - Frio site: test of a single retrofit well
  - SWCARB test of 35 years of injection at SACROC – surface and aquifer
  - SECARB – above-zone monitoring as a test of well performance

Gulf Coast Characteristics

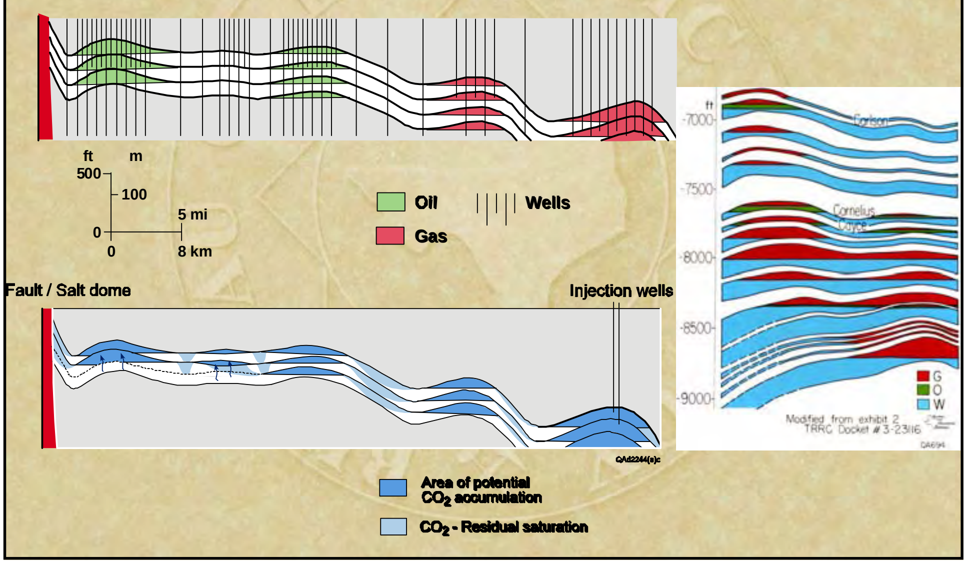


Source: Galloway (1982) and Galloway et al. (1982)

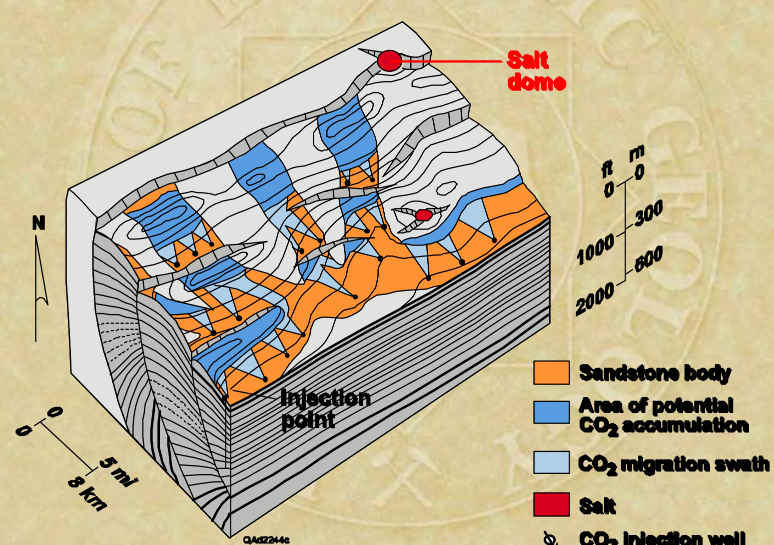
Leakage Pathways

- Spill points
- Leaky faults
- Poor seal quality
- Seal failure
- Abandoned, inadequately plugged wells

Stacked Traps



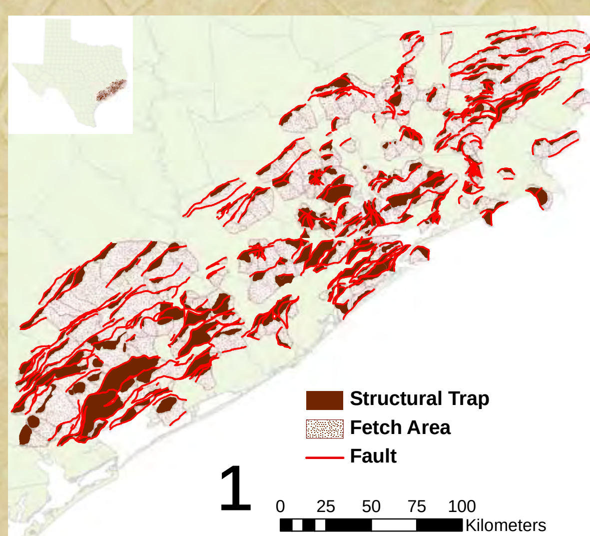
Model for CO2 Migration



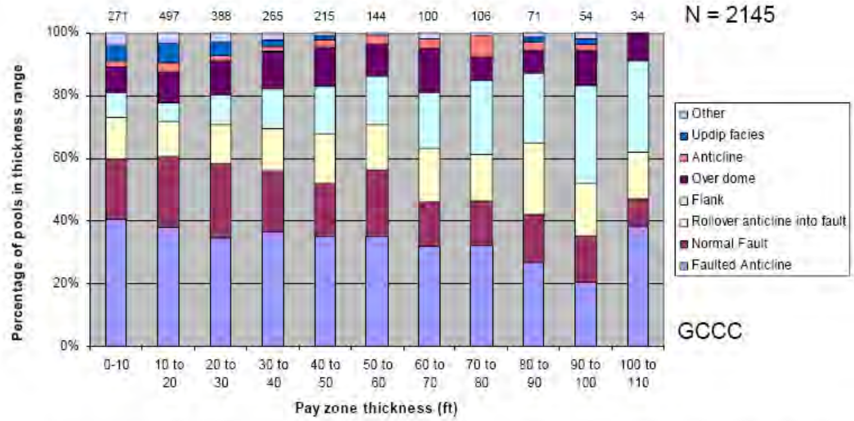
Faults: seals or conduits

- Many faults act as seals
- Fault gouge can be a very effective capillary seal
- A fault may be sealing at one depth and a conduit at another
- A key issue is whether exposure to CO2 can degrade the sealing properties of fault gouge

Closure and Fetch Areas (Top Frio)



Common environments for economic hydrocarbon accumulations
Example: Offshore Gulf of Mexico



- Majority of HC environments involve faults: provide structure
- Faults demonstrably sealing with respect to hydrocarbons

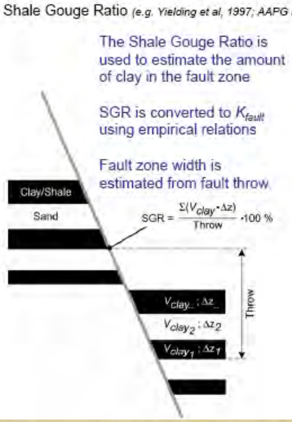
Meckel, 2007

Prediction – Integrate knowledge

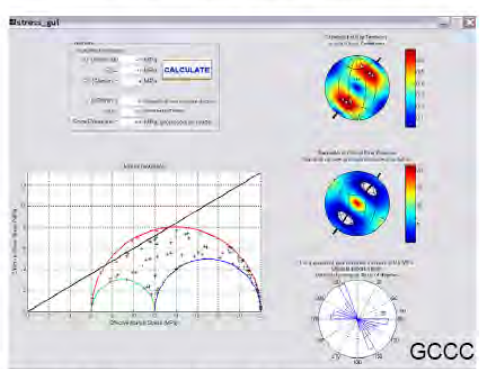
- Future performance knowable

TRANSMISSIVE PROPERTIES:
Predicting fluid flow

Shale Gouge Ratio *(e.g. Yielding et al, 1997; AAPG Bull.)*

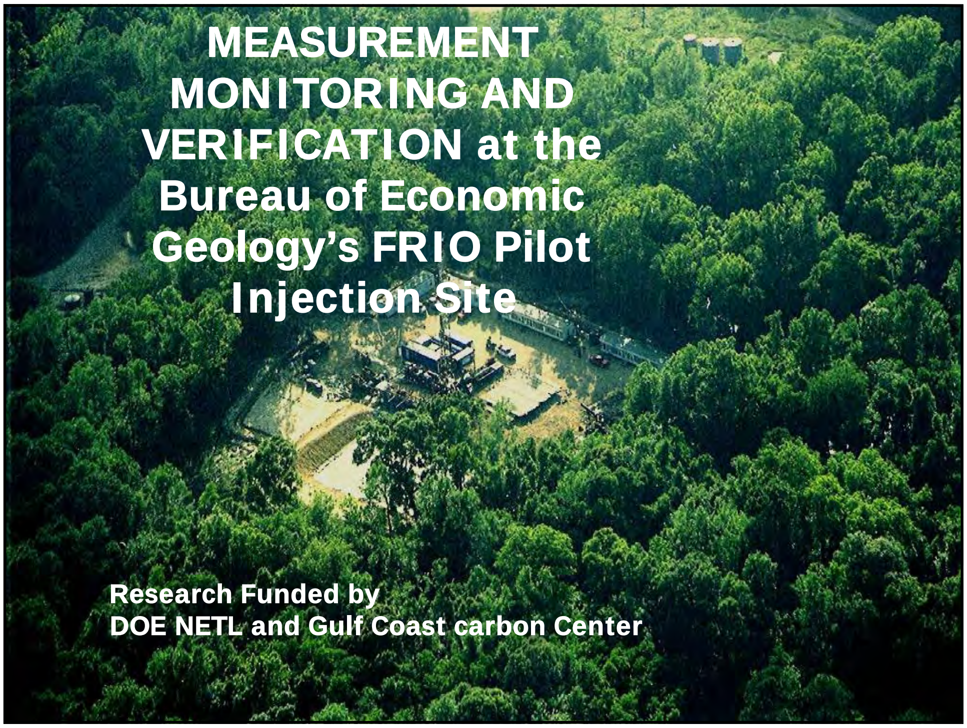


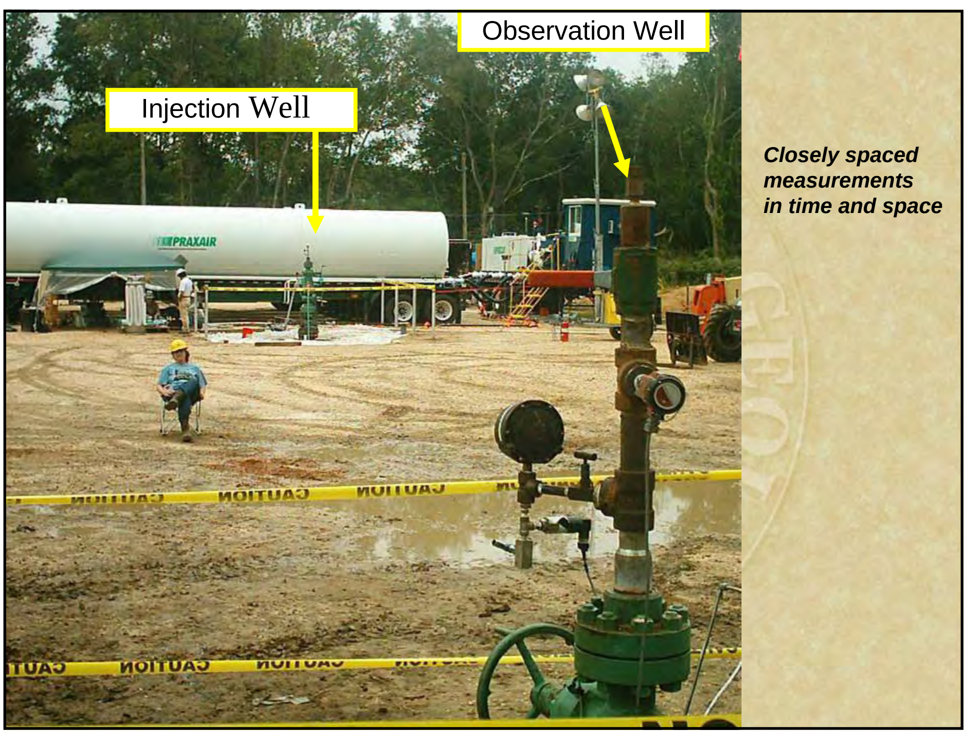
DYNAMICS:
Predicting slip tendency
with increases in fluid pressure



After Streit and Hillis, 2004: Energy 29:1445-1456.

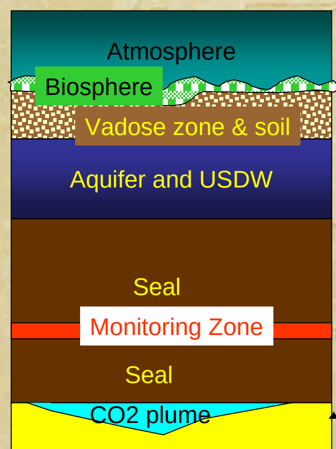
Meckel, 2007





The role of Existing Wells in Projecting Performance Standards for Engineered Saline Reservoirs

Early Warning Monitoring Options



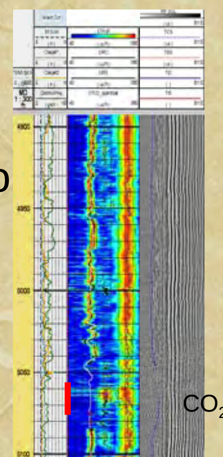
- Atmosphere
  - Ultimate receptor but dynamic
- Biosphere
  - Assurance of no damage but dynamic
- Soil and Vadose Zone
  - Integrator but dynamic
- Aquifer and USDW
  - Integrator, slightly isolated from ecological effects
- Above injection monitoring zone
  - First indicator, monitor small signals, stable.
- In injection zone - plume
  - Oil-field type technologies. Will not identify small leaks
- In injection zone - outside plume
  - Assure lateral migration of CO_2 and brine is acceptable

Groundwater Monitoring

- Standard technique in contaminated sites
- Good regional integrator
- Signal of leakage may be complex
- Might be used in combination with natural or introduced tracers

Wireline Well Logging

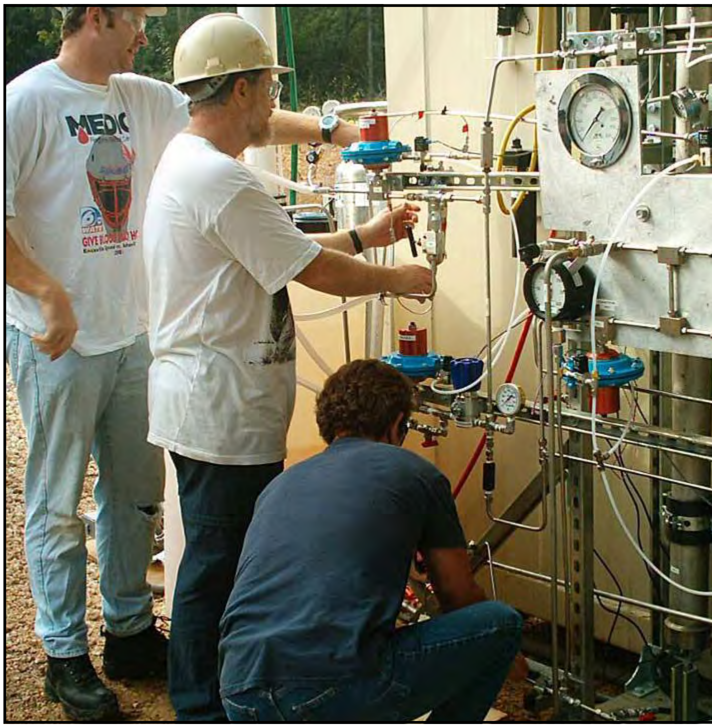
- Well-known oilfield activity
- Match tools to rock/fluid characteristics
- Typically good vertical resolutio quantitative, interpretable
- Well bore effects and damage may lead to errors
- Interpolate the interwell areas



Frio post injection cased hole sonic log, Sakurai BEG/Mueller Schlumberger

Using Inert Tracers

- Introduced materials that travel with CO_2 can uniquely fingerprint migration
  - Nobel gasses
  - PFT's and other chemically unique materials
  - Detection at very low concentrations
- CO_2 can be geochemically unique –
  - C isotopes
  - Impurities
- Natural indicators of potential leak paths

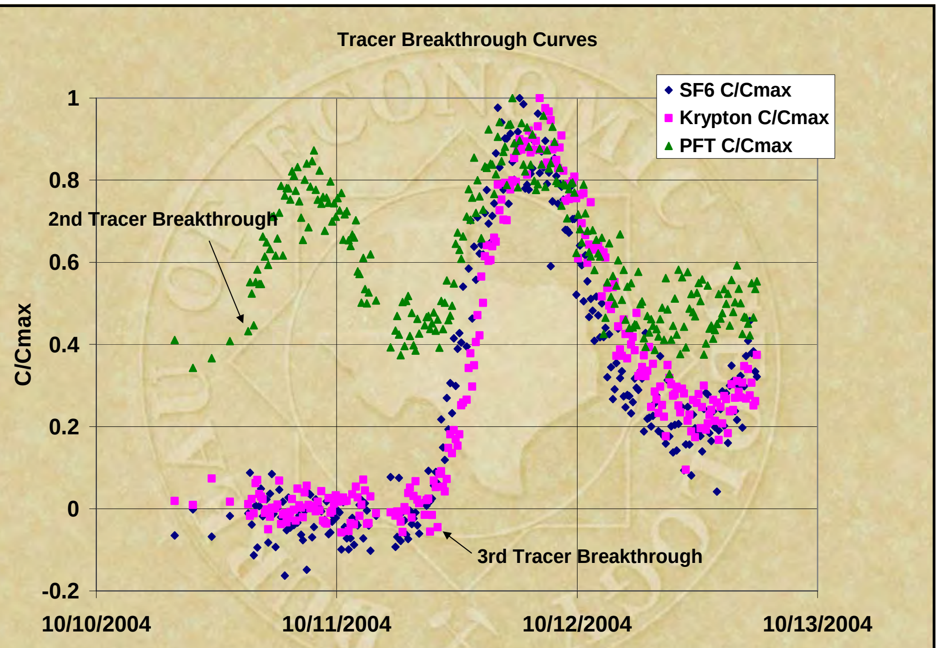


New tool to do the job: LBNL U-tube

instrument to collect high frequency, high quality two-phase samples

Tommy Phelps
Dave Ristenburg
Oak Ridge National Lab

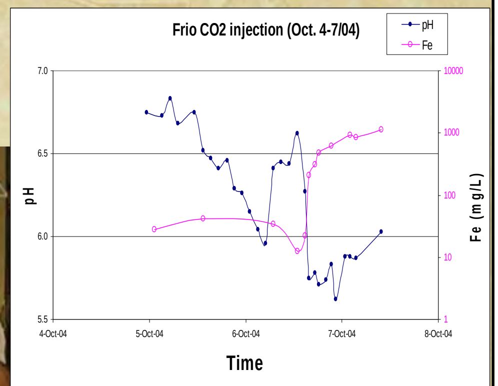
Seay Nance
BEG



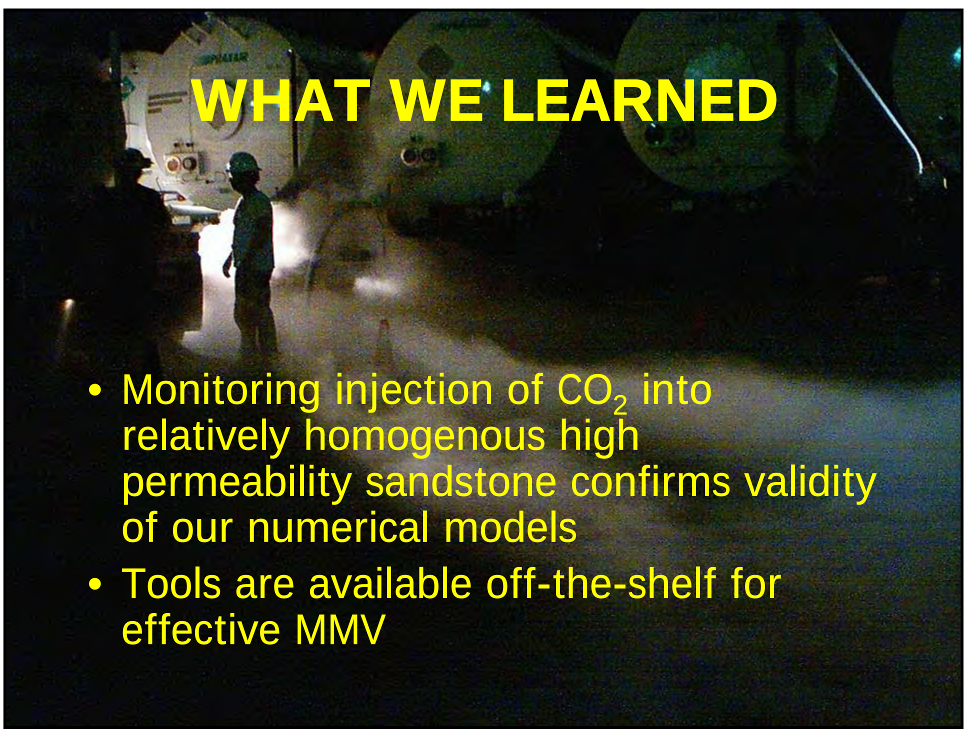
Frio noble gas and PFT analysis, Barry Freifeld (LBNL) and Timmy Phelps (ORNL)

Rapid Dissolution of CO_2 in Field Tests – a significant factor in reducing plume size

Within 2 days, CO2 has dissolved into brine and pH falls, dissolving Fe and Mn



Yousif Kahraka USGS



WHAT WE LEARNED

- Monitoring injection of CO_2 into relatively homogenous high permeability sandstone confirms validity of our numerical models
- Tools are available off-the-shelf for effective MMV

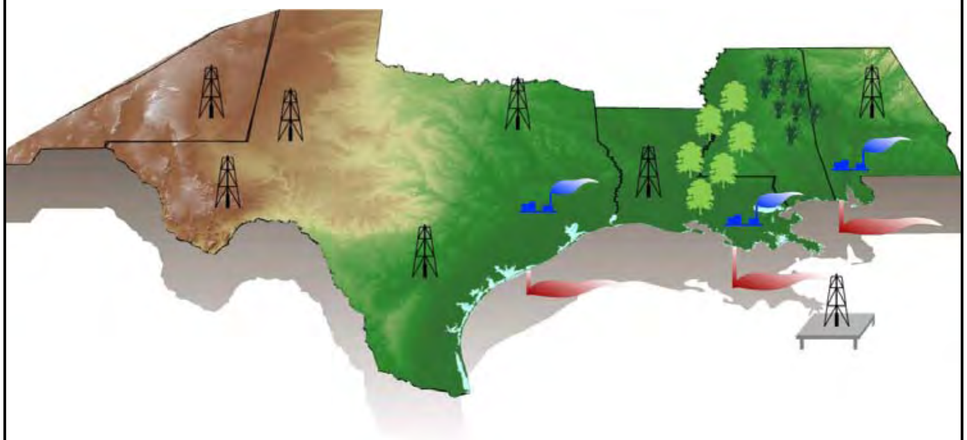
Conclusions

- Region of Influence depends on the injected volumes. Current UIC procedures break down for large injected volumes
- Permitting should be performance-based
- Siting criteria :
  - away from salt domes
  - below maximum penetration of most wells

Conclusions

- Even in heavily drilled areas large volumes of brine-filled capacity lie beneath most well penetrations
- MMV should be an integral part of regulatory framework

Thanks!



For more information: www.gulfcoastcarbon.org

Relevance of Geological Carbon Storage Capacity Assessments to Area of Review Studies

Sean Brennan

USGS

U.S. Department of the Interior
U.S. Geological Survey

Overview

- How large will subsurface storage projects be? (Specific Storage Volumes)
- Discussion of some natural and anthropogenic analogs for geologic storage of CO_2.

Specific Sequestration Volume (SSV)

Volume of geologic target formation per unit mass of CO_2

Or … how many cubic meters of a given geologic setting are needed to store one tonne of CO_2

USGS

Purpose

- What is the “footprint” for a typical storage project?
- Because “CO_2 storage volume” is a finite *resource* that will be *consumed* by CO_2 sequestration, we want to know:
  - The rate of “storage volume” consumption per point source.
  - For the “Lifetime” of a sequestration project, what is the mass of CO_2 that will be injected and the subsurface volume needed for sequestration?

USGS

SSV's: What we need to know

- SSV's are variable because the properties of CO_2 change as a function of Temperature and Pressure.
- To provide an example of this method we will assume one set of T&P conditions
- *However* SSV's can be modified to any situation.

SSV's: Example conditions

- T&P for this example are 60°C and 150 bars
- Density of CO_2 at these conditions:
  - 604 kg/m^3
- Need to know:
  - Mass of CO_2 sorbed by coal
  - Solubility of CO_2 in aqueous fluids
- Assume no mineral trapping

SSV's for bituminous coal

- Used data from Krooss et al. (2002). Only published study with CO_2 isotherms >120 bars.
- CO_2 sorption @ 60°C and 150 bars:
  - High value of 31 cm^3 CO_2/g coal (~1000 SCF/short ton).
  - Low value of 14 cm^3 CO_2/g coal (~450 SCF/short ton).
- SSV's for these sorption values:
  - 13 m^3 bituminous coal/tonne CO_2.
  - 29 m^3 bituminous coal/tonne CO_2.

USGS

SSV's for aqueous fluids

- According to The Duan Group online solubility model* at 60°C and 150 bars:
  - 41 kg CO_2 will dissolve in 1 m^3 of pure H_2O.
  - 22 kg CO_2 will dissolve in 1 m^3 of 4m NaCl solution. (4m NaCl = ~190,000 TDS)
- SSV's are:
  - 24 m^3 H_2O/tonne CO_2.
  - 45 m^3 4m NaCl solution/tonne CO_2.

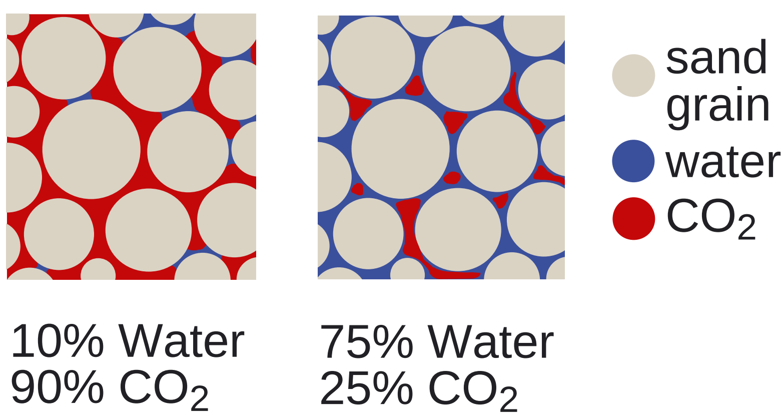
USGS

*Duan et al. (2003, 2006)

SSV's for saline reservoirs

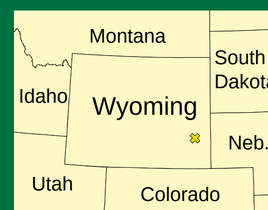
- Reservoir conditions:
  - Sandstone with 10% porosity and residual water saturation ranging from 0 to 100 percent.
  - 4m NaCl
  - Space not filled by residual water saturation is assumed to be pure CO_2 (604 kg/m^3)

Residual Water Saturation ("RWS"): Percentage of porosity (open space) filled by water



Laramie River 2&3 power plant

- Coal-fired power plant
- 1100 MW Capacity
- Operated for 85% of the year in 1998
- 8.7 million metric tons of CO_2 emitted in 1998
- Equal to ~2.4 MtC (or 0.0024 GtC)



USGS

Sequestration volumes

Setting	SSV (m^3/tonne CO_2)	Power plant sequestration volumes: m^3	Hectare-m	Acre-ft
100% space	1.7	$1.4x10^7$	$1.4x10^3$	$1.2x10^4$
Coal, high sorption	13	$1.2x10^8$	$1.2x10^4$	$9.4x10^4$
Coal, low sorption	29	$2.6x10^8$	$2.6x10^4$	$2.1x10^5$
pure H_2O	20	$1.7x10^8$	$1.7x10^4$	$1.4x10^5$
4m NaCl	36	$3.1x10^8$	$3.1x10^4$	$2.5x10^5$

Mass of CO_2 emissions : $8.7x10^6$ metric tons ($9.6x10^6$ short tons)

USGS

Sequestration volumes

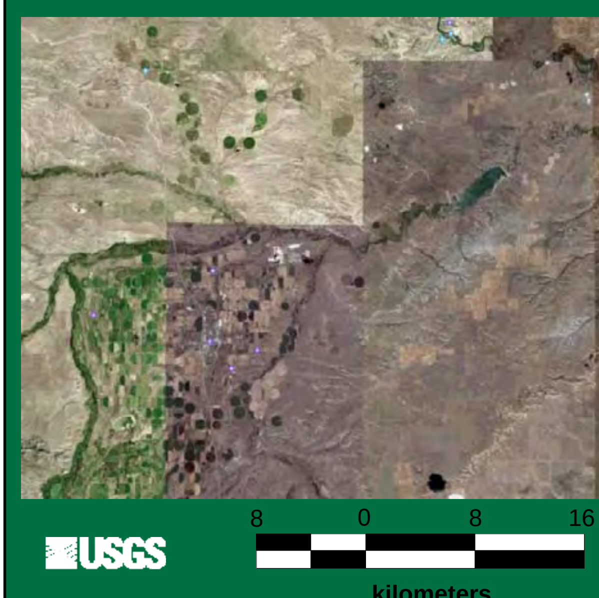
Sandstone with ten percent porosity and 4m NaCl fluid

Residual water saturation	SSV (m^3/tonne CO_2)	Power plant sequestration volumes		
		m^3	Hectare-m	Acre-ft
5%	17	$1.5x10^8$	$1.5x10^4$	$1.2x10^5$
50%	32	$2.8x10^8$	$2.8x10^4$	$2.2x10^5$
75%	58	$5.1x10^8$	$5.1x10^4$	$4.1x10^5$
100%	357	$3.1x10^9$	$3.1x10^5$	$2.5x10^6$

Mass of CO_2 emissions : $8.7x10^6$ metric tons
($9.6x10^6$ short tons)

USGS

Sequestration volume through time



Target formation:

- 100 m sandstone
- 10% porosity
- 75% residual 4m NaCl saturation

Laramie River Plant 2 & 3
Year 1 (510 hectares)
Year 10 (5,100 hectares)
Year 50 (25,500 hectares)

N

USGS

Comparison of CO_2 emissions to petroleum field class size

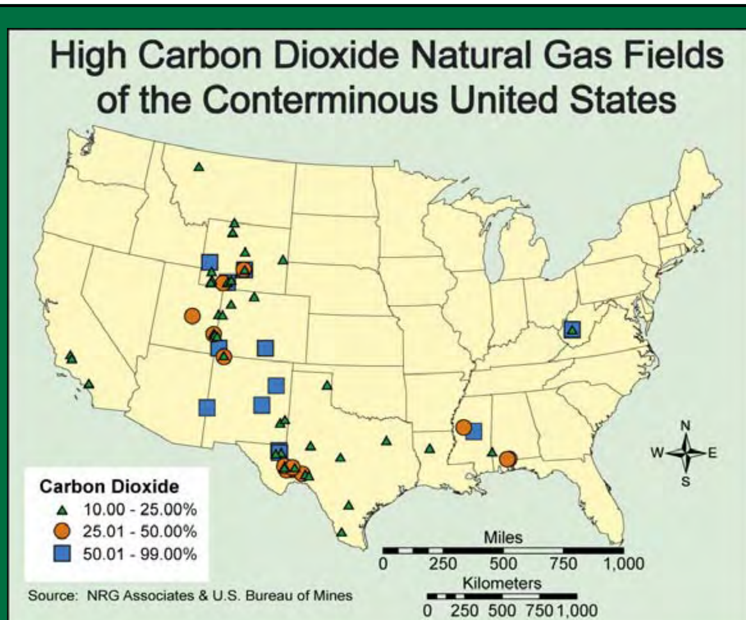
Years	Tonnes CO_2	MMBOE	Field-Size Class[a]
1	$8.70x10^6$	91	10
10	$8.70x10^7$	910	13
50	$4.35x10^8$	4550	16

169 Power plants with > 1100 MW capacity

64 power plants > $8.7x10^6$ tonnes CO_2 emissions in 1998

128 Petroleum fields with Size Classes > 13

[a] Field size classes from NRG Associates (2001)



Rationale

- Petroleum and CO_2 are buoyant fluids that behave similarly in the subsurface
- Traps that have contained petroleum on geologic time scales are ideal storage sites for CO_2
- Therefore, we need to look at petroleum fields with high CO_2 concentrations as they are natural analogs for such storage.

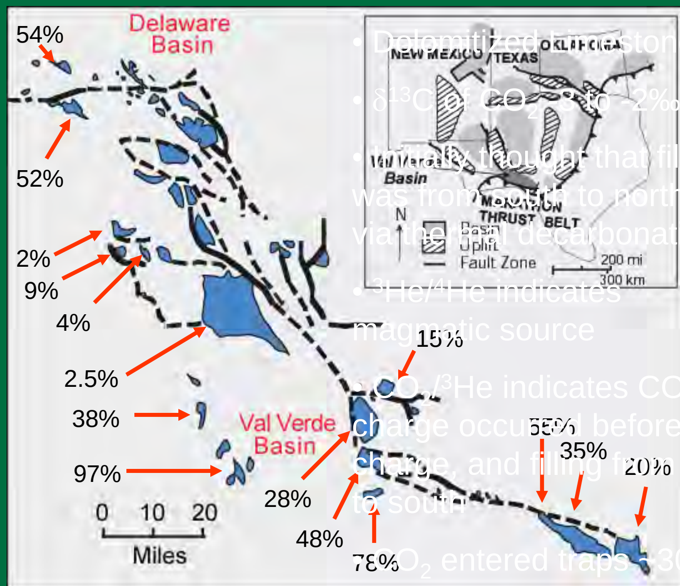
USGS

CO_2 System

- Based on Petroleum System, which ties together the source with the ultimate migration of the hydrocarbons into traps
- Therefore need to identify:
  - CO_2 Source
  - Timing of CO_2 generation
  - Migration pathways
  - Timing of migration
  - Timing of charge
  - Traps containing CO_2 with the same sources
  - Seals

USGS

Ellenburger Fields, West Texas

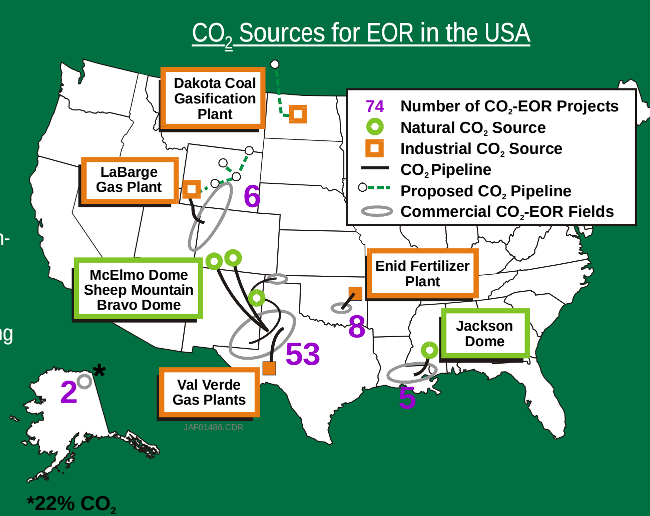


- Dolomitized Limestone
- $\delta^{13}C$ of CO_2 -3 to -2‰
- Initially thought that filling was from south to north, and via thermal decarbonation
- $^3He/^4He$ indicates magmatic source
- $CO_2/^3He$ indicates CO_2 charge occurred before CH_4 charge, and filling from north to south
- CO_2 entered traps ~300 Ma

USGS

Geologic Sequestration of CO_2 – Early "Value Added" Markets

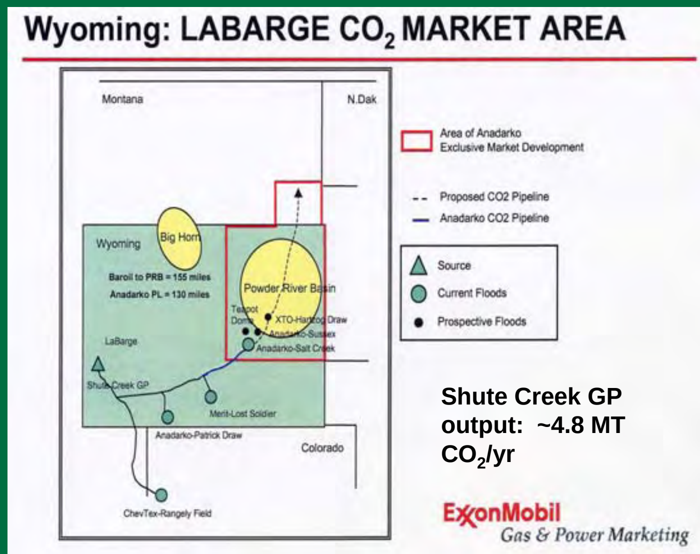
- **EOR market served mostly by natural CO_2 sources now**
  - 30 Mt/yr total, 7Mt/yr man-made
  - Average delivered price $10-12/t
  - Current cost from existing power plants $40-60/t



USGS

Modified from Thomas, 2002, IOGCC testimony
Original in ARI report for DOE

Industrial CO_2 infrastructure for EOR in CO and WY



USGS

Modified from Hargrove, 12/04, Midland CO_2 Conference

Uinta-Piceance Province and Rangely Field

USGS

Weber Sandstone Fields

KR (MMBOe)

Rangely:

1,084

Ashley Valley:

21.7

Maudlin Gulch:

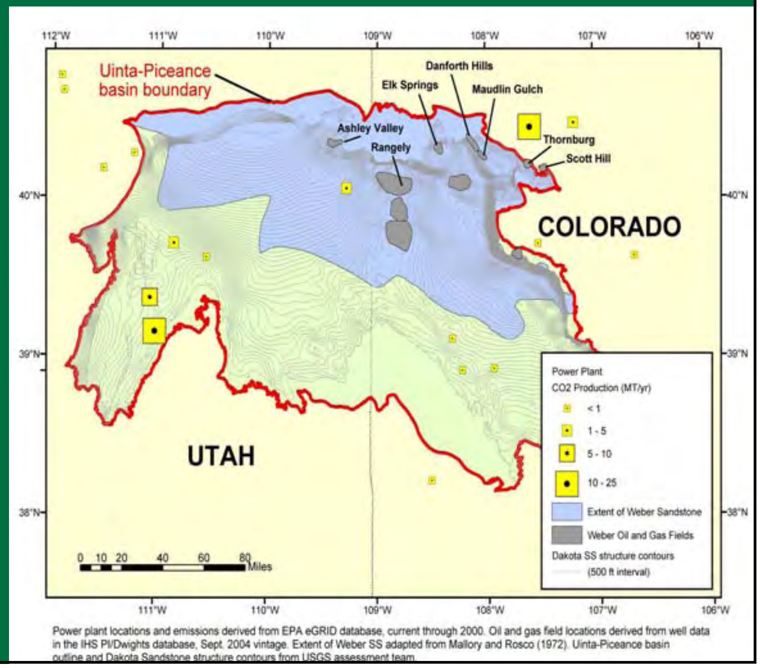
2.3

Thornburg:

1.9

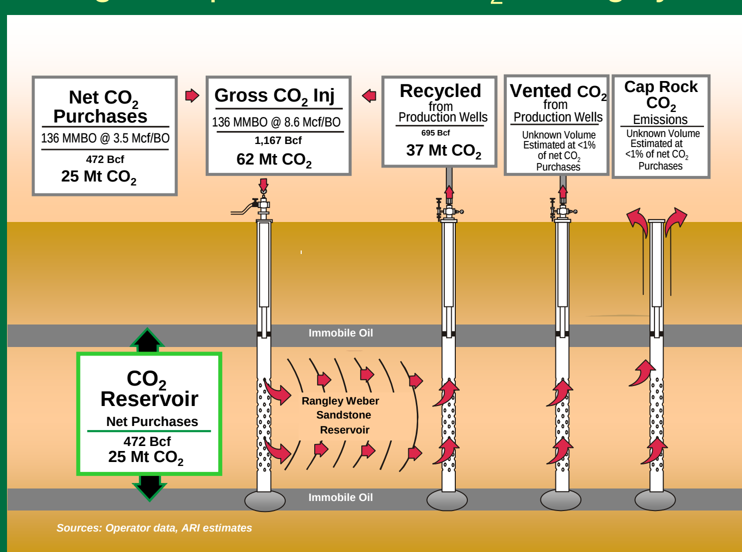
All others:

< 1



Power plant locations and emissions derived from EPA eGRID database, current through 2000. Oil and gas field locations derived from well data in the IHS PI/Dwights database, Sept. 2004 vintage. Extent of Weber SS adapted from Mallory and Rosco (1972). Uinta-Piceance basin outline and Dakota Sandstone structure contours from USGS assessment team

Geologic Sequestration of CO_2 - Rangely EOR example



Note:

Incremental oil:net CO_2 (purchased):

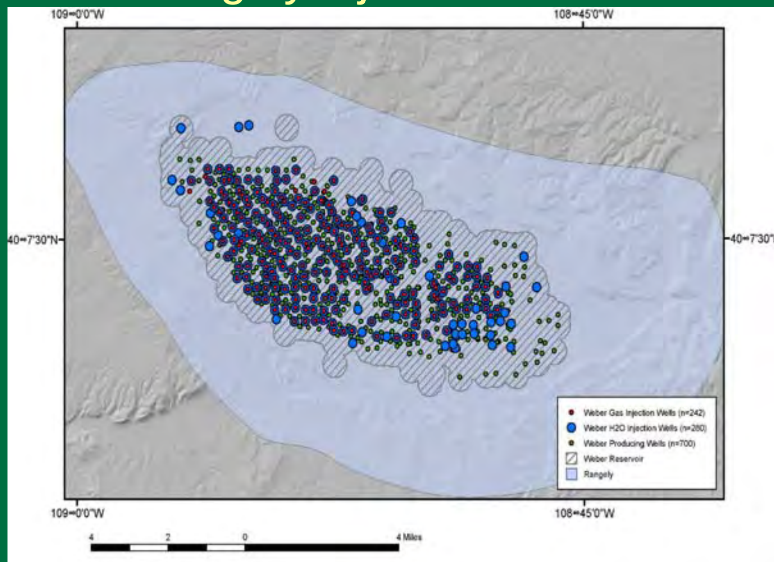
5.4 BO/ton CO_2

Incremental oil:gross CO_2 (purchased + recycled):

2.1 BO/ton CO_2

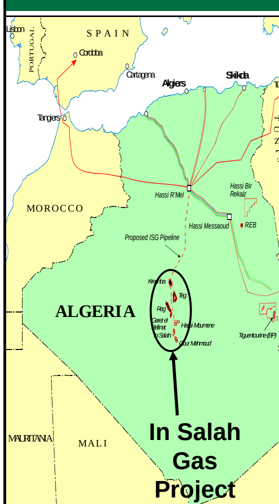
Modified from Thomas, 2002, IOGCC testimony
Original from Stevens, ARI report to DOE

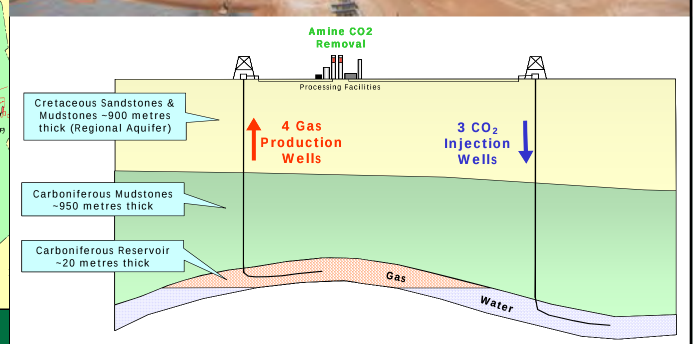
Rangely injection wells



USGS

In Salah, Algeria, BP CO_2 storage project





USGS

1 Mt/yr CO_2 separated from produced gas being injected into aquifer below gas zones.

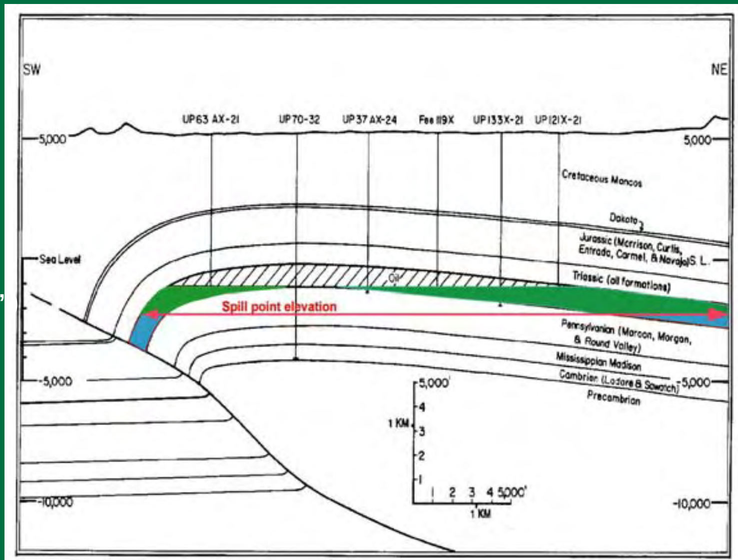
Source: Ian Wright, BP, 2005

CO_2 storage growth into saline aquifer, "fill to spill"

Mass of CO_2 to replace cum. production:
147 MT

Mass of CO_2 displacing form. water ("saline formation" to spill point:
270 MT

"Total" CO_2 storage in Rangely structure
417 MT



USGS

Conclusions

- Storage projects will be large, and will affect relatively large areas
- There are abundant natural and anthropogenic analogs for geological storage of CO_2
- Geologic and chemical evidence has shown that geologic storage can be stable over millions of years

USGS

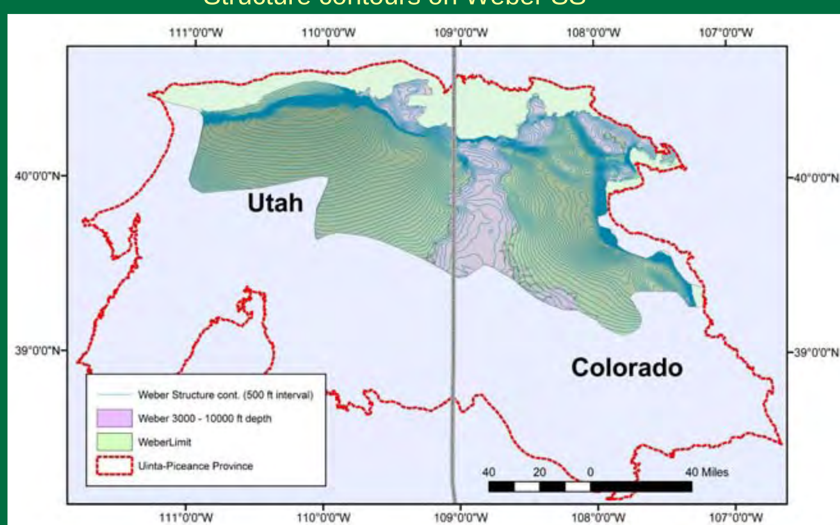
“Storage growth” linkage between oil and gas reservoirs and saline formations:

Increasing Storage volume

- CO_2 for EOR: ~ 15% of KR
- Cumulative production + reserves (“100 %” of KR or 20 - 40% of OOIP)
- Fill to spill point or seal capacity (max. CO_2 column)
- Overfill of traps and “spill” into water-leg or saline formation

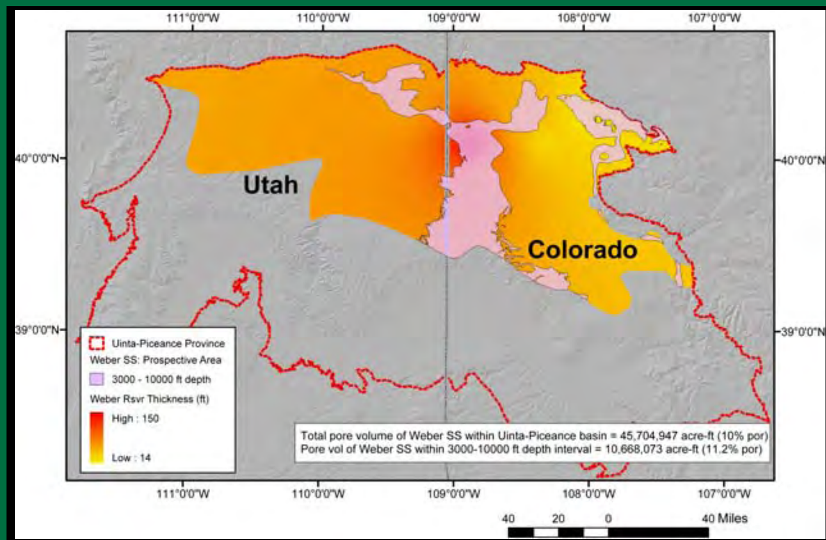
USGS

Structure contours on Weber SS

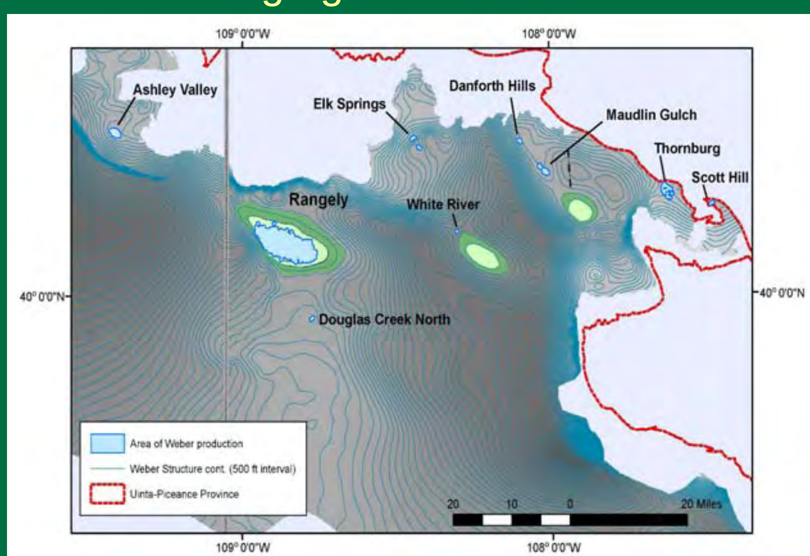


USGS

Reservoir pore volume calculation



Potential storage growth in Weber SS fields



CO_2 Storage potential in the Weber SS, Rangely Field, CO

- Ultimate recoverable oil volume: 939 MMBO (149 x 10^6 m^3)
- OOIP: ~1580 to 1800 MMBO (water saturation ~ 27 %)
- Current mass of injected CO_2: 25 MT
- Density of CO_2 at reservoir conditions (71°C, 210 b): 672 kg/m^3
- Therefore: CO_2 occupies ~ 233 MMBOe (37 x 10^6 m^3) pore space
- Furthermore: if CO_2 replaces all of the OOIP then about 125 -150 MT storage, larger volumes require “growth” into the water-leg (saline aquifer) of the Weber SS.

USGS

Perspectives from the Field

PERMITTING THE SECARB MISSISSIPPI TEST SITE

Prepared for:

EPA Geologic Sequestration Technical Workshop:
Geological Considerations and Area of Review Studies

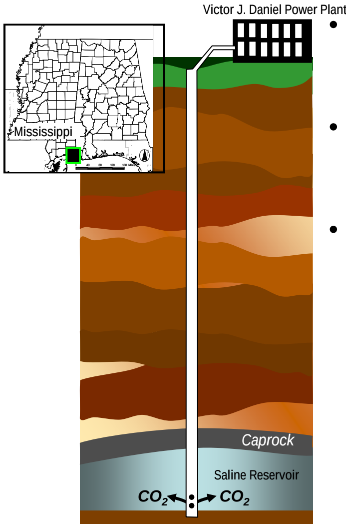
Prepared by:

George J. Koperna
Advanced Resources International, Inc.
gkoperna@adv-res.com

July 10 and 11, 2007
Grand Hyatt, Washington, DC

Introduction to the Test Site

Mississippi Saline Reservoir CO2 Injection Project

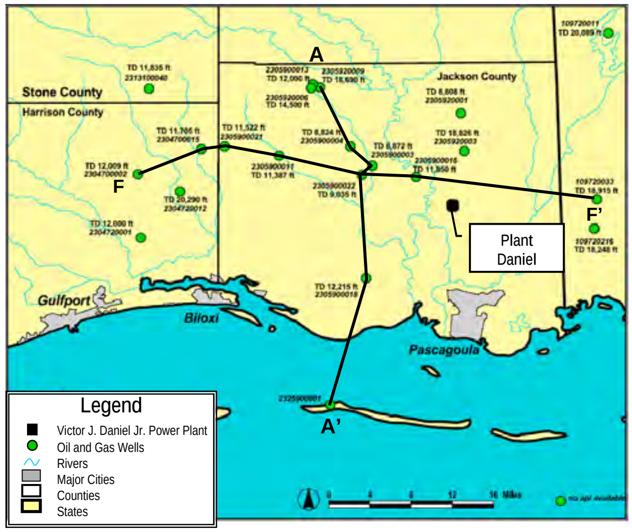


- **Purpose:** Locate and test suitable geological sequestration sites in proximity to large coal-fired power plants in Southeast U.S.
- **Initial Target:** Deep saline reservoirs along MS Gulf Coast with high potential CO2 storage capacity
- **Objectives:**
  - Build geological and reservoir maps for test site
  - Conduct reservoir simulations to estimate injectivity, storage capacity, and long-term fate of injected CO2
  - Address state/local regulatory and permitting issues
  - Foster public education and outreach
  - Drill one injection and one observation well
  - Inject 3,000 tons of CO2
  - Conduct longer-term monitoring

Regional Cross Sections

A total of 24 wells - - 20 oil & gas plus 4 Class II wells - - provided the essential deep subsurface information for the Mississippi Gulf Coast area.

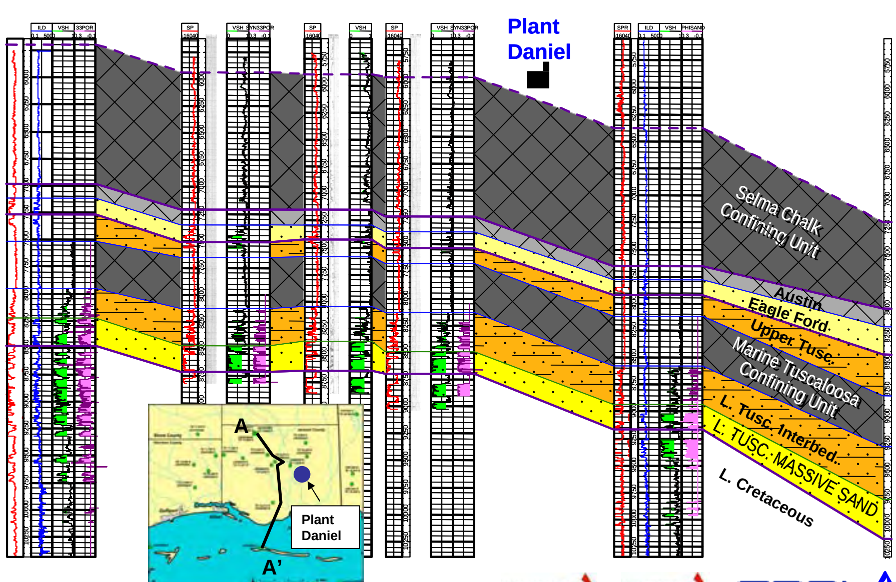
The nearest deep wells are about 5 to 10 miles away, limiting available geologic information for the plant area.



MISSISSIPPI POWER SOUTHERN COMPANY EPRI

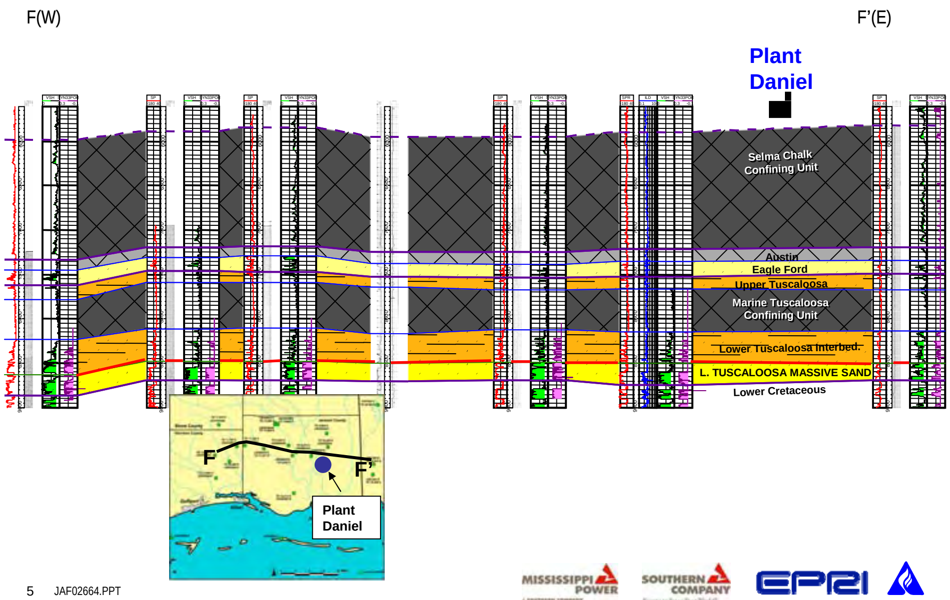
The Mississippi Test Site

North-South Geologic Cross Section



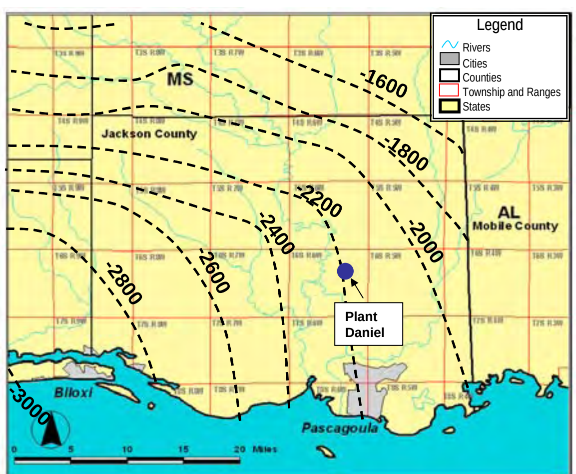
MISSISSIPPI POWER SOUTHERN COMPANY EPRI

West-East Geologic Cross Section



Southern Mississippi Hydrogeology

EPA defined "Low Salinity" waters (<10,000 mg/l) are protected and exist at a depth of about 1,600 to 2,800 feet below surface in Jackson County. The freshwater (<1,000 mg/l) zone exists in shallower formations.



(modified from USGS Open-File Report 81-550)

Permitting Efforts

- NEPA – Environmental compliance questionnaire. Submitted to US DOE prior to field activities.
- Drilling Permit – Allows penetration of the subsurface to access injection zone. Issued from MS Oil and Gas Board (MOGB).
- Underground Injection Control (UIC) Permit – Allows underground injection of CO_2. Issued by the MS Department of Environmental Quality (MDEQ).
- Financial Assurance Report – Supplied to MOGB to show financial ability of lease owner to properly abandon the test wells.

NEPA Status

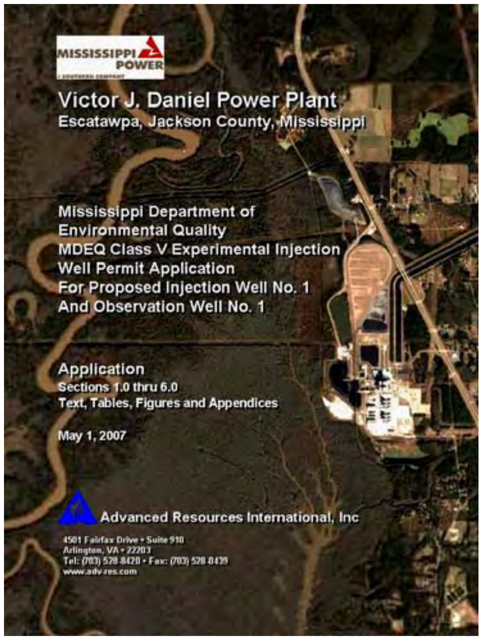
- Environmental questionnaire was prepared and submitted to US DOE on August 31,2006.
- A Categorical Exclusion for the project was granted on September 28, 2006:
  - No violation of applicable environmental safety and health requirements.
  - No adverse effects to environmentally sensitive areas.

Drilling Permit and Financial Assurance Status

- Conducted well site survey in 2006 for planned injection and observation wells.
- Plan to submit drilling permit and financial assurance for the injection and observation wells to MOGB in July or August 2007.
  - Filing subject to six month expiration date
- Well drilling activity expected to begin in September or October of 2007.
  - Approximately two month total duration to complete both wells

Public Outreach

- Press release issued early November 2006 announcing project and notifying of public meeting.
- Prior meeting held with local newspapers resulting in two newspaper articles.
- Informal open house held in Moss Point, MS on November 9, 2006.
- No formal statements made by MS Power Company during the event.
- Technical project leads manned informational posters describing the project.
- 20± attendees from local area



MDEQ UIC Process

- Initial Draft Submission in January 2007
- Final Permit Submission in May 2007
- MDEQ preparing public notice (30 days)
- Hearing to be held August 16, 2007
- Permitting timeline is 15 days following meeting

UIC Permit Application Sections

1. Administrative Information
2. Geology
3. Reservoir Modeling
4. Area of Review
5. Well Construction
   - Injection Well
   - Observation Well
6. Monitoring, Measurement, and Verification

The Mississippi Test Site

1. ADMINSTRATIVE INFORMATION

1.1 SITE BACKGROUND

1.2 GENERAL IDENTIFICATION DATA

1.3 REGULATORY CLASSIFICATION

1.4 WELL DATA – PROPOSED INJECTION WELL NO. 1

1.5 WELL DATA – PROPOSED OBSERVATION WELL NO. 1

1.6 PROPOSED PERMIT APPROVAL CONDITIONS

1.7 QUALITY ASSURANCE/ QUALITY CONTROL

Mississippi Power Company's
Victor J. Daniel Power Plant Location

13 JAF02664.PPT

The Mississippi Test Site

2. GEOLOGY

2.1 INTRODUCTION

2.2 REGIONAL GEOLOGY

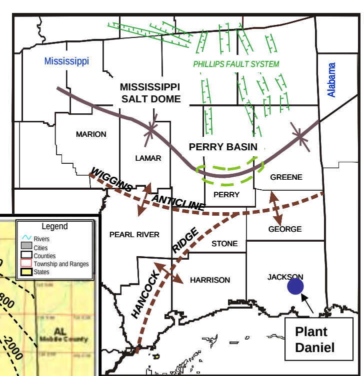
2.3 LOCAL GEOLOGY

2.4 GEOCHEMISTRY

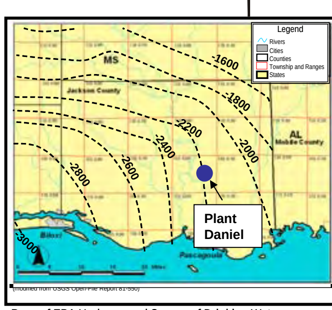
2.5 HYDROLOGY

2.6 MINERAL RESOURCES

2.7 SUMMARY



Southeastern Mississippi Subsurface Structure



Base of EPA Underground Source of Drinking Water
Protected Water (<10,000 mg/l) Below Jackson County

14 JAF02664.PPT

3. RESERVOIR MODELING

3.1 RESERVOIR MODELING OF THE INJECTION ZONE

3.2 MODEL DESCRIPTION

3.3 INJECTION ZONE STRATIGRAPHY AND LITHOLOGY

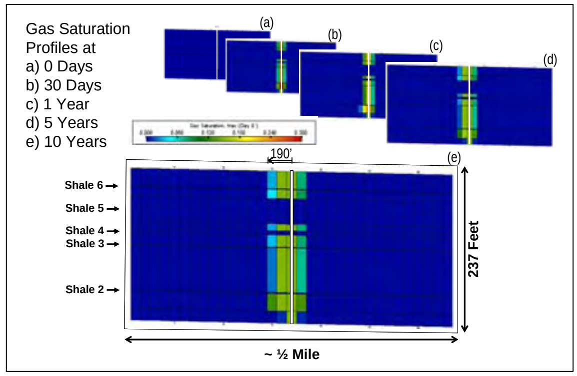
3.4 MODEL INPUTS

3.5 CO2 TRAPPING MECHANISMS

3.6 GEOPHYSICAL SIMULATION RESULTS

3.7 LONG-TERM FATE OF INJECTED CO2

3.8 MODELING SUMMARY



Reservoir Modeling CO_2 Injection/Plume (vertical view)

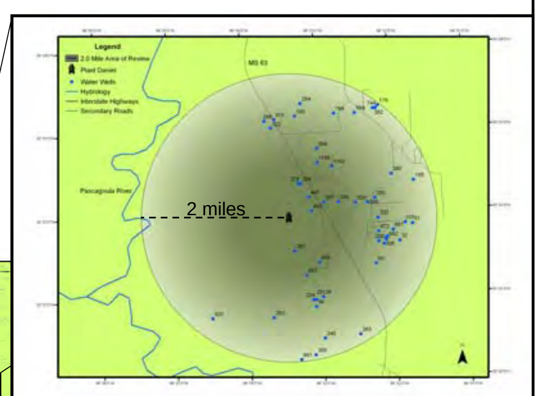
4. AREA OF REVIEW

4.1 INTRODUCTION

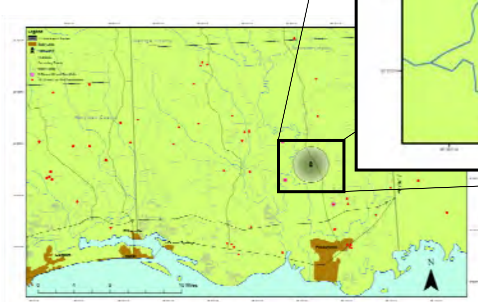
4.2 SHALLOW WATER WELLS

4.3 OIL AND GAS WELLS

4.4 SUMMARY



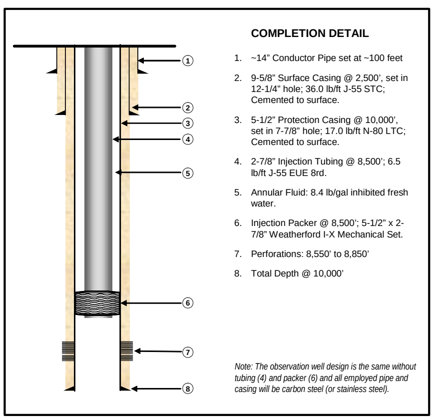
Depth and Location of Surrounding Water Wells in the Area of Review



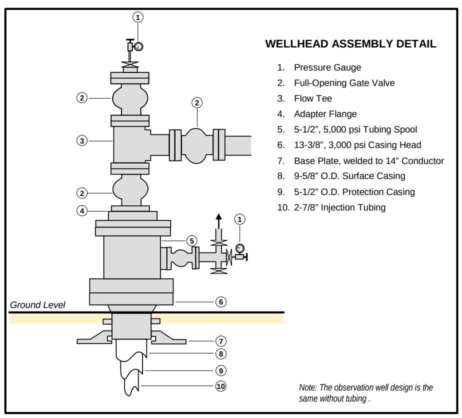
Location of Oil and Gas Wells Surrounding the Area of Review

5. WELL CONSTRUCTION

5. WELL CONSTRUCTION (Cont.)

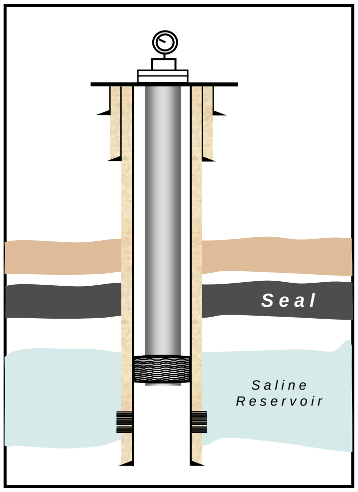


Proposed Injection No. 1 Well Completion Schematic



Proposed Injection Well No 1 Wellhead Schematic

Further Reservoir Characterization



The drilling of the observation and injection wells will allow for local data collection that will be used for geologic characterization and subsequent reservoir modeling input data.

Key Data:

- Taking core from the caprock (seal) and proposed storage formation
  - Permeability , porosity and lithology
- Wireline geophysical logging
  - Depth, thickness and porosity
- Pressure transient testing
  - Permeability and completion efficiency
- Stress testing
  - Fracture gradient and injectivity

6. MONITORING, MEASUREMENT, AND VERIFICATION

6.1 INTRODUCTION

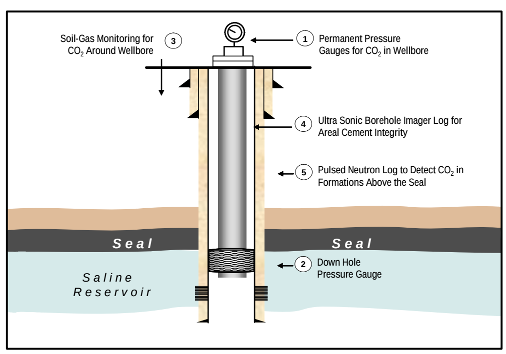
6.2 ASSURING WELL-INTEGRITY

6.3 MONITORING RESERVOIR PRESSURE

6.4 MONITORING CO2 PLUME MOVEMENT

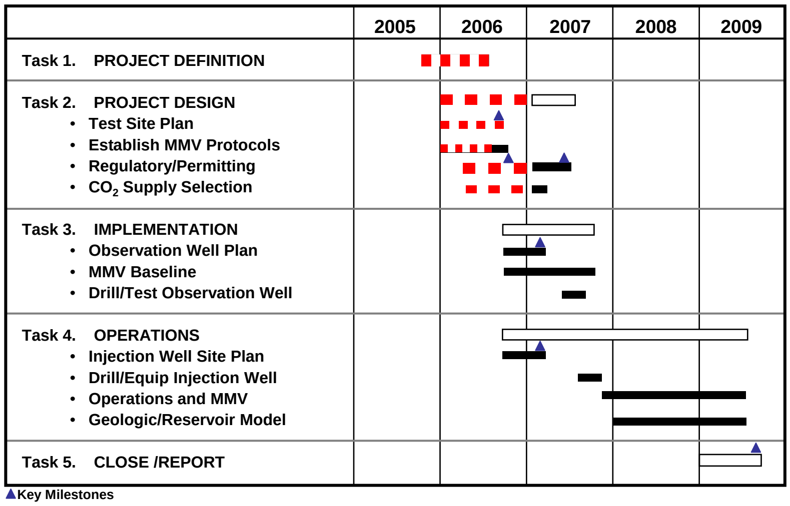
6.5 MONITOR FOR CO2 LEAKAGE

6.6 ADDITIONAL RESERVOIR CHARACTERIZATION TOOLS



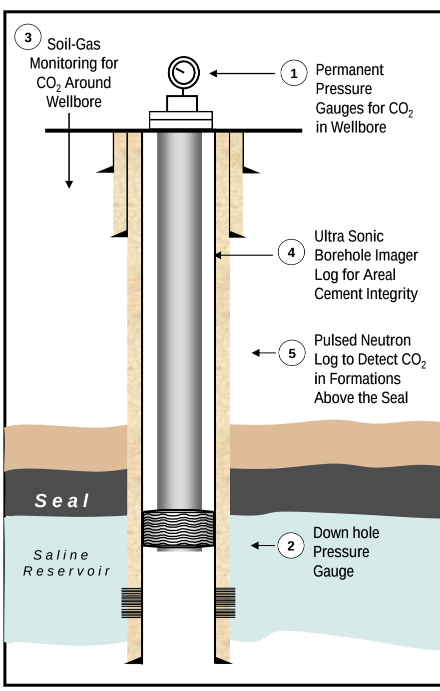
General Measurement, Monitoring, and Verification Protocols to be Employed at the Mississippi Saline Reservoir Test Site

Project Schedule



Backup

Location: Mississippi Power Company's Victor J. Daniel Power Plant



Well Integrity and Pressure Monitoring

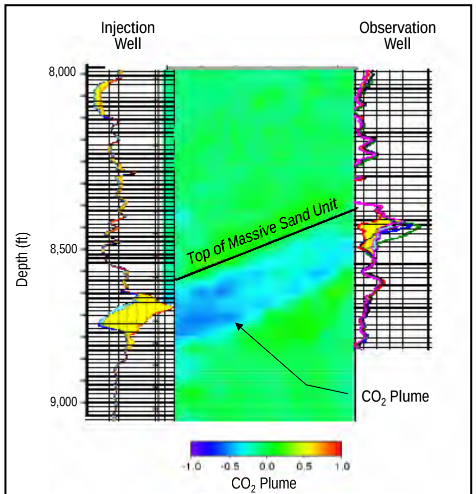
The project will include a series of MMV activities to assure well integrity:

- To assure well integrity at the surface, we will: (1) install a pressure gauge on the wellhead to measure sustained casing pressure (CO_2 leakage in the well); (2) conduct continuous monitoring of annular and down hole pressure; and, (3) conduct near-surface soil gas measurements.
- To assure downhole well integrity, we will: (4) use an Ultra Sonic Borehole Imager (advanced version of the Cement Bond Log) both after cementing and after CO_2 injection; and, (5) run a series of RST Logs to detect CO_2 above the reservoir seal.

CO_2 Plume Monitoring

To monitor the flow and storage of CO_2 in the saline reservoir, we will use well logs, seismic and other tools:

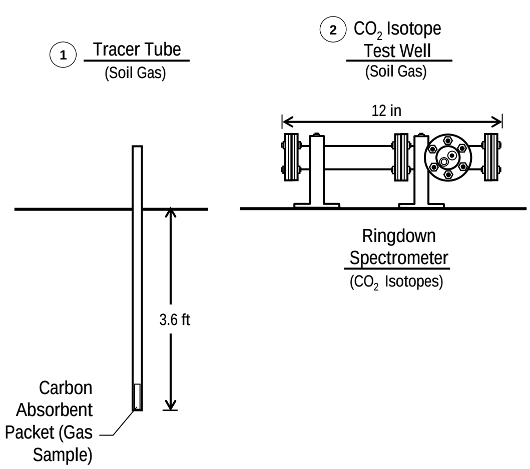
- For monitoring the areal profile of the CO_2 plume, we will use time-lapse Vertical Seismic Profiles (VSP) before CO_2 injection and about 1 month after CO_2 injection.
- For monitoring the vertical profile of the CO_2 plume, we will use: (1) a time lapse series of RST (Reservoir Saturation Tool) logs (in both wells) and (2) also use time-lapse VSP.



Yellow Area = deviation from the baseline log caused by CO_2 displacement of brine

Source: Frio Brine Test, 2004

Near-Surface Monitoring



To detect any CO_2 seepage from the well, through the seal or other leakage points, we will use near-surface monitoring to establish a baseline and to detect variations from this baseline using:

- Soil flux
- Tracer injection
- Isotopic signature
- Shallow groundwater

SECARB's Coal Seam Sequestration Projects

Nino Ripepi
Virginia Center for Coal & Energy Research / Virginia Tech

EPA Geologic Sequestration Technical Workshop: Geological Considerations and Area of Review Studies
July 11, 2007

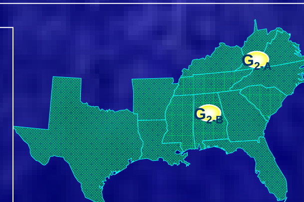
SECARB
SECARB Coal Group

SECARB Coal Group Phase II

- Project duration:
  - October 2005 – September 2009
- Support:
  - Funding from the U.S. Department of Energy
  - Industrial partners support through well donation, data, property access and direct funding

CO_2 ECBM recovery:
- Unmineable coals can provide sequestration and add economic value
- At least 1,000 MMT CO_2 of feasible capacity in the targeted areas

Two target areas:
- Central Appalachian Basin, $G_{2\text{-}A}$
- Black Warrior Basin, $G_{2\text{-}B}$
- 1,000 tons of CO2 injected on each site



SECARB Coal Group Team

- Southern States Energy Board
- Virginia Center for Coal and Energy Research – Virginia Tech
- Marshall Miller and Associates, Inc.
- Geological Survey of Alabama
- University of Alabama
- Southern Company
- Kentucky Geological Survey
- Advanced Resources International
- Eastern Coal Council

Participating Organizations

- Alpha Natural Resources
- Alawest
- AMVEST
- Buckhorn Coal
- CCP2 Project
- CDX Gas
- CONSOL,CNX Gas
- Cumberland Resources Corporation
- Dart Oil & Gas
- Denbury Resources
- Dominion E&P
- Dominion Resources
- EPRI
- Equitable Production
- Institute for Clean Energy Technology (MSU)
- GeoMet
- McJunkin Appalachian
- Norfolk Southern
- Natural Resource Partners
- Oak Ridge National Laboratory
- Penn Virginia
- Pine Mountain Oil & Gas
- Piney Land
- Pocahontas Land
- Univ. British Columbia
- Alabama OGB
- Virginia DMME

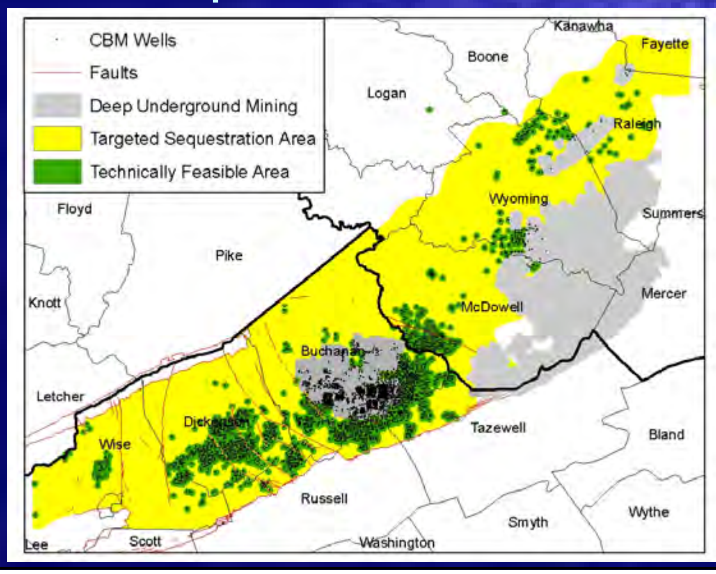
The Case for CO_2 Sequestration in Coal Seams

- Significant coal resources near major CO_2 emission sources (i.e., power plants)
- Favorable coal characteristics and depositional environments
- Potential capacity to sequester considerable amounts of CO_2
- Shallow reservoir with low P & T can reduce compression cost
- Potential of CO_2-stimulated Enhanced Coal Bed Methane (ECBM) recovery provides an economic incentive

Carbon Sequestration Characterization Parameters for Coal Seams

- Coal rank
- Gas content
- Coal depth
- Reservoir thickness
- Reservoir characteristics
- Cross-sections
- Horizontal Development
- Seam integrity
- Permeability
- Water quality
- Mining areas
- CBM development
- Infrastructure
- Land Ownership

Central App. Evaluated Sequestration Area



Central App. Sequestration Potential

Phase II Study Areas	
Storage capacity in all non-mining areas[1]	23.1 Tcf (1,341 MMt)
Storage only in developed CBM areas[2]	6.86 Tcf (398 MMt)

[1] Assumes no carbon sequestration potential in Pocahontas No. 3, No.4 and Beckley seam mining areas.

[2] Assumes sequestration feasibility is limited to established CBM development areas.

[3] WV portion of study area has 8.88 Tcf total storage capacity and 1.49 Tcf feasible storage capacity.

Central App. ECBM Potential

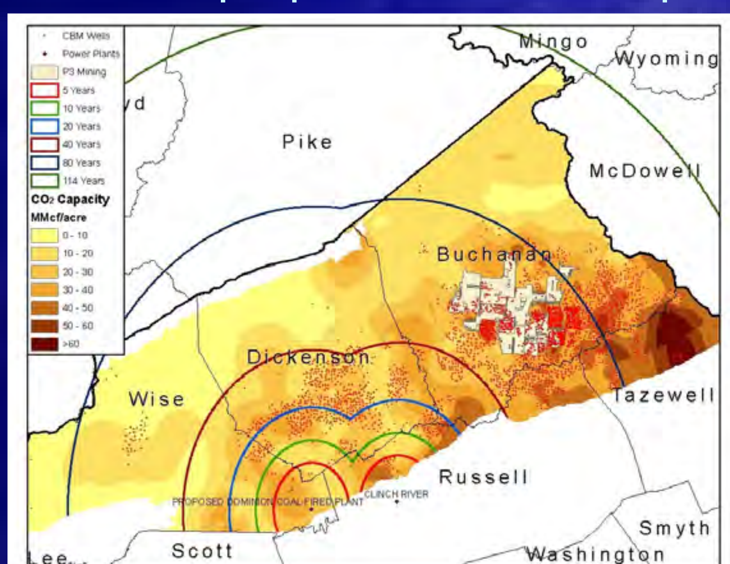
Phase II Study Areas	
ECBM potential in all non-mining areas[1]	2.49 Tcf
ECBM only in developed CBM areas[2]	0.79 Tcf

[1] Assumes no ECBM potential in Pocahontas No. 3, No.4 and Beckley seam mining areas and horizontal CBM well development areas.

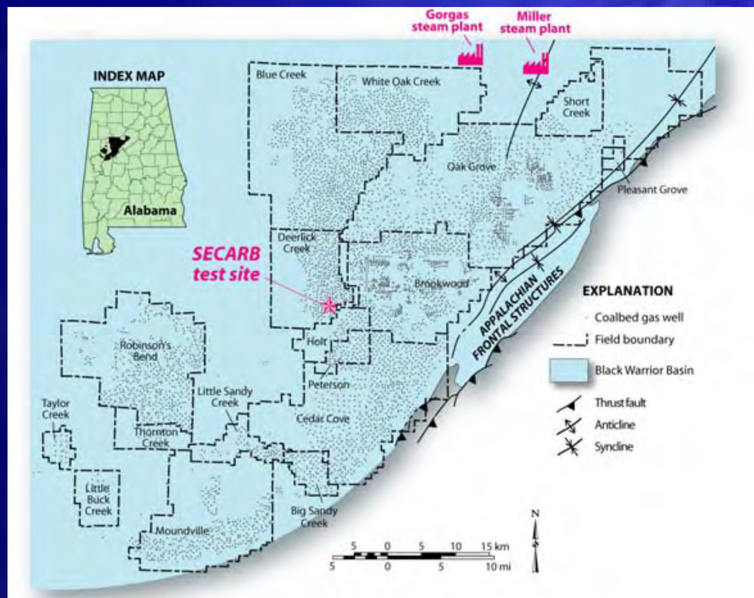
[2] Assumes ECBM feasibility is limited to established CBM development areas.

[3] WV portion of study area has 0.80 Tcf total ECBM and 0.14 Tcf feasible ECBM.

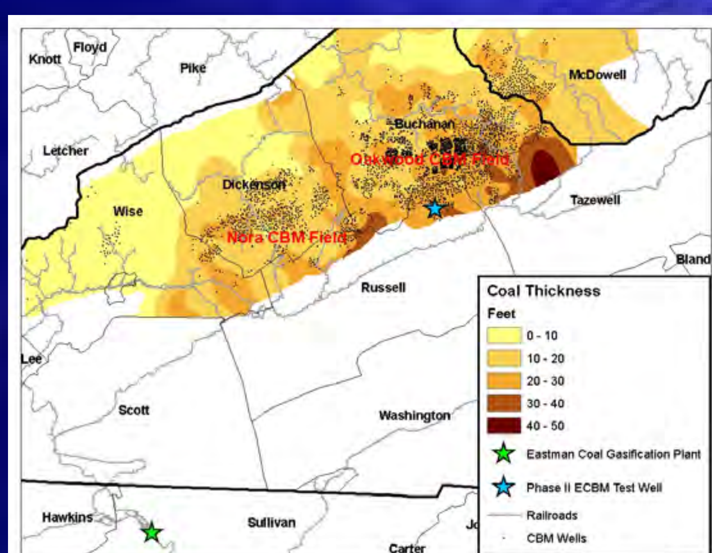
100% Carbon Sequestration from Clinch River and proposed Dominion plant



Black Warrior Basin Project Site

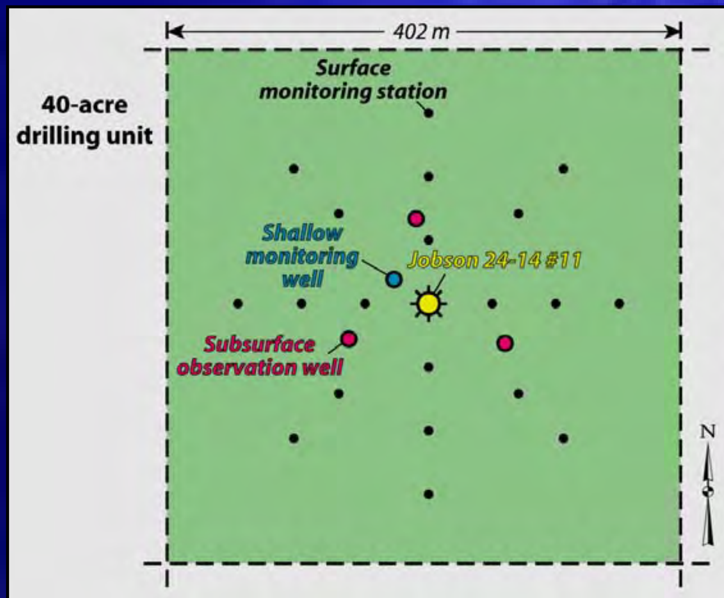


Central App. Project Site

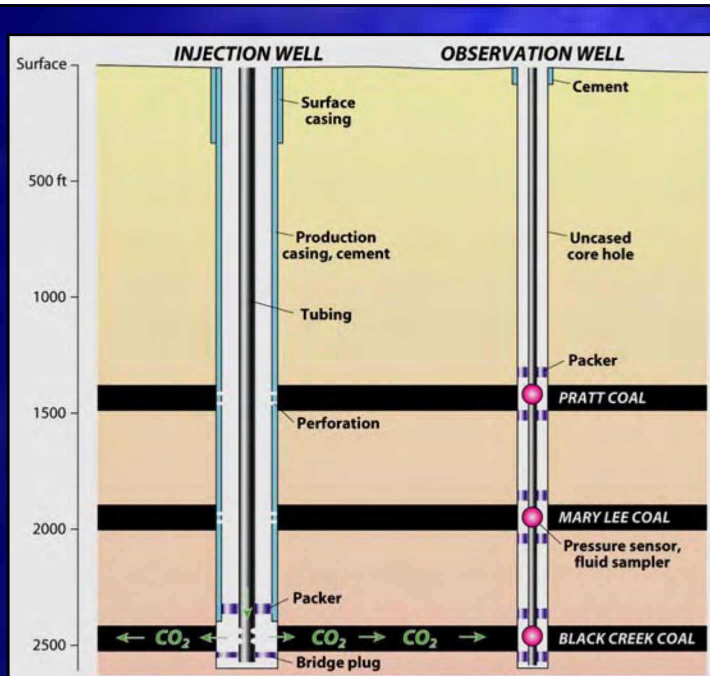


SECARB's Coal Seam Sequestration Projects

Project Site Schematic



Core Hole Testing



Test Schedule

Site selection – Completed

Monitoring – In Progress

Education & Outreach – In Progress

Permitting – In Progress

Coring – Fall 2007

Injection Testing – Begins Winter ’08

Site closure – 2009

WEST COAST REGIONAL CARBON SEQUESTRATION PARTNERSHIP
westcarb.org

WESTCARB

Field Siting Experiences 101

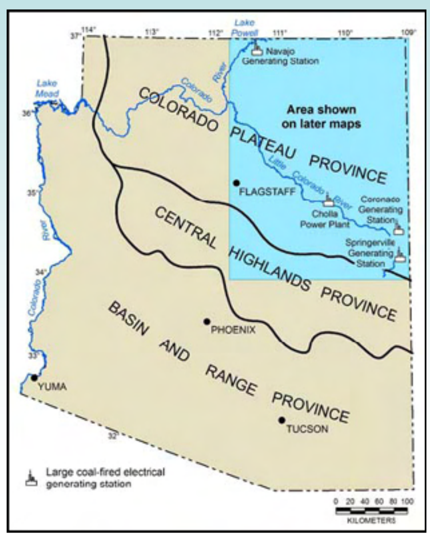
Rob Trautz[1] and Larry Myer[1,2]

[1]Lawrence Berkeley National Laboratory
Berkeley, California 94720, rctrautz@lbl.gov

[2]California Energy Commission, Sacramento, California

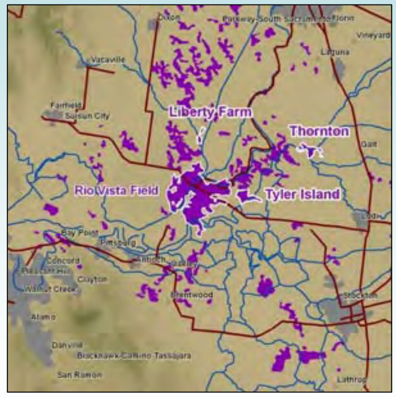
Washington, DC
July 10-11, 2007

Rosetta Resources CO2 Storage Project
Arizona Utilities CO2 Storage Pilot



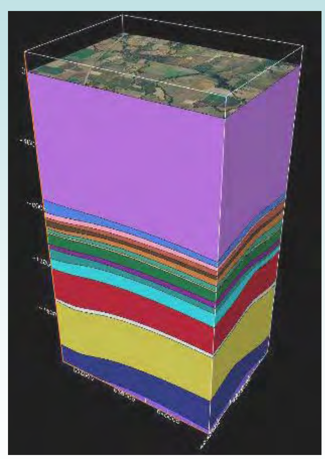
Site Selection Process

- Developed detailed site selection criteria:
  - Public Safety
  - Scientific
  - Logistics
- Prioritized and ranked criteria
- Reviewed site data
- Ranked sites based on criteria
- Selected Thornton Gas Field out of 9 sites



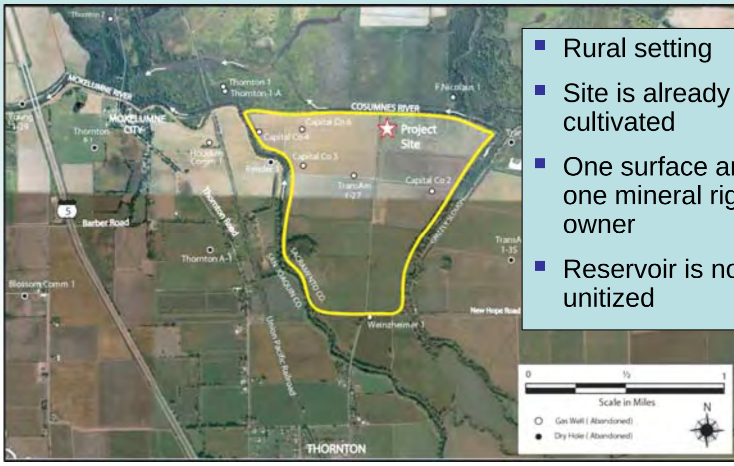
Thornton Gas Field Geologic Attributes …

- Stacked reservoir with multiple seals
- Thin depleted gas reservoir
- Well defined anticline structure
- Existing wells and field have been abandoned
- Located in the Central Valley where earthquake activity is relatively low.
- Representative of numerous gas fields in CA (1.8 Gt CO_2 capacity)



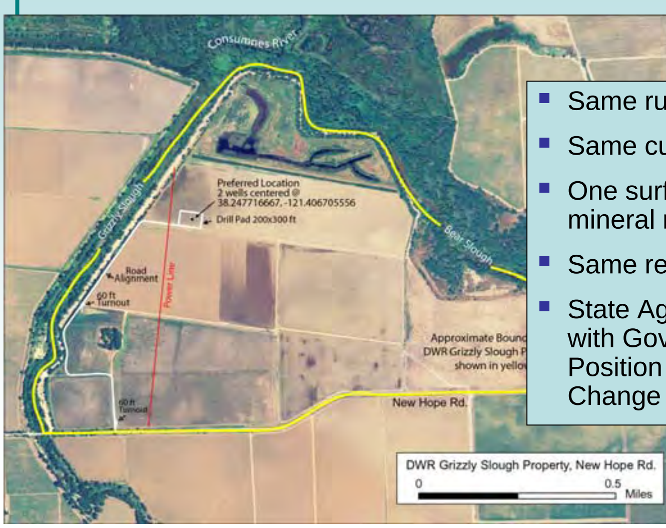
Thornton Geologic Model (courtesy Jeff Wagoner and Julio Freidmann, LLNL)

Thornton Gas Field
Site Negotiations – Private Property



- Rural setting
- Site is already cultivated
- One surface and one mineral right owner
- Reservoir is not unitized

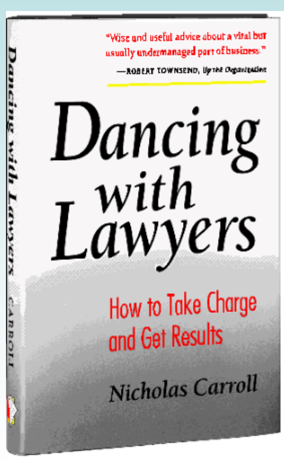
California Department of Water Resources
Grizzly Slough Property



- Same rural setting
- Same cultivation
- One surface and one mineral right owner
- Same reservoir
- State Agency aligned with Governor's Position on Climate Change

The Best-laid Plans of Mice and Men Often Go Awry

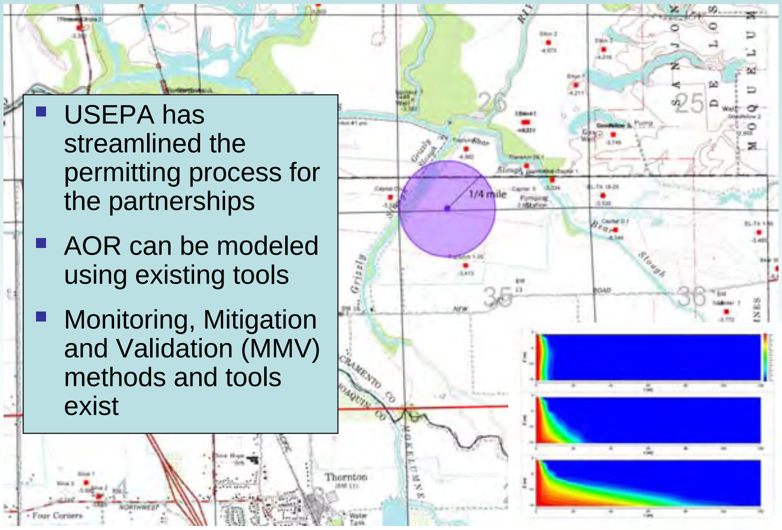
Legalese of CO_2 Sequestration



- Lease agreements
- Access agreements
- CO_2 sequestration agreements
- Indemnification
- Operational and long-term liability
- Minimizing risk

"Wise and useful advise about a vital but usually undermanaged part of business"

UIC Permitting Process
Daunting or Slam Dunk?



- USEPA has streamlined the permitting process for the partnerships
- AOR can be modeled using existing tools
- Monitoring, Mitigation and Validation (MMV) methods and tools exist

Many Issues Remain Before Deployment…

- A skeptic public
- Regulation of CO_2 is the catalyst!
- Who owns the pore space?
  - Surface owner, mineral owner or state
  - How will property owners be compensated for loss or use?
- Long-term liability and viability of owners/operators
- Long-term monitoring and land use changes
- When is an AOR an AOR?
- Flexibility is the key!