Southeast Regional Carbon Sequestration Partnership (SECARB)

Large Scale CO_2 Storage in the Lower Tuscaloosa Massive Sand Formation

NETL RCSP Annual Project Review Meeting

Pittsburgh, Pennsylvania

December 12, 2007

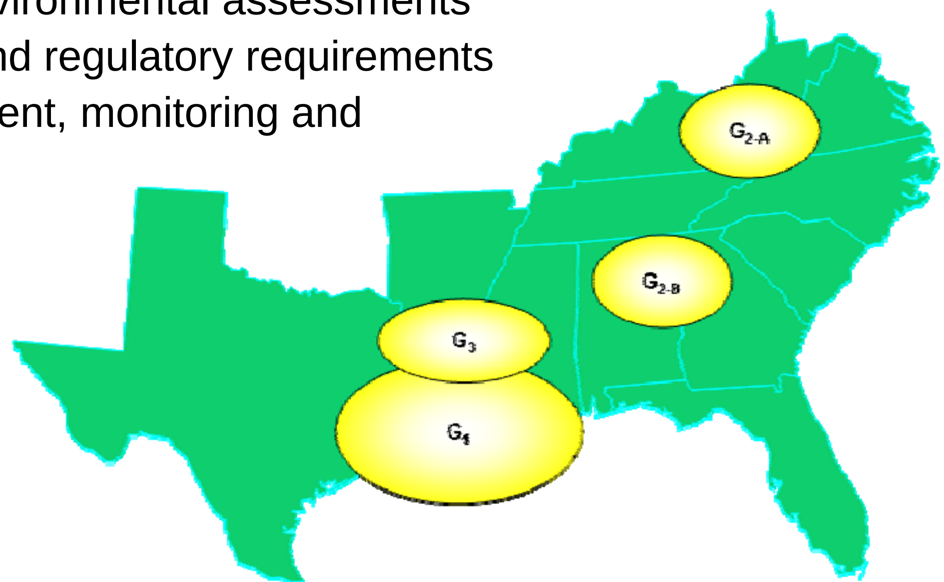
Presented by:

Gerald R. Hill, Ph.D.

SECARB Technical Coordinator

SECARB Partnership Objectives

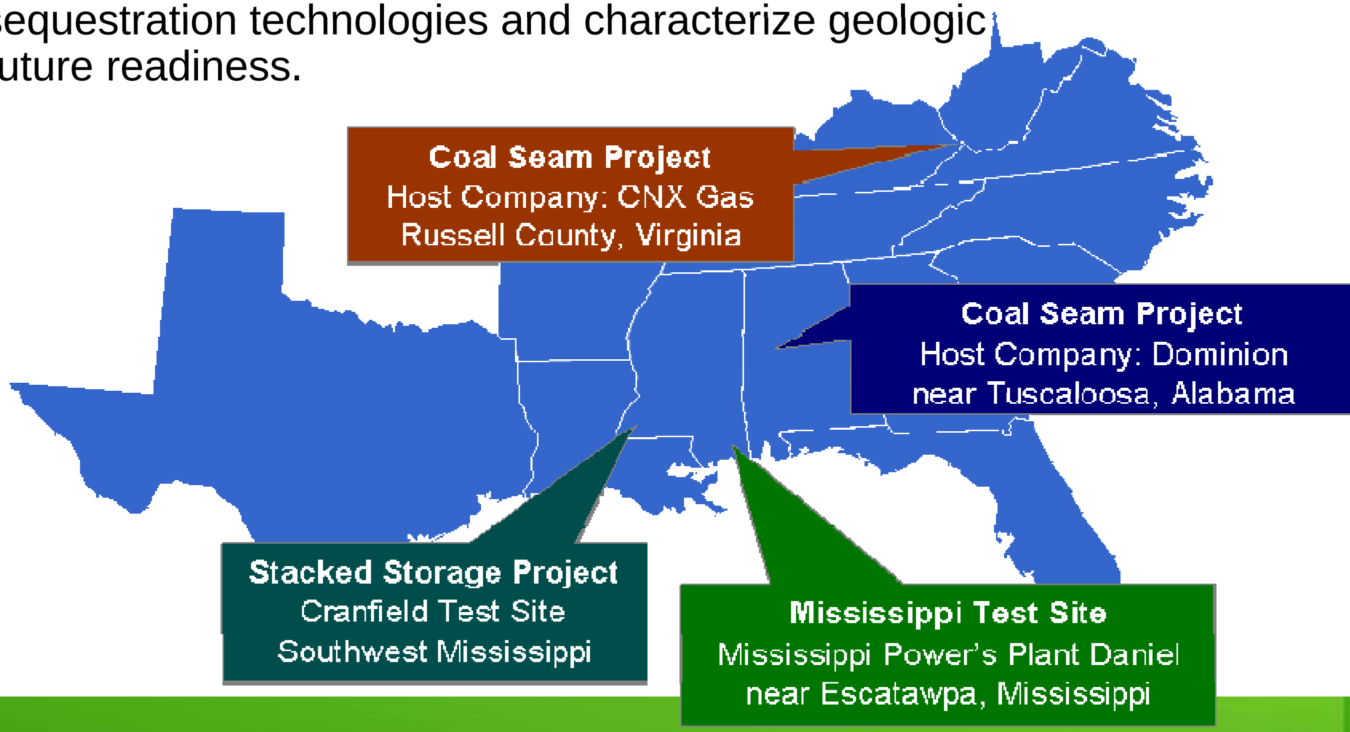
- **Phase I: Characterization**
  - Describe CO_2 sources, sinks and transport requirements
  - Develop outreach plan
  - Conduct risk and environmental assessments
  - Review permitting and regulatory requirements
  - Establish measurement, monitoring and verification protocols
  - Establish accounting frameworks (including Section 1605(b) of EPAct)
  - Identify most promising capture and sequestration opportunities
  - Develop Phase II field validation test plans



G_1	Gulf Coast Stacked Storage Sequestration Project
$G_{2\text{-}A}$ and $G_{2\text{-}B}$	Coal Seam Sequestration Project
G_3	Saline Reservoir Test Center Sequestration Project

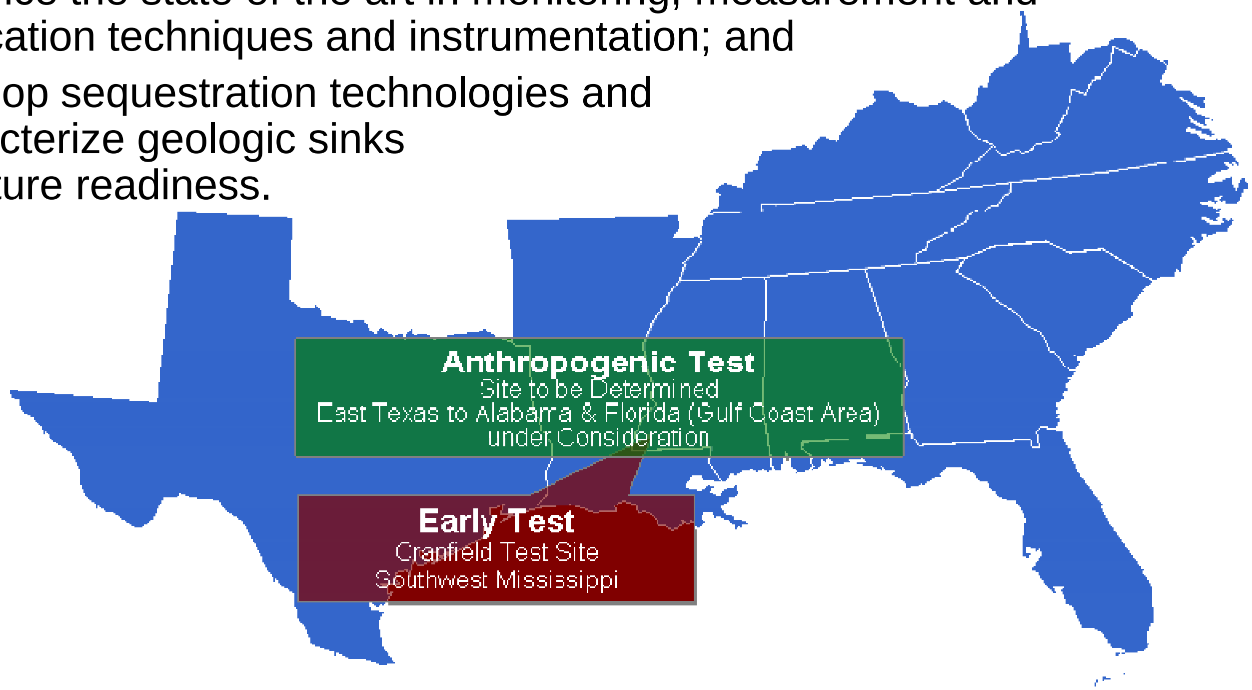
SECARB Partnership Objectives

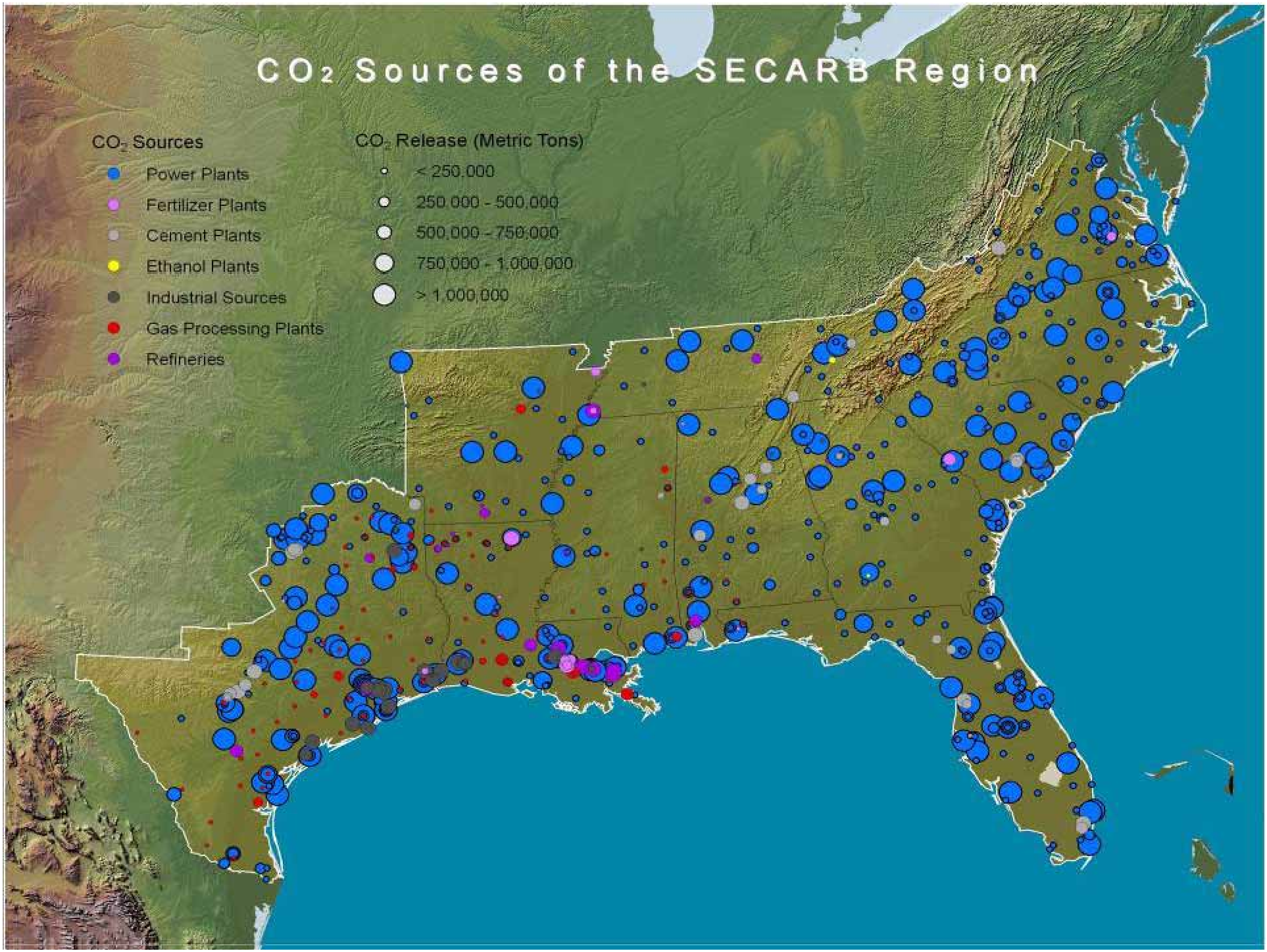
- **Phase II: Implementation**
  - Further characterize the potential carbon sequestration sinks in the Southeast;
  - Conduct three field verification studies in some of the most promising geologic formations in the region;
  - Advance the state of the art in monitoring, measurement and verification techniques and instrumentation; and
  - Develop sequestration technologies and characterize geologic sinks for future readiness.



SECARB Partnership Objectives

- **Phase III: Demonstration**
  - Characterize the potential carbon sequestration sinks in the Southeast;
  - Conduct field verification studies in the most promising geologic formations in the region;
  - Advance the state of the art in monitoring, measurement and verification techniques and instrumentation; and
  - Develop sequestration technologies and characterize geologic sinks for future readiness.




CO2 Sources of the SECARB Region
CO2 Sources
Power Plants
Fertilizer Plants
Cement Plants
Ethanol Plants
Industrial Sources
Gas Processing Plants
Refineries
CO2 Release (Metric Tons)
< 250,000
250,000 - 500,000
500,000 - 750,000
750,000 - 1,000,000
> 1,000,000

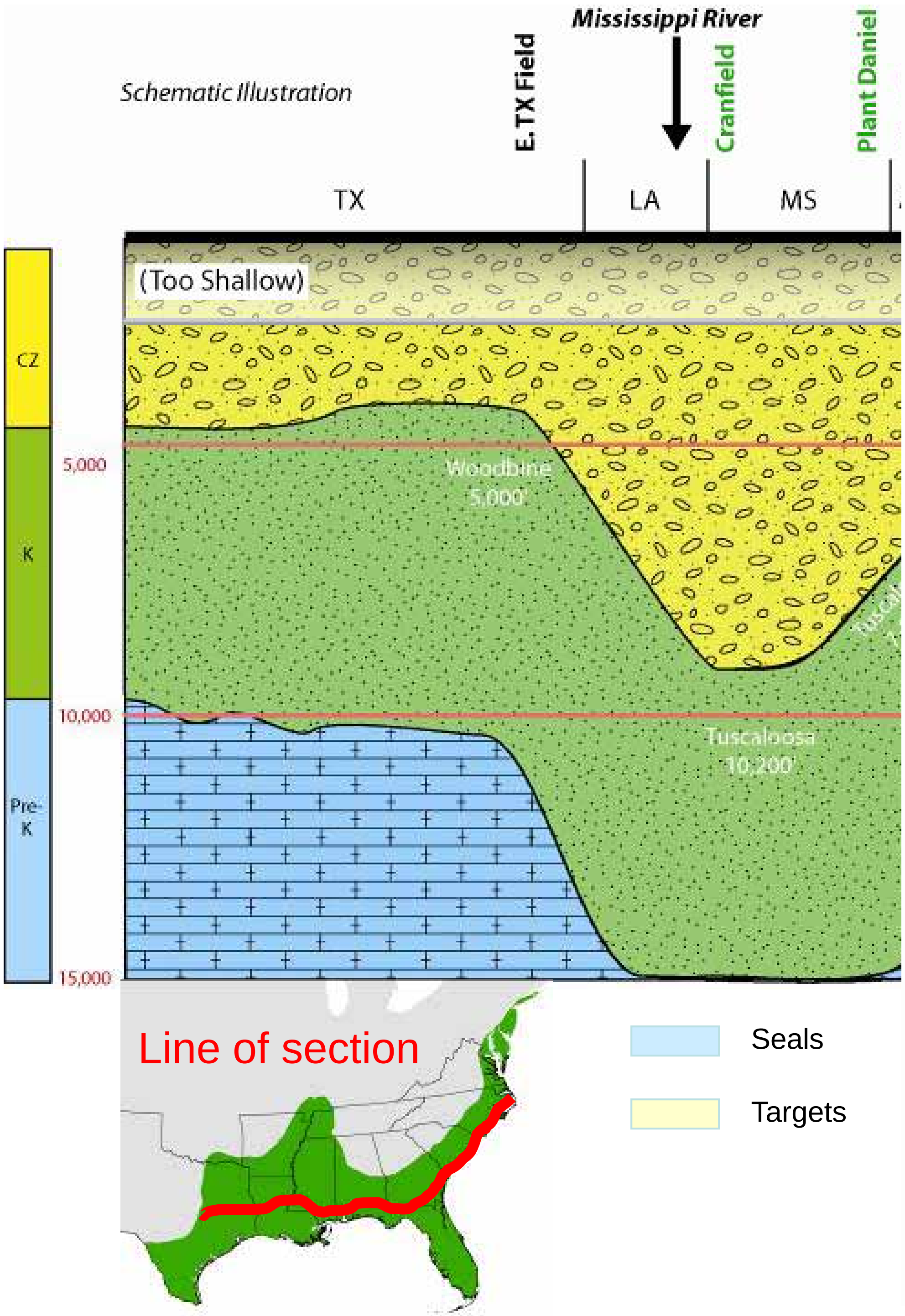
SECARB Regional and National Involvement

Regional Involvement: 100+ Participants

- Member States (Executive, Legislative and Regulatory)
- Industry and Electric Utilities
- Universities and National Laboratories
- NGOs and Trade Associations

National Involvement in RCSP Working Groups

- Storage
- MMV
- Outreach and Education
- Regulatory
- Modeling



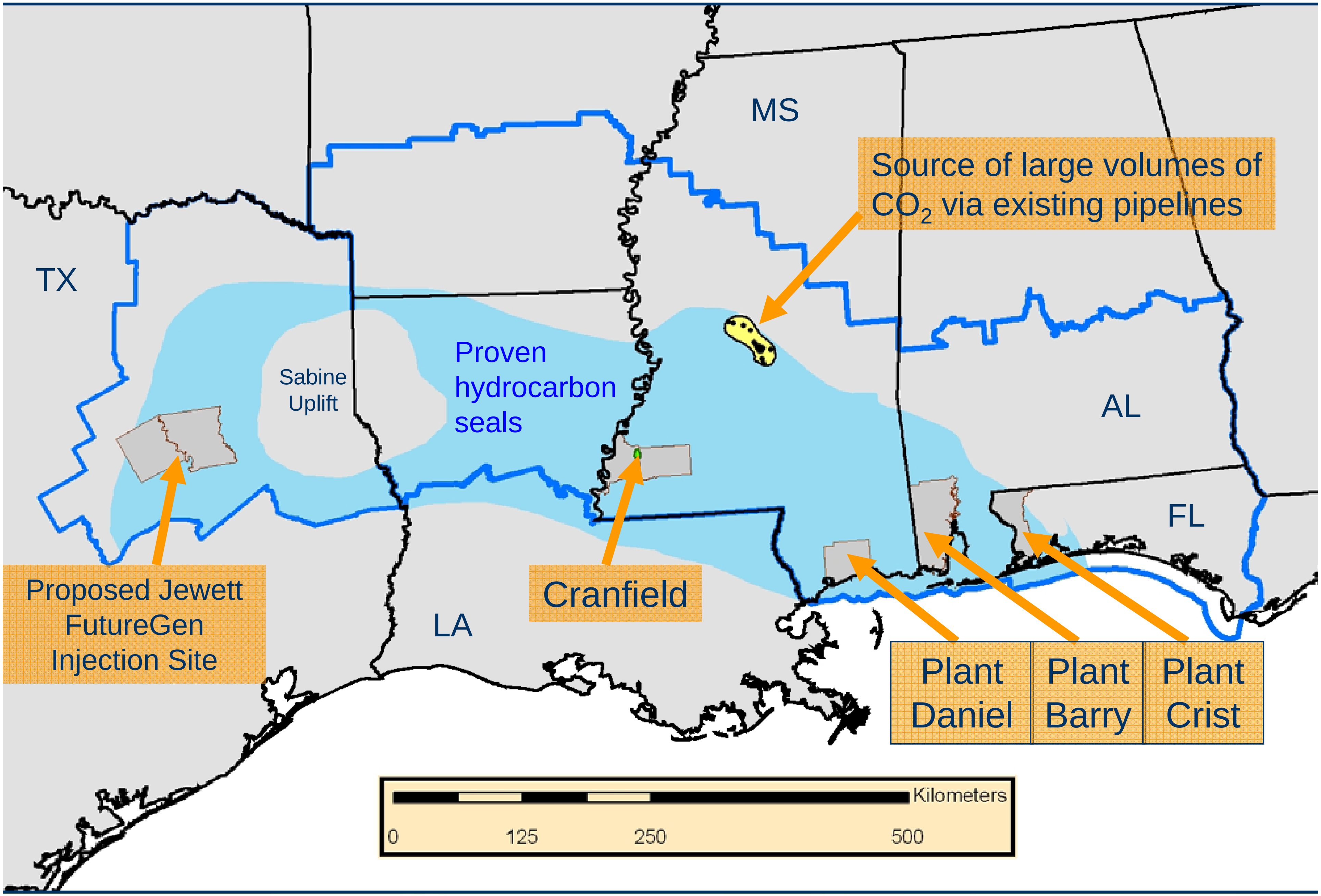
SYSTEM	SERIES	STRATIGRAPHIC UNIT: EAST TEXAS	S. ARKANSAS, N. LOUISIANA	S. MISSISSIPPI	SW ALABAMA, FLORIDA
TERTIARY	Miocene				
TERTIARY	Oligo.	Frio	Frio	Frio	Tampa
TERTIARY	Oligo.		Vicksburg	Vicksburg	Tampa
TERTIARY	Eocene		Jackson	Jackson	Jackson
TERTIARY	Eocene	Yegua			
TERTIARY	Eocene	Cook Mountain	Claiborne Group	Claiborne Group	Claiborne Group
TERTIARY	Eocene	Sparta	Claiborne Group	Claiborne Group	Claiborne Group
TERTIARY	Eocene	Queen City	Claiborne Group	Claiborne Group	Claiborne Group
TERTIARY	Eocene	Reklaw	Claiborne Group	Claiborne Group	Claiborne Group
TERTIARY	Eocene	Carrizo	Claiborne Group	Claiborne Group	Claiborne Group
TERTIARY	Paleo-cene	Wilcox Group	Wilcox Group	Wilcox Group	Wilcox Group
TERTIARY	Paleo-cene	Midway	Midway / Monroe Gas Rock	Midway / Selma Gas Rock	Midway
CRETACEOUS	Upper	Navarro	Nacatoch	Selma	Selma
CRETACEOUS	Upper	Taylor	Ozan/Annona	Selma	Selma
CRETACEOUS	Upper	Austin	Austin/Tokio	Eutaw	Eutaw
CRETACEOUS	Upper	Eagleford	Eagleford	Eagleford	Tuscaloosa Group
CRETACEOUS	Upper	Woodbine Group	Tuscaloosa Group	Tuscaloosa Group	Tuscaloosa Group
CRETACEOUS	Lower	Buda Limestone	Washita / Fredericksburg	Washita / Fredericksburg	
CRETACEOUS	Lower	Georgetown	Washita / Fredericksburg	Washita / Fredericksburg	
CRETACEOUS	Lower	Fredericksburg	Washita / Fredericksburg	Washita / Fredericksburg	
CRETACEOUS	Lower	Paluxy	Paluxy	Paluxy	Paluxy
CRETACEOUS	Lower	Glen Rose subgroup	Glen Rose subgroup	Glen Rose subgroup	Glen Rose subgroup
CRETACEOUS	Lower	James Limestone	James Limestone	James Ls.	Glen Rose subgroup
CRETACEOUS	Lower	Pettet	Sligo	Sligo	Sligo
CRETACEOUS	Lower	Travis Peak	Hosston	Hosston	Hosston
JURASSIC	Upper	Cotton Valley Gp.	Cotton Valley Gp.	Cotton Valley Gp.	Cotton Valley Gp.
JURASSIC	Upper	Gilmer Ls.	Gilmer Ls.		
JURASSIC	Upper	Haynesville	Haynesville	Haynesville	Haynesville
JURASSIC	Upper	Buckner	Buckner	Buckner	Buckner
JURASSIC	Upper	Smackover	Smackover	Smackover	Smackover
JURASSIC	Upper	Norphlet	Norphlet	Norphlet	Norphlet
JURASSIC	Middle	Louann Salt	Louann Salt	Louann Salt	Louann Salt
JURASSIC	Middle	Werner	Werner	Werner	Werner
TRIASSIC		Eagle Mills	Eagle Mills	Eagle Mills	Eagle Mills

Power Generation Capacity and CO_2 Emissions by Fuel and State (2004)

State	Gas			Oil			Coal		
	Number	Capacity (MW)	CO_2 Emissions (Mt)	Number	Capacity (MW)	CO_2 Emissions (Mt)	Number	Capacity (MW)	CO_2 Emissions (Mt)
AL	23	8,976	5.6	2	28	0.0	12	11,690	65.5
AR	15	6,132	4.1	3	202	0.0	4	4,115	28.8
FL	57	22332	32.9	26	17,827	32.8	16	13,893	71.3
GA	23	13,010	3.5	16	1,172	0.1	20	16,318	84.4
LA	47	19,377	21.4	1	8	0.0	6	5,386	31.2
MS	23	7,629	3.3	5	2,510	2.8	6	4,211	22.2
NC	6	4,960	1.3	17	2,040	0.1	29	14,806	75.3
SC	12	5,872	2.1	12	495	0.0	17	7081	34.0
TN	5	1,122	0.1	2	1,041	0.1	14	12,873	61.6
TX*	125	62,938	91.0	3	355	0.0	16	19,452	146.6
VA	14	7,849	3.9	18	1,458	0.2	23	7780	40.5
Total	350	160,197	169	105	27,135	36	163	117,604	661

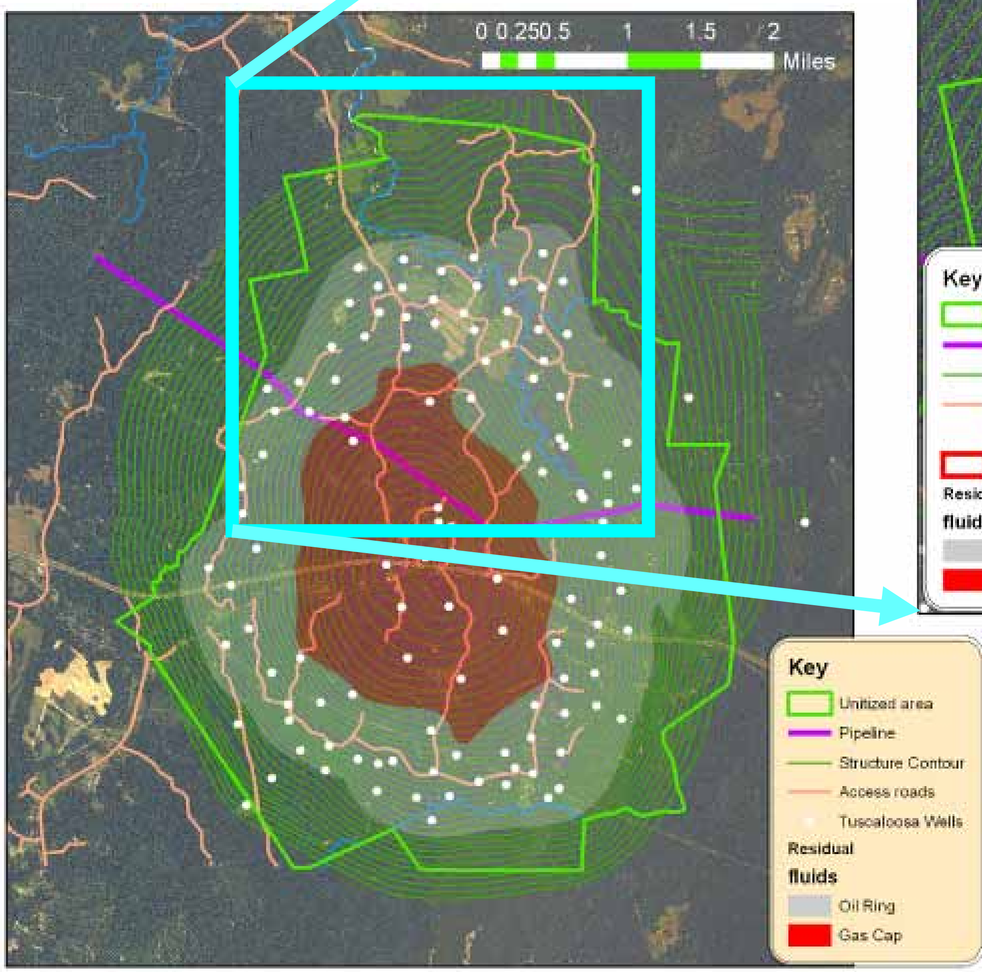
* eastern Texas

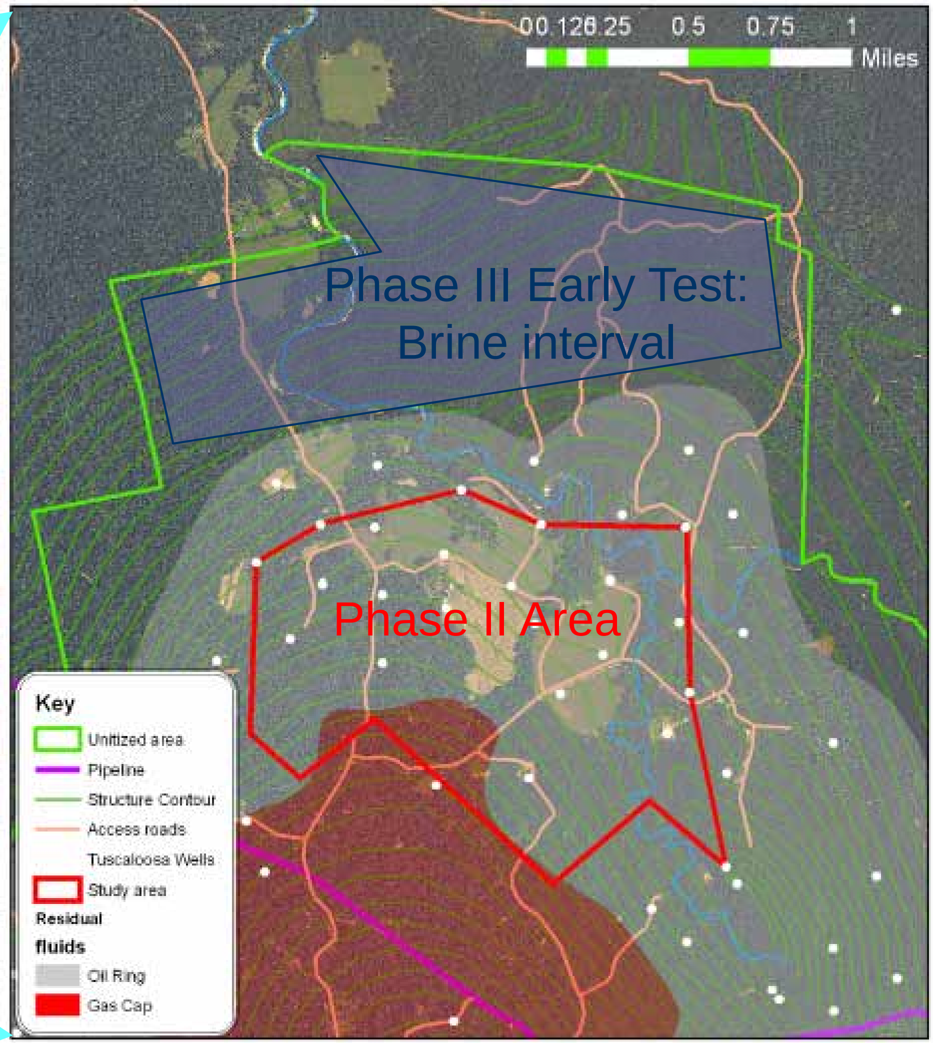
Geographic Focus of SECARB Phase III Program



Site Selection for SECARB Phase III Early Test

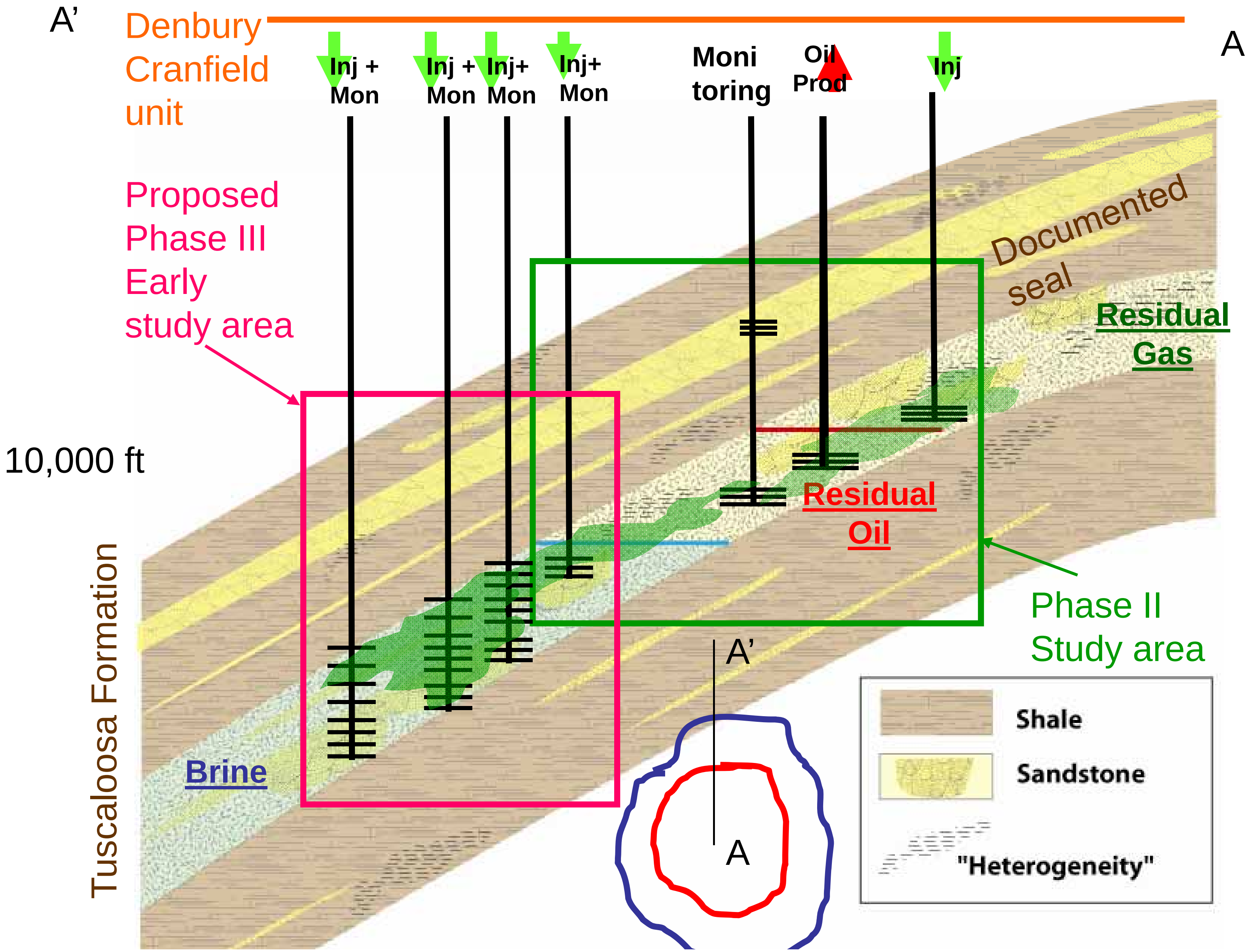
- Large volumes of low-cost CO_2 available 2008
  - Denbury Sonat pipeline
- Well-known geologic environment in saline aquifer
  - injectivity and seal are demonstrated
  - 3-D seismic available
- Mineral and surface rights available in short time
  - Minerals rights owned by Denbury
  - Surface ownership well known and owners likely to welcome monitoring for standard use fee
- Permitting streamlined
  - EQ similar to Phase II EQ





The area selected for the Phase III Early Test is immediately north of the SECARB Phase II “Stacked Storage” study underway, within unitized field.

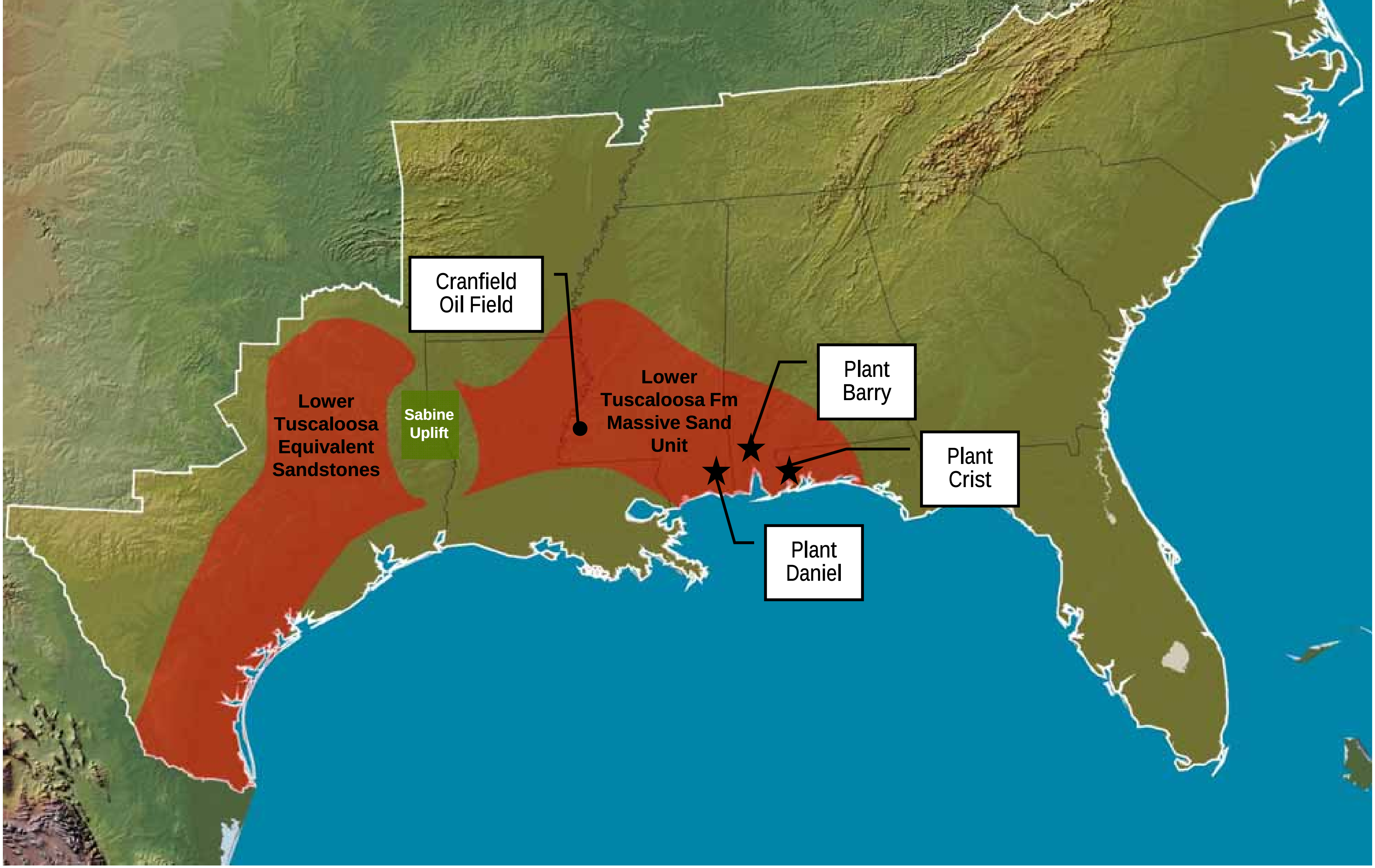
Cranfield Program Overview



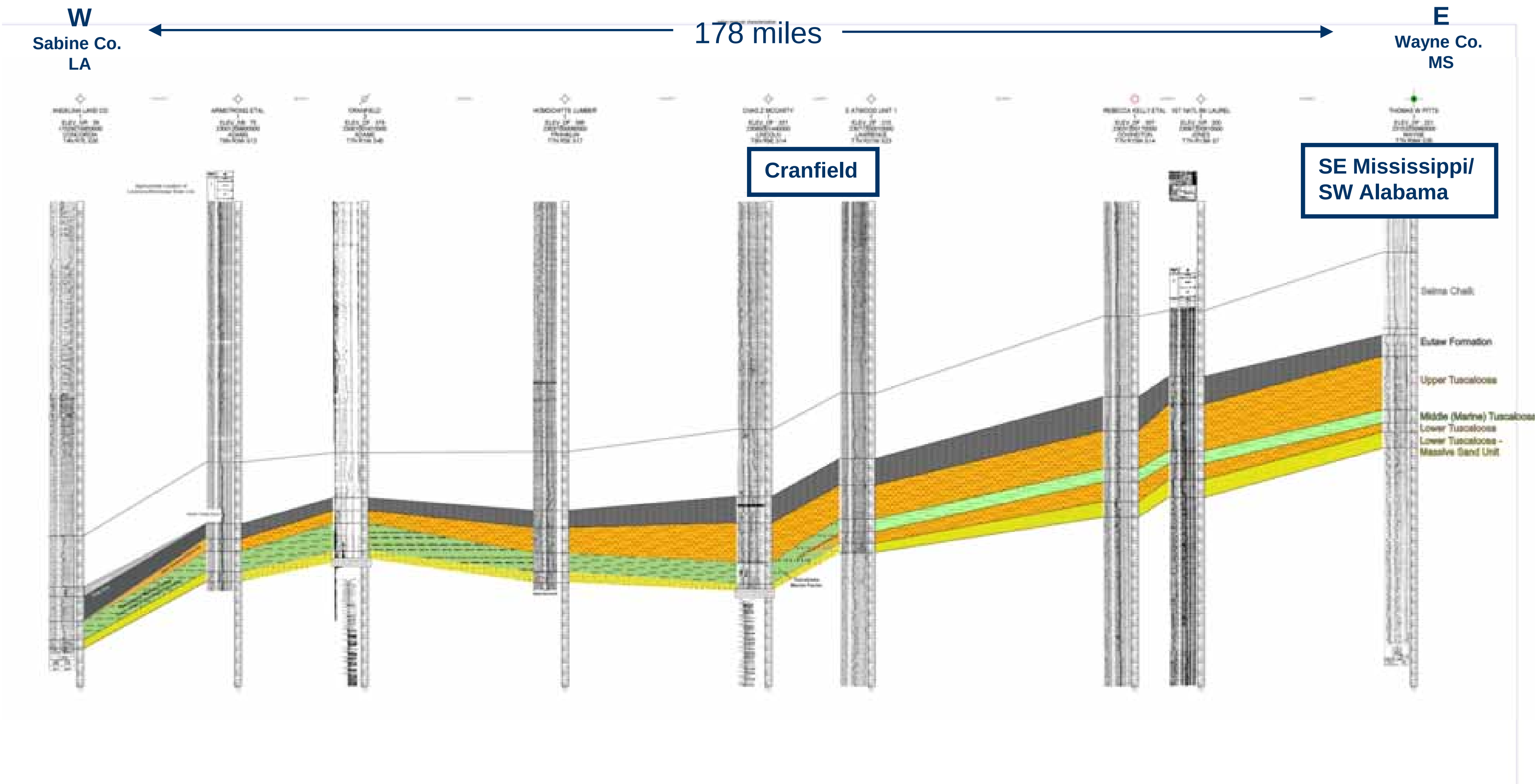
SECARB Phase III Anthropogenic Test

- **Unique opportunity to demonstrate storage and MMV at a coal coal-fired power plant**
  - Seek to transfer lessons learned from Cranfield test and apply lessons learned at a power plant site
  - Will help determine appropriate MMV techniques and protocols as they apply to a power plant site (what works/what doesn't)
  - Defines business and legal issues that make a power plant site unique, i.e., demonstration in light of electrical reliability and cost of commercialization
- **Appropriately planned and implemented MMV is the pathway to public acceptance. This is a high priority for SECARB at a coal-fired power plant as it will:**
  - Assure operator & public safety (often the same)
  - Support regulatory and institutional framework and public outreach
  - Support long-term management, liability, and compliance considerations
  - Help address siting criteria for future CCS coal-fired power plants
  - Support utility owner's engineer understanding

The Lower Tuscaloosa Massive Sand Unit and Equivalent Sandstones

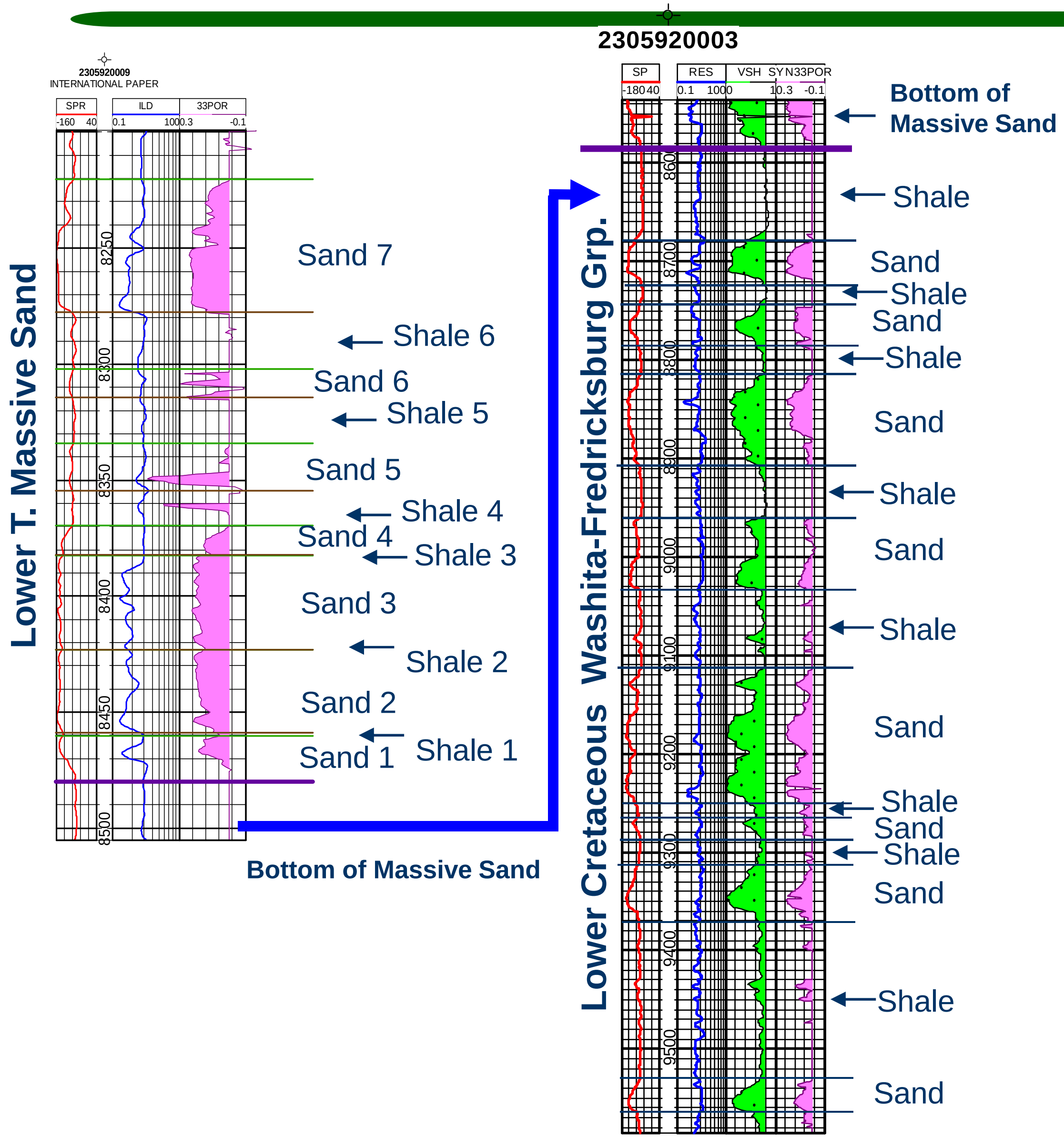


Regional Cross Section D-D'
W-E Structural Cross-Section from Sabine Co., LA, to Wayne Col, MS



Identifying Flow Units and Shale Baffles

Tuscaloosa (Massive Sand Unit) and Lower Cretaceous Sands



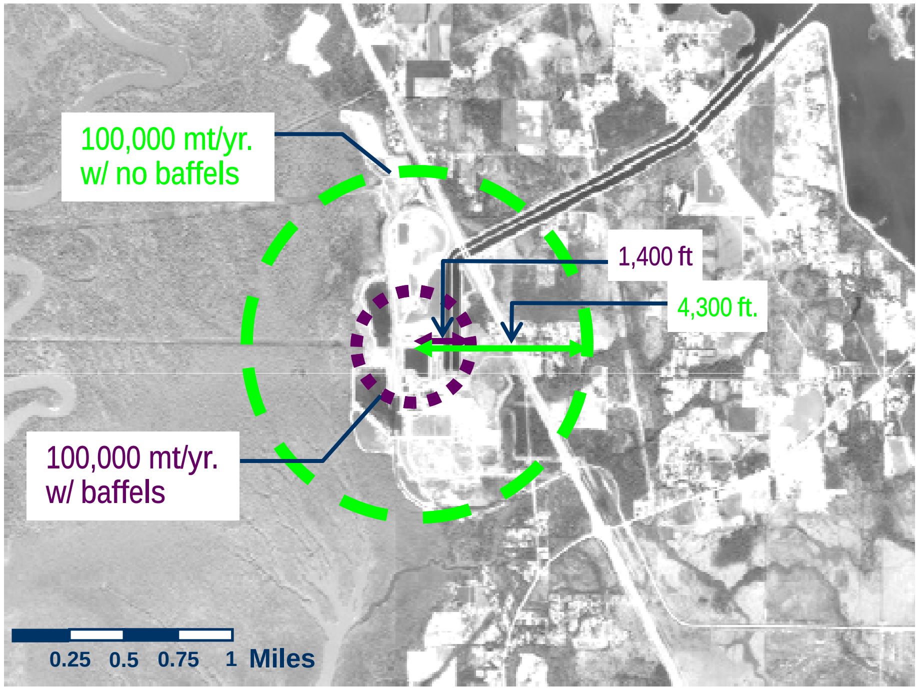
We plan on using logs and core to define the internal architecture of the CO_2 storage formations at the field test sites:

- Type log for the Lower Tuscaloosa Massive Sand Unit and Lower Cretaceous Dantzler Fm. in S. Mississippi.
- Characterization of the type log shows multiple flow units and shale breaks over a 1,300 ft interval.

Optimizing and Concentrating CO_2 Storage

Extent of the CO_2 Plume

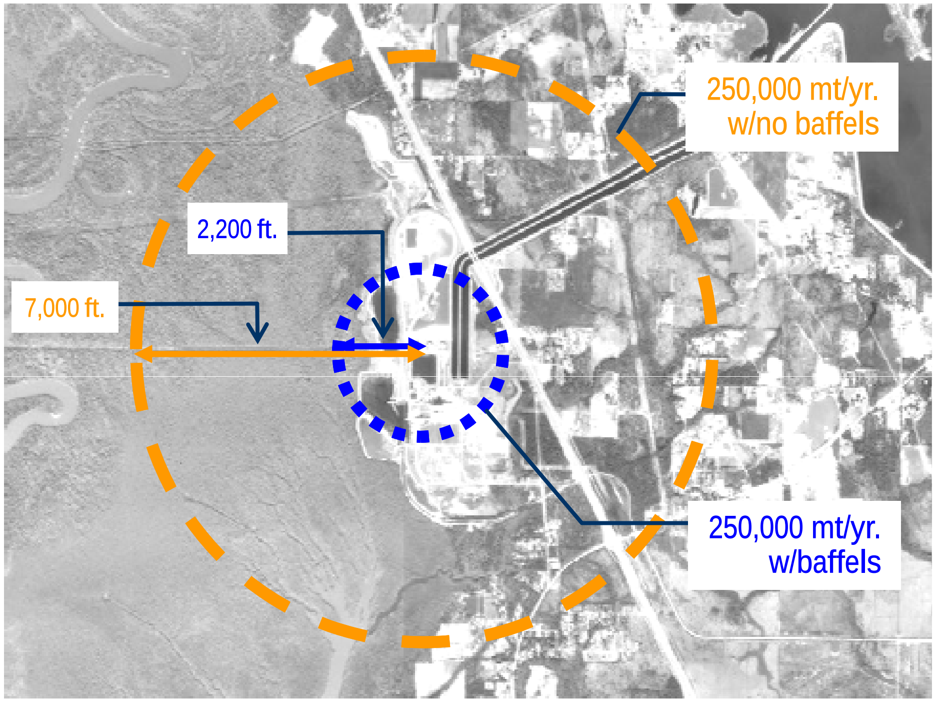
(4 years of CO_2 injection @ 100,000 mt/yr; 10 years of time)



Extensive use of reservoir architecture increases CO_2 storage by nearly 10 fold.

Extent of the CO_2 Plume

(4 years of CO_2 injection @ 250,000 mt/yr; 10 years of time)



Extensive use of reservoir architecture reduces the areal extent of the CO_2 plume by 90%.

SECARB Phase III MMV Goals

Brian Strazisar – NETL (Isotopes)

- Demonstrate that geologic storage of CO_2 is environmentally safe with public acceptance of science-based monitoring protocols
- Demonstrate protocols capable of surveying large areas and identifying seepage over project life cycle
- Understand the relationship between site characterization, storage mechanisms, and leakage
- Validate and calibrate model predictions and monitoring tools for fate and transport
- Transfer knowledge and technologies:
  - lessons learned from Phase II to Phase III
  - unique opportunity to deploy MMV at a coal-fired power plant

Glen Thompson – Praxair Tracer Research Division (PFTs)

Adam Dayan – University of Alabama (Soil Flux)

Update on SECARB Modeling Activities at Cranfield, MS

Jean-Philippe Nicot, Jong-Won Choi, K.-Won Chang, Tip Meckel, Ramon Trevino, and Susan Hovorka

Gulf Coast Carbon Center
Bureau of Economic Geology
Jackson School of Geosciences
The University of Texas at Austin

presented by JP Nicot

RCSP Simulation and Risk Assessment Working Group Meeting

Pittsburgh, PA - October 8, 2008

Phase II SECARB Test Sites

Bureau of Economic Geology

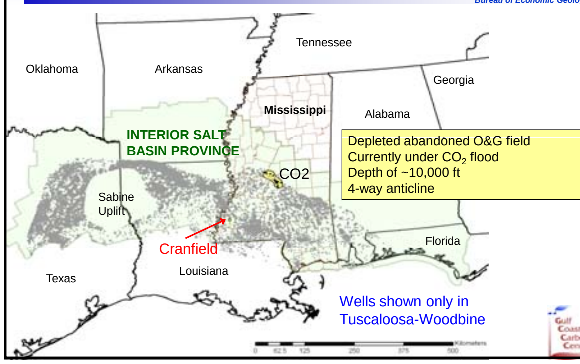
2

Denbury specializes in CO_2 Floods

Bureau of Economic Geology

Gulf Coast Stacked Storage Project Test Site: Cranfield, MS – Phase II and Phase III

Bureau of Economic Geology



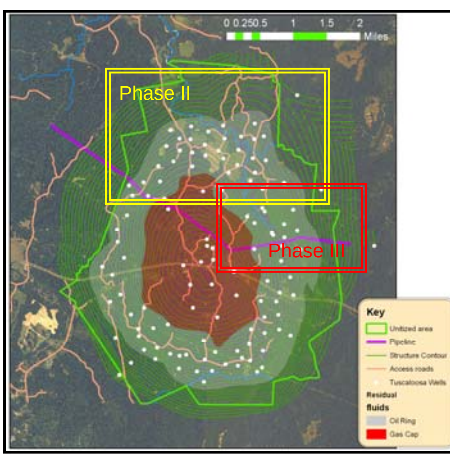
Modeling Overview

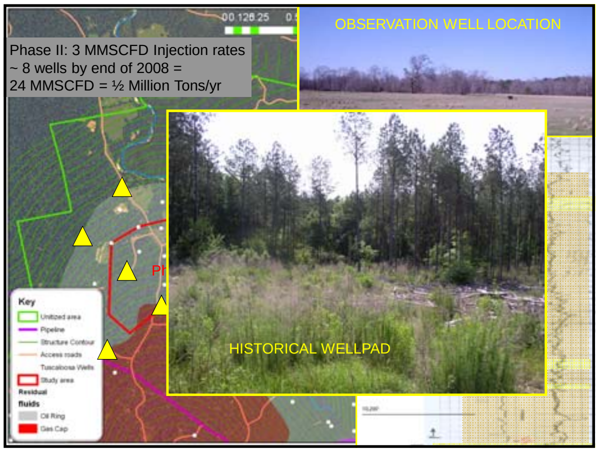
Bureau of Economic Geology

- Deep subsurface Modeling:
  - Phase II (validation):
    - fluid flow modeling with CMG-GEM
    - risk assessment handled by EOR operator (in commercial/financial context, and not available to partnerships)
  - Phase III (deployment):
    - fluid flow modeling with CMG-GEM
    - flow/thermal/geomechanical modeling using CMG-STARS, loosely coupled with CMG-GEM results
    - risk assessment with "Certification Framework" developed by LBL/UT
- Shallow subsurface modeling (Phase III)
  - fluid flow coupled with reactive transport: TOUGHREACT

5

Bureau of Economic Geology





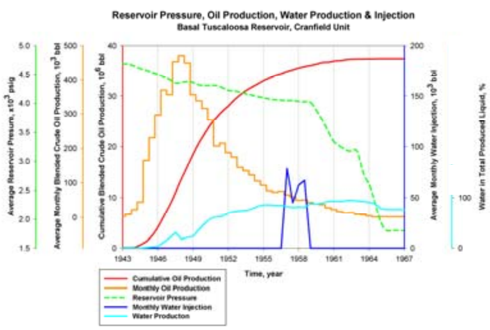
Available Data

Bureau of Economic Geology

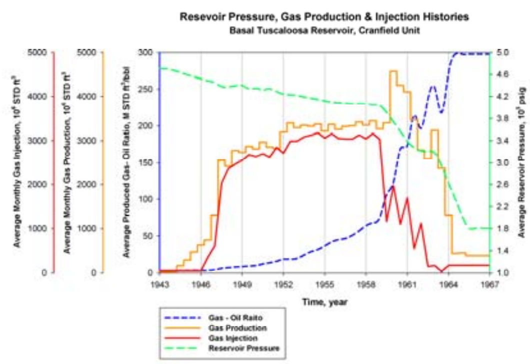
- 1966 summary paper:
  - Oil and gas composition and other PVT data
  - Overall oil (~38 MMbbl) and gas (~0.7 Tcf including reinjection) production, water cut (from ~0 to ~100%)
  - OOIP = 114 MMbbl + 24 MMbbl condensate
  - OGIP = 0.34 Tcf gas cap + 0.12 Tcf solution gas
  - Some relative permeability data
  - Average permeability (280 md), porosity (0.255), average water saturation (0.473?)
  - Operational history

Weaver and Anderson, 1966, US Department of Interior Bureau of Mines and Interstate Oil and Gas Compact Commission, Monograph 13, p.42-58

8



9



Oil/Gas Composition

Bureau of Economic Geology

- Black oil vs. compositional model

Component	Gas Cap (Mole Fraction)	Oil Rim (Mole Fraction)	Gas Liberated (Mole Fraction)
Carbon dioxide	2.81%	1.84%	2.71%
Methane	79.90%	53.76%	80.60%
Ethane	6.49%	7.17%	10.30%
Propane	2.75%	3.34%	3.71%
Iso-butane	0.62%	1.04%	0.78%
Normal butane	1.03%	1.58%	0.97%
Iso-pentane	0.63%	1.23%	0.34%
Normal Pentane	0.47%	0.95%	0.22%
Hexane	1.17%	2.48%	0.27%
Hexane plus	4.13%	26.61%	0.10%

11

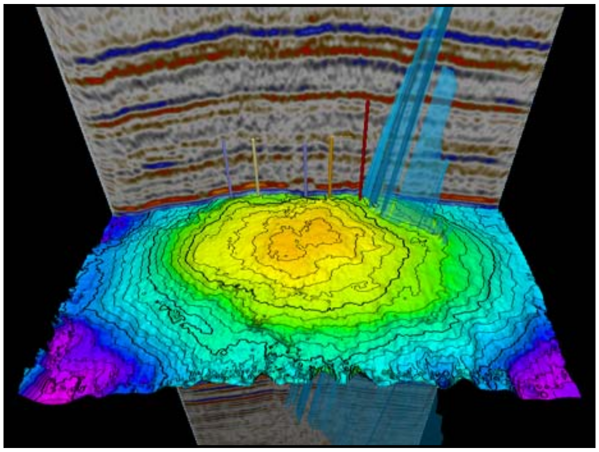
Available Data

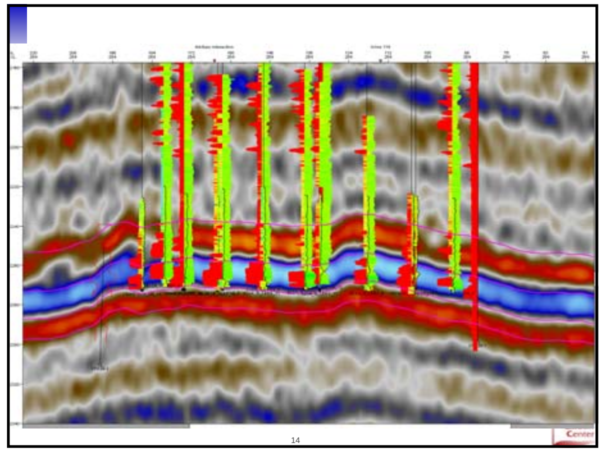
Schlumberger

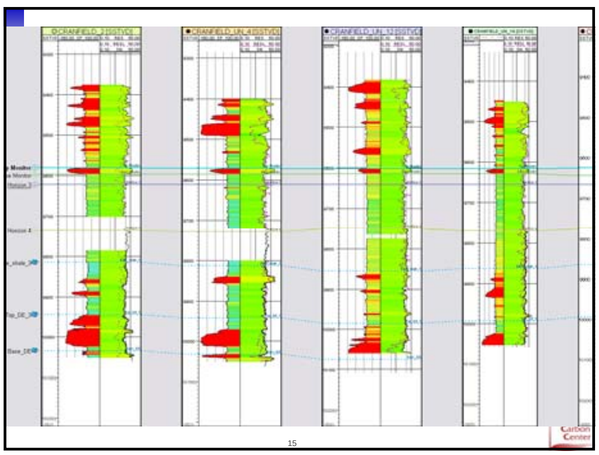
Bureau of Economic Geology

- Individual production of most wells (IHS)
- Data integrated in PETREL
  - 3D-seismic
  - New and old well logs: structure, porosity, water saturation
  - 100's sidewall cores plugs
  - Petrographic analyses
- Upscaled and exported into 500×500 ft^2 41×28×16 GEM grid
- Regular weekly updates on rate and pressure from Denbury operations

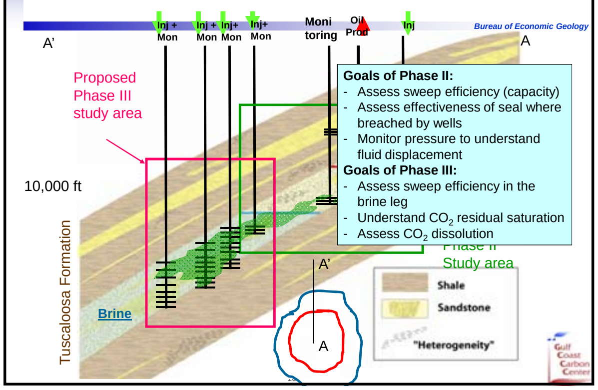
12







Cranfield Schematic Overview



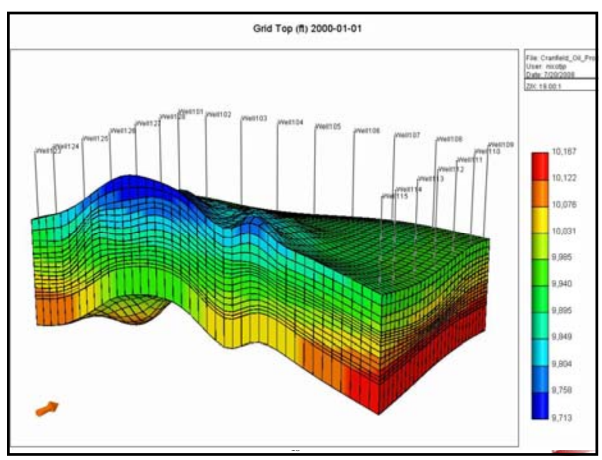
Modeling Approach 1

Bureau of Economic Geology

- Goals:
  - Understand system
  - Ability to make predictions
- Objectives:
  - Reproduce production history in the general sense
  - Reproduce CO_2 injection monitoring data
  - Understand pressure variations in and above inj. Fm.
- General history match:
  - Initial flow parameters
    - Rock types
    - Permeability, porosity, water saturation
    - Boundary conditions

Gulf Coast Carbon Center

17



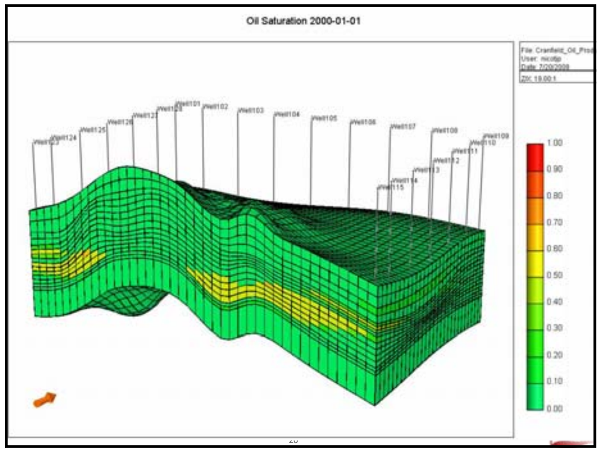
Modeling Approach 2

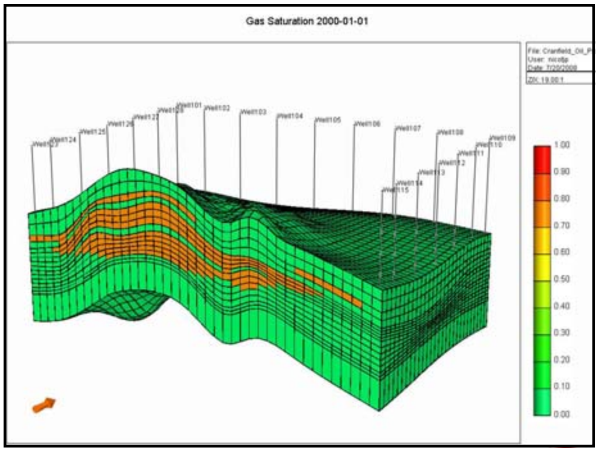
Bureau of Economic Geology

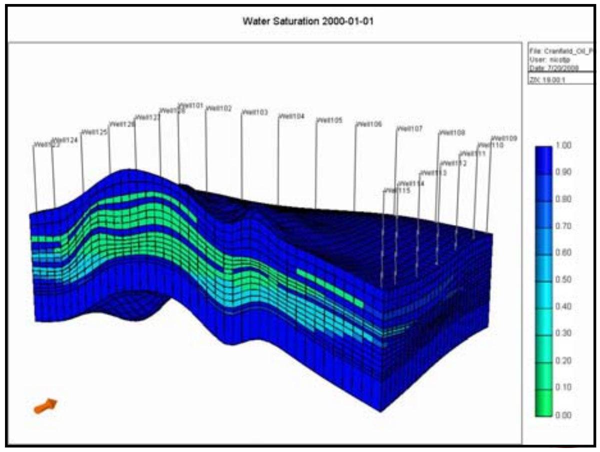
- General history match (continued)
  - Initial conditions:
    - w/o and o/g contacts at right locations
    - acceptable material balance for oil and gas originally in place
  - Sensitivity analysis on critical parameters:
    - Oil/gas composition; relative permeability end points; flow barrier
  - Reproduce general production and water cut history
    - Produce oil
    - Produce gas
    - Mimic water drive, back to hydrostatic pressure

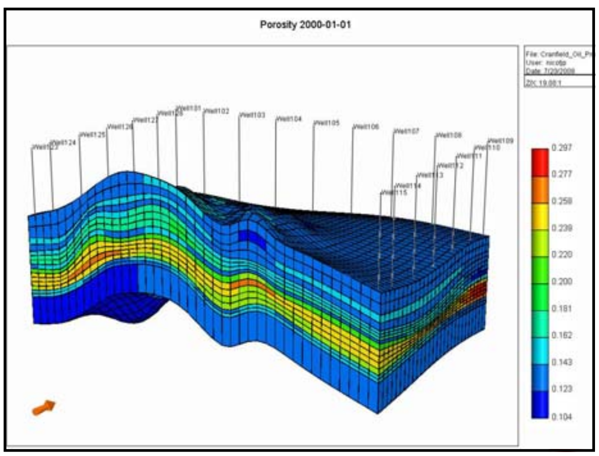
Gulf Coast Carbon Center

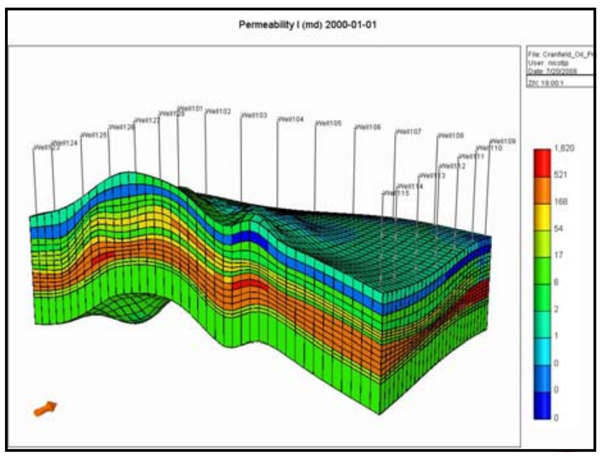
19





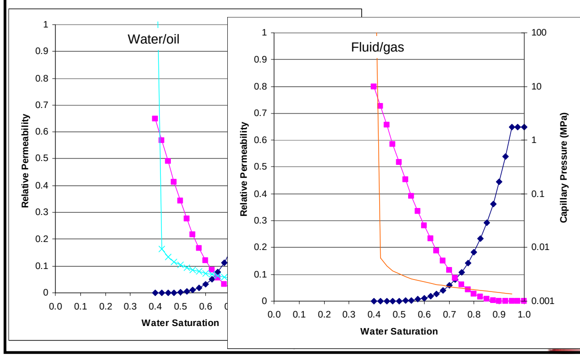






Porosity/permeability transform
Relative permeability

Bureau of Economic Geology



Modeling steps

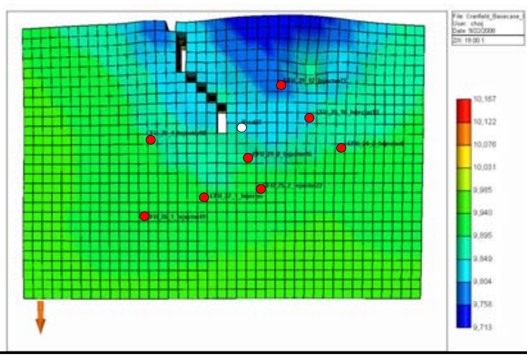
Bureau of Economic Geology

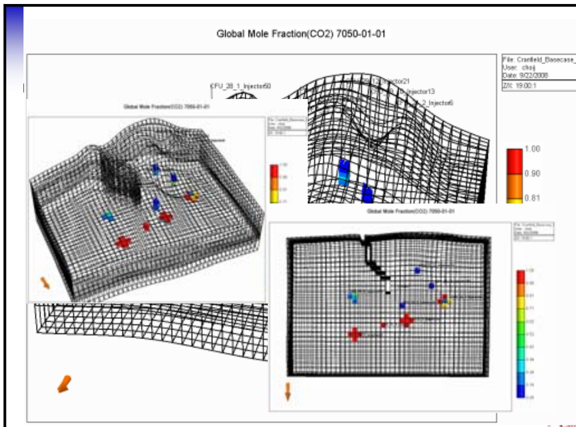
- Oil production with pressure maintenance
- Gas cap blow down
- Natural water drive and pressure buildup
- CO_2 injection and calibration
- CO_2 breakthrough and pressure history prediction

26

Location of CO_2 injection wells and monitoring well

Bureau of Economic Geology

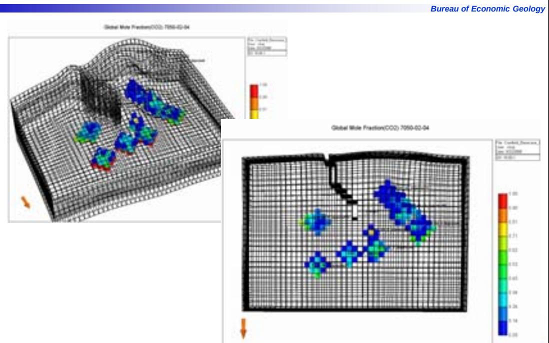




28

2 months after start of injection

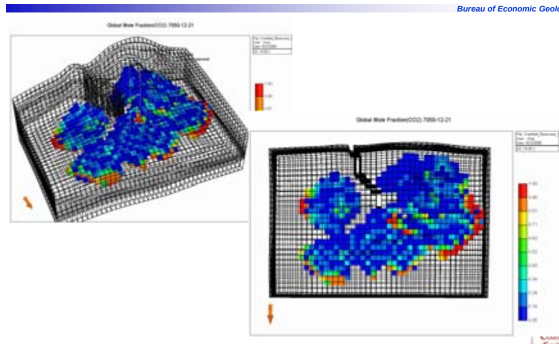
Bureau of Economic Geology



29

12 months after start of injection – no production

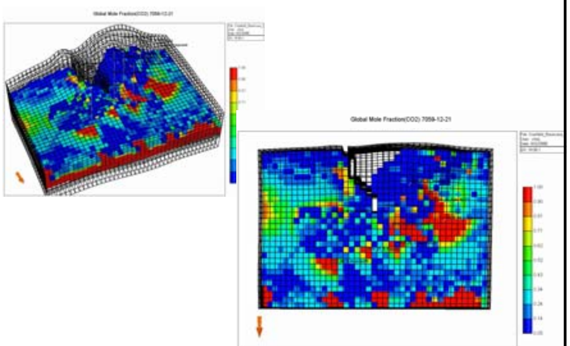
Bureau of Economic Geology



30

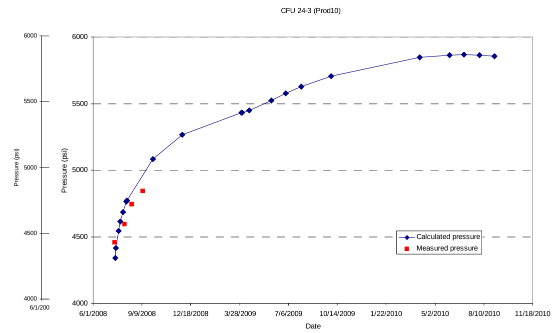
10 years after start of injection – no production

Bureau of Economic Geology



Some pressure results

Bureau of Economic Geology



Future deep subsurface modeling work

Bureau of Economic Geology

- Stochastic analysis of heterogeneity within PETREL; upscaled models exported to GEM
- Revisit Phase III area stratigraphic structure
- Continuing history matching
- Develop geomechanical model

33

Risk Assessment

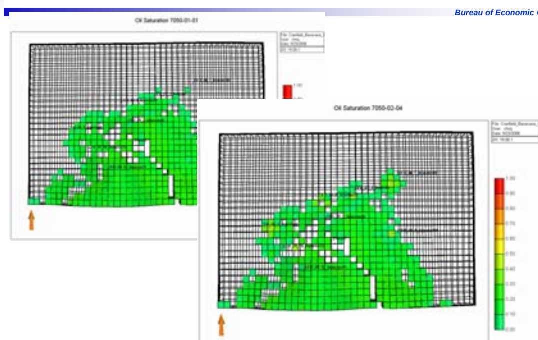
Bureau of Economic Geology

- Will be formally done according to the "Certification Framework" approach
- Favorable factors:
  - Deep formation, multiple seals
  - Pressure attenuation owing to compressibility of residual oil and gas
  - Oil production, no large pressure buildup
  - Pressure depletion in overlying Wilcox
  - Improved dissolution because of residual oil (Tus., Wilcox)
  - Experienced operating company
- Possible weaknesses:
  - Multiple well penetrations from the 40's to 60's
  - Possible fault but attenuated upwards

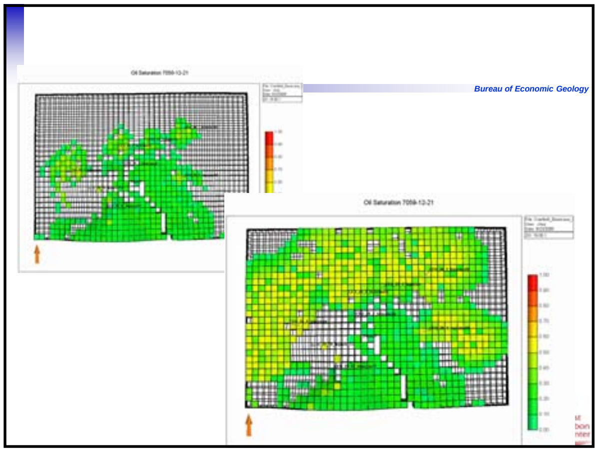
34

QUESTIONS?

Bureau of Economic Geology



36


Bureau of Economic Geology
Oil Saturation 7059-12-21
Oil Saturation 7059-12-21

Southeast Regional Carbon Sequestration Partnership Phase III Update

Regional Carbon Sequestration Partnerships
Annual Review Meeting

Pittsburgh, Pennsylvania
November 18, 2009

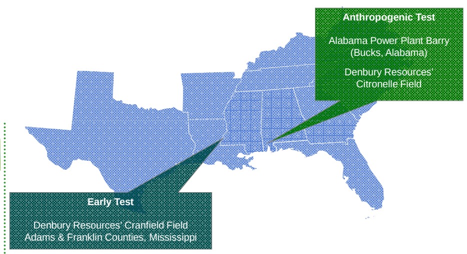
Gerald R. Hill, Ph.D.
SSEB Technical Coordinator

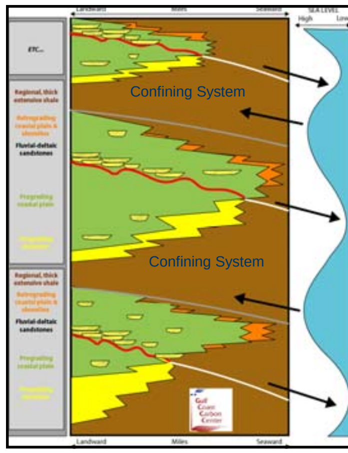
Acknowledgements

- This material is based upon work supported by the U.S. Department of Energy National Energy Technology Laboratory.
- Cost share and research support provided by SECARB/SSEB Carbon Management Partners

---

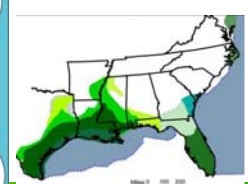
Phase III Geographic Region & Field Test Site Locations





Continued Characterization During 2009 and 2010

Assessments will be conducted in the Gulf of Mexico, South Georgia Basin and along the Carolina coast.



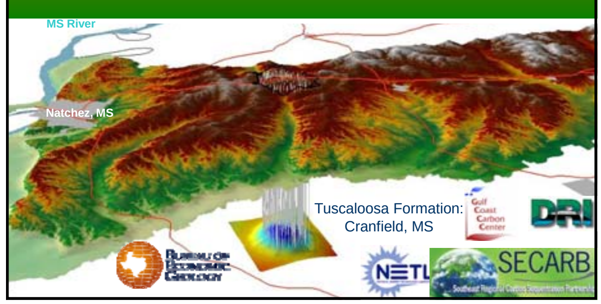
SECARB Phase III Projects - Overview

- **Phase III Early Test:** Large volume saline injection "down-dip" of EOR activity at Cranfield Unit – 1.5 million tonne injection started in April 2009
- **Phase III Anthropogenic Test:** Large volume saline injection with power plant capture & separation source – 125,000 metric tons per year for 4 years – with injection starting FY2011

SECARB Early Large Volume Injection Tests

Cranfield Unit operated by Denbury Resources Inc

Depth >10,300 ft
Injection Zone – lower Tuscaloosa Formation
Injection rate>1 Million Tones per year



Management of SECARB

Project Management
Gerald Hill
Bruce Lani/Bruce Brown

Cranfield Research Team

University of Texas at Austin

Denbury Resources Inc

Sandia Technologies LLC

LBNL LLBL USGS ORNL
QEA
U Mississippi
Miss State

Schlumberger Carbon Services

Gulf Coast Carbon Center

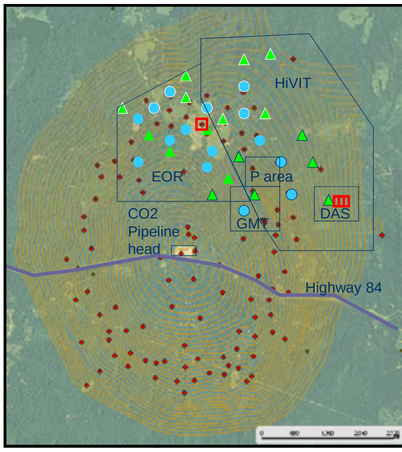
Other SECARB tests

SECARB coal seam tests
Geological Survey of Alabama
Virginia Tech

SECARB Power Plant tests
EPRI
Southern Co
ARI

Scientific and Technical Objectives & Benefits

Objective	Anticipated Benefit
DAS Detailed Area of Study Sweep efficiency brine system	Well-quantified measure of how CO_2 occupies pore volumes
HiVIT High Volume injection Test - Account for volume input	Add rigor to measurement for storage prediction
GMT GeoMechanical Test Measure microseismicity	Assess energy input and pressure increase
P-Area Pits- pad plants Effectiveness of surface monitoring - deep water table	Reliable leakage detection in deep water table/ complex site
EOR- Pressure based in-zone & above monitoring methods for area with many well penetrations	Technique development for EOR permanence



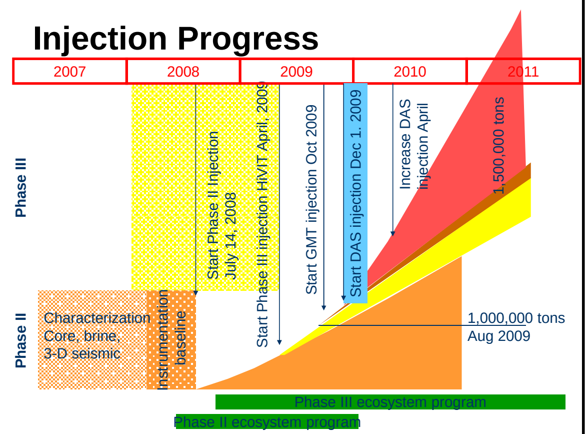
Injector

Monitoring Point (producer)

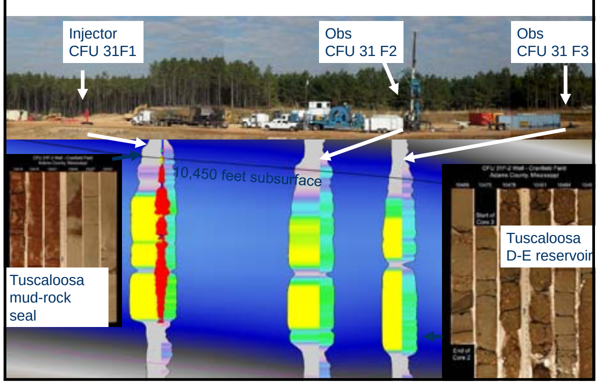
Observation Well

DAS	Detailed Area of Study
HiVIT	High Volume Injection Test
GMT	GeoMechanical Test
P-Area	Pits, Pad, Plants
EOR	Enhanced Oil Recovery

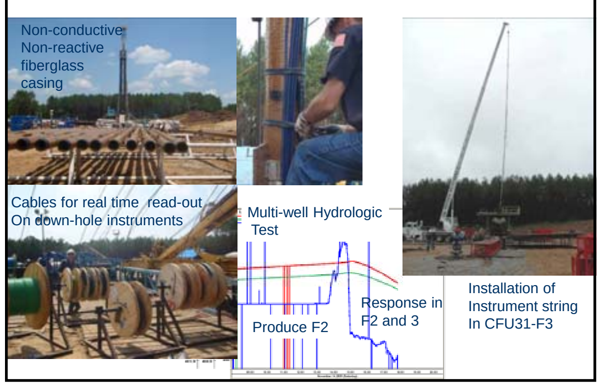
Injection Progress



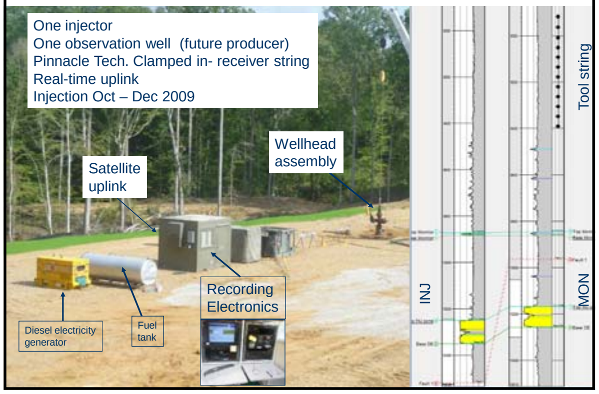
DAS: Detailed Area of Study



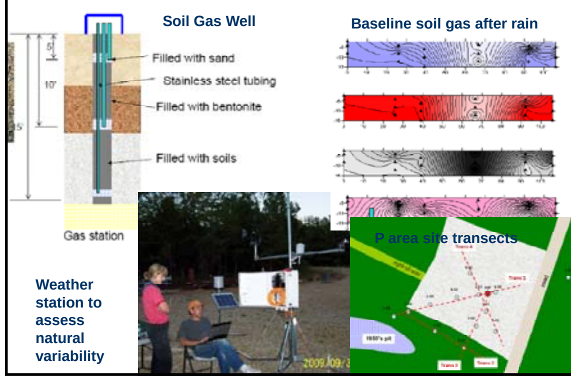
DAS: Detailed Area of Study



GMT: GeoMechanical Test



"P" Area: Plants, Pad, Pit



Pressure Monitoring EOR

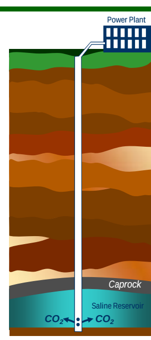
FY2009 Activities: Phase III Anthropogenic Test

- Capture technology announced in May 2009
- Site hosts announced in May 2009
  - Plant Barry: CO_2 Source
  - Denbury Resources: CO_2 injection at Citronelle Field
- CX received in August 2009 for site characterization at Citronelle Field
- UIC permit application preparation underway
- Detailed geologic assessment underway
- Reservoir simulations began/ongoing
- Data collection for EIVs underway
- Regular coordination/planning meetings with ADEM
- Regular Anthropogenic Test team meetings and conference calls

SECARB NETL SSEB

Anthropogenic Test

- **Purpose:** Locate suitable geological sequestration sites in proximity to the 25 MW MHI post-combustion CO_2 capture pilot at Plant Barry and inject CO_2
  - One of the first integrated capture, transport and storage demonstration projects on an existing coal-fired power plant in the U.S.
- **Sequestration Target:** Lower Cretaceous Gulf Coast saline reservoirs with high CO_2 storage capacity and injectivity



SECARB NETL SSEB

Anthropogenic Test

- **Sequestration Objectives:**
  - Build geological and reservoir maps for test site
  - Conduct reservoir simulations to estimate injectivity, storage capacity, and long-term fate of injected CO_2
  - Address state/local regulatory and permitting issues
  - Foster public education and outreach
  - Inject 125,000 metric tons of CO_2 per year for four years
  - Conduct longer-term monitoring for 3-4 years post-injection

Anthropogenic CCS Team:

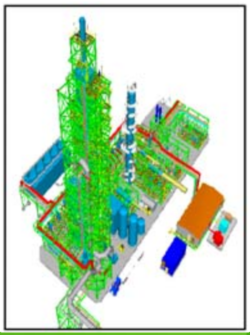
EPRI
EPRI's Utility Partners
Advanced Resources International
Geological Survey of Alabama
Alabama Power
Southern Company
Denbury Resources
Mitsubishi Heavy Industries

SECARB NETL SSEB

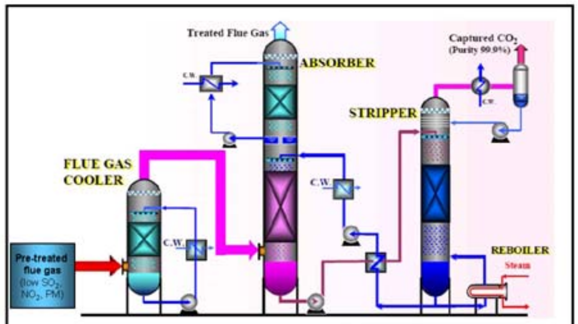
Capture Unit at Alabama Power's Plant Barry

MHI advanced amine capture unit

- 25 MW post combustion slip stream
- Fabricate off-site and barge to Plant Barry
- Compress CO_2 to 2000 psi
- Scheduled start up First Quarter, FY2011
- Separately funded; CO_2 provided to SECARB for sequestration at Citronelle Field



Simplified CO_2 Scrubbing Process (Amine)

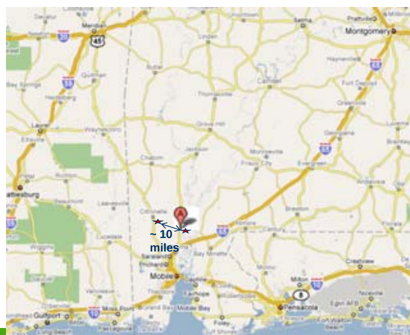


Key Points: needs >99% SO_2 removal; consumes process steam

CO_2 Transportation from Plant Barry to Citronelle Field

~10 mile pipeline, separately planned and financed by Denbury Resources

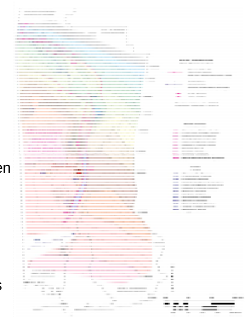
125 TPY of pipeline capacity for SECARB Phase III CO_2



Geologic Overview for Plant Barry and Citronelle Field

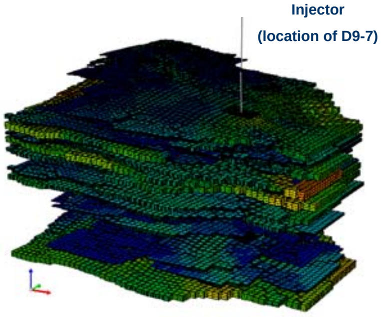
Proposed sequestration site is on the southeast flank of the Citronelle Dome

- Proven four-way closure
- No evidence of faulting or fracturing
- Multiple confining units between potential injection targets and base of USDW
- However, historic oil and gas wells and a lack of local characterization of saline reservoirs presents challenges



Structural contour map of the top of the Smackover Formation (Upper Jurassic) in southwest Alabama (GSA 2008)

Model 3-D View: Citronelle Field Phase III Injection Site



- 17 sand bodies from geological model
- Average permeability of 88 mD
- Average porosity of 19.3%
- Identical permeability and porosity in all layers

Expected Reservoir Intersection Depths at Citronelle

Formation Tops	Anticipated Depth Feet	Interval Thickness Feet
Bottom of Fresh Water (<1,000 mg/l)	~ 1,000	1,000
Bottom of Potable Water (<10,000 mg/l)	Max ~ 2,000	1,000
Selma Chalk Group	4,550	1,150
Eutaw Group	5,700	300
Upper Tuscaloosa Formation	6,000	700
Marine Tuscaloosa Formation	6,700	250
Lower Tuscaloosa Formation	6,950	300
Washita-Fredericksburg Undifferentiated	7,250	2,150
Paluxy Formation	**9,400**	**1,100**
Mooringsport Formation	10,500	250
Ferry Lake Anhydrite	10,750	200
Rodessa Formation (oil reservoir)	10,950	-

Gerald R. Hill, Ph.D.
SECARB Technical Coordinator
hill@sseb.org

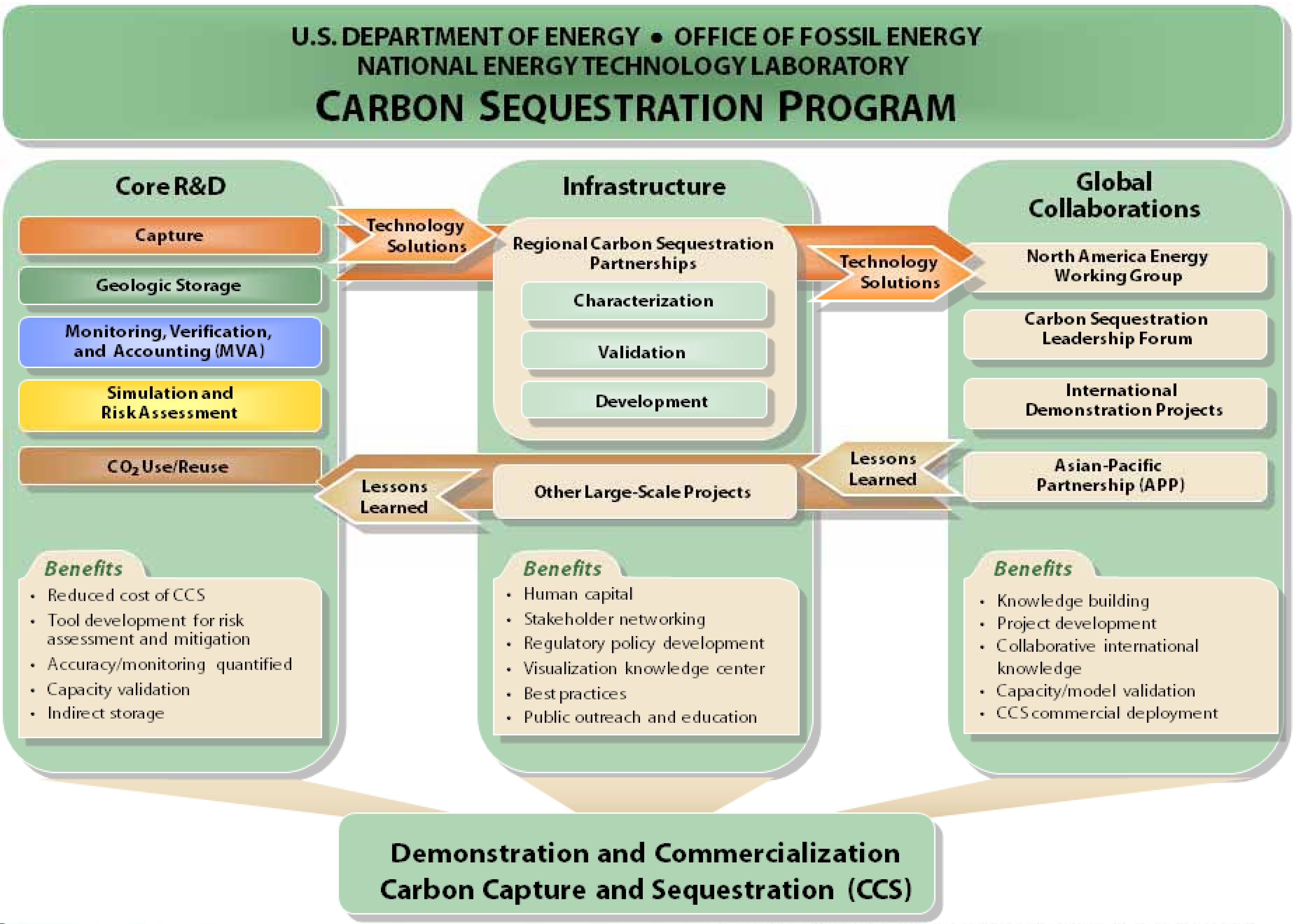
Southern States Energy Board
6325 Amherst Court
Norcross, Georgia 30092 USA
Phone: (770) 242-7712
www.sseb.org
www.secarbon.org

Southeast Regional Carbon Sequestration Partnership (SECARB)

U.S. Regional Partnerships
From Pilot to Demonstration

Capture and Geological Storage of
CO_2 – Accelerating Deployment
3rd International Symposium
5 November, 2009

Gerald R. Hill, Ph.D.
SECARB Technical Coordinator


U.S. DEPARTMENT OF ENERGY • OFFICE OF FOSSIL ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY
CARBON SEQUESTRATION PROGRAM
Core R&D
Capture
Geologic Storage
Monitoring, Verification, and Accounting (MVA)
Simulation and Risk Assessment
CO_2 Use/Reuse
Technology Solutions
Lessons Learned
Infrastructure
Regional Carbon Sequestration Partnerships
Characterization
Validation
Development
Other Large-Scale Projects
Technology Solutions
Lessons Learned
Global Collaborations
North America Energy Working Group
Carbon Sequestration Leadership Forum
International Demonstration Projects
Asian-Pacific Partnership (APP)
Benefits
• Reduced cost of CCS
• Tool development for risk assessment and mitigation
• Accuracy/monitoring quantified
• Capacity validation
• Indirect storage
Benefits
• Human capital
• Stakeholder networking
• Regulatory policy development
• Visualization knowledge center
• Best practices
• Public outreach and education
Benefits
• Knowledge building
• Project development
• Collaborative international knowledge
• Capacity/model validation
• CCS commercial deployment
Demonstration and Commercialization
Carbon Capture and Sequestration (CCS)

Regional Carbon Sequestration Partnerships

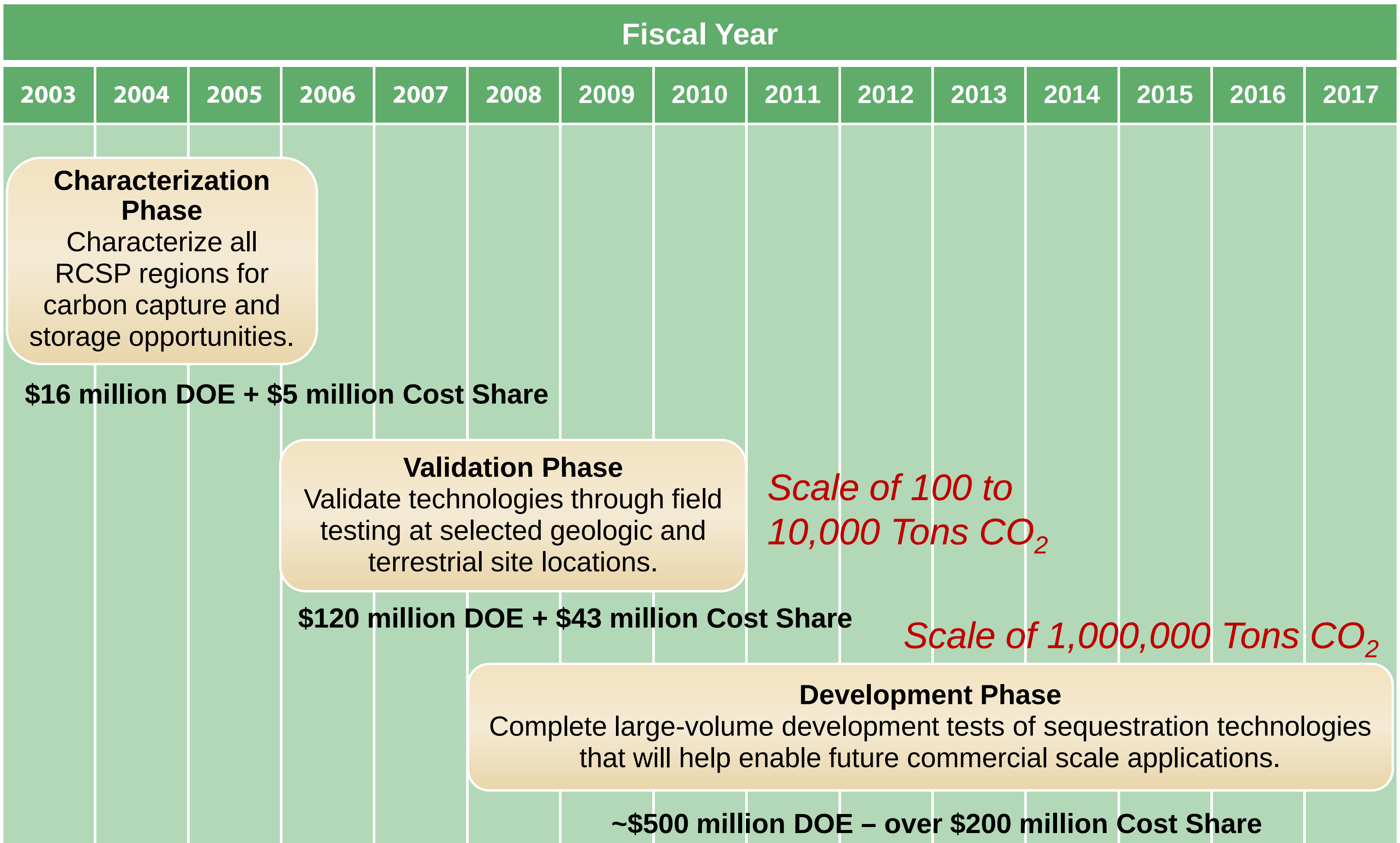
- Engage regional, state, and local governments
- Determine regional sequestration benefits
- Baseline region for sources and sinks
- Establish monitoring and verification protocols
- Address regulatory, environmental, and outreach issues
- Validate sequestration technology and infrastructure

- 7 Regional Partnerships
- 43 States, 4 Canadian Provinces
- 350+ distinct organizations

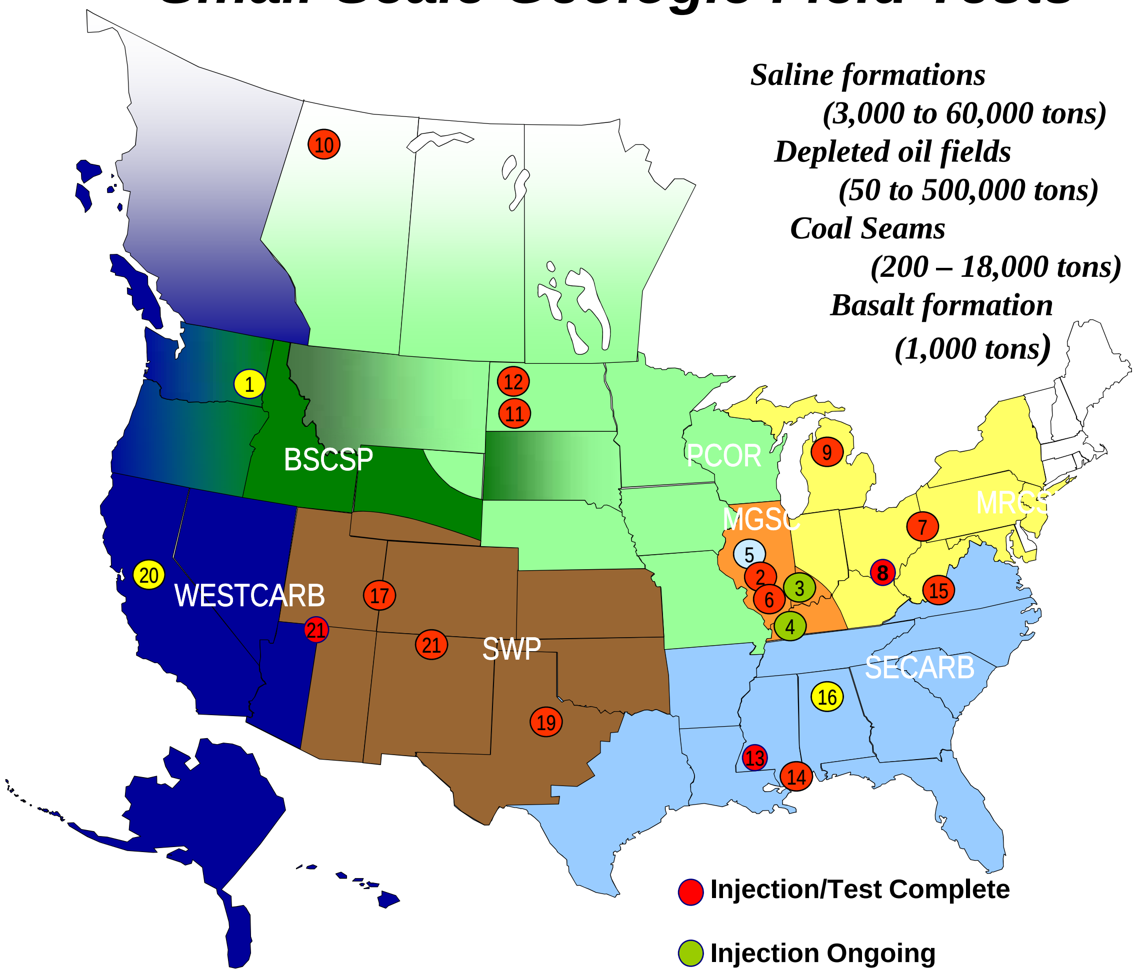
Developing the Infrastructure for Wide-Scale Deployment

Regional Carbon Sequestration Partnerships

Program Phases



RCSP Validation Phase: *Phase II*
Small-Scale Geologic Field Tests

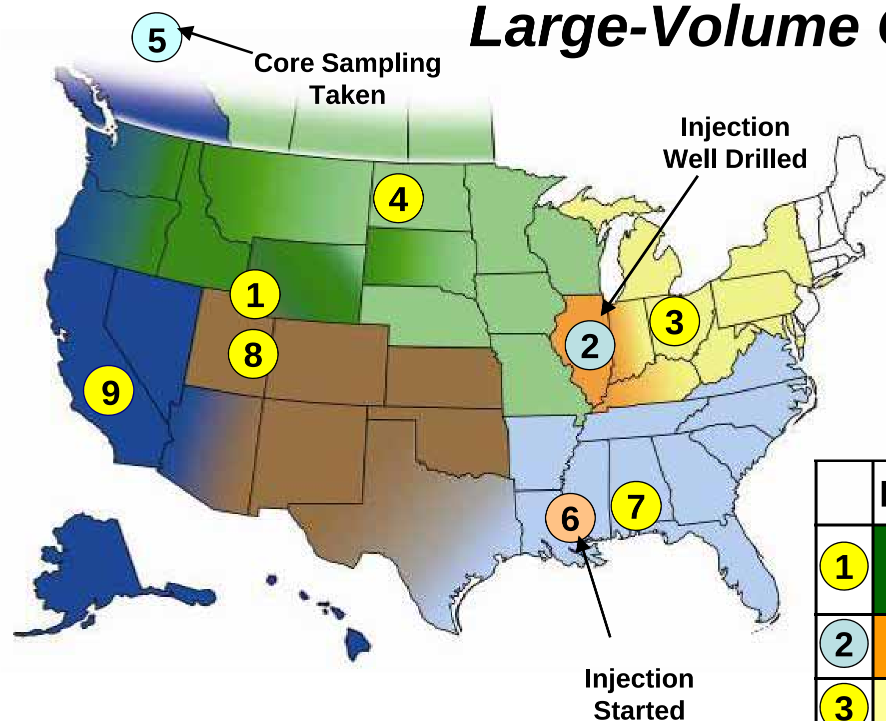


RCSP	Formation Type	Geologic Province
Big Sky	Saline 1	Columbia Basin
MGSC	Oil-bearing 2 3 4 Saline 5 Coal seam 6	Illinois Basin
MRCSP	Saline 7 8 9	Cincinnati Arch, Michigan Basin, Appalachian Basin
PCOR	Oil-bearing 10 11 Coal seam 12	Keg River, Duperow, Williston Basin
SECARB	Oil-bearing 13 Saline 14 Coal seam 15 16	Gulf Coast, Mississippi Salt Basin, Central Appalachian, Black Warrior Basin
SWP	Oil-bearing 17 18 Coal seam 19	Paradox Basin, Aneth Field, Permian Basin, San Juan Basin
WESTCARB	Saline 20 21	Sacramento Valley, Colorado Plateau

Data current as of April 2009

RCSP Phase III: Development

Large-Volume Geologic Field Tests



- ✓ ***Nine large-volume tests***
- ✓ ***Injections initiated 2009 – 2011***

2009 Injection Scheduled

2010 Injection Scheduled

2011 Injection Scheduled

	Partnership	Geologic Province	Type
1	Big Sky	Triassic Nugget Sandstone / Moxa Arch	Saline
2	MGSC	Deep Mt. Simon Sandstone	Saline
3	MRCSP	Shallow Mt. Simon Sandstone	Saline
4	PCOR	Williston Basin Carbonates	Oil Bearing
5		Devonian Age Carbonate Rock	Saline
6	SECARB	Lower Tuscaloosa Formation Massive Sand Unit	Saline
7			
8	SWP	Regional Jurassic & Older Formations	Saline
9	WESTCARB	Central Valley	Saline

Big Sky Carbon Sequestration Partnership Geologic Projects

MRCSP Geologic Test Sites*

Michigan Basin: DTE and Core Energy gas and oil operations, Gaylord, Michigan

- Permitting: EPA Region 5, Class V, Granted Jan 2007.
- Target: Bass Islands Dolomite, 3500 ft
- Status: Injected 10,000 tonnes 2008. Additional 50,000 tonnes injected February-July 2009
- Host: DTE Energy, Core Energy

Appalachian Basin: FirstEnergy's RE Burger Power Plant, Shadyside, Ohio

- Permitting: Ohio EPA, Class V, Granted Sep 2008
- Target: Oriskany, Salina, and Clinton, 6500-8000 ft
- Status: Injection testing completed, report in progress
- Host: FirstEnergy

Cincinnati Arch -- Mount Simon: Duke's East Bend Power Station, Rabbit Hash, Kentucky

- Permitting: EPA Region 4, Class V, Granted Feb 2009.
- Target: Mt. Simon Sandstone, 3,500 ft
- Status: Drilling Jun 2009, Injection completed Sep 2009
- Host: Duke Energy

Large Scale (1 million tonnes of CO_2) Phase III Site

- Various sites under evaluation

* All deep saline tests

Illinois Basin-Decatur Project

Observation/sampling well to be drilled Spring 2010

Injection of 1 million metric tons of CO_2 at a depth of 7,000 feet will begin August 2010

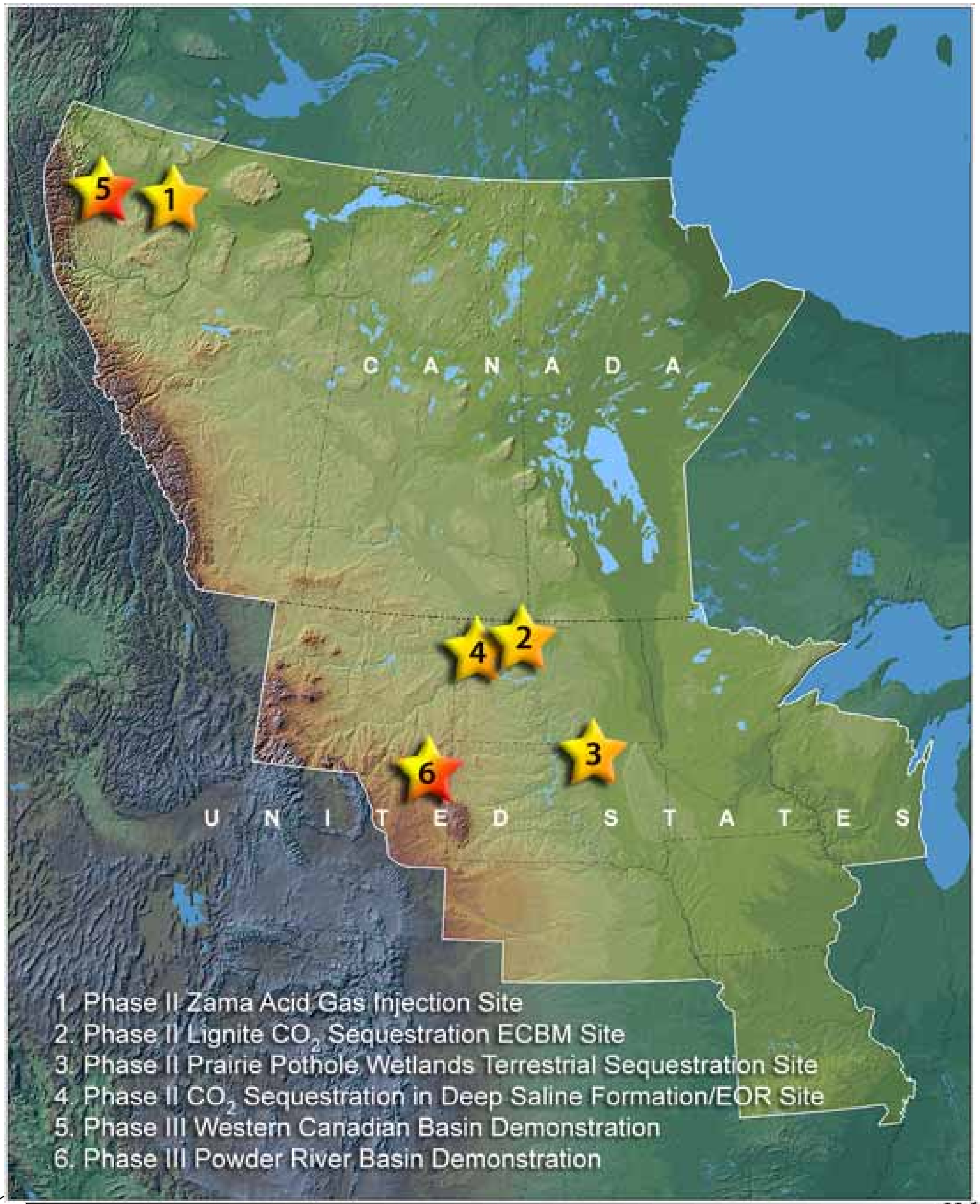
MGSC

U.S. DEPARTMENT OF ENERGY

ADM

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

NATIONAL ENERGY TECHNOLOGY LABORATORY



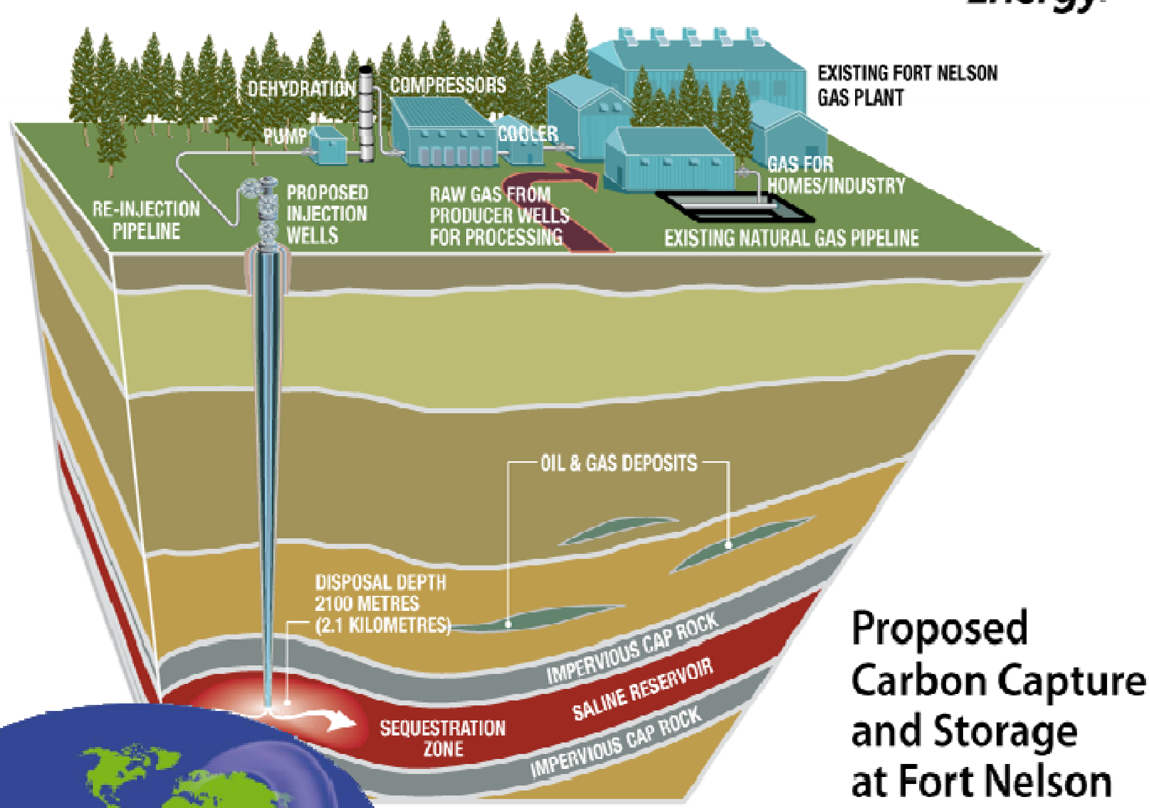
PCOR Partnership

The PCOR Partnership has completed four Phase II validation tests. The final report will be out early 2010.

We have two Phase III commercial-scale demonstrations planned.

Phase III Canadian Project Overview

Injecting Sour CO_2 (approx. 90% CO_2 and 10% H_2S)



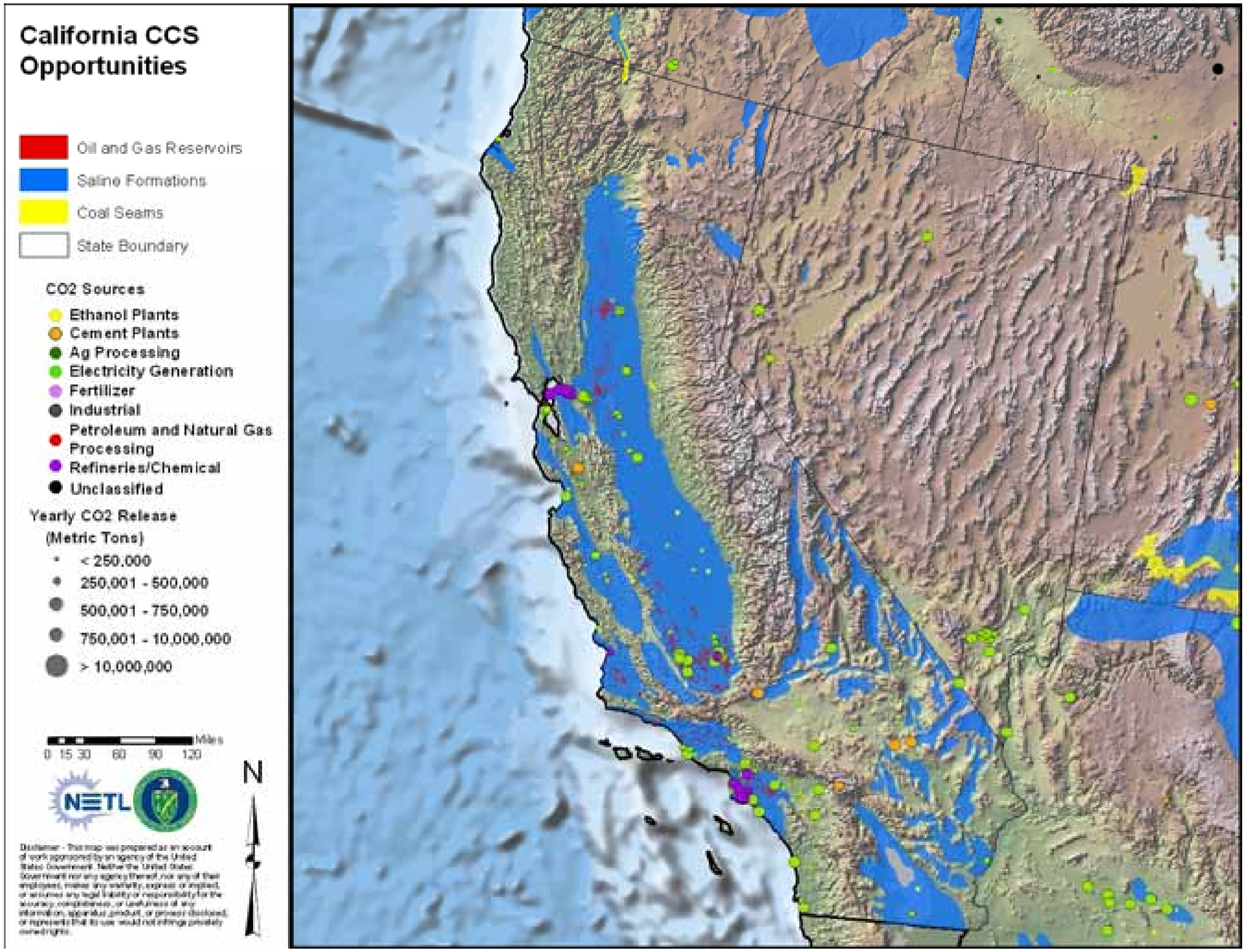
Major Features:

- Saline sequestration at 7000 to 8000 ft deep to maximize storage capacity.
- Inject and permanently store 1 to 2 Mt/yr CO_2.
- Fort Nelson gas plant owned 100% by Spectra Energy.
- Access and storage rights for deep saline formations of interest are obtained.

Meeting DOE Phase III:

- Greater than 1 Mt/yr carbon capture and storage (CCS) project in saline formation means that Fort Nelson is a world-scale CCS project
- Control over source and sink expedites rapid deployment of CCS in saline formation.
- Development of legal and regulatory framework for CCS.
- Development of MMV protocols for CCS in saline formations that can be applied more globally.
- International nature of the project.

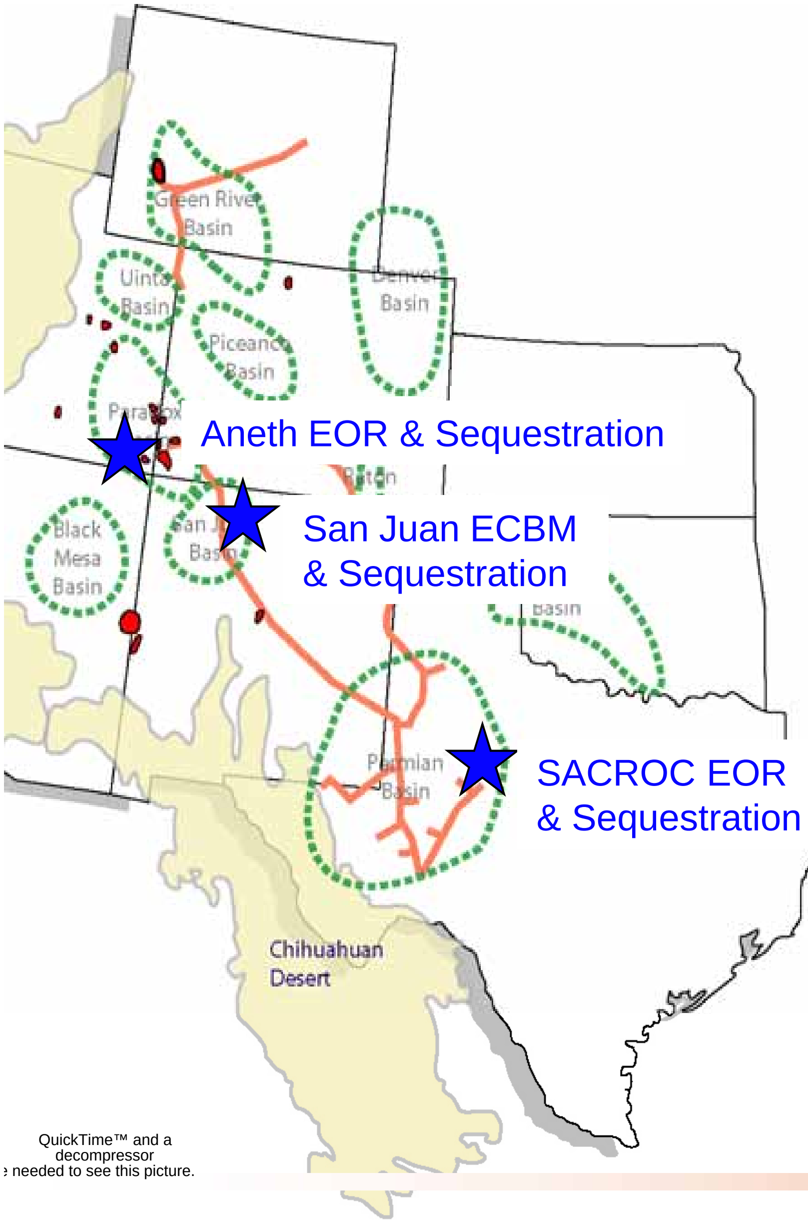
California CCS Opportunities



California Statistics*	
CO_2 Stationary Source Emissions	104 Million Metric Tons/Year
Saline CO_2 Storage Resource	303,502 Million Metric Tons**
Oil and Gas CO_2 Storage Resource	7,692 Million Metric Tons

*Statistics reported in Carbon Sequestration Atlas of the United Stated and Canada (2008).
** High Estimate.

Southwest Regional Partnership on Carbon Sequestration



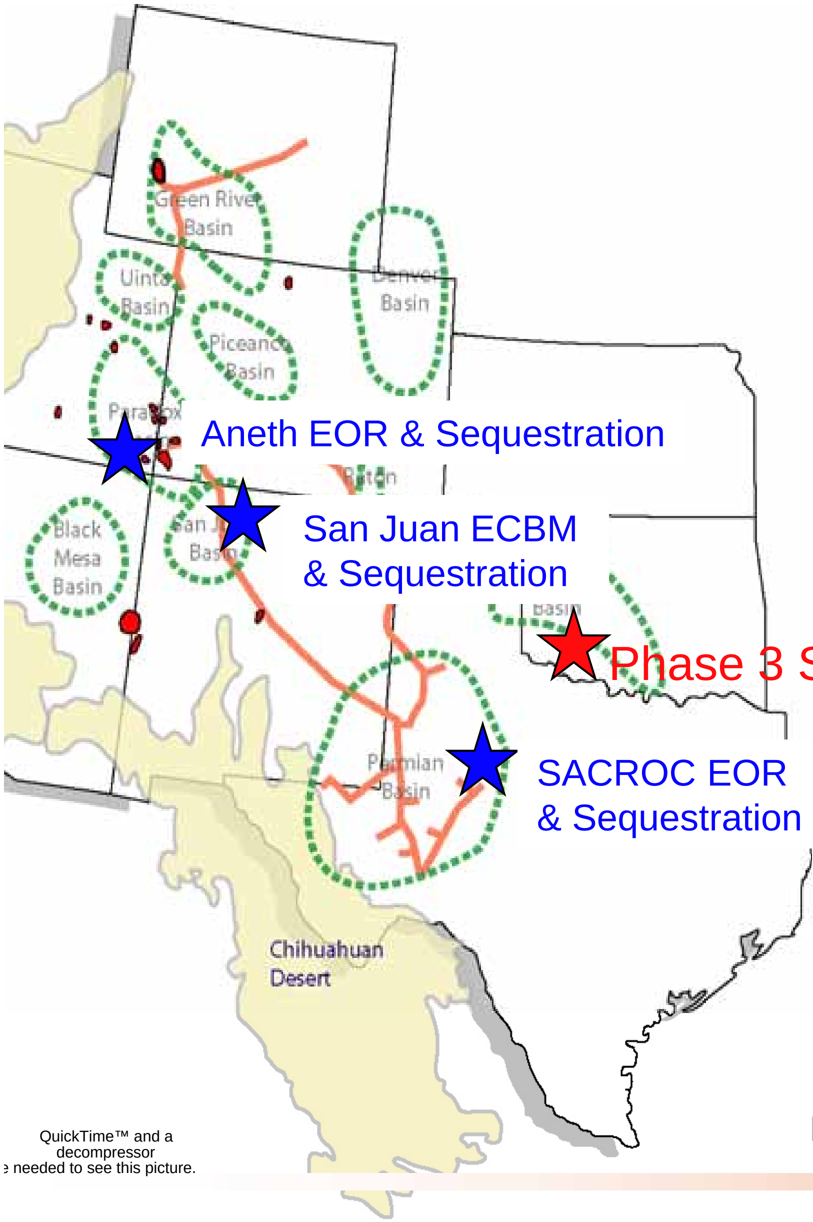
Aneth EOR & Sequestration:

- Injection began August 2007 and is ongoing
- 292,300 tons total injected in SWP wells
- Successful seismic imaging
- Successful tracer monitoring
- Successful concomitant EOR with net CO_2 storage

San Juan ECBM & Sequestration

- Injection began July 2008 and ended July 2009
- 18,400 tons injected in SWP injection well
- Successful vertical seismic profiling, tiltmeter deployment, tracer testing
- Successful enhanced methane recovery with net CO_2 sequestration

Southwest Regional Partnership on Carbon Sequestration

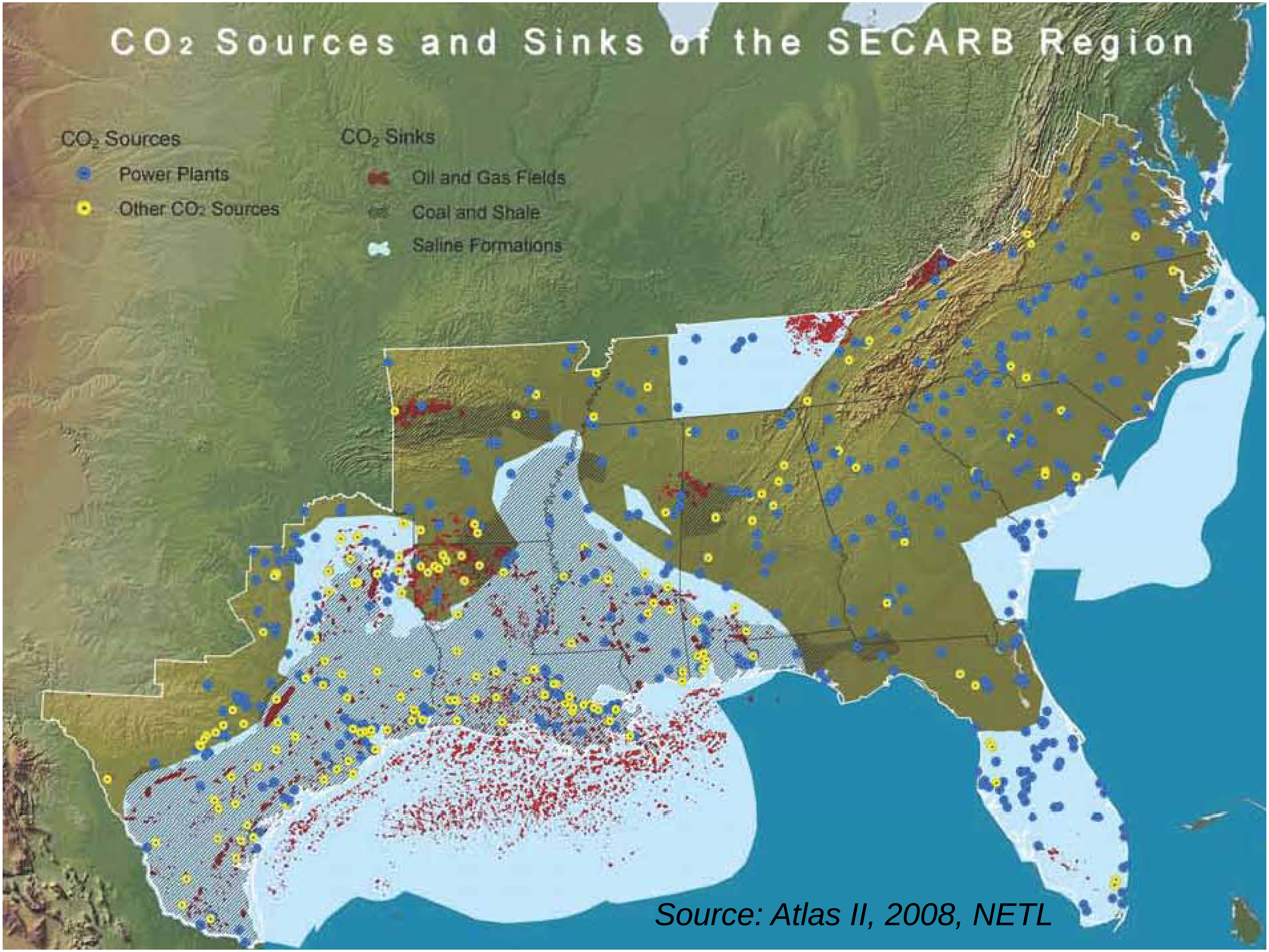


SACROC EOR & Sequestration:

- Injection began October 2008 and is ongoing
- Approximate 350,000 tons/year injection rate
- 4-D seismic imaging analysis ongoing
- Groundwater impacts methods developed
- Complete analysis of all trapping mechanisms and their relative roles, following 35 years of CO_2 injection for EOR
- Successful concomitant EOR and net CO_2 sequestration

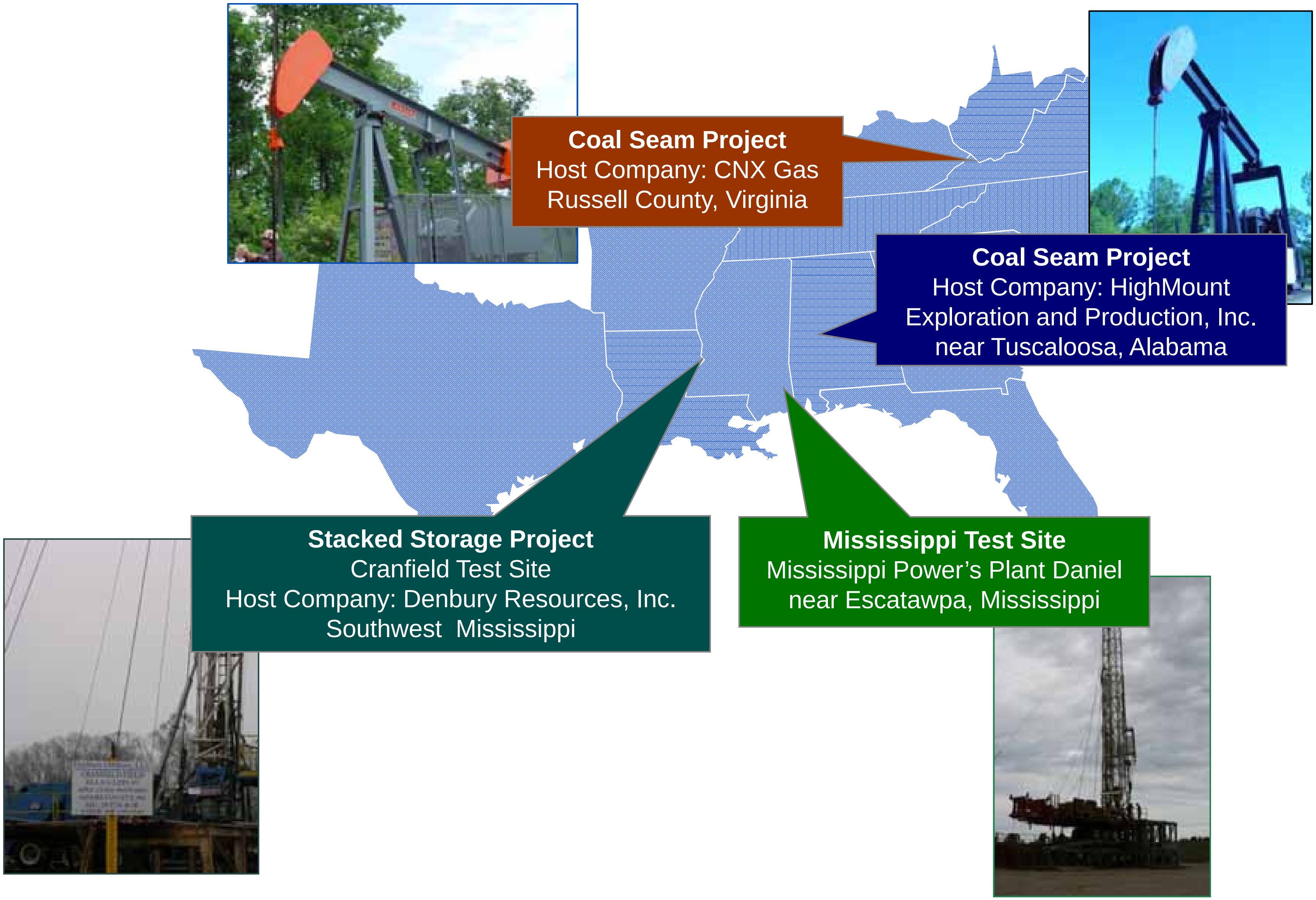
Large-Scale Deep Saline Sequestration Test (Phase 3)

- Site evaluation to be completed this month
- Top candidates include these Phase 2 sites plus a new site in Oklahoma

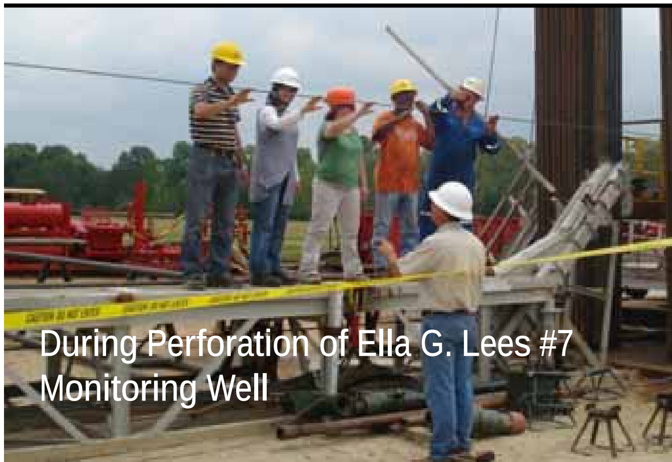

CO₂ Sources and Sinks of the SECARB Region
CO₂ Sources
Power Plants
Other CO₂ Sources
CO₂ Sinks
Oil and Gas Fields
Coal and Shale
Saline Formations
Source: Atlas II, 2008, NETL

SECARB
Southeast Regional Carbon Sequestration Partnership

SECARB Phase II Geographic Region and Field Test Site Locations



SECARB Phase II - Cranfield Unit



During Perforation of Ella G. Lees #7 Monitoring Well

Injection Well

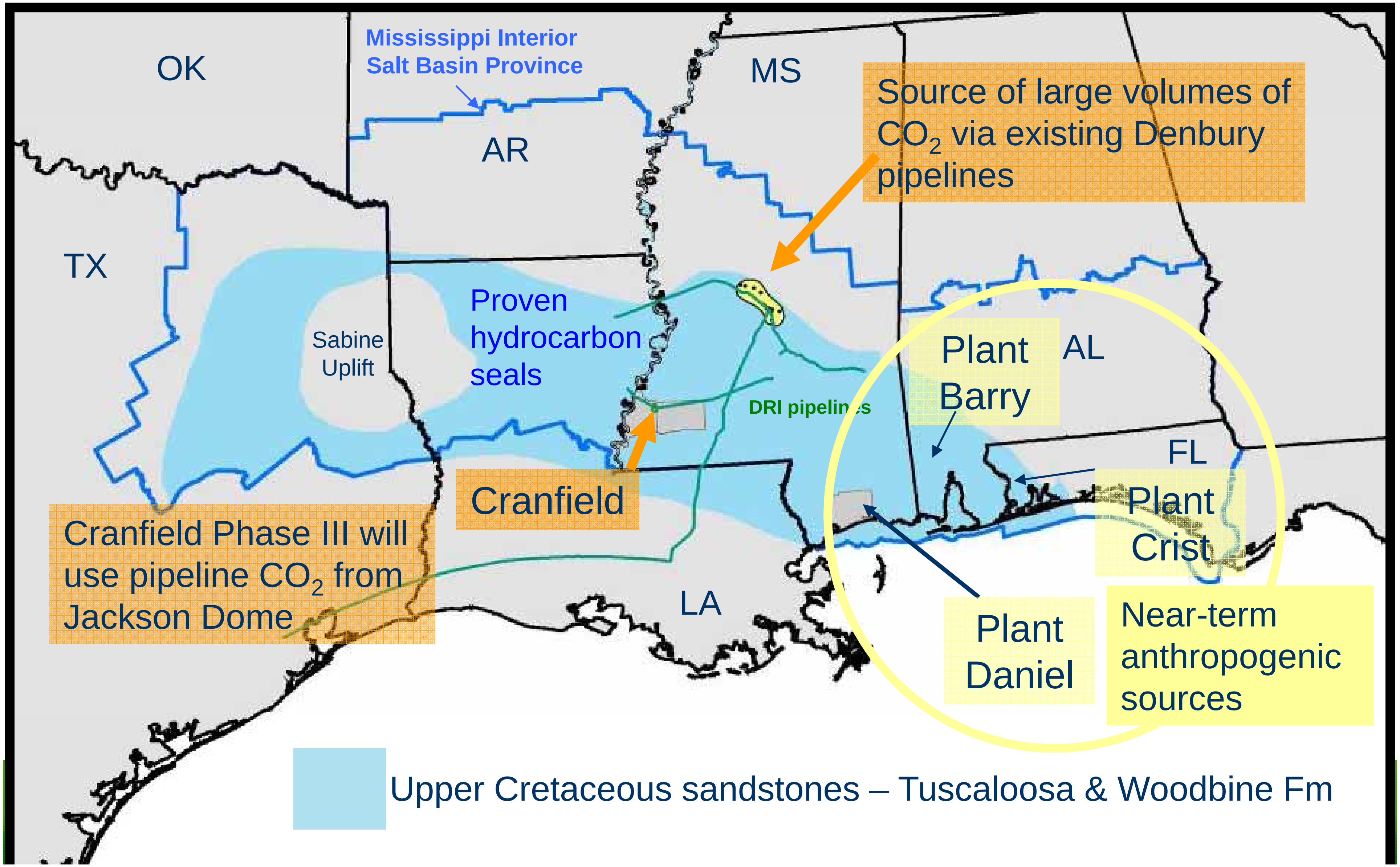
Perforating Gun Used for Workover of Ella G. Lees #7 Monitoring Well

Workover Rig on
Ella G. Lees #7 Well
Phase II Monitoring Well

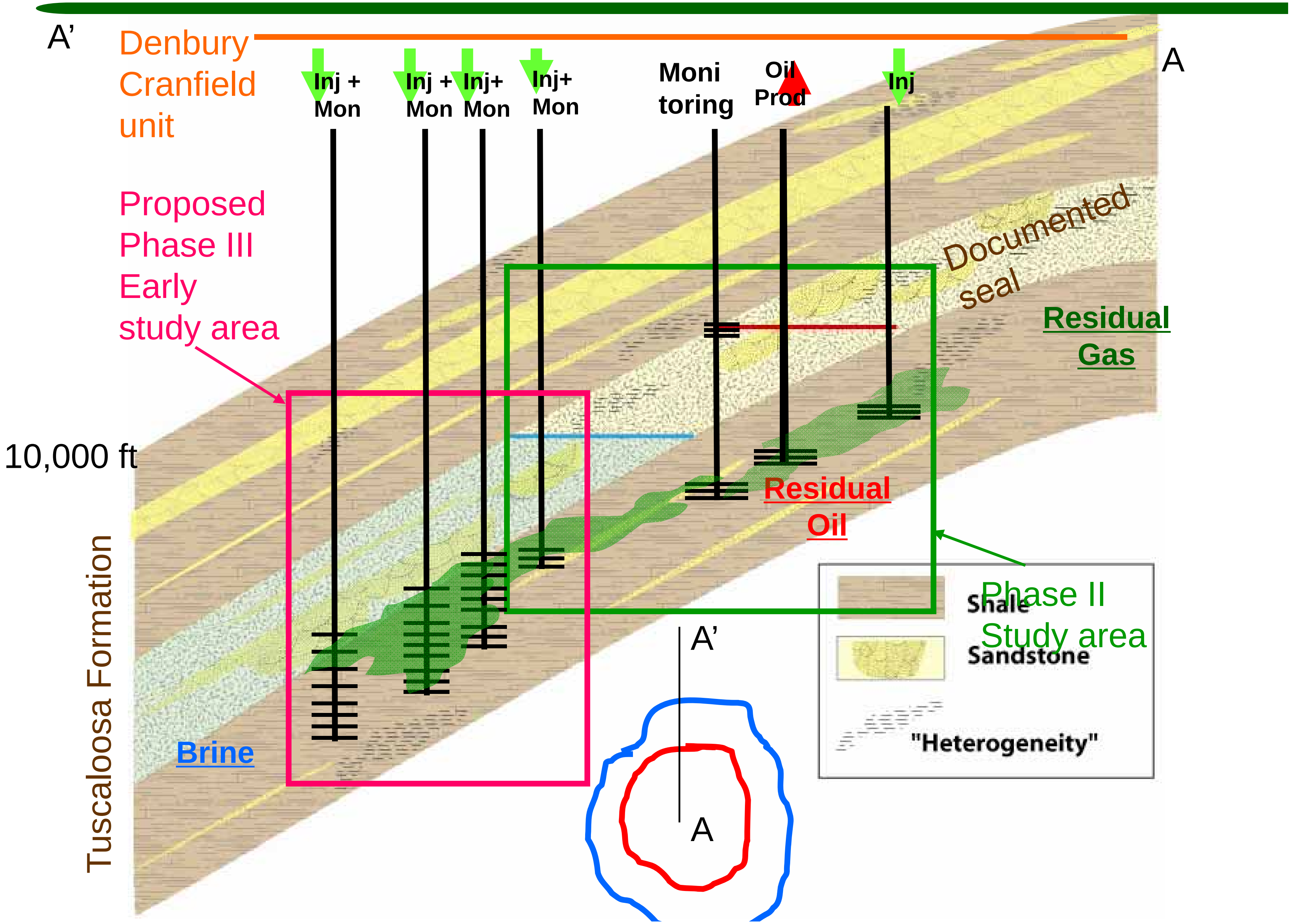
Lone Wolf Drilling Rig
CO_2 Injector

Satellite Uplink

Sites for SECARB Phase III Linked to near-term CO_2 sources



Cranfield Program Overview



SECARB Phase III Anthropogenic Test

- CO_2 injection at Citronelle Field (existing oil field owned and operated by Denbury Resources) near Citronelle, AL
  - Beginning in 2011, between 100,000 and 150,000 tonnes of CO_2 per year
  - Injection target: Paluxy Formation below 9,000 feet
- CO_2 Source: anthropogenic CO_2 from Alabama Power Company's Plan Barry (near Mobile) 25 MW slip stream using MHI advanced amine
- Transportation: approximately 10 miles, dedicated CO_2 pipeline built to commercial specifications

Offshore Storage of Carbon Dioxide

Pilot Study

- Determine the potential size and storage capacity of offshore oil and natural gas fields in the southeast
- Map the offshore resources of the southeast region (integrate with NATCARB)
- Examine the current legal and regulatory structures/opportunities for emerging technologies
- Deploy a comprehensive outreach and awareness plan

SECARB Risk Management

IEA Greenhouse Gas R&D Programme

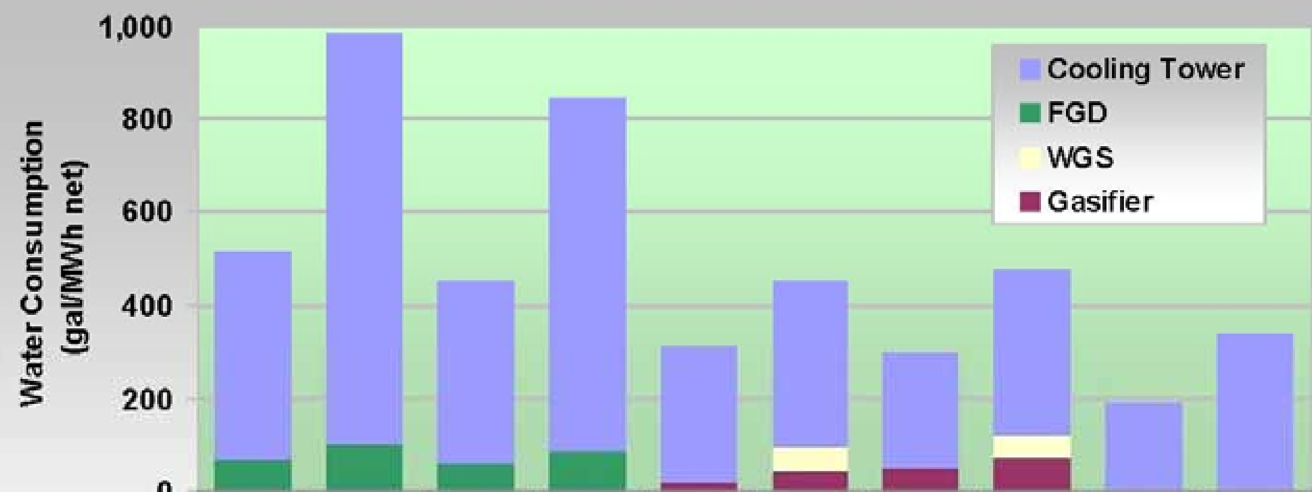
Peer Review of Partnerships – March 2008

Recommendation:

"…*better convey risk management strategies*…"

- Subsurface Risk – Capacity; Injectivity; Seal Integrity
- Well Risk – MIT; CO_2 Compatibility; P&A; Existing Penetrations
- Liability – CO_2 Migration/Leakage; USDW; Air
- EPC – Performance; Schedule; Cost Escalation; Regulatory; Financing

Water Use ***With*** and ***Without*** Carbon Capture



	Subcritical PC		Supercritical PC		IGCC (slurry fed)		IGCC (dry fed)		NGCC	
	No CDR	CDR	No CDR	CDR	No CDR	CDR	No CDR	CDR	No CDR	CDR
Total	517	985	452	844	309	452	295	475	192	338
Cooling Tower	449	884	392	759	290	355	243	355	192	338
FGD	68	101	59	86						
WGS						52		49		
Gasifier					19	45	53	71		

Comparison of water consumption factors with and without carbon capture for greenfield plants using wet recirculating cooling towers - net power basis. (Note: FGD refers to flue gas desulfurization; WGS refers to water gas shift; and CDR refers to carbon dioxide recovery.)

Source: Gerdes 2008, DOE/NETL, Section 4

CCS Development, Demonstration & Deployment

- **Development of Large Scale Injection Tests**
  - Regional Diversity in Target Formations
  - 100,000 – 1,000,000 TPY CO_2 Injection Rates
  - Strong Monitoring, Verification & Accounting (MVA) Component
- **Demonstration of CCS Systems**
  - Integration of Capture/Separation, Transportation and Sequestration
  - High Purity CO_2 Sources and Power Plant Slip Streams
  - Four- to Six-year Periods of Monitored Injection
- **Barriers to CCS Deployment**
  - Regulatory and Institutional Frameworks Needed
  - Private-Public Funding Mechanisms Required for First Movers
  - Cost and Performance Issues Until N^{th} Plant

The SECARB Anthropogenic Test: CO_2 Capture/Transportation/Storage

Project # DE-FC26-05NT42590

Jerry Hill, Southern Sates Energy Board
Richard A. Esposito, Southern Company

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

Presentation Outline

- Benefit to the Program
- Project Overview
- Technical Status
  - CO_2 Capture
  - CO_2 Transportation
  - CO_2 Storage
- Accomplishments to Date
- Organization Chart
- Gantt Chart
- Bibliography
- Summary

Benefit to the Program

1. Predict storage capacities within +/- 30%

- Conducted high resolution reservoir characterization of the Paluxy saline formation key reservoir parameters for calculating CO_2 storage capacity.
- Incorporated geologic model of the Citronelle Dome/Paluxy Formation CO_2 storage site into a state-of-the-art reservoir simulator to predict storage capacity and CO_2 plume.
- Established extensive subsurface monitoring to measure areal extent of CO_2 plume and actual CO_2 storage capacity.

2. Demonstrate that 99% of CO_2 is retained

- Selected CO_2 storage site with 4-way closure, multiple confining units and secondary storage horizons.
- Reservoir characterization completed to identify residual CO_2 phase (pore space trapping), CO_2 dissolution in water; completed seismic- and log-based assessment of the integrity of the reservoir caprock.
- Established within and above zone pressure monitoring systems, CO_2 tracer programs, multiple cross-well seismic shoots and repeated use of cased hole neutron logging.

3. Conduct Field Tests supporting the development of Best Practices Manuals

- Served on the Review Board of the DOE/NETL Drilling Manual; edited the DOE/NETL Reservoir Simulation Manual; and wrote chapter on CO_2 leakage mitigation for California report on CCS.

Project Overview

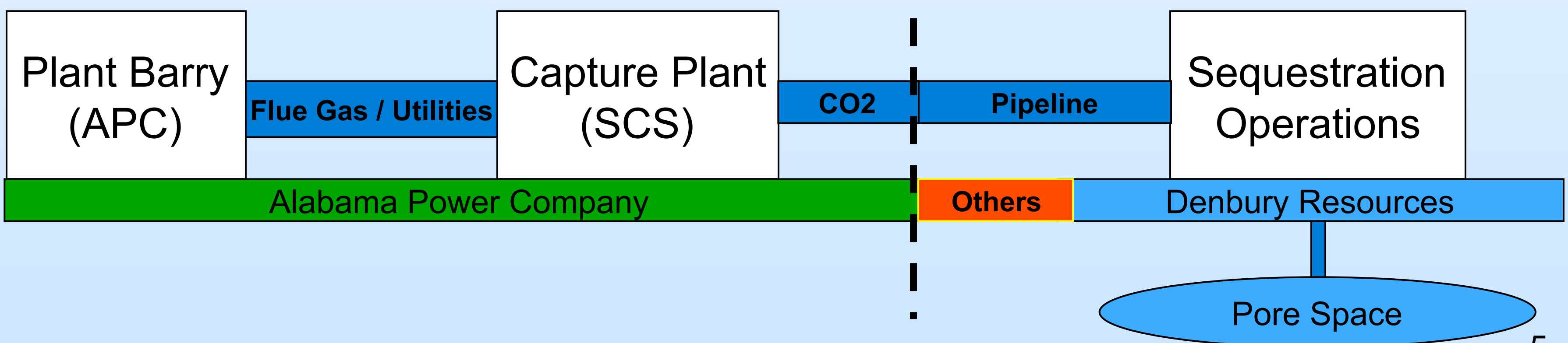
- Fully integrated capture, transport and storage project
- Construct and operate a 25 MW (182,500 Mt) equivalent CO_2 capture unit at Alabama Power Plant Barry
- Construct and operate a pipeline that will transport CO_2 from Plant Barry to a saline formation in Citronelle Dome
- Inject > 200,000 metric tons of CO_2 into a saline reservoir over a period of 2 years
- Conduct 3 years of monitoring after CO_2 injection is concluded and then close the site

Capture Project

- SO collaborating with MHI
- Location: APC's Plant Barry
- Execution/contracting: SO

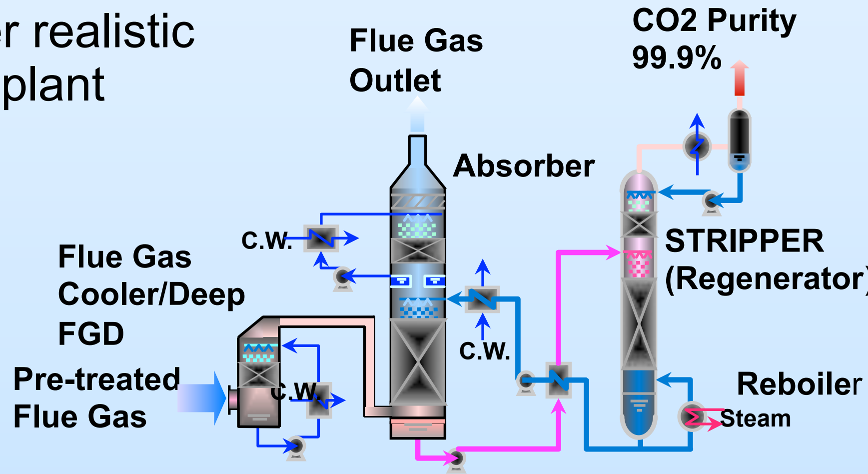
Sequestration Project

- Project: DOE's SECARB Phase III
- Prime contractors: SSEB and EPRI
- CO_2 : SO supplying
- Sequestration: Citronelle Oil Field



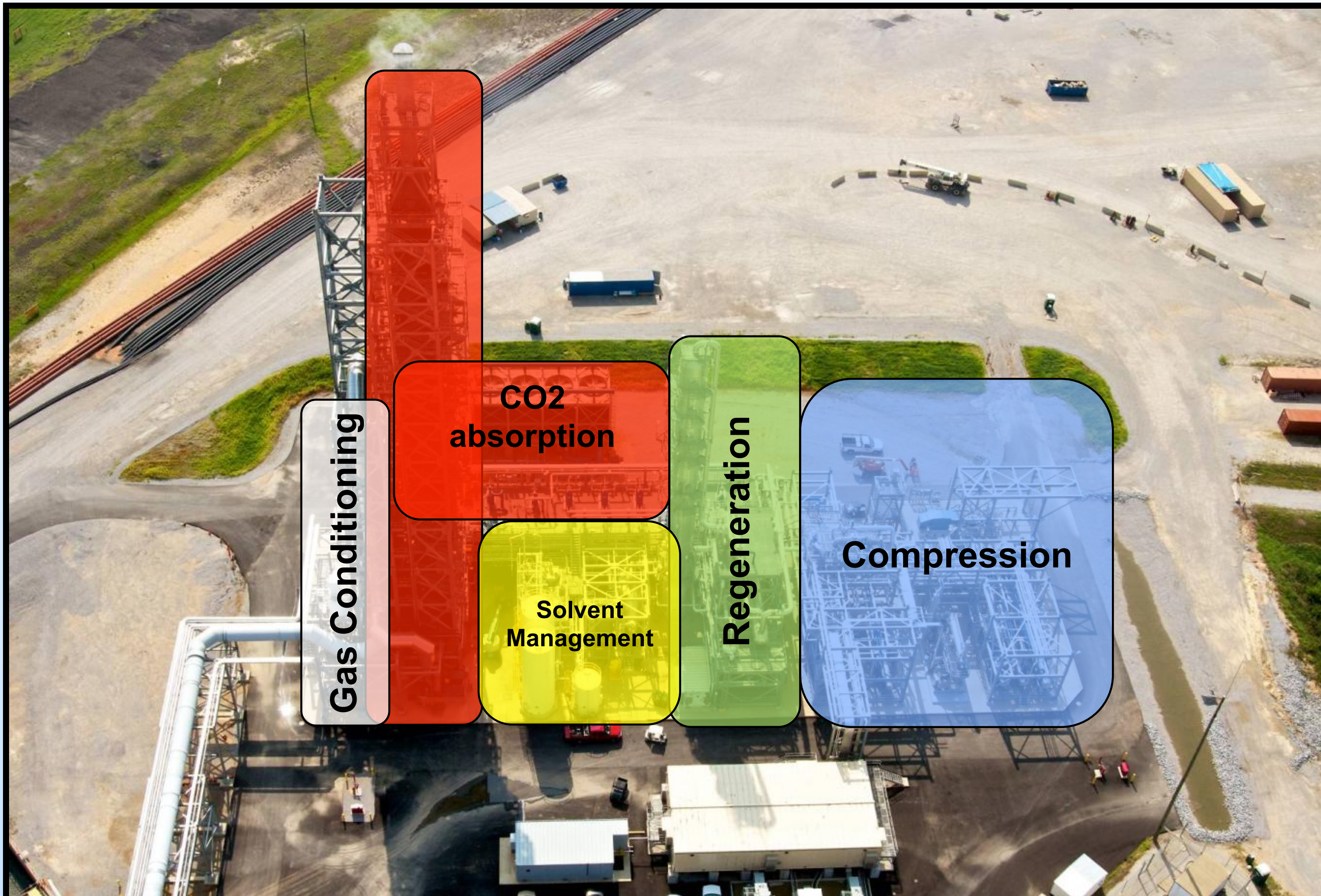
Capture Project Scope & Objectives

- **Project Scope:**
  - Demonstrate post-combustion capture of CO_2 from flue gas using MHI's advanced amine process
- **Project Philosophy:**
  - Fully representative of full scale design
  - Establish and demonstrate a contracting and execution strategy
  - Operation and maintenance in realistic conditions
  - Establish partnerships for future commercial projects
- **Project Objectives:**
  - Demonstrate integrated CO_2 capture under realistic operating conditions typical of a coal-fired plant
  - Establish values for the energy penalty
  - Test reliability of solvent-based capture
  - Source CO_2 for injection demonstration



Simplified schematic post-combustion solvent process

25MW, 500 TPD Demonstration




11/04/2010

Capture Plant Update

2010

2012

Capture plant & compressor started operations on June 4, 2011 with 70,000 metric tons CO_2 captured to date.

CO_2 Pipeline Overview

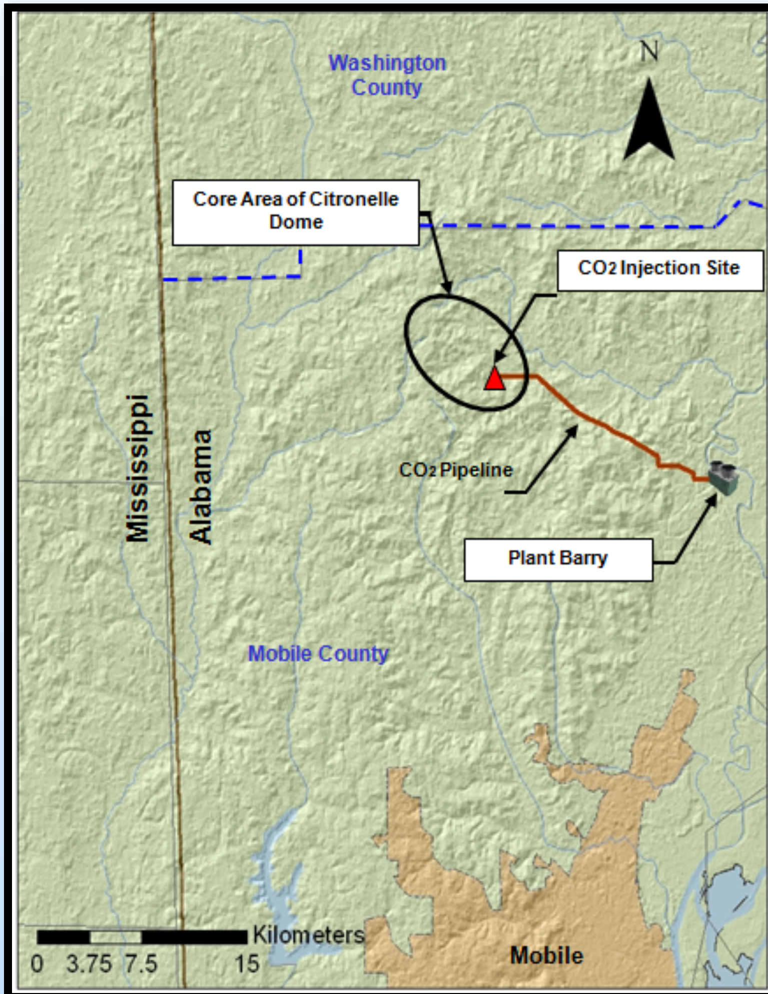
- Approx. 12mi (19km) to the SE operators unit in Citronelle Field
- Pipe specifications
  - 4-in (10cm) pipe diameter
  - X42/52 carbon steel
  - Normal operating pressure of 1,500 psig (10.3 MPa)
  - DOT 29 CFR 195 liquid pipeline; buried 5 feet with surface re-vegetation and erosion control
- Denbury pipeline purity requirement:

> 97% dry CO_2 at 115ºF (46ºC)

< 0.5% inerts (including N2 & argon)

< 30 lb water per 1MMSCF

< 20 ppm H2S



Pipeline Right-of-Way

- Right-of-Way Ownership
  - 1¼ mi (2 km) inside Plant Barry property
  - 8 mi (13 km) along existing power corridor
  - 2 mi (3 km) undisturbed forested land
  - Permanent cleared width 20 ft (6 m)
  - Temporary construction width 40 ft (12 m)
- Right-of-Way Habitat
  - 9 mi (14.5 km) of forested and commercial timber land
  - 3 mi (5 km) of emergent, shrub, and forested wetlands
  - Endangered Gopher Tortoise habitat
    - 110 burrows in or adjacent to construction area

DOT 29 CFR 195 liquid pipeline; buried 5 feet with surface vegetation maintenance

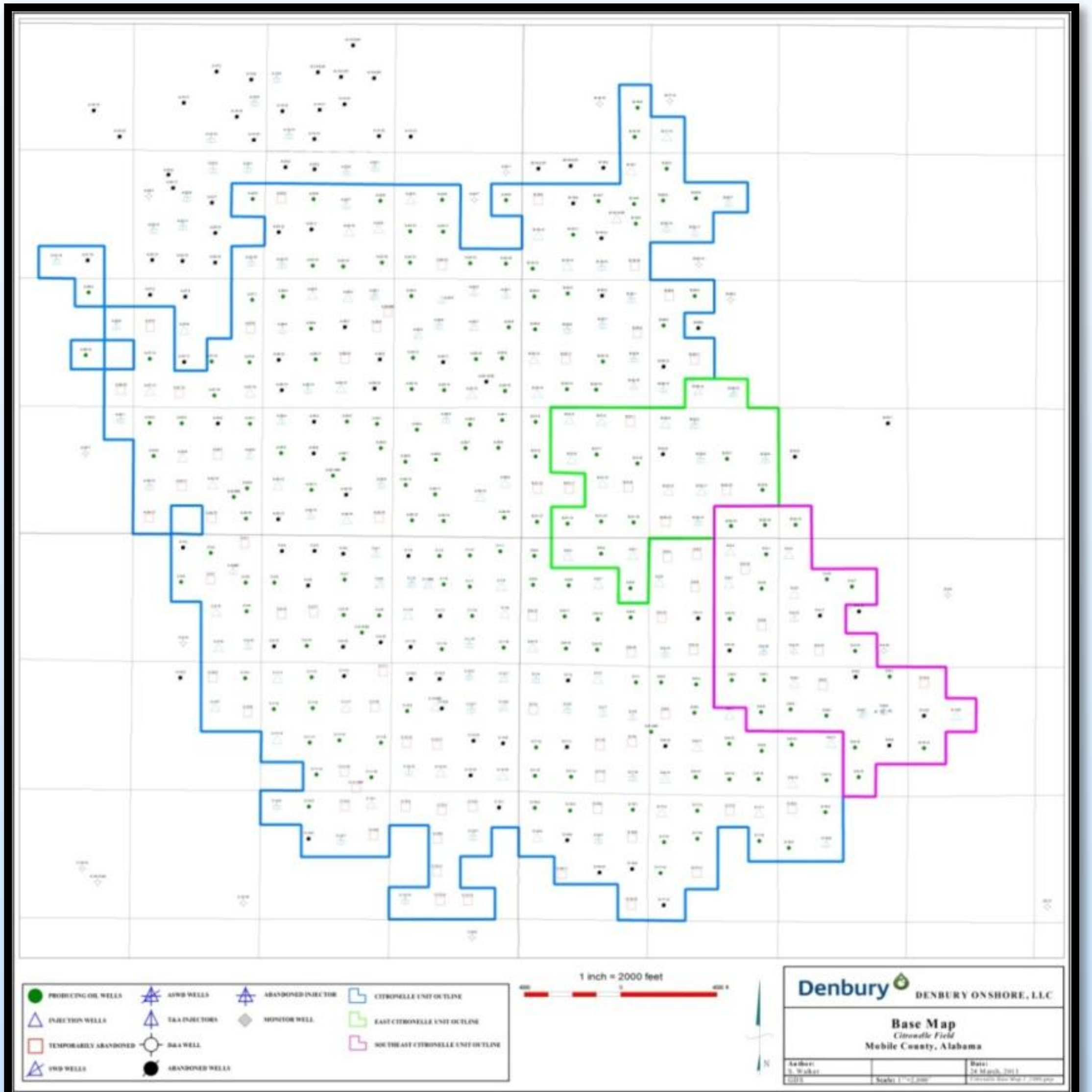
Directional drilled 18 sections of the pipeline under roads, utilities, railroad tracks, tortoise colonies, and wetlands (some up to 3,000 feet long and up to 60 ft deep).

Storage Scope & Objectives

- **Scope:**
  - Demonstrate safe, secure CO_2 injection and storage in regionally significant saline reservoirs in the southeast U.S. region
- **Objectives:**
  - Identify potential leakage risk
  - Evaluate local storage capacity, injectivity and trapping mechanisms of saline reservoir
  - Test the adaptation of commercially available oil field tools and techniques for monitoring CO_2 storage
  - Permit pipeline and injection, stakeholder acceptance through outreach & education

NETL SECARB Southeast Regional Carbon Sequestration Partnership EPRI Denbury Advanced Resources International, Inc. SOUTHERN COMPANY

Citronelle Field – Basic Facts



- Citronelle Field located in & around the City of Citronelle
  - Approx. 1 hour north of Mobile, AL
- Field is comprised of 3 active units: Main, East & Southeast
- There are 423 wells in the 3 Denbury operated units
  - 168 active producers
  - 62 active injectors
  - 7 SWD wells
  - 93 TA/TP wells
  - 88 plugged
  - 5 SECARB
- Denbury took over operations on Feb. 1, 2006 from Merit Energy

System	Series	Stratigraphic Unit	Major Sub Units	Potential Reservoirs and Confining Zones
Tertiary	Plio-Pliocene		Citronelle Formation	Freshwater Aquifer
	Miocene	Undifferentiated		Freshwater Aquifer
	Oligocene		Chicasawhay Fm.	Base of USDW
		Vicksburg Group	Bucatunna Clay	Local Confining Unit
	Eocene	Jackson Group		Minor Saline Reservoir
		Claiborne Group	Talahatta Fm.	Saline Reservoir
		Wilcox Group	Hatchetigbee Sand Bashi Marl Salt Mountain LS	Saline Reservoir
	Paleocene	Midway Group	Porters Creek Clay	Confining Unit
Cretaceous	Upper	Selma Group		Confining Unit
		Eutaw Formation		Minor Saline Reservoir
		Tuscaloosa Group	Upper Tusc.	Minor Saline Reservoir
			Mid. Tusc. – Marine Shale	Confining Unit
			Lower Tusc. – Pilot Sand Massive sand	Saline Reservoir
Cretaceous	Lower	Washita-Fredericksburg	Dantzler sand	Saline Reservoir
			Basal Shale	Primary Confining Unit
		Paluxy Formation	'Upper' 'Middle' 'Lower'	Proposed Injection Zone
		Mooringsport Formation		Confining Unit
		Ferry Lake Anhydrite		Confining Unit
		Donovan Sand	Rodessa Fm. 'Upper'	Oil Reservoir
			'Middle'	Minor Saline Reservoir
			'Lower'	Oil Reservoir

Stacked Storage Reservoirs with Multiple Seals

Tertiary Injection Zone (Eutaw Fm.)

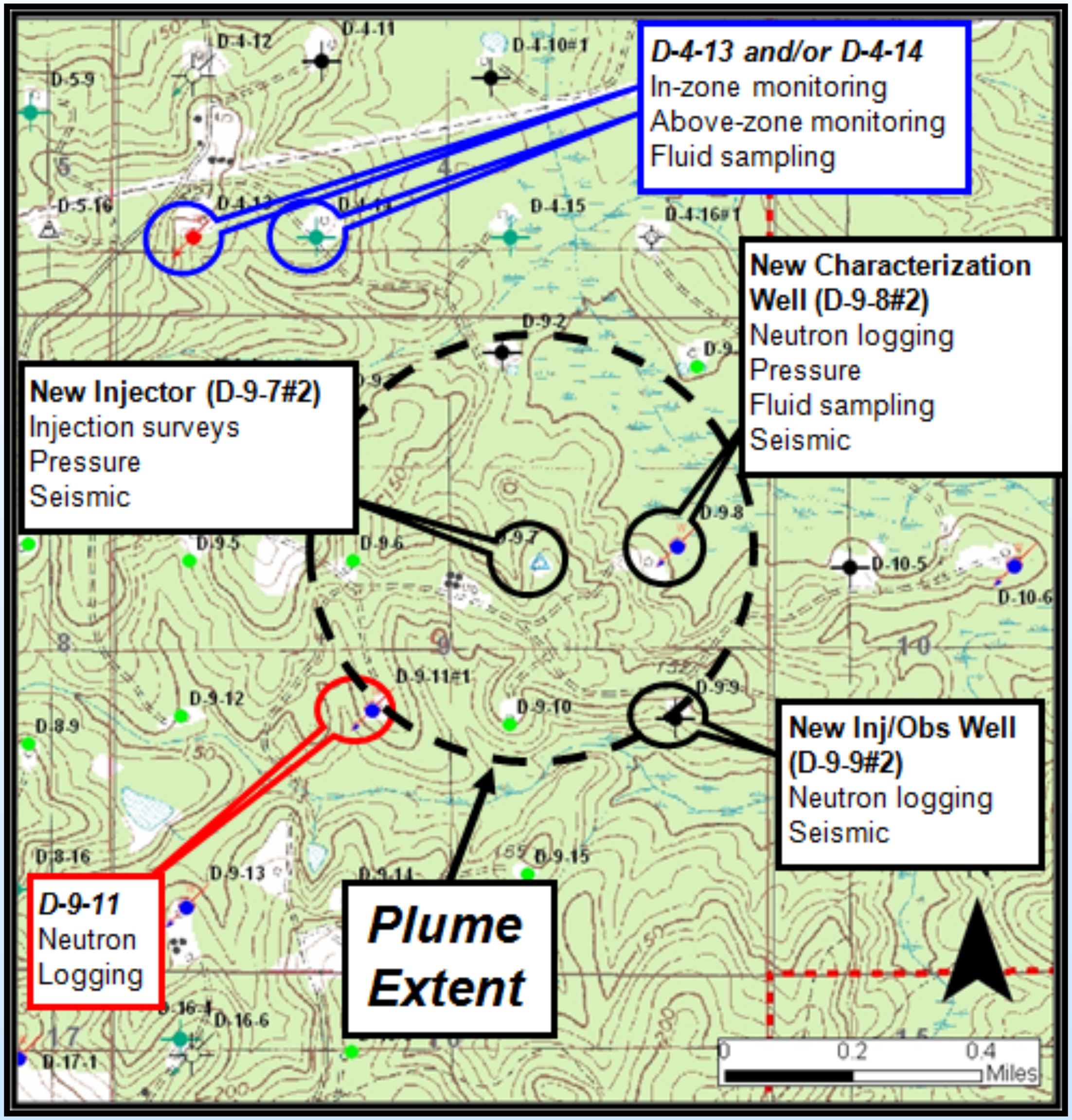
Secondary Injection Zone (Tuscaloosa Fm.)

Proposed Injection Zone (Paluxy Fm.)

Injection Zone Characteristics

Top Depth (ft, log)	Gross Sand Thickness (ft)	Net 'Clean Sand' Thickness (ft)	Log Porosity (%)	Sidewall Core Porosity (%)	Permeability (md) *from porosity - permeability cross plot*
9,437	**41**	**36**	**20.9**	**21.3-21.9**	**450**
9,507	**20**	**11**	**20.3**	**21.6**	**360**
9,531	**18**	**13**	**18.6**	**n/a**	**190**
9,560	**23**	**9**	**19.0**	**n/a**	**220**
9,594	41	38	20.0	18.4-23.0	320
9,656	23	4	17.4	n/a	120
9,695	**24**	**21**	**18.9**	**18.6-19.8**	**210**
9,729	**20**	**13**	**19.2**	**19.2-21.2**	**230**
9,771	**36**	**27**	**16.9**	**16.0-19.2**	**100**
9,830	12	6	16.6	n/a	90
9,881	**22**	**10**	**17.7**	**16.3**	**130**
9,954	**23**	**3**	**13.7**	**n/a**	**30**
10,014	11	6	16.9	n/a	100
10,034	13	8	19.5	n/a	260
10,091	16	10	16.7	n/a	90
10,118	15	11	15.5	n/a	60
10,297	17	7	14.7	n/a	40
10,356	20	5	14.0	n/a	30
10,392	17	1	14.7	n/a	40
10,454	**30**	**13**	**15.9**	**n/a**	**70**
10,487	28	17	15.6	n/a	60
	Total Gross Thickness: 470	**Total Net Thickness: 263**	**Weighted Average: 18.2**		**Weighted Average: 208**

Monitoring Program



The test will use 5 deep wells to track the CO_2 plume and 3 shallow water monitoring wells.

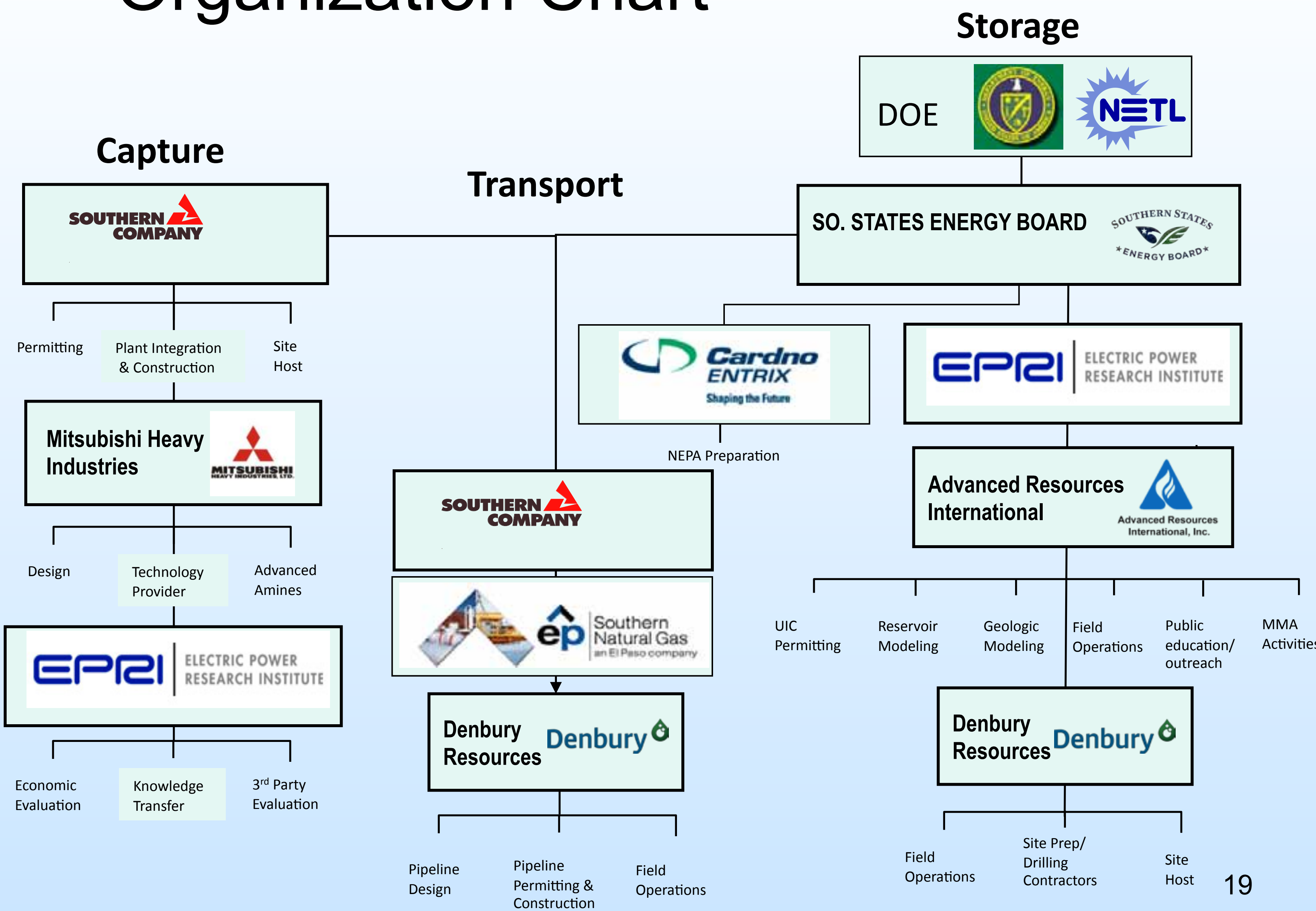
- Near-surface and deep reservoir fluid sampling.
- In-zone and above-zone pressure and temperature monitoring.
- Cased-hole neutron logging.
- Crosswell seismic and VSP.
- Surface soil flux and tracer surveys

Results will be used to update the reservoir model and UIC Area of Review.

Accomplishments to Date

- Design, construction, and operation of the world's largest carbon capture on a coal fired power plant with over 70,000 metric tonnes of CO_2 captured to date.
- Design, permitting, construction, commissioning, and operation of a 12 mile CO_2 pipeline.
- Development of a sequestration demonstration including site characterization, detailed geologic analysis, and construction and UIC of injection wells.
- Integration of CO_2 injection operations with pipeline transport and capture unit operations.
- MVA baseline monitoring including significant experimental/innovative technologies such as the modular borehole monitoring tool.
- First of a kind permit received for injection of CO_2 in the SE USA for geologic sequestration.

Organization Chart



Gantt Chart

- Baseline monitoring began in late 2011
- Permission to inject received on August 8, 2012
- CO_2 injection operations begin on August 13, 2012, continue for 2 years
- 3 years of post-injection monitoring, then close site

	Fiscal Year									
Anthropogenic Test	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Public Outreach & Education				■	■	■	■	■	■	■
Site Permitting		■	■	■						
Site Characterization and Modeling		■	■	■						
Well Drilling and Completion				■	■					
Transportation and Injection Operations					■	■	▨			
Operational Monitoring and Modeling					■	■	▨			
Site Closure									■	■
Post Injection Monitoring and Modeling								■	■	■
Project Assessment				■	■	■	■	■	■	■

Bibliography

- Esposito, R., Rhudy, R., Trautz, R., Koperna, G., and Hill, J., "Integrating Carbon Capture with Transportation and Storage," presented at the 10th International Conference on Greenhouse Gas Technologies, 19-23 September 2010, Amsterdam, Netherlands.
- Esposito, R., Harvick, C. , Shaw, R, Mooneyhan, D., Trautz, R., Hill, G, "Integration of Pipeline Operations Sourced with CO_2 Captured at a Coal-fired Power Plant and Injected for Geologic Storage: SECARB Phase III CCS Demonstration" presented at the 11th International Conference on Greenhouse Gas Technologies, 19-22 November, 201, Kyoto, Japan.
- Koperna, G., Riestenberg, D., Kuuskraa, V., et al. 2012. , "The SECARB Anthropogenic Test: Status from the Field," presented at the 11th International Conference on Greenhouse Gas Technologies, 19-22 November, 201, Kyoto, Japan.
- Koperna, G., Riestenberg, D., Rhudy, R., Trautz, R., Hill, J., and Esposito, R., "The SECARB Anthropogenic Test: The First U.S. Integrated CO_2 Capture, Transportation and Storage Project," presented at the 2011 AIChE Spring Meeting, March 13-17, 2011, Chicago, IL.
- Koperna, G., Kuuskraa, V., Riestenberg, D., Rhudy, R., Trautz, R., Esposito, R., And Hill, G. "The SECARB Anthropogenic Test: The First U.S. Integrated Co2 Capture, Transportation And Storage Test," The 28th Annual International Pittsburgh Coal Conference. September, 2011, Pittsburgh, PA.
- Riestenberg, D., Koperna, G., Kuuskraa, V., Rhudy, R., Trautz, R., Hill, G., and Esposito, R. "Initial Lessons Learned From the SECARB Anthropogenic Test: The First U.S. Integrated CO_2 Capture, Transportation and Storage Test," 11th Annual Conference on Carbon Capture and Sequestration, May 2012, Pittsburgh, PA.
- Petrusak, R., Riestenberg, D., and Cyphers, S. "Core and Log Analyses for Reservoir Characterization of the Paluxy Formation at Citronelle Dome for the Southeast Regional Carbon Sequestration (SECARB) Partnership Phase III Anthropogenic Test," 10th Annual Conference on Carbon Capture and Sequestration, May 2011, Pittsburgh, PA.

Lessons Learned

1. Planning and operating a fully integrated, commercial prototype CO_2 capture, transportation and storage project requires extensive negotiations and flexibility in plans and schedules.

> Accomplishment. The Anthropogenic Test storage team has adapted its schedule and managed its activities to match the Alabama Power's CO_2 capture schedule and Denbury Resource's CO_2 transportation schedule.

2. Selecting and gaining approval for a high quality, regionally significant saline formation for storing CO_2 is a major challenge.

> Accomplishment. The Anthropogenic Test storage team identified and gained access to the regionally extensive, low risk but geologically challenging Paluxy saline formation for storing CO_2.

Lessons Learned *(continued)*

3. Investing significant up-front time and effort in problem identification and risk avoidance was crucial for securing a safe, secure CO_2 storage site.

> Accomplishment. The Anthropogenic Test storage team conducted extensive evaluation of the casing programs and cement integrity of the older wells surrounding the CO_2 storage site to assure an acceptable "area of review" for CO_2 injection and storage.

4. Investing in detailed site and reservoir characterization, particularly in a fluvial, complex formation such as the Paluxy, is essential for ensuring adequate CO_2 storage capacity, safe CO_2 injection operations, and effective CO_2 monitoring.

> Accomplishment. The Anthropogenic Test storage team conducted flow unit descriptions of reservoir continuity and injectivity to enable the team formulate a well design and completion scheme that minimizes the areal extent of the CO_2 plume.

Future Plans

- Continue monitoring the CO_2 capture, transportation, and injection operations and maximizing the efficiency of the integrated system.
- Maintain risk registry with capture, transportation, injection and monitoring operations reviews.
- Share lessons learned from the Anthropogenic Test with a broad audience through:
  - knowledge sharing opportunities;
  - community and stakeholder briefings;
  - posters and presentations at national and international conferences;
  - news and journal articles;
  - RCSP Working Groups;
  - SECARB website (secarbon.org) and social media (FB: SECARB1; Twitter: @SECARB1); and site visits.

Southeast Regional Carbon Sequestration Partnership
Citronelle Project: Experiences with Permitting and Regulations on CCS

SECARB

Carbon Storage R&D
Project Review Meeting
August 21, 2013

Kimberly Sams
Assistant Director, Geoscience Programs
Southern States Energy Board

Permitting Outline & Project Location

- National Environmental Protection Act (NEPA)
- Alabama Historical Commission
- U.S. Fish and Wildlife
- U.S. Army Corps of Engineers
- Alabama Department of Environmental Management (ADEM)

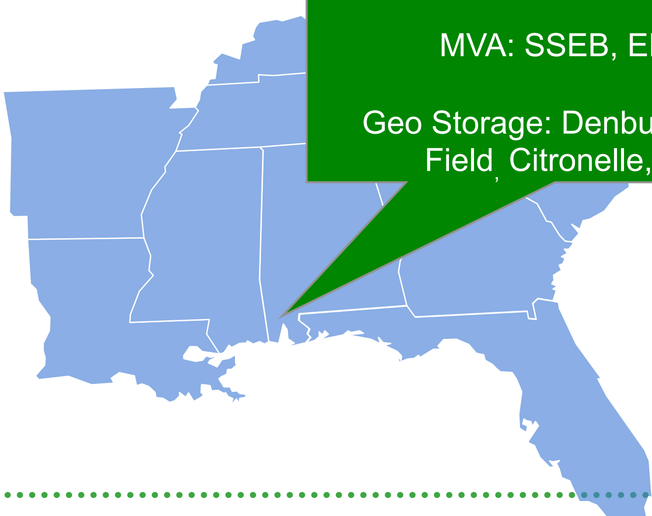
Anthropogenic Test

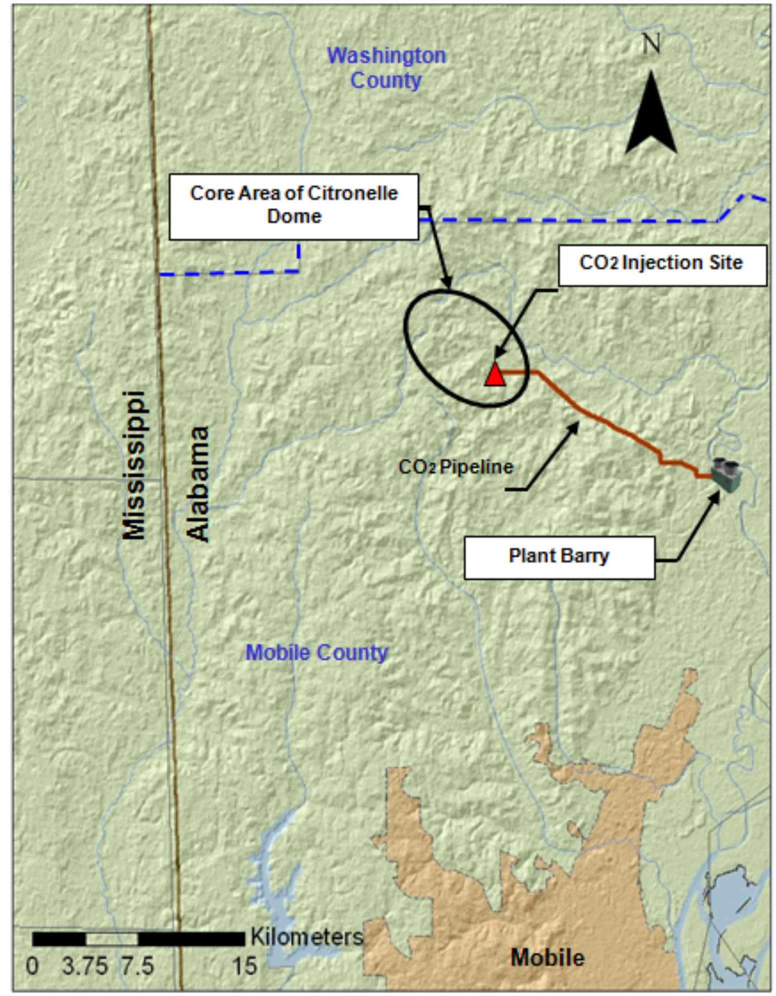
Capture: Alabama Power 's Plant Barry, Bucks, Alabama

Transportation: Denbury

MVA: SSEB, EPRI, ARI

Geo Storage: Denbury's Citronelle Field, Citronelle, Alabama

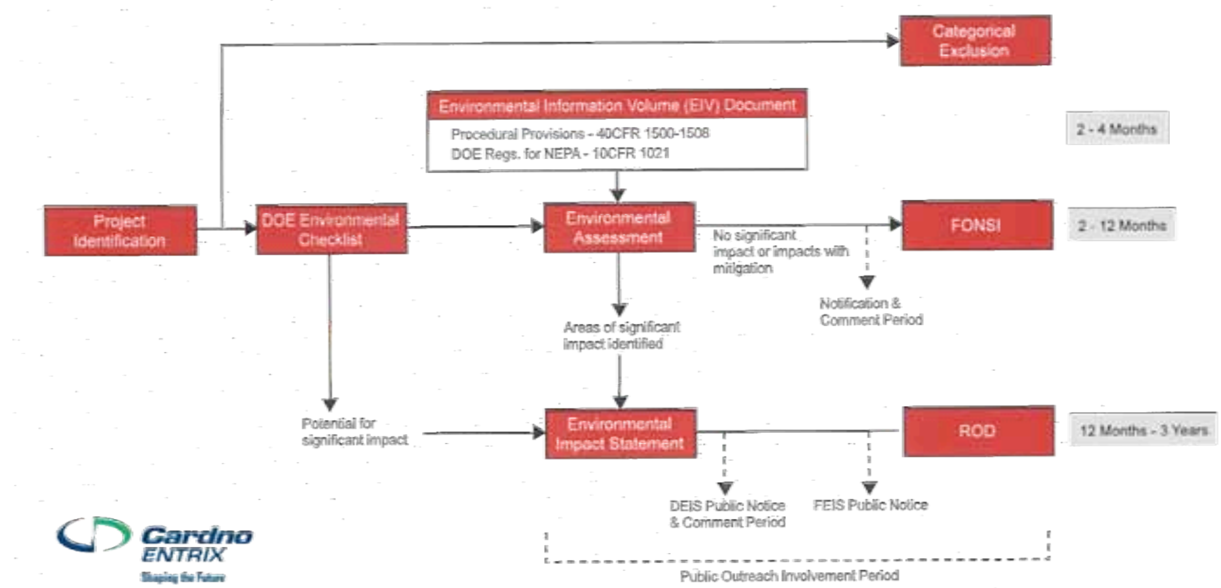




National Environmental Protection Act

Environmental Impacts

- Categorical Exclusion: All locations performing office work, planning, coordination, etc.
- Environmental Assessment (EA)
  - Environmental Information Volume and Supplements for Pipeline and Electric Transmission Line
  - Finding of No Significant Impact (FONSI) issued by NETL on March 18, 2011



Alabama Historical Commission

State Cultural or Archaeological Assets

- 2 cultural resources assessments
- 4 archaeological sites discovered in the Transmission Line survey, though not eligible under the National Register of Historic Places – no further investigations warranted
- No cultural resources were discovered – no further investigations warranted
- Following review of EA, "…agree with the EA as it pertains to no effect to National Register eligible cultural resources" by State Historic Preservation Officer, April 2011

U.S. Fish and Wildlife

Threatened and Endangered Species

- Endangered Gopher Tortoise habitat
- 110 burrows in/adjacent to construction area
- Directional drilling of pipeline
- Marked burrows at well pad site

SECARB Southeast Regional Carbon Sequestration Partnership · NETL · Southern States Energy Board · Bureau of Economic Geology · Gulf Coast Carbon Center · EPRI · Advanced Resources International, Inc. · Southern Company · Denbury

U.S. Army Corps of Engineers

Wetlands

- Pipeline route
  - 12 miles
  - Directional drilled 18 sections of the pipeline, 30-60 ft deep, under wetlands, roads, utilities, railroad tracks, and tortoise colonies
  - Surface re-vegetation and erosion control
- Well pad construction
  - Wetlands impacts mitigated after drilling completed

AL Dept. of Environmental Management

Underground Sources of Drinking Water

- Class V Experimental UIC Permit issued by the Alabama Department of Environmental Management (ADEM) on November 22, 2011
  - U.S. Environmental Protection Agency Headquarters Involvement
    - Provided comments to ADEM regarding permit requirements
    - Many Class VI standards applied to the Class V Permit (see below)
- Permission to Inject issued by ADEM on August 8, 2012
- Injection began in August 20, 2012

Injection Area of Review (AOR) determined by annual modeling
Periodic AOR updates based on monitoring and modeling results
Extensive deep, shallow and surface CO_2 monitoring
Monthly reporting of injection pressures, annular pressures and injection stream composition
Injection stream monitoring
Periodically updated Corrective Action Plan
Site closure based on USDW non-endangerment demonstration (5-yr renewal)
Pressurized annulus throughout injection (+/- 200 psig)
Emergency and remedial response plan
Post-injection site care plan

Southeast Regional Carbon Sequestration Partnership

Partnering with Industry for Large Scale CCS Projects

Carbon Storage R&D
Project Review Meeting
August 22, 2013

Kimberly Sams
Asst. Director, Geoscience Programs
Southern States Energy Board

Richard A. Esposito, Ph.D., P.G.
Principal Research Geologist
Southern Company

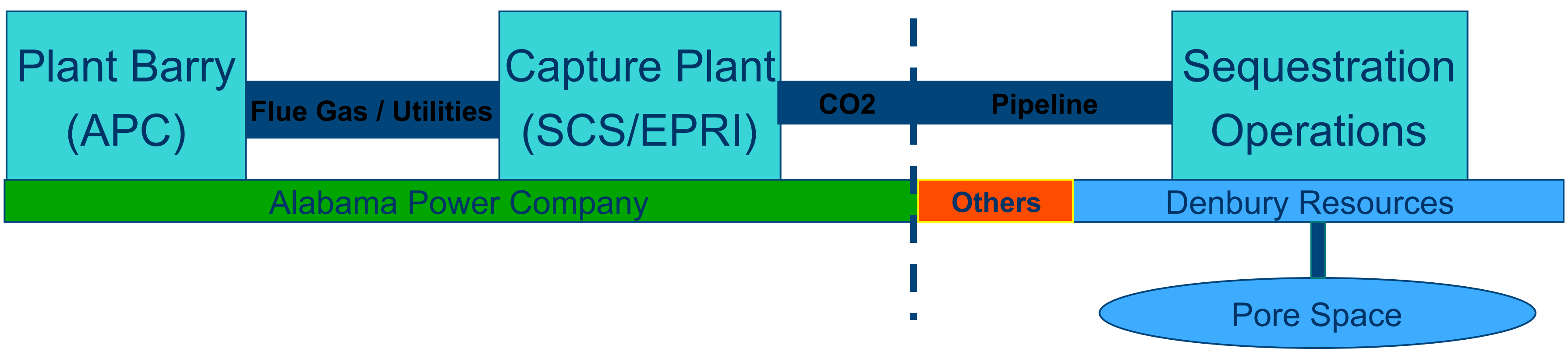
Project Partner Framework

Capture Project

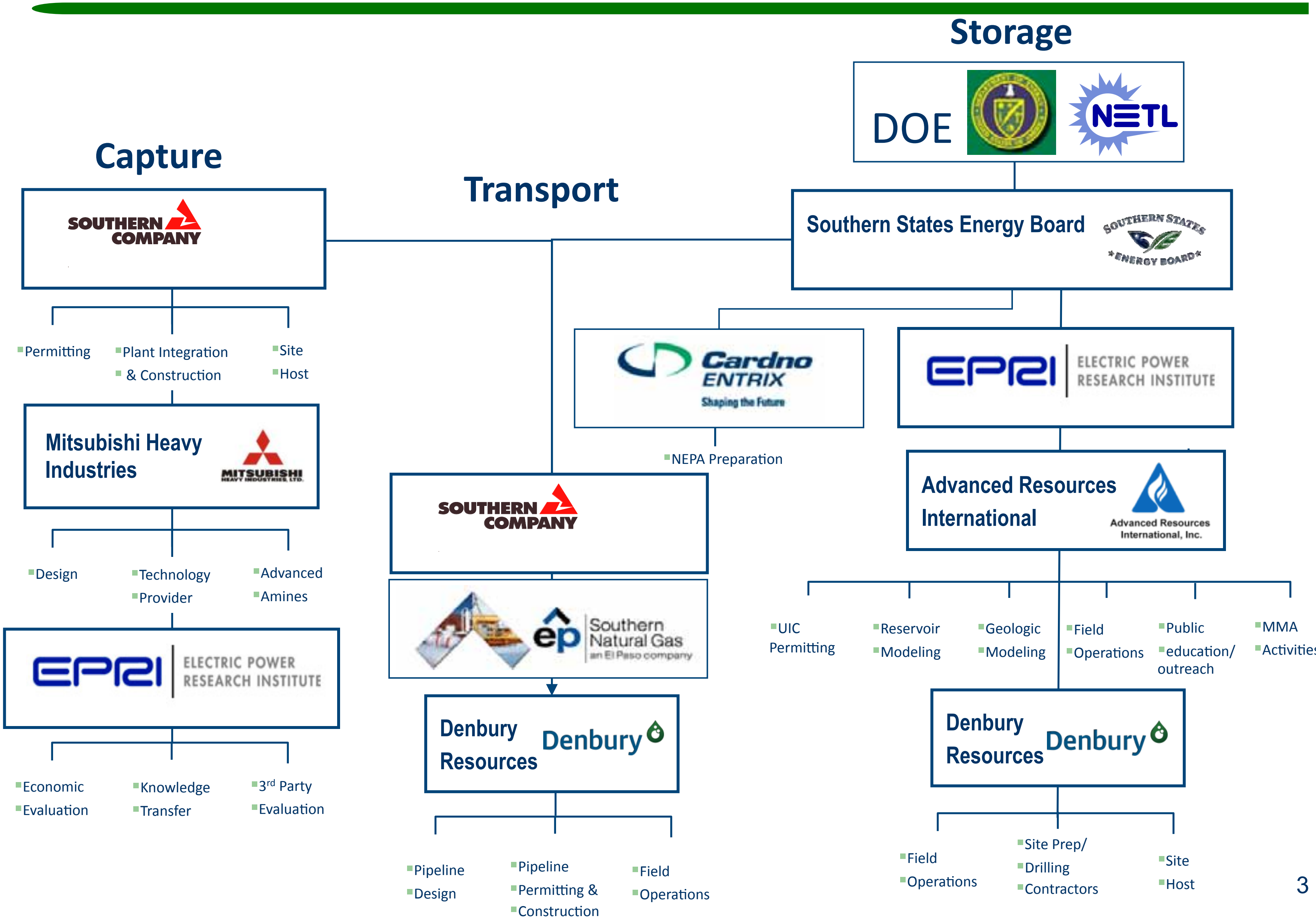
- Southern Company collaborating with Mitsubishi Heavy Industries
- Location: Alabama Power Company's Plant Barry
- Execution/contracting: Southern Company

Sequestration Project

- Project: DOE's SECARB Phase III
- Prime contractors: Southern States Energy Board (SSEB) and Electric Power Research Institute (EPRI)
- CO_2: Southern Company supplying
- Sequestration: Denbury Citronelle Field
- MVA: SSEB, EPRI, Advanced Resources International, Inc.



Organization Chart



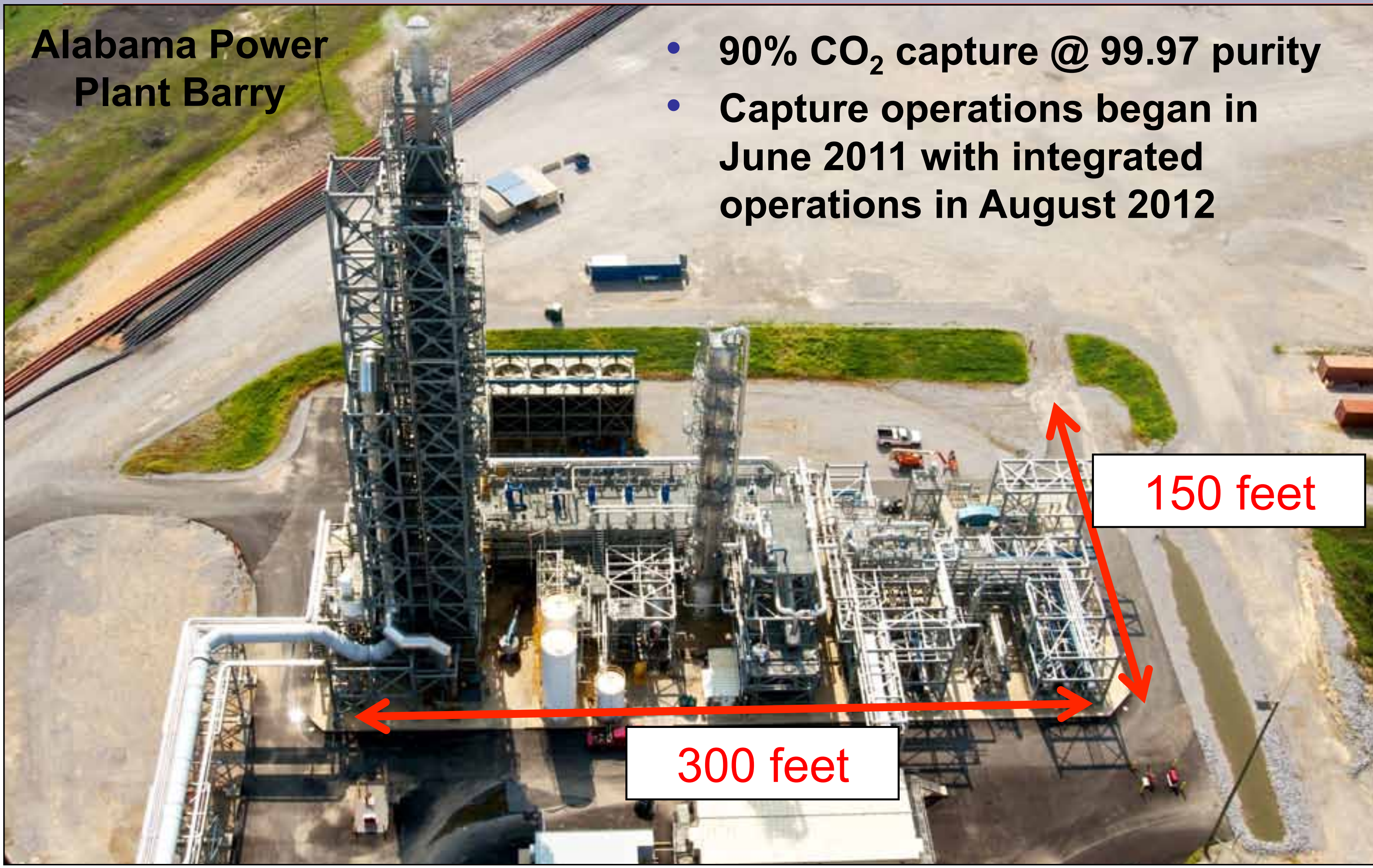
Agreements

- **CO_2 Off-take Agreement**
  - Southern Company & Denbury
  - Supply and off-take of anthropogenic CO_2 for transportation and use
- **Construction Terms & Considerations Agreement**
  - Southern Company & Denbury
  - Construction of CO_2 pipeline on Alabama Plant property
- **Backstop Agreement**
  - Southern Company & Denbury
- **Transportation Services Agreement**
  - SSEB & Denbury
  - Scope and terms of CO_2 delivery to Citronelle
- **MVA Service and Access Agreement**
  - ARI & Denbury
  - Commitment to provide a site, and to provide services required for MVA of injected CO_2

25-MW CCS Demo

"World's largest carbon capture facility on a fossil-fueled power plant"

SOUTHERN COMPANY



- 90% CO_2 capture @ 99.97 purity
- Capture operations began in June 2011 with integrated operations in August 2012

CO_2 Pipeline and Measurement Design

Check meter station & building at Denbury Citronelle Field

Check meter station to horizontal pump

Discharge side of horizontal pump

D-9-7#2 Wellhead with injection line

Keys to Success (and motivation)

- **Partners are "risk sophisticated"**
  - Perceived risks vs. real risks
  - Risk workshops at critical stages of the project to identify potential risk scenarios and risk owners and to develop mitigation plans"
- **"Learning by Doing" approach**
  - Understand the the coordination required to successfully integrate all components of a CCS project
  - Develop the business agreements for integrated projects and allocating risk among capture plant constructors/operators, CO_2 pipeline constructors/ operators, and injection field developers/operators was a complex process that has provided extremely useful information for future commercial CCS projects

Likelihood						
	Frequent					
	Probable	25	3	31		
	Possible		41	1, 11, 14, 30, 32, 34, 38		
	Unlikely	46, 48	4, 12, 15, 19, 37,39, 40, 43, 44	6, 18, 26, 36	8, 21	23, 24
	Remote	22	20, 35, 45, 47	2, 13, 16, 33, 42	5, 7, 27, 29	9, 10
Total risk June 2011		Slight	Minor	Moderate	Severe	Persistent Severe
		Consequence				

Likelihood						
	Certain / Frequent					
	Probable	25				
	Possible		41	38		
	Unlikely	46, 48	4, 12, 15, 19, 37, 39, 40	11, 14, 18, 26, 32, 36	8, 21, 29	23
	Remote		20, 45, 47	1, 2, 6, 7, 13, 16, 17, 33, 42	27	9, 10, 31
Total risk Jan. 2012		Slight	Minor	Moderate	Severe	Persistent severe
		Consequence				

Likelihood						
	Certain / Frequent					
	Probable					
	Possible		38			
	Unlikely	46, 48	4, 12, 15, 19, 37, 39, 40	14, 18, 21, 32, 50	8, 23, 41, 52	
	Remote	25, 26	20, 45, 47	1, 2, 6, 17, 29, 33, 36, 42	27	9, 10
Total risk May 2013		Slight	Minor	Moderate	Severe	Persistent severe
		Consequence				

SECARB Anthropogenic Test – Evolution of Risks over time (June 2011 to May 2013)

Keys to Success (and motivation)

- **Commercial deployment of CCS technologies is a win-win situation**
  - Southern Company: CO_2 mitigation technologies; avoidance of stranded assets and related technology investments
  - Denbury: sources of anthropogenic CO_2 to supplement natural CO_2 supply from the Jackson Dome
  - NETL: fully integrated, large-scale project to demonstrate feasibility of CCS technologies and remove barriers to commercial deployment
  - SSEB members: low electricity prices for residents; low electricity rates attracts new businesses and new jobs; retention of jobs in our coal states

Plant Barry - Citronelle Field Project Southeast Regional Carbon Sequestration Partnership (SECARB)

Prepared for:

Carbon Storage R&D Project Review Meeting

Pittsburgh, PA

Presented By:

Robert C. Trautz, Principal Technical Leader, EPRI
Steven M. Carpenter, VP Advanced Resources

13 August 2014

ELECTRIC POWER RESEARCH INSTITUTE

Advanced Resources International, Inc.

Acknowledgement

This presentation is based upon work supported by the Department of Energy National Energy Technology Laboratory under **DE-FC26-05NT42590** and was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Topics of Discussion

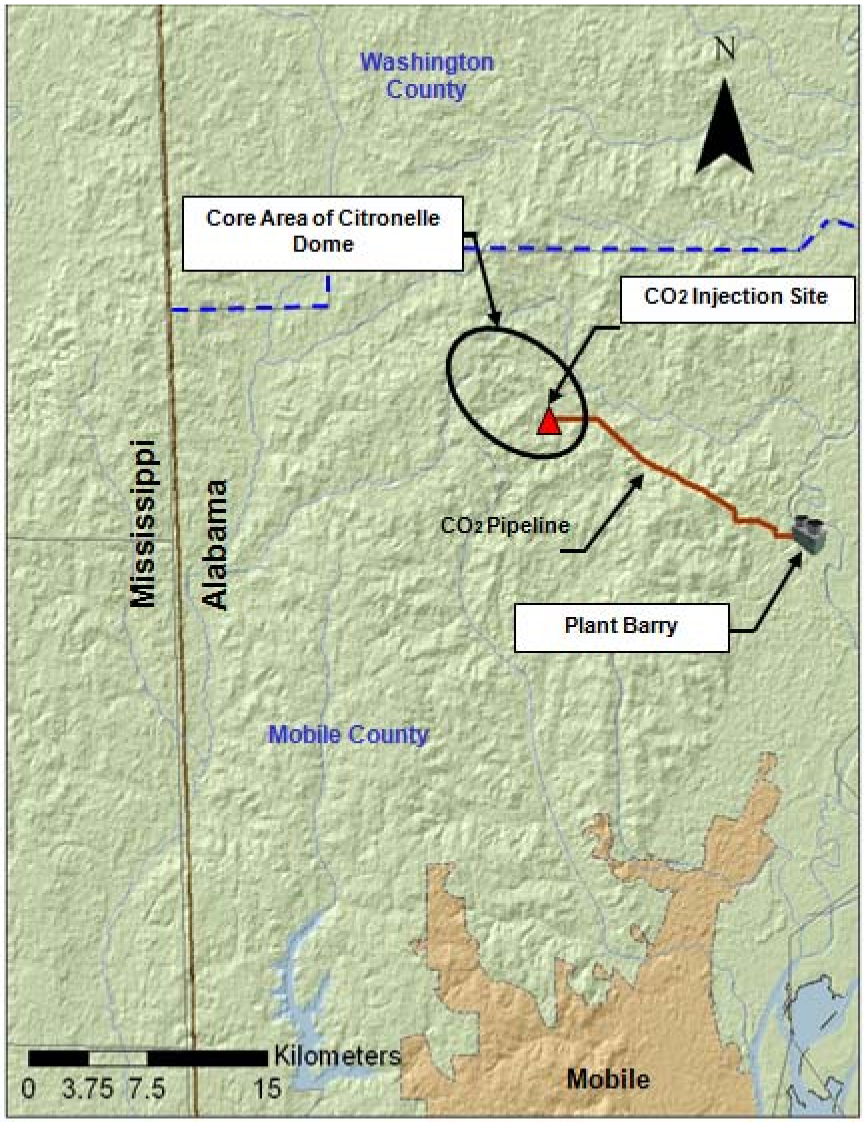
1. Citronelle Field Project Overview
2. Surface and Shallow MVA
3. Deep MVA
4. Experimental MVA
5. Questions, Answers, Discussion

Project Objectives

Baseline	Injection	Post
1 year	2 years	3 years
APR 2011 to AUG 2012	*SEPT 2012 to DEC 2014*	*JAN 2015 to SEPT 2017*

1. *Support the United States' largest prototype CO_2 capture and transportation demonstration with injection, monitoring and storage activities;*
2. *Test the CO_2 flow, trapping and storage mechanisms of the Paluxy;*
3. *Demonstrate how a saline reservoir's architecture can be used to maximize CO_2 storage and minimize the areal extent of the CO_2 plume;*
4. *Test the adaptation of commercially available oil field tools and techniques for monitoring CO_2 storage*
5. *Test experimental CO_2 monitoring activities, where such technologies hold promise for future commercialization;*
6. *Begin to understand the coordination required to successfully integrate all four components (capture, transport, injection and monitoring) of the project; and*
7. *Document the permitting process for all aspects of a CCS project.*

Citronelle Storage Overview



Project Schedule and Milestones

The CO_2 capture unit at Alabama Power's (Southern Co.) Plant Barry became ***operational in 3Q 2011.***

A newly built 12 mile CO_2 pipeline from Plant Barry to the Citronelle Dome ***completed in 4Q 2011.***

A characterization well was drilled in ***1Q 2011 to confirm geology.***

Injection wells were drilled in ***4Q 2011****.*

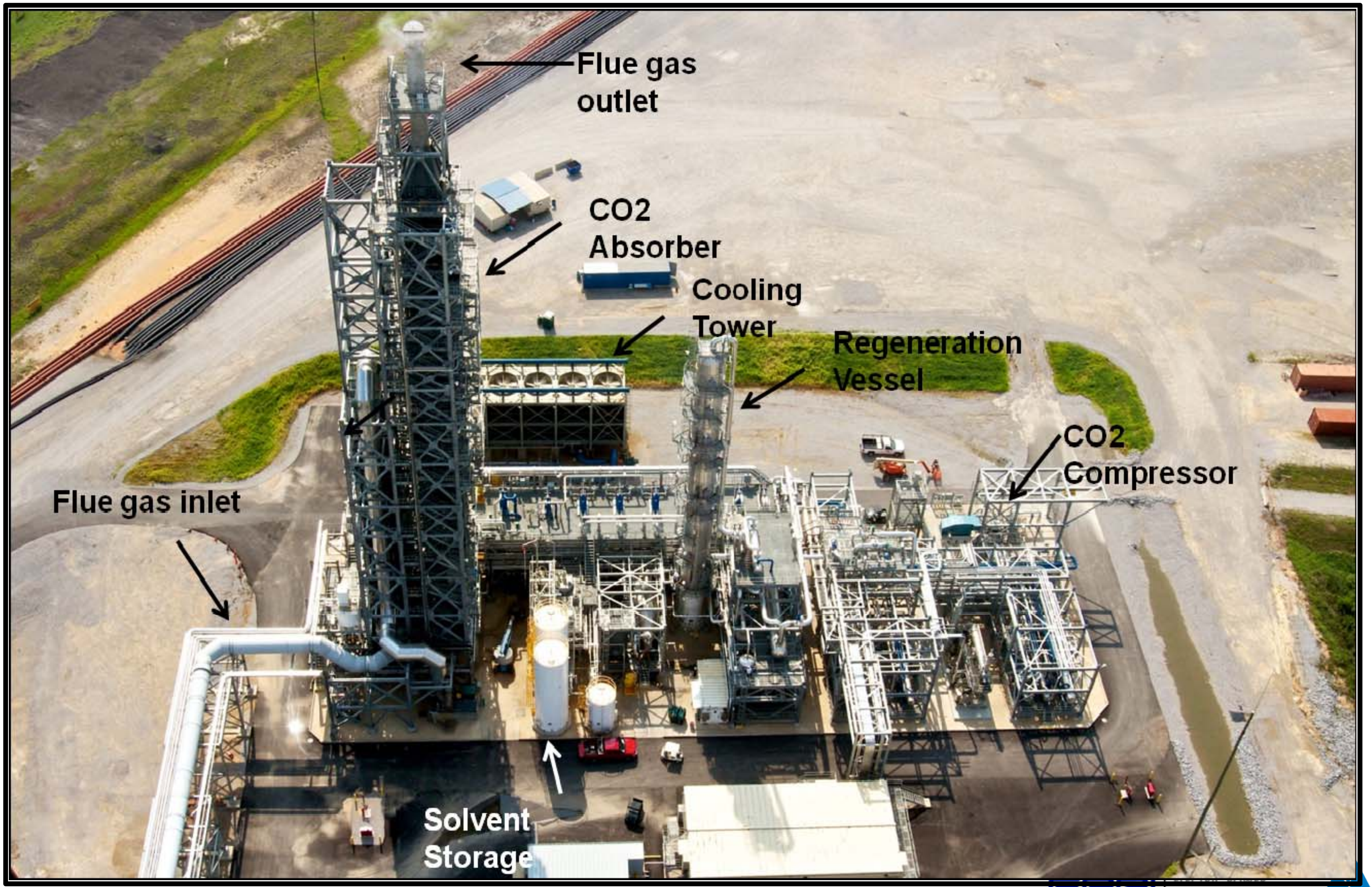
100k – 150k metric tons of CO_2 will be injected into a saline formation ***beginning 3Q 2012.***

3 years of post-injection monitoring*.*

ELECTRIC POWER RESEARCH INSTITUTE

Advanced Resources International, Inc.

Barry Carbon Capture Overview



Geologic Overview

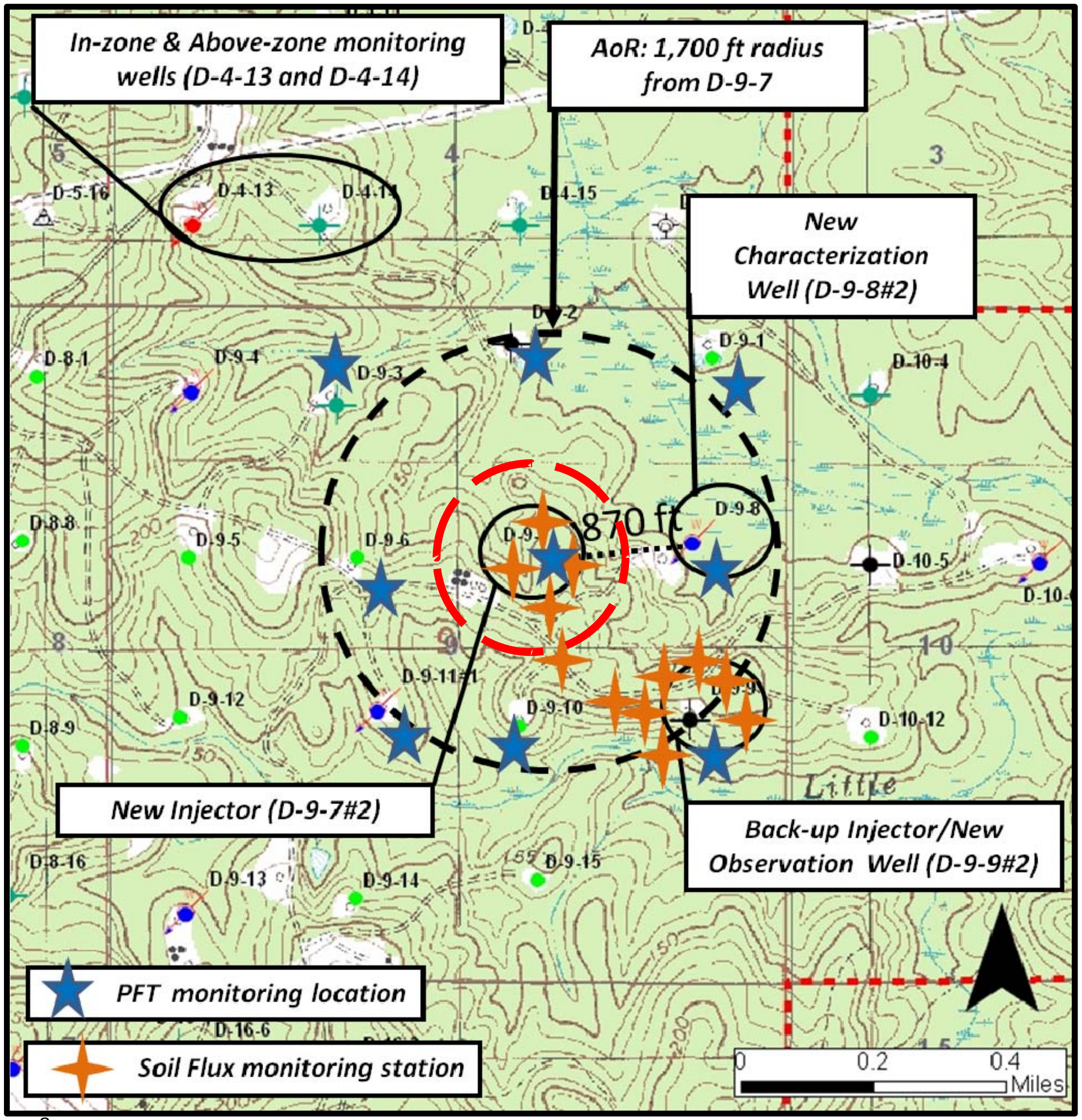
System	Series	Stratigraphic Unit	Major Sub Units	Potential Reservoirs and Confining Zones
Tertiary	Plio-Pliocene		Citronelle Formation	Freshwater Aquifer
Tertiary	Miocene	Undifferentiated		Freshwater Aquifer
Tertiary	Oligocene		Chickasawhay Fm.	Base of USDW
Tertiary	Oligocene	Vicksburg Group	Bucatunna Clay	Local Confining Unit
Tertiary	Eocene	Jackson Group		Minor Saline Reservoir
Tertiary	Eocene	Claiborne Group	Talahatta Fm.	Saline Reservoir
Tertiary	Eocene	Wilcox Group	Hatchetigbee Sand	Saline Reservoir
Tertiary	Paleocene		Bashi Marl	Saline Reservoir
Tertiary	Paleocene		Salt Mountain LS	Saline Reservoir
Tertiary	Paleocene	Midway Group	Porters Creek Clay	Confining Unit
Cretaceous	Upper	Selma Group		Confining Unit
Cretaceous	Upper	Eutaw Formation		Minor Saline Reservoir
Cretaceous	Upper	Tuscaloosa Group	Upper Tusc.	Minor Saline Reservoir
Cretaceous	Upper	Tuscaloosa Group	Mid. Tusc. – Marine Shale	Confining Unit
Cretaceous	Upper	Tuscaloosa Group	Lower Tusc. – Pilot Sand, Massive sand	Saline Reservoir
Cretaceous	Lower	Washita-Fredericksburg	Dantzler sand	Saline Reservoir
Cretaceous	Lower	Washita-Fredericksburg	Basal Shale	Primary Confining Unit
Cretaceous	Lower	Paluxy Formation	'Upper' 'Middle' 'Lower'	Injection Zone
Cretaceous	Lower	Mooringsport Formation		Confining Unit
Cretaceous	Lower	Ferry Lake Anhydrite		Confining Unit
Cretaceous	Lower	Donovan Sand	Rodessa Fm. Upper'	Oil Reservoir
Cretaceous	Lower	Donovan Sand	'Middle'	Minor Saline Reservoir
Cretaceous	Lower	Donovan Sand	'Lower'	Oil Reservoir

- Proven four-way closure at Citronelle Dome
- Injection site located within Citronelle oilfield where existing well logs are available
- Deep injection interval (9,400 ft)
- Numerous confining units
- Base of USDWs ~1,400 feet
- Existing wells cemented through primary confining unit
- No evidence of faulting or fracturing, based on oilfield experience, new geologic mapping and reinterpretation of existing 2D seismic lines.

ELECTRIC POWER RESEARCH INSTITUTE

Advanced Resources International, Inc.

Field Overview

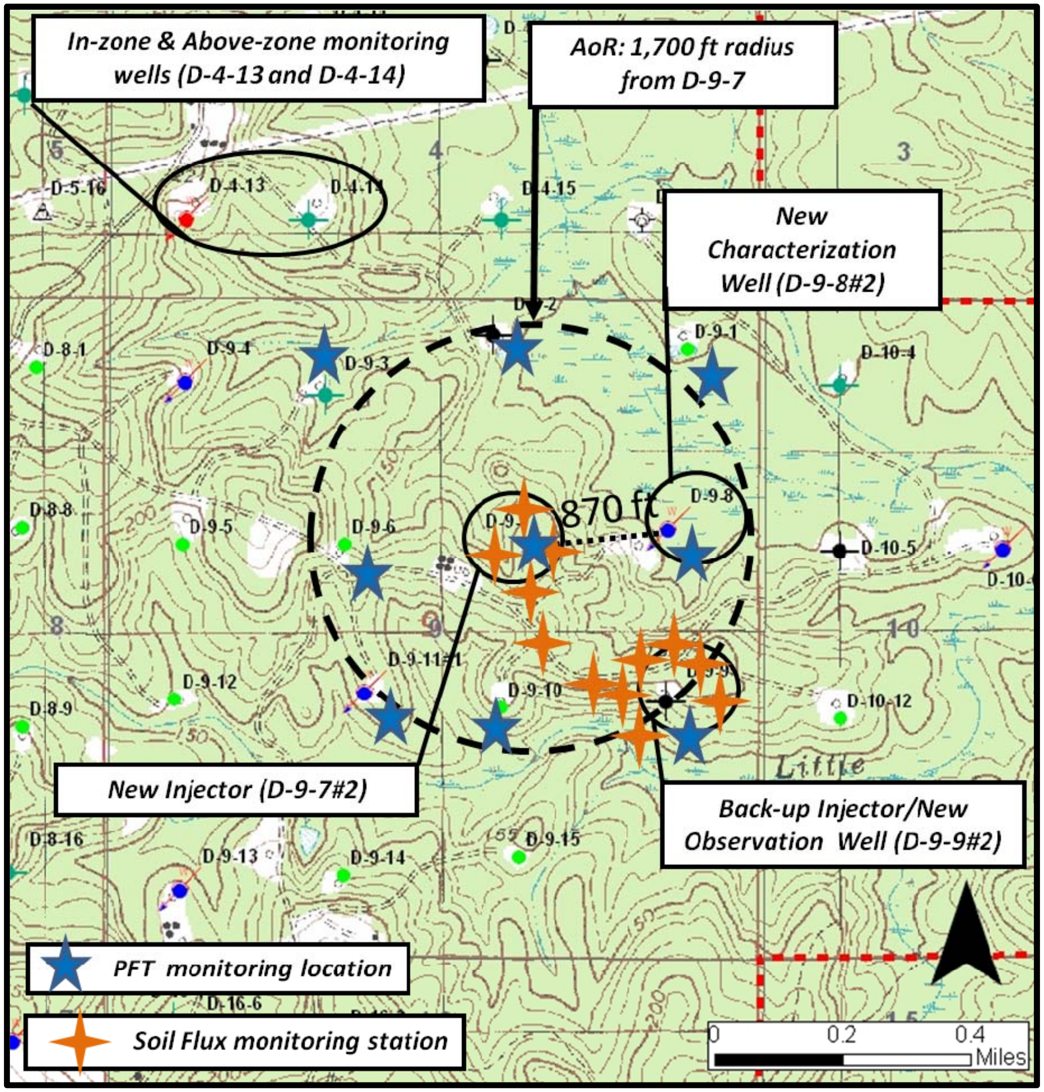


- *One Injector (D-9-7 #2)*
- *Two deep Observation wells (D-9-8 #2 & D-9-9 #2)*
- *Two in-zone & above zone Monitoring wells (D-4-13 & D-4-14)*
- *One PNC logging well (D-9-11)*
- *Four shallow groundwater monitoring wells*
- *Twelve soil flux monitoring stations*

ELECTRIC POWER RESEARCH INSTITUTE

Advanced Resources International, Inc.

Surface and Shallow MVA



Goal #1: Operational monitoring

- *Injection rate and wellhead pressure*
- *CO_2 stream composition*

Goal #2: Identification of fast-flow pathways (nearby abandoned well)

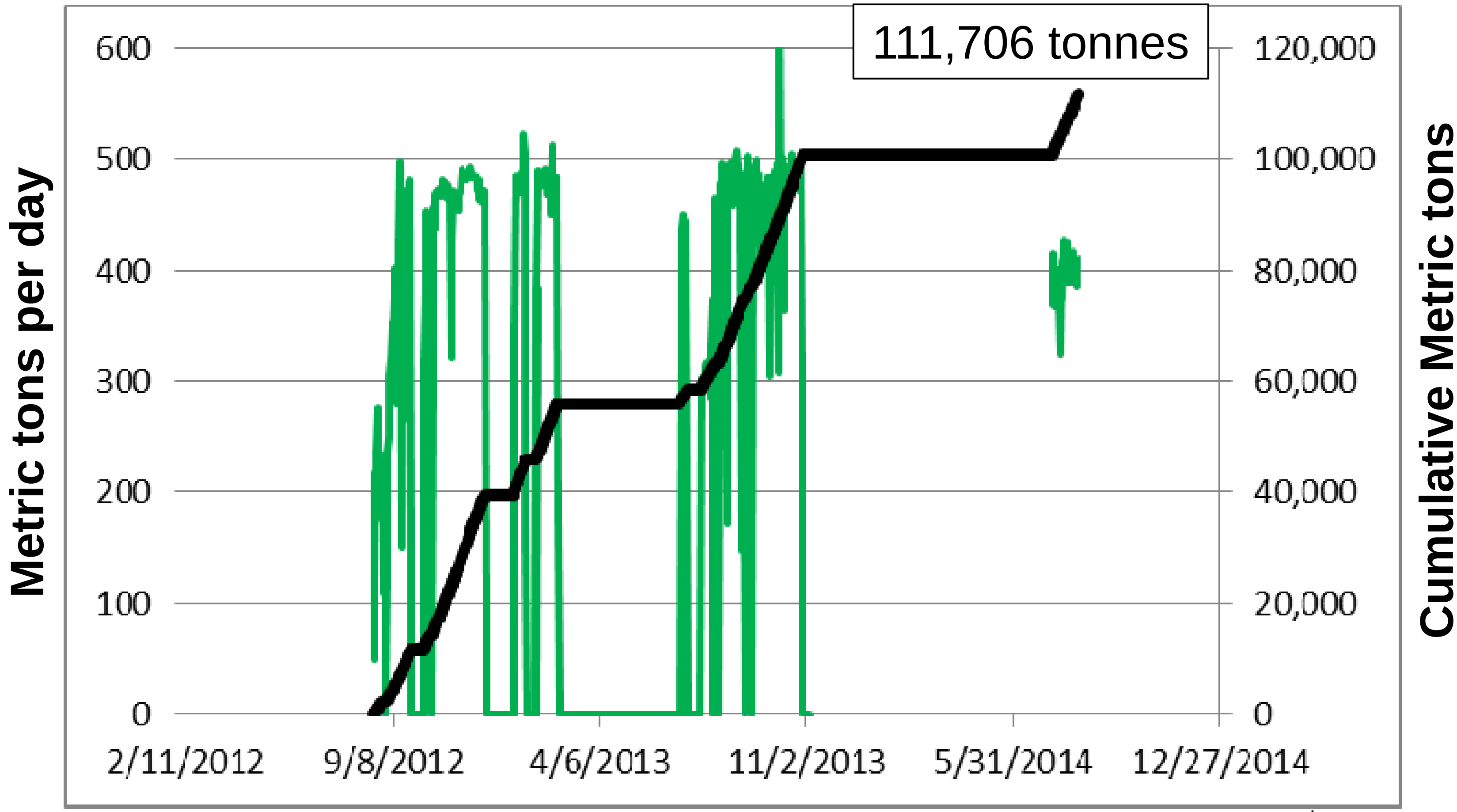
- *Perfluorocarbon tracers*
- *Soil CO_2 flux measurements*
- *Groundwater sampling*

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Advanced Resources International, Inc.

Injection Rate and CO_2 Composition Summary

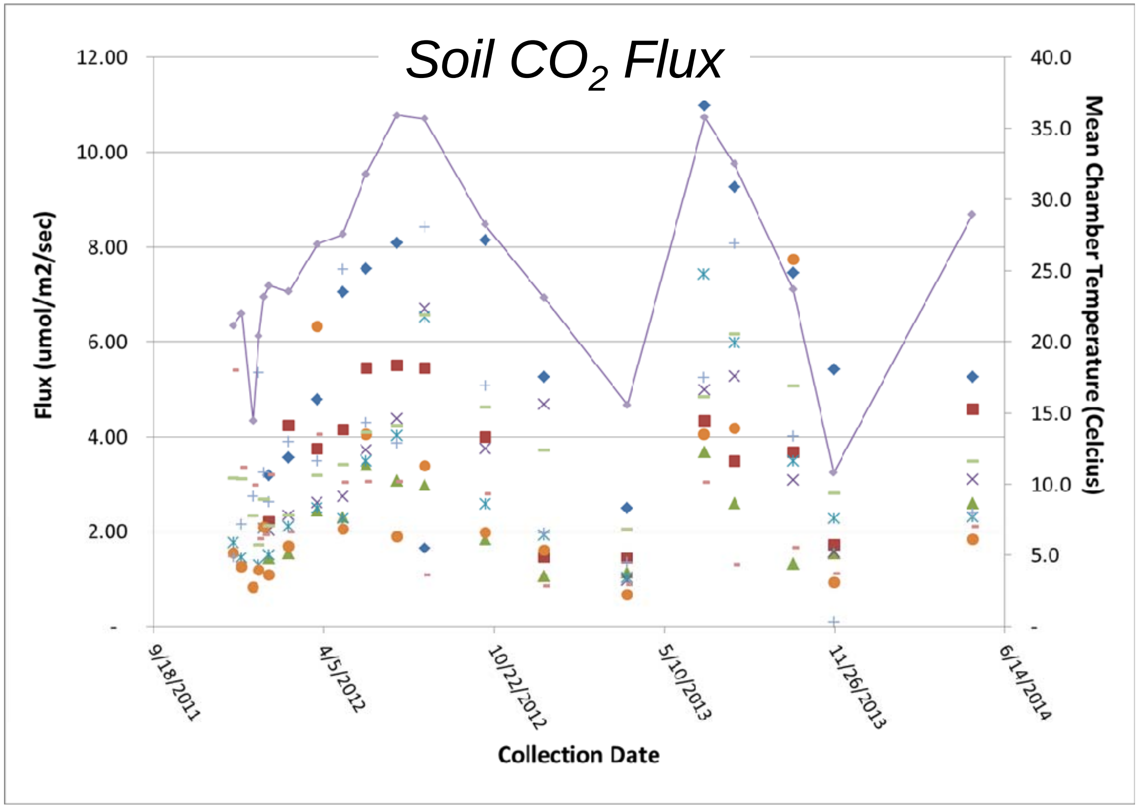
- Average quality of the captured gas is 99.933% CO_2, 0.015% O_2 and 0.052% N_2.



ELECTRIC POWER RESEARCH INSTITUTE

Advanced Resources International, Inc.

Shallow MVA-CO_2 Flux and Tracer Sampling



Tracer Results

	Inoculation	Testing	
Well/Sample	**AUG 2012**	**JUN 2013**	**NOV 2013**
D-9-1	ND	ND	ND
D-9-2	ND	ND	ND
D-9-3	ND	ND	ND
D-9-6	ND	ND	ND
D-9-7-1	ND	ND	ND
D-9-8	Invalid Data	ND	ND
D-9-9	ND	ND	ND
D-9-10	Invalid Data	ND	ND
D-9-11	ND	ND	ND
Air Blank 1	ND		
System Blank		ND	ND

Soil CO_2 results appear to vary as a function of mean temperature and PFT have been non-detect

ELECTRIC POWER RESEARCH INSTITUTE

Advanced Resources International, Inc.

Shallow MVA - USDW Monitoring

3 - Background Monitoring Events:

- January 2012 (N=1) through July 2012 (N=3)

7 - Injection Period Monitoring Events:

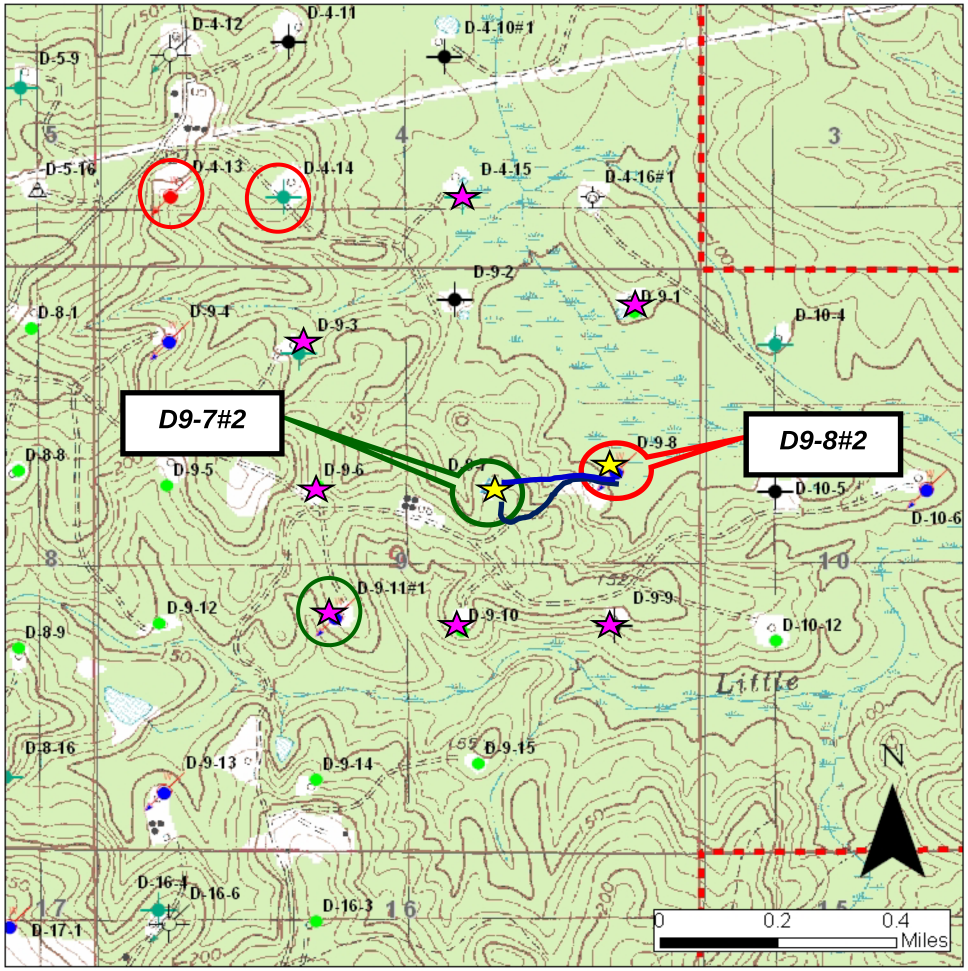
- November 2012 (N=4) through May 2014 (N=10)

Background anomalies of Manganese, Iron, and Chloride above UIC permit. To evaluate the potential exceedance of regulatory standard (*e.g.*, UIC permit discharge limit), the EPA GW Unified Guidance recommends the collection of >4 data points before performing statistical comparisons (*e.g.* confidence limit determinations)

ELECTRIC POWER RESEARCH INSTITUTE

Advanced Resources International, Inc.

Deep MVA



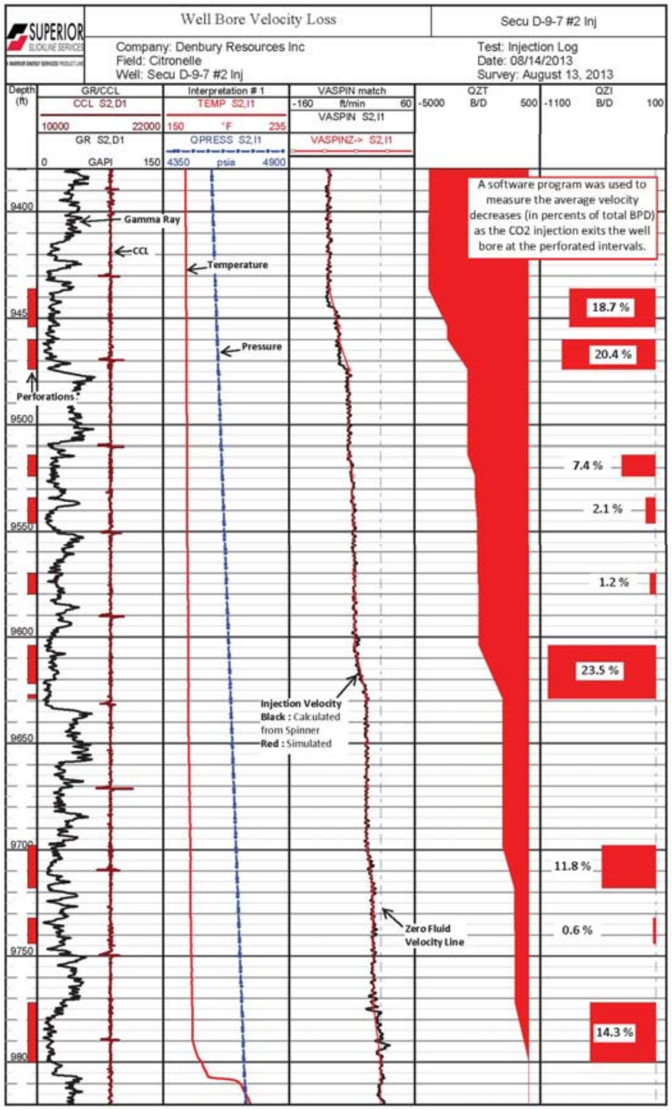
VSP source offset locations (stars), receiver locations (D9-7#2 and D9-8#2), and walk-away lines (blue and red lines)

- *Goal #1: Operational monitoring*
  - Well logging (PNC and spinner surveys)
- Goal #2: In-zone CO_2 migration, leak detection and pressure monitoring
  - Downhole pressure monitoring
  - Cross-well seismic surveys
  - Offset vertical seismic profile (VSP) surveys
  - Walkaway VSP

ELECTRIC POWER RESEARCH INSTITUTE

Advanced Resources International, Inc.

Deep MVA-Spinner Surveys



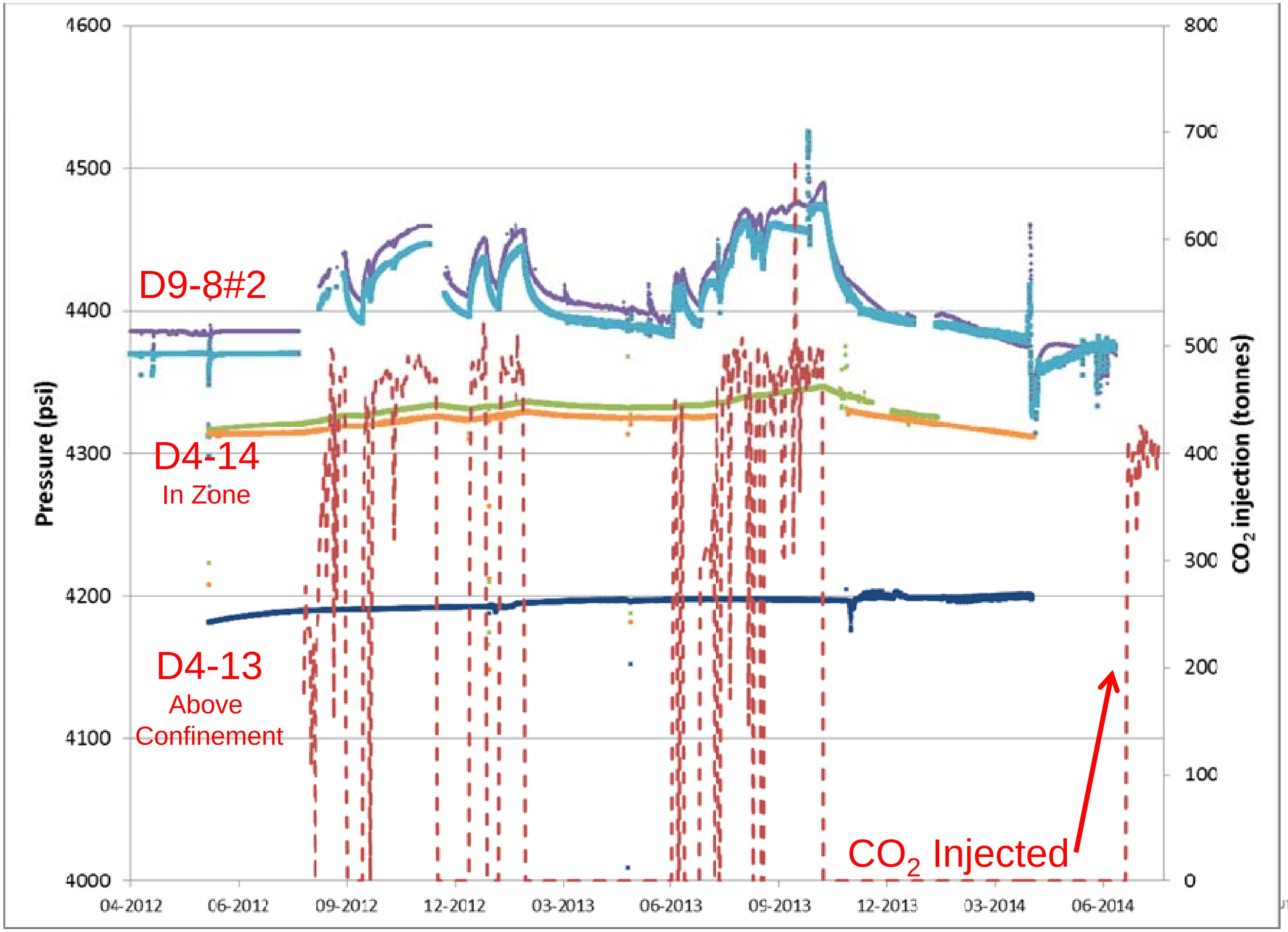
Sand	Sand Unit Properties (ft)			Nov 2012	Aug 2013	Oct 2013
Unit	Bottom	Top	Thickness	Flow %	Flow %	Flow %
J	9,454	9,436	18	14.8	18.7	16.7
I	9,474	9,460	14	8.2	20.4	19.6
H	9,524	9,514	10	2.8	7.4	7.7
G	9,546	9,534	12	2.7	2.1	0.9
F	9,580	9,570	10	0.0	1.2	1.2
E	9,622	9,604	18	26.8	23.5	30.8
D	9,629	9,627	2	0.0	0.0	0.0
C	9,718	9,698	20	16.5	11.8	10.3
B	9,744	9,732	12	4.9	0.6	0.4
A	9,800	9,772	28	23.3	14.3	12.4

Caged Fullbore Flowmeter (6 arm CFBM)

ELECTRIC POWER RESEARCH INSTITUTE

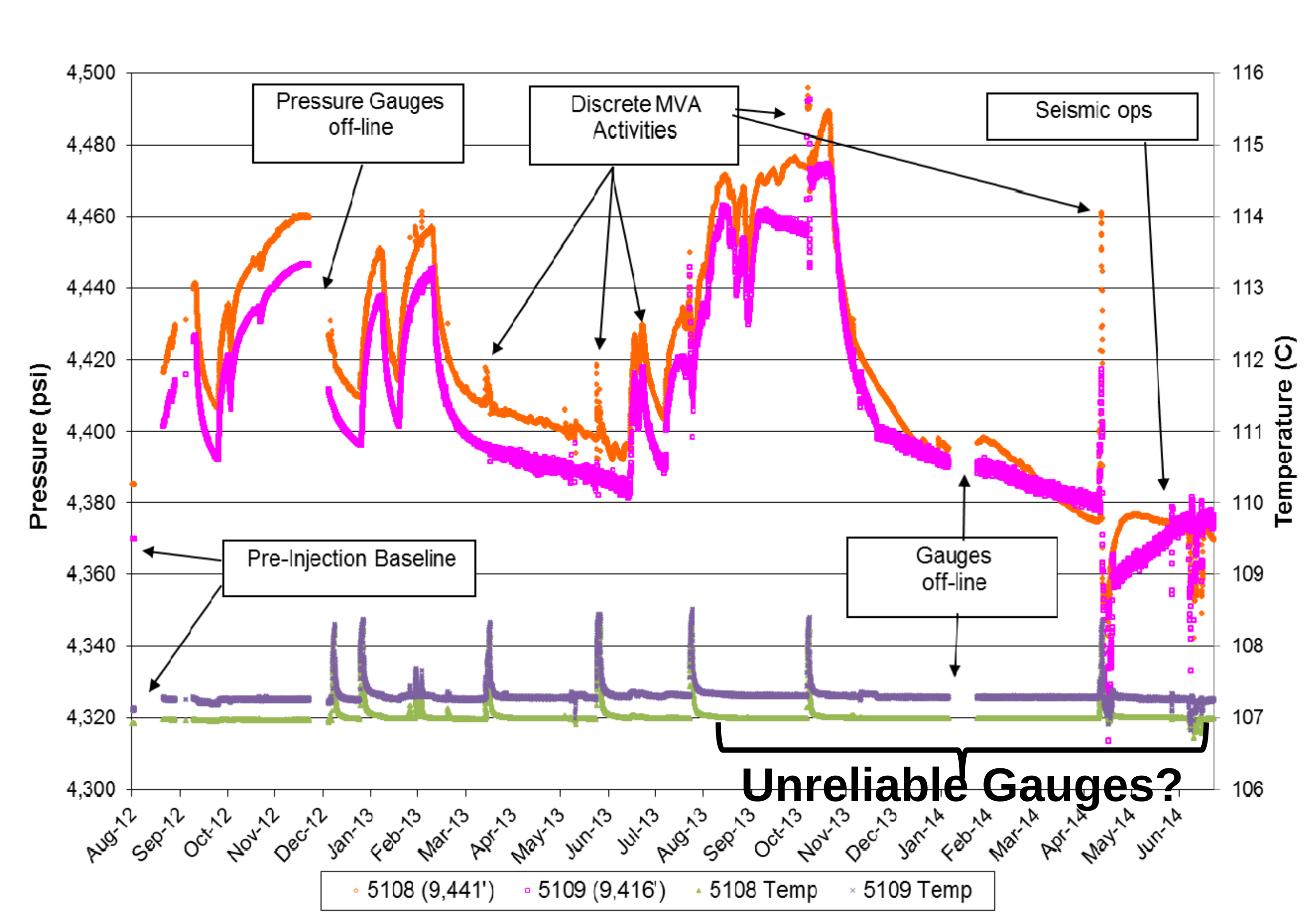
Advanced Resources International, Inc.

Deep MVA - Pressure Response



Advanced Resources International, Inc.

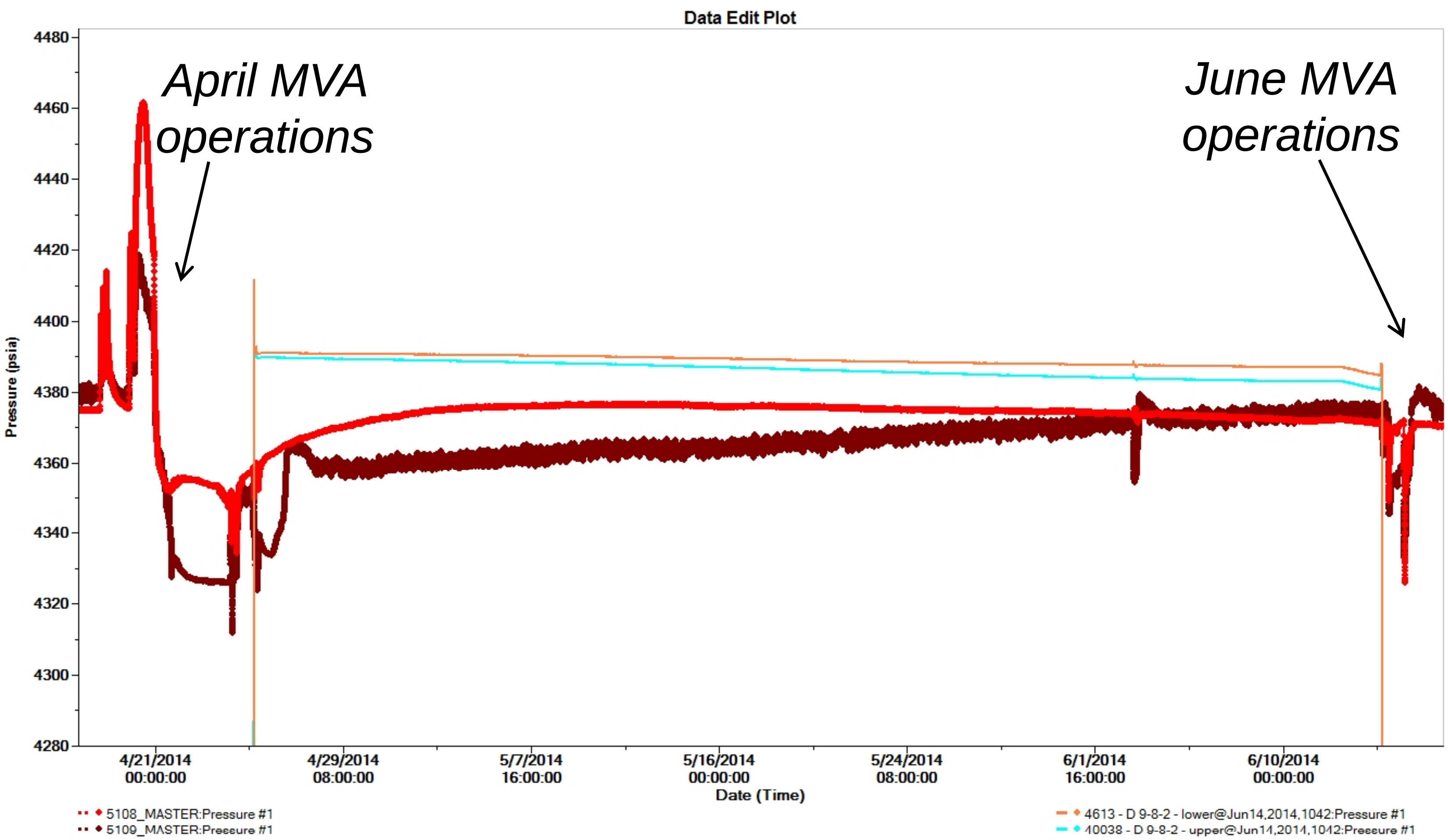
Deep MVA – Pressure Response



ELECTRIC POWER RESEARCH INSTITUTE

Advanced Resources International, Inc.

Permanent MBM vs Removable Memory Gauge

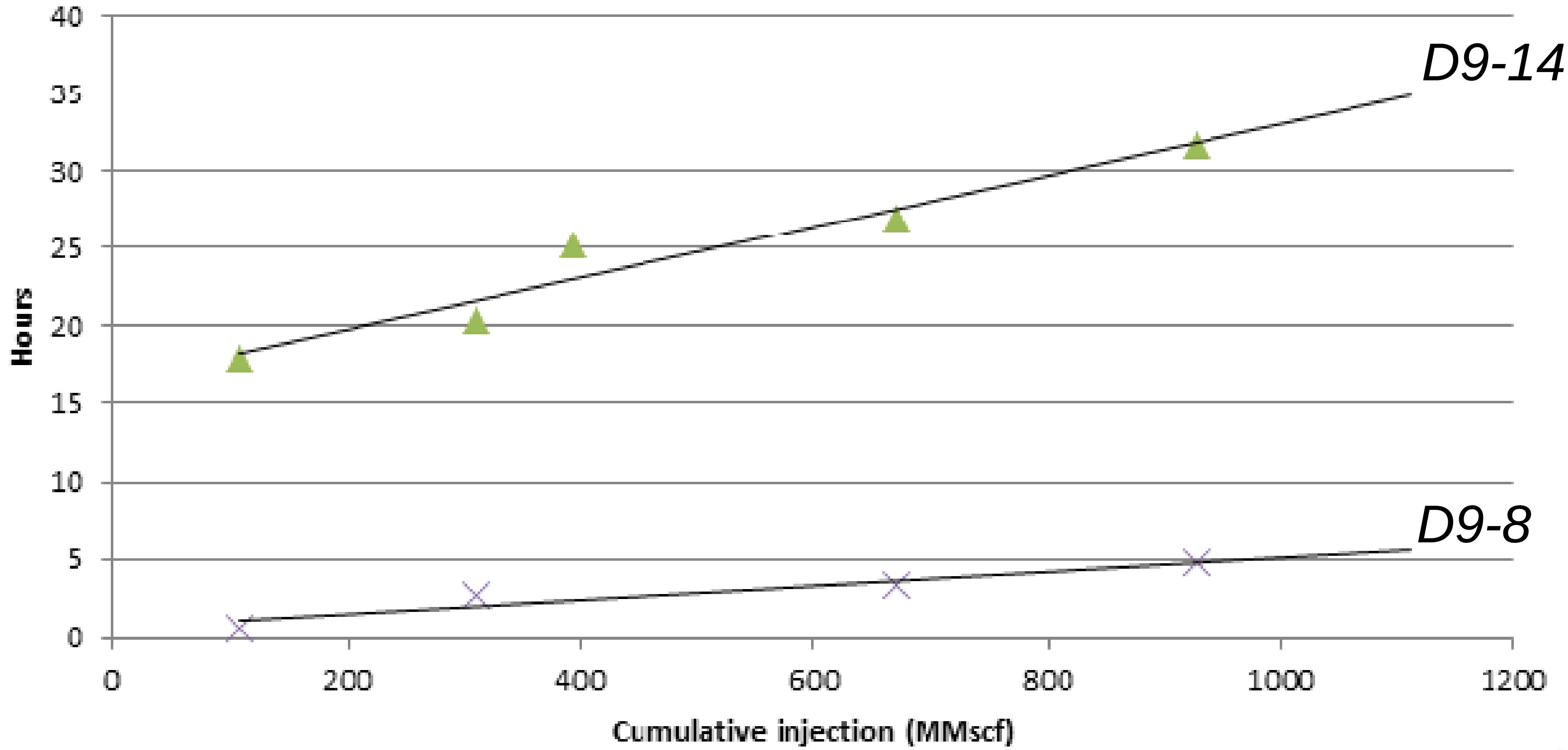


ELECTRIC POWER RESEARCH INSTITUTE

Advanced Resources International, Inc.

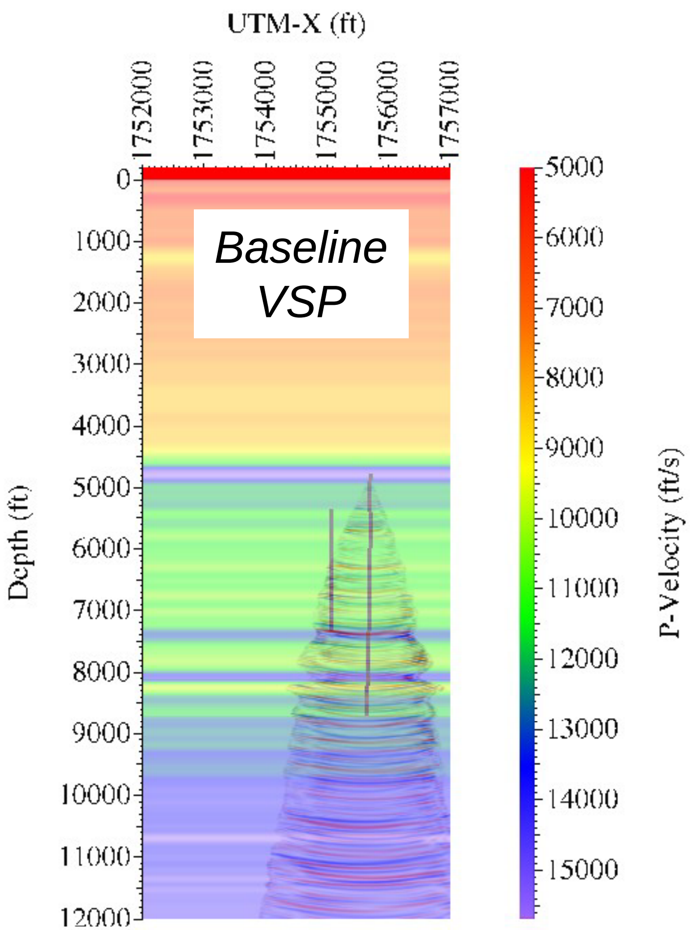
Deep MVA – Pressure Response

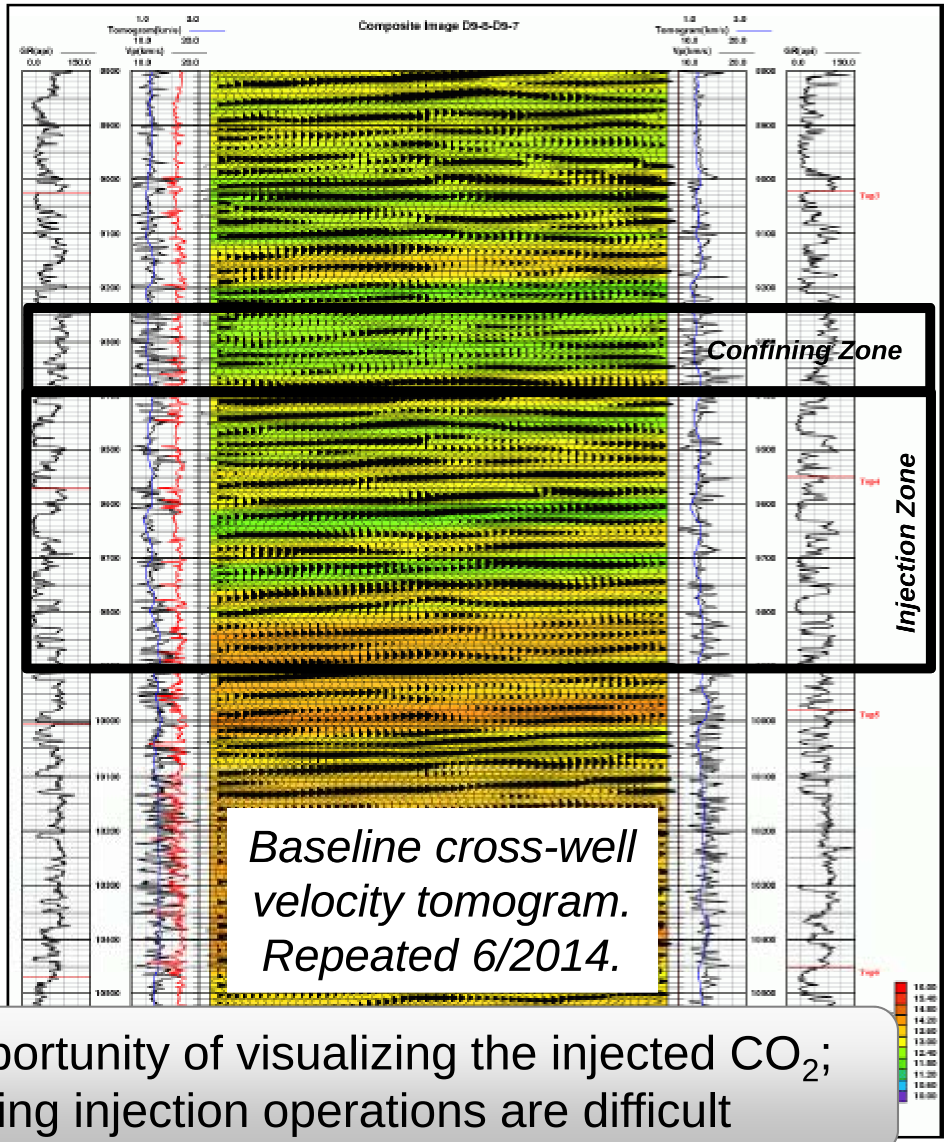
- The system, as expected, is getting more compressible with continued injection. As a result, the response time (observed initiation of injection) at the offset observation wells continues to grow. This tells us something about the saturation between the wells, when calibrated to reservoir models.



Advanced Resources International, Inc.

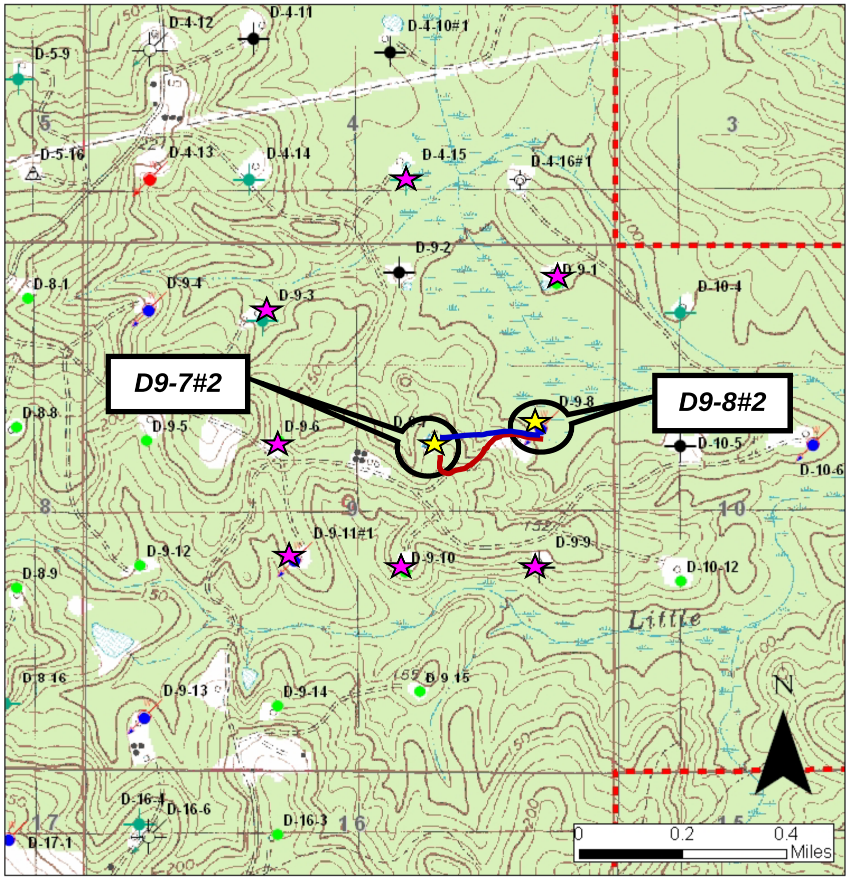
Deep MVA - Seismic Operations





Crosswell seismic may hold the best opportunity of visualizing the injected CO_2; however, time-lapse acquisition during injection operations are difficult

Experimental MVA-Modular Borehole Monitoring (MBM) System



VSP source offset locations (stars), receiver locations (D9-7#2 and D9-8#2), and walk-away lines (blue and red lines)

- *Motivation: Deep monitoring wells are expensive to drill and complete and have limited space available for instrumentation*

✓*Monitor CO_2 plume location*

✓*Reservoir pressure and temperature*

✓*Fluid sampling*

✓*Leak detection*

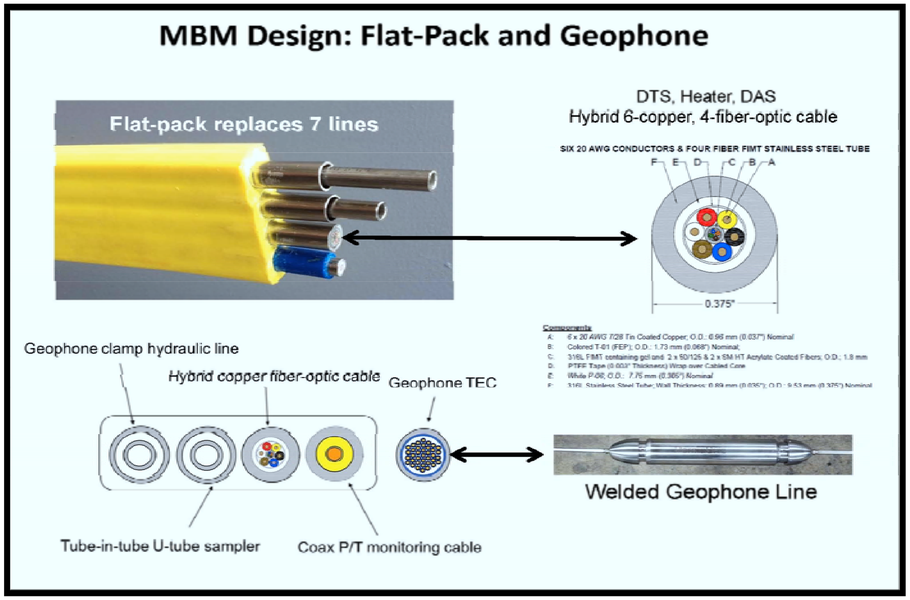
✓*CO_2 saturations*

- An experimental, semi-permanent geophone deployment was desired to act as a “fence-post” during time-lapse VSP acquisition

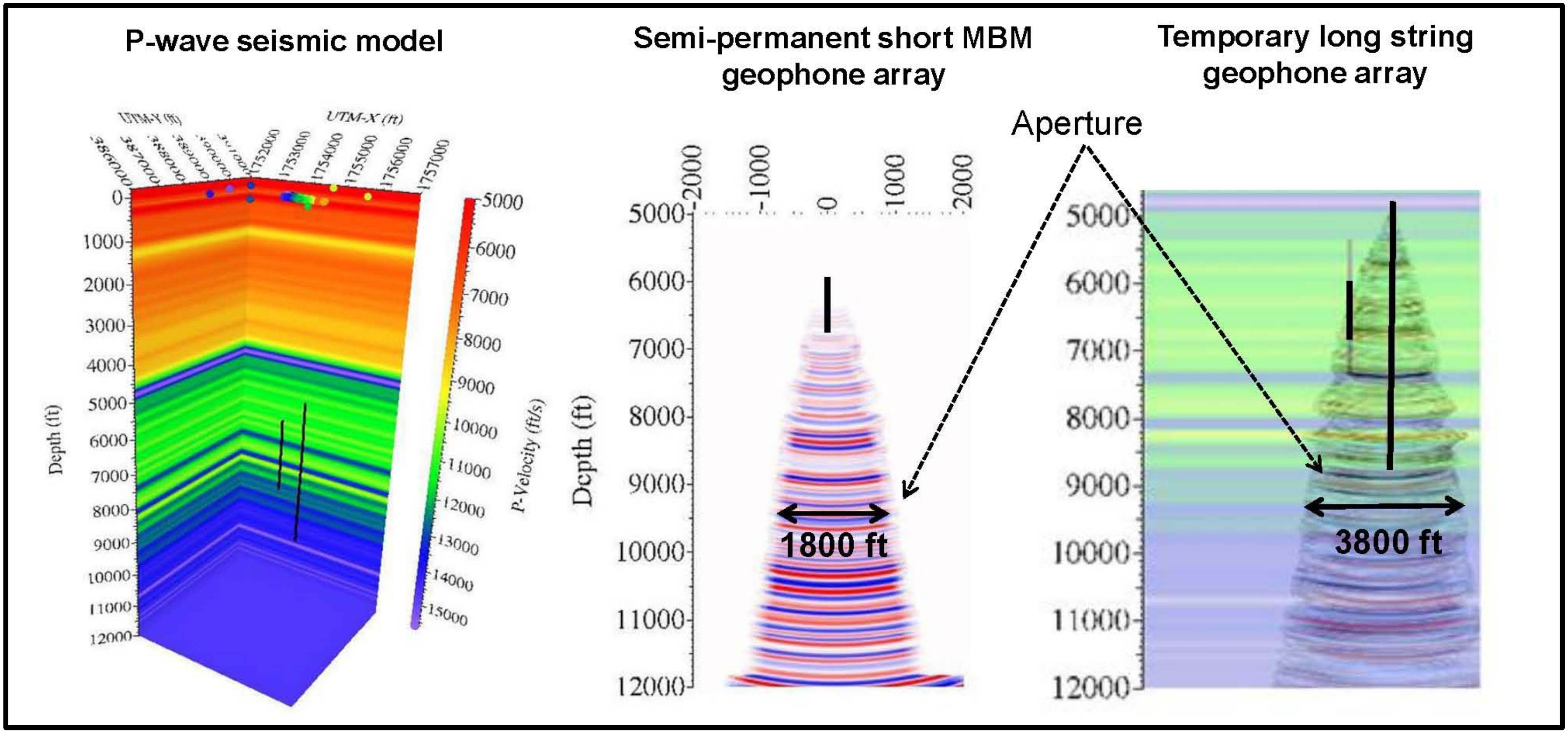
SECARB Southeast Regional Carbon Sequestration Partnership
CO2 Capture Project

MBM Design and Monitoring Capabilities

- 18 Level, tubing deployed, clamping geophone array (6,000-6,850 ft)
- Two in-zone quartz pressure/ temperature gauges for reservoir diagnostics
- U-tube for high frequency, in-zone fluid sampling (tube-in-tube design)
- Fiber optic cable for distributed temperature and acoustic measurements
    - Heat-pulse monitoring for CO_2 leak detection
    - Acoustic array for CO_2
- 2 7/8” production tubing open for logging

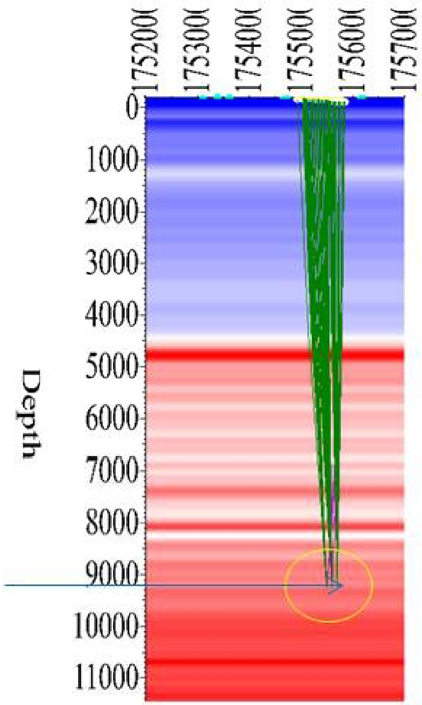


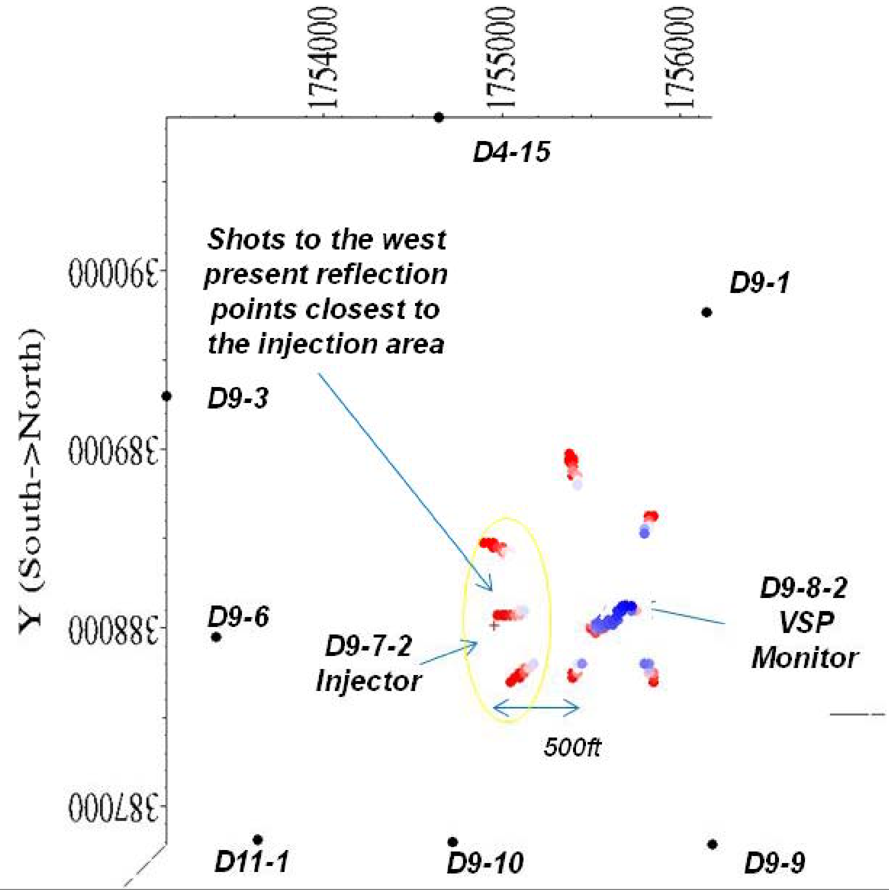
Time-Lapse Difference, MBM, VSP



Shorter MBM array has an lateral image area that is smaller, but it should be able to see changes in the gather response and images over time due to CO_2 injection

DEEP MVA – MBM VSP



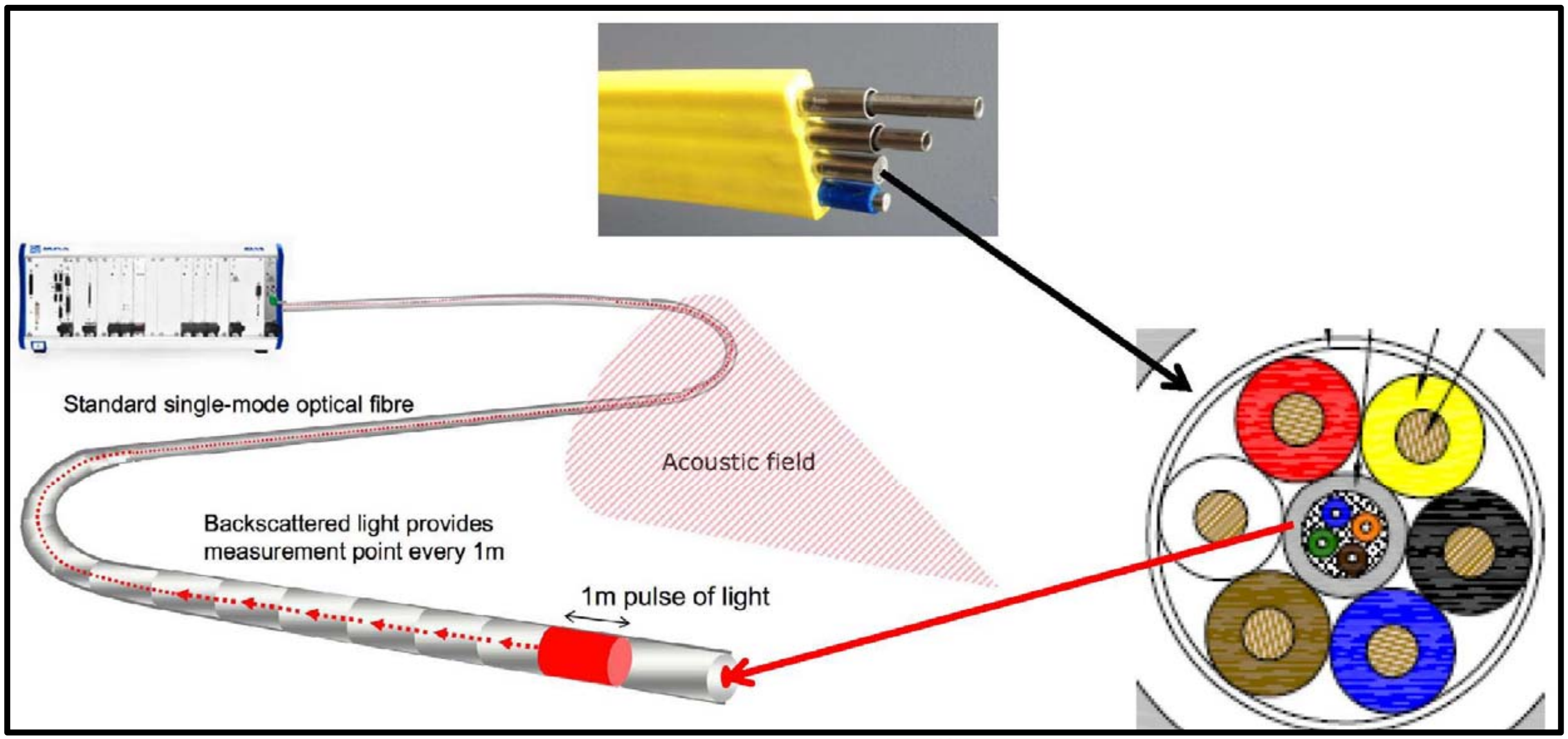


Difference between the monitor and baseline surveys reveal subtle changes in the amplitudes at depth; however the changes may not be significant because of noise

Distributed Acoustic Sensing (DAS)

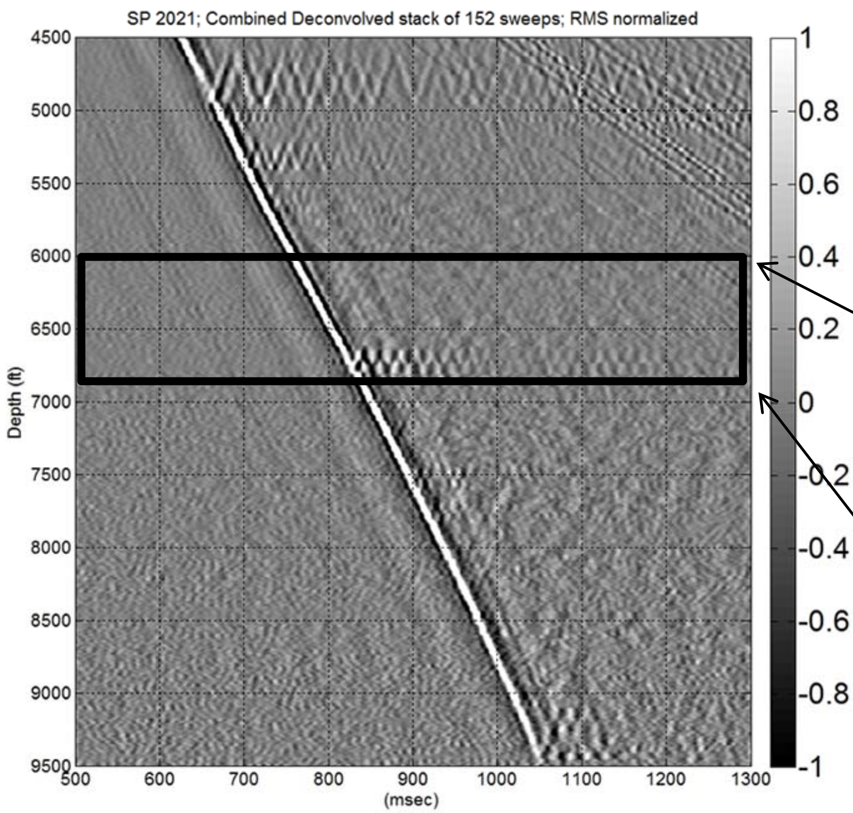
DAS allows seismic monitoring with fiber optics

- Sensitivity less than standard geophone, but 3000 sensors versus 18
- Spatial sampling and ease of deployment much greater



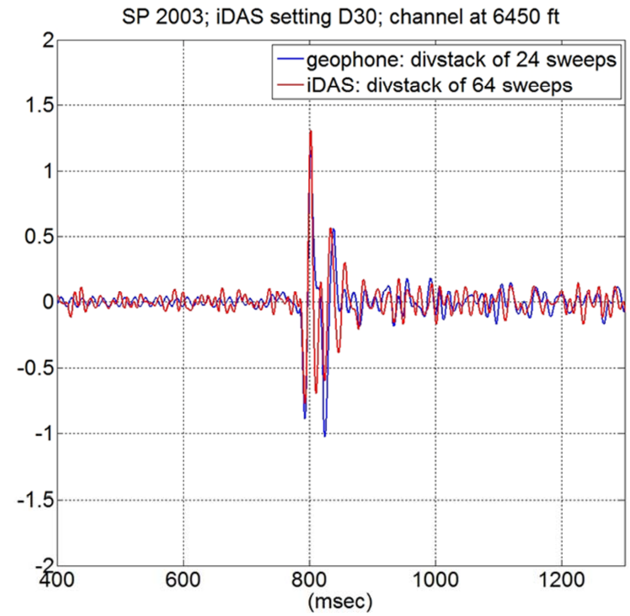
Citronelle DAS-Geophone Comparison from Walkaway

DAS Data

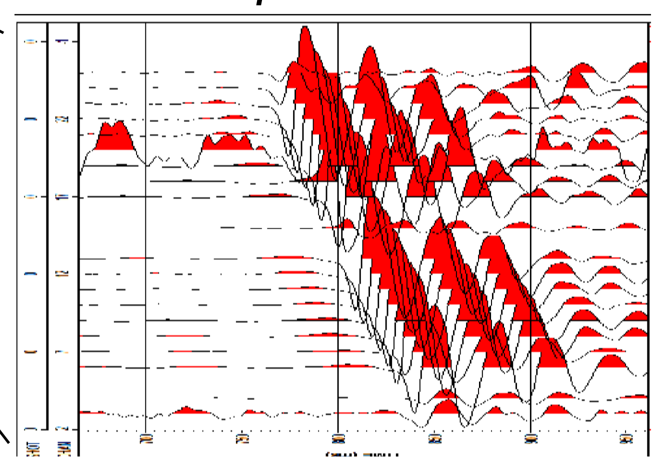


Processed by D. Miller, Silixa

DAS vs. Geophone



Geophone Data

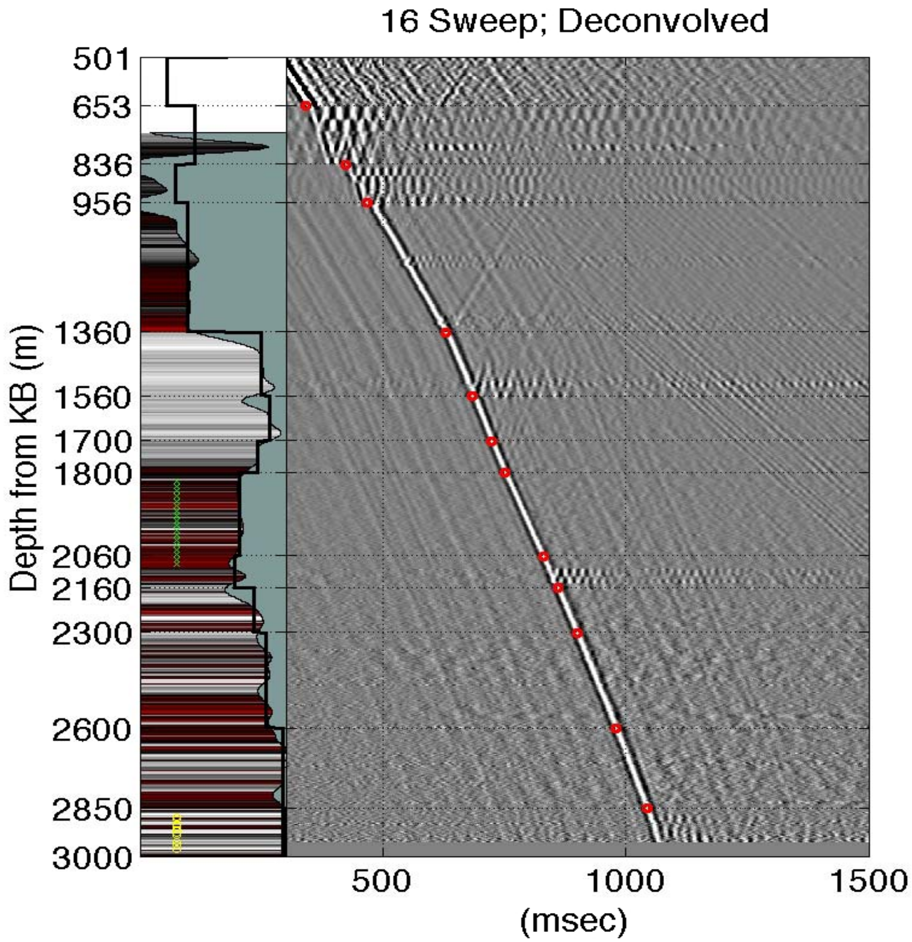


Acquisition of stacked source sweeps improved DAS data signal to noise ratio, producing traces that match those from more sensitive geophones

Improved DAS VSP Processing

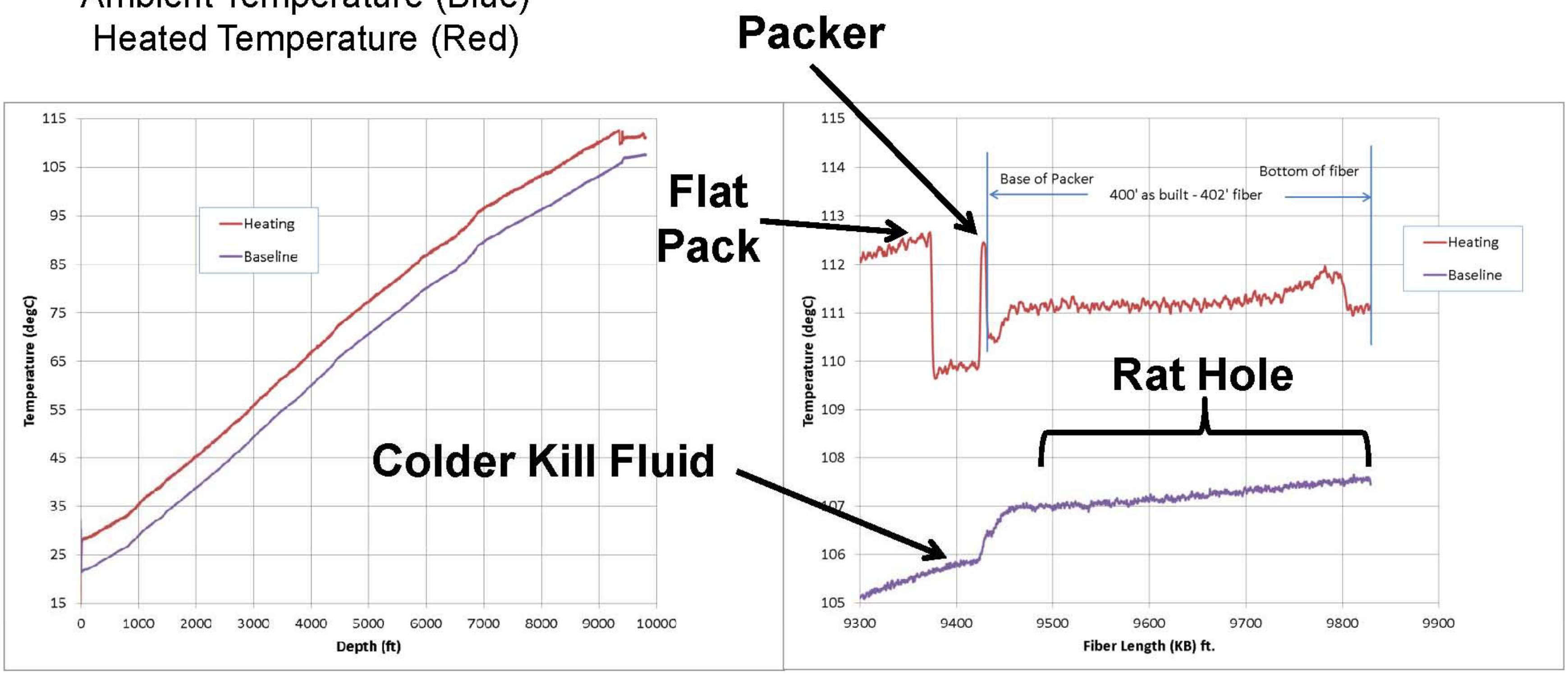
- Downgoing Deconvolution
- Travel Time Picks
- Velocity Model
- Comparison to Well Logs (Sonic, Gamma)

> - *Good tie to logs*
> - *Reflections clear*
> - *Strong 'ringing' in some zones*



Heat Pulse Testing and Fiber Optic Distributed Temperature Sensing (DTS)

Ambient Temperature (Blue)
Heated Temperature (Red)



Temperature Profile along Entire Cable (0 – 9,800 ft +/-)

Temperature Profile Across Bottomhole Assembly (9,300-9,900 ft)

Deep Groundwater Sampling

- In- and above-zone monitoring may be used as a compliance tool to detect CO_2 leakage
- Samples undergo geo-chemical transformation when collected from deep wells, e.g.,
  - Exsolution of dissolved gases
  - Changes in dissolved CO_2 concentrations that control pH and alkalinity
  - Exposure to the atmosphere causes changes in redox conditions

USGS photo: Fluid Sampling during Pumping at D9-8#2

ELECTRIC POWER RESEARCH INSTITUTE

Advanced Resources International, Inc.

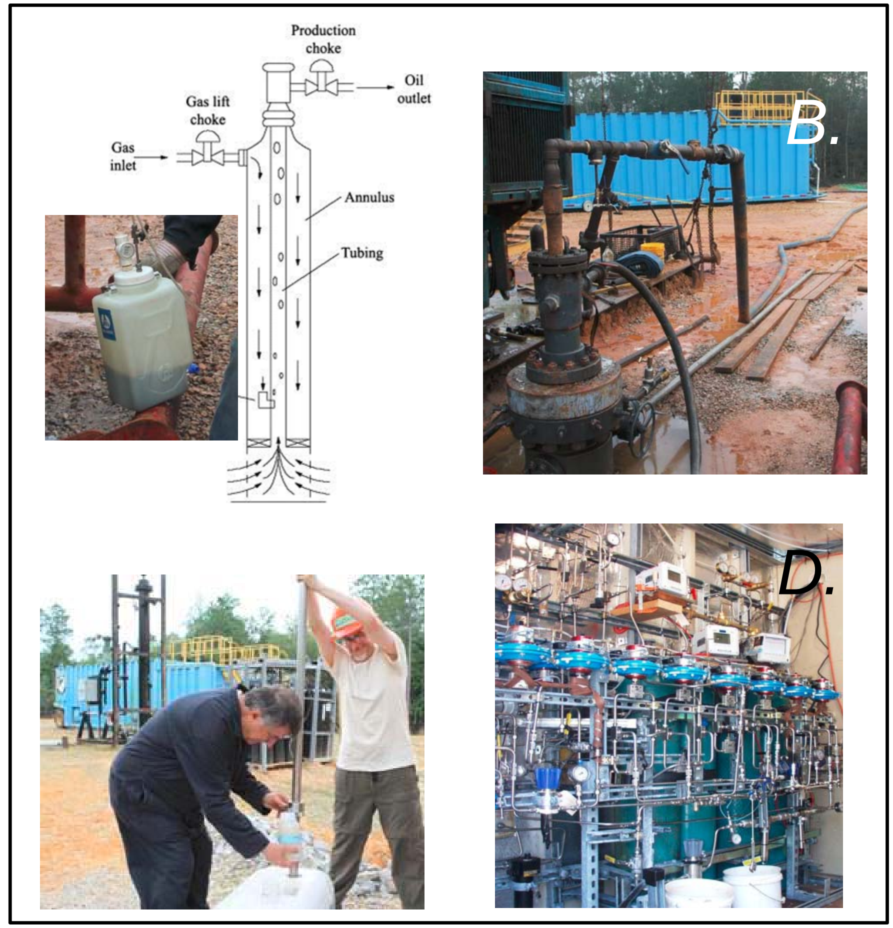
Testing & Monitoring: In-zone Comparison Deep Groundwater Sampling Methodologies

A. Gas-lift
- Samples had the highest pH indicating possible loss of dissolved gas
- Sampling method should be limited to major and unreactive solutes

B. Pumping
- Relatively high Fe concentrations compared to other methods, showing evidence of contamination or geochemical changes in samples
- Sampling method should be limited to major and unreactive solutes

C. Kuster sampler:
- Field measurements of initial pH had the lowest value
- Geochemical data consistent in repeated sampling

D. U-tube:
- In general, sample results are comparable to the Kuster method



USGS collecting in-zone groundwater samples using: A. gas-lift; B. electric submersible pump; C. Kuster sampler; and D. u-tube sampler

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Advanced Resources International, Inc.

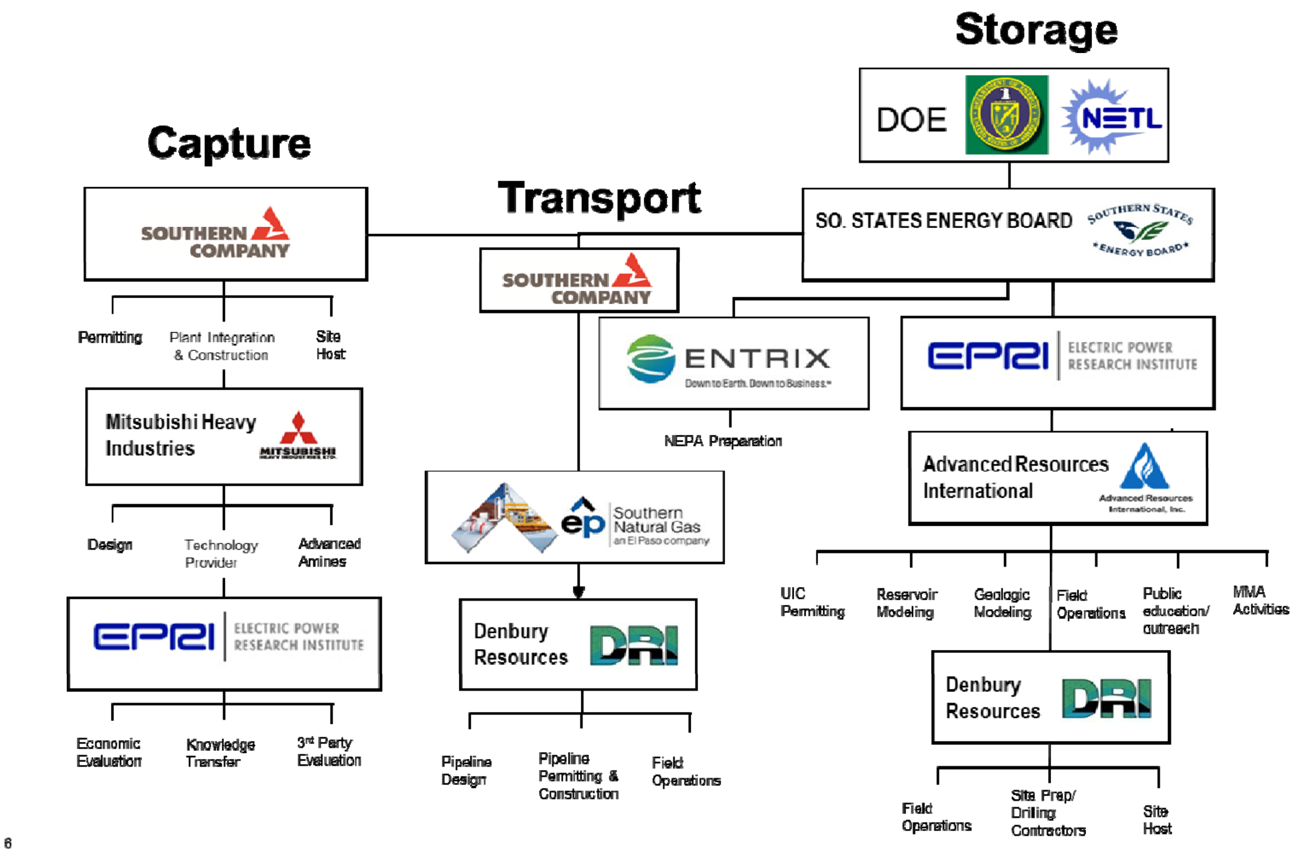
Accomplishments

- Injected over 110,000 metric tons to date from the world's largest CO_2 capture system using advanced amines on a coal-fired unit
- Fully integrated carbon capture, transportation and storage project
- Demonstrating monitoring technologies at a commercial-scale (i.e., oil field setting) within the regionally extensive Paluxy saline formation
- Unique opportunity to evaluate performance of different seismic survey configurations and sensors
- Research effort is focused on developing, testing and validating borehole-based monitoring technologies and methods

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Advanced Resources International, Inc.

Thank You from the SECARB Team

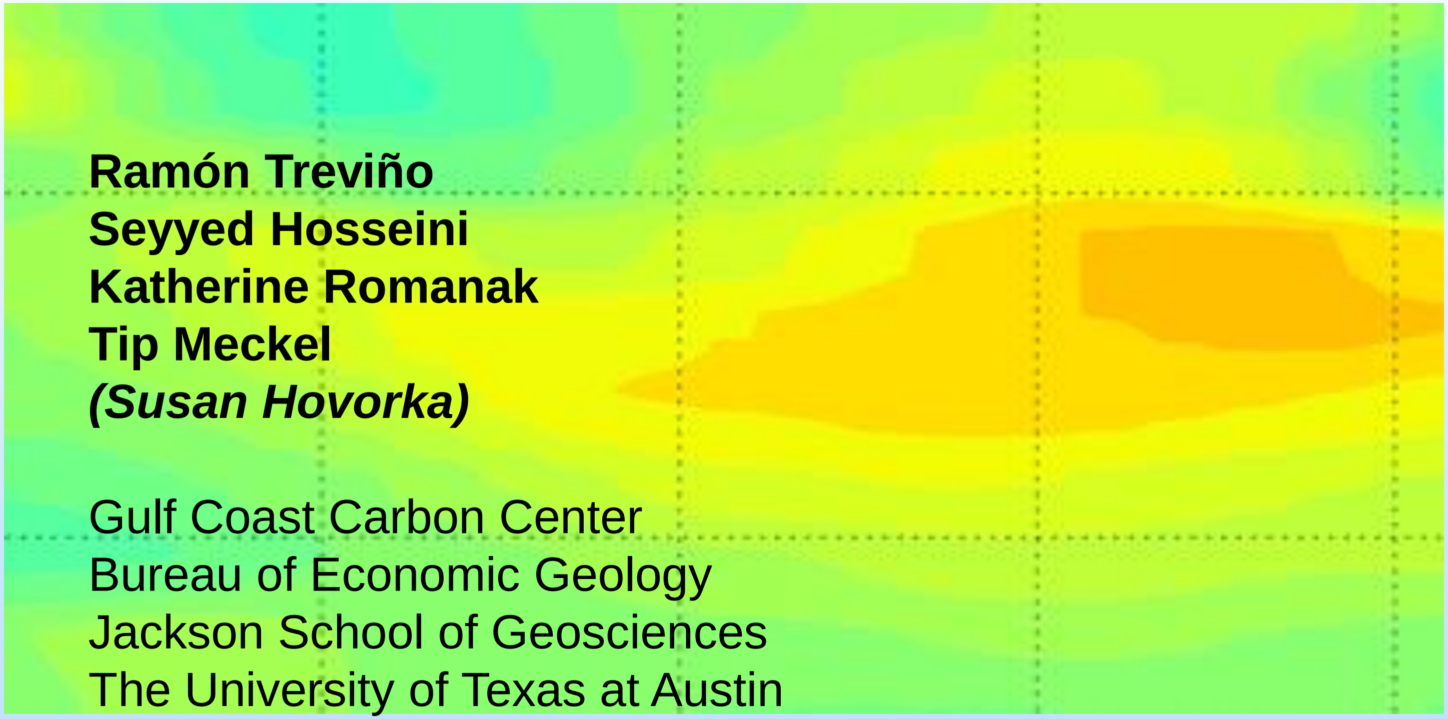


- Questions
- Comments
- Discussion

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Advanced Resources International, Inc.

SECARB's Early Test at Cranfield, Mississippi

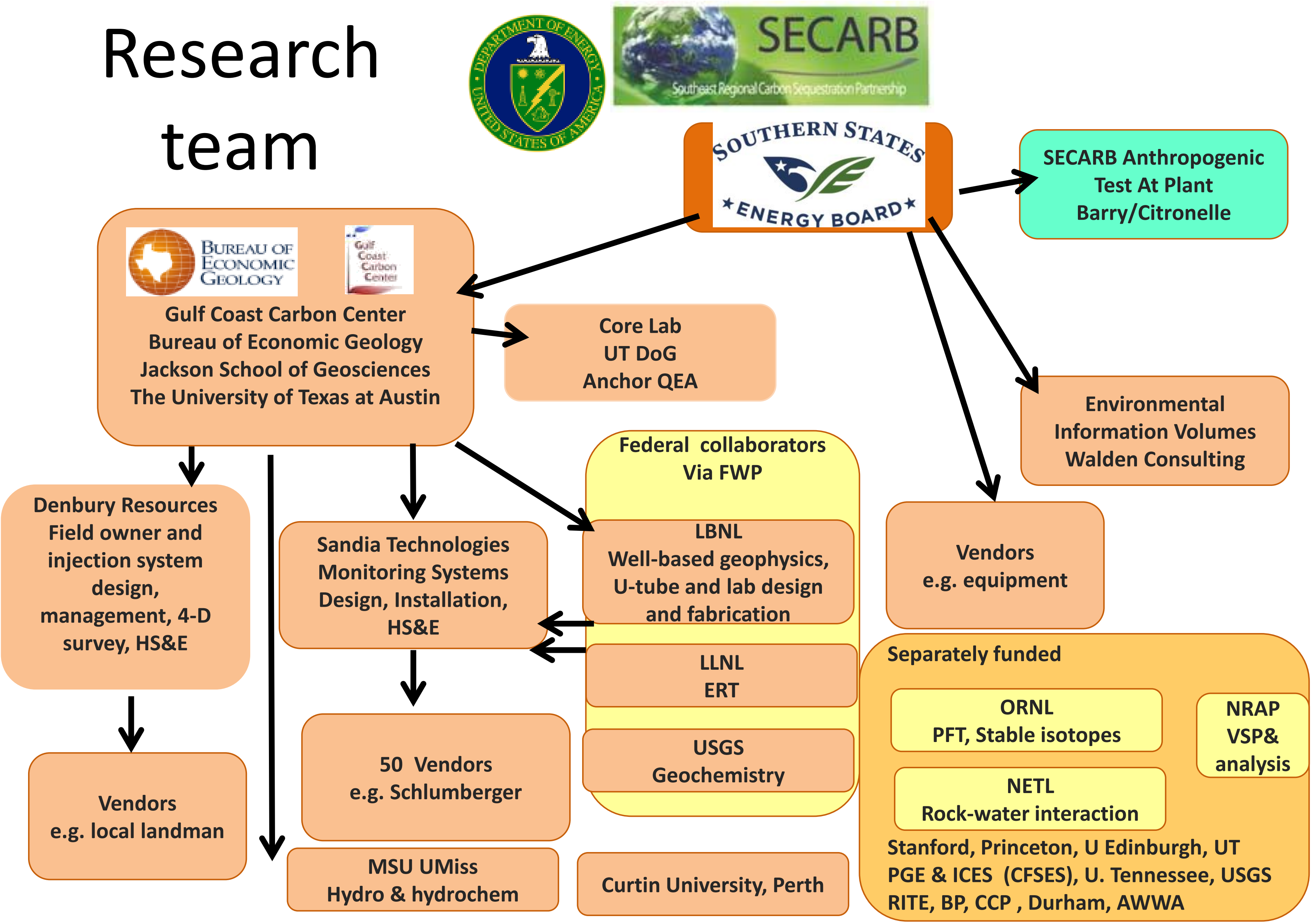


Ramón Treviño
Seyyed Hosseini
Katherine Romanak
Tip Meckel
(Susan Hovorka)

Gulf Coast Carbon Center
Bureau of Economic Geology
Jackson School of Geosciences
The University of Texas at Austin

ERT Image of CO_2 plume: X Yang LLNL

Early Test Research team



Presentation Outline

- SECARB Early Test Goals
- Site Characterization
- Monitoring and modeling response to injection in the deep subsurface
- Monitoring the shallow subsurface – what would response to leakage or migration look like?
- Remaining work

Presentation Outline

- SECARB Early Test Goals
- Site Characterization
- Monitoring and modeling response to injection in the deep subsurface
- Monitoring the shallow subsurface – what would response to leakage or migration look like?
- Remaining work

Goal: Regional Carbon Sequestration Program goal: Improve prediction of storage capacities

Existing data on reservoir volumetrics

Production history
37,590,000 Stock tank barrels oil
672,472,000 MSCU gas
(Chevron, 1966))

7,754 acres x 90 ft net pay x 25.5% porosity
(Chevron, 1966)

X E [pore volume occupancy (storage efficiency)] = Storage capacity

injection rate – limited by pressure response

Measure saturation during multiphase plume evolution

Increase predictive capabilities by validating numerical models

Observation: pore volume occupancy was rate and pressure dependent: not a single number

Goal: Regional Carbon Sequestration Partnership program goal: Evaluate protocols to demonstrate that CO_2 is retained

High confidence in storage permanence through characterization

Oil and gas trapped over geologic time

Material Impact: failing to retain

Uncertainty and risk assessment

Semi-quantitative assessment via Certification Framework

Research Questions

- P&A well performance in retention?
- Limited analogy between injected and natural fluid retention
- Off structure migration?
- Response to pressure elevation?

Selected assessment approach

shallow

- Well-pad vadose gas
- Ground water chem.
- AZMI pressure
- 4-D Seismic
- 4-D VSP
- IZ pressure
- Microseismic

deep

Protocol Sensitivity & reliability

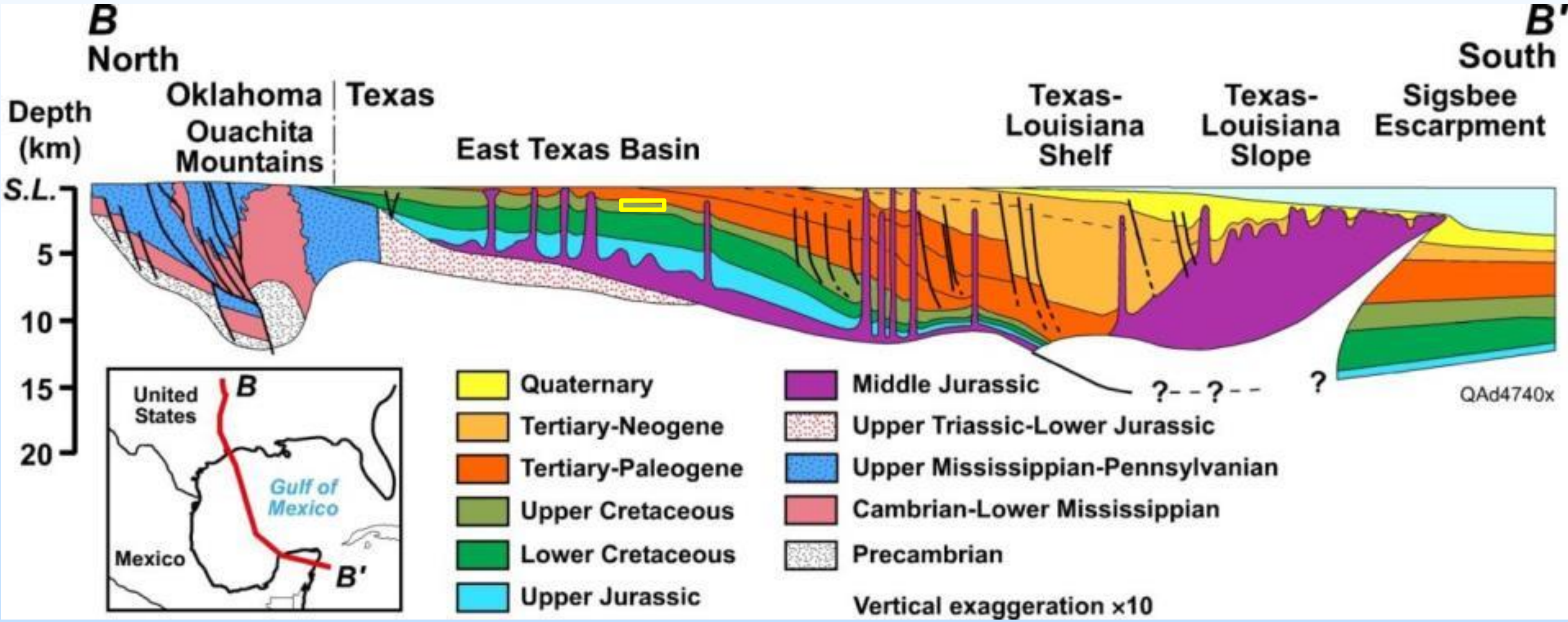
Presentation Outline

- SECARB Early Test Goals
- Site Characterization
- Monitoring and modeling response to injection in the deep subsurface
- Monitoring the shallow subsurface – what would response to leakage or migration look like?
- Remaining work

Characterization

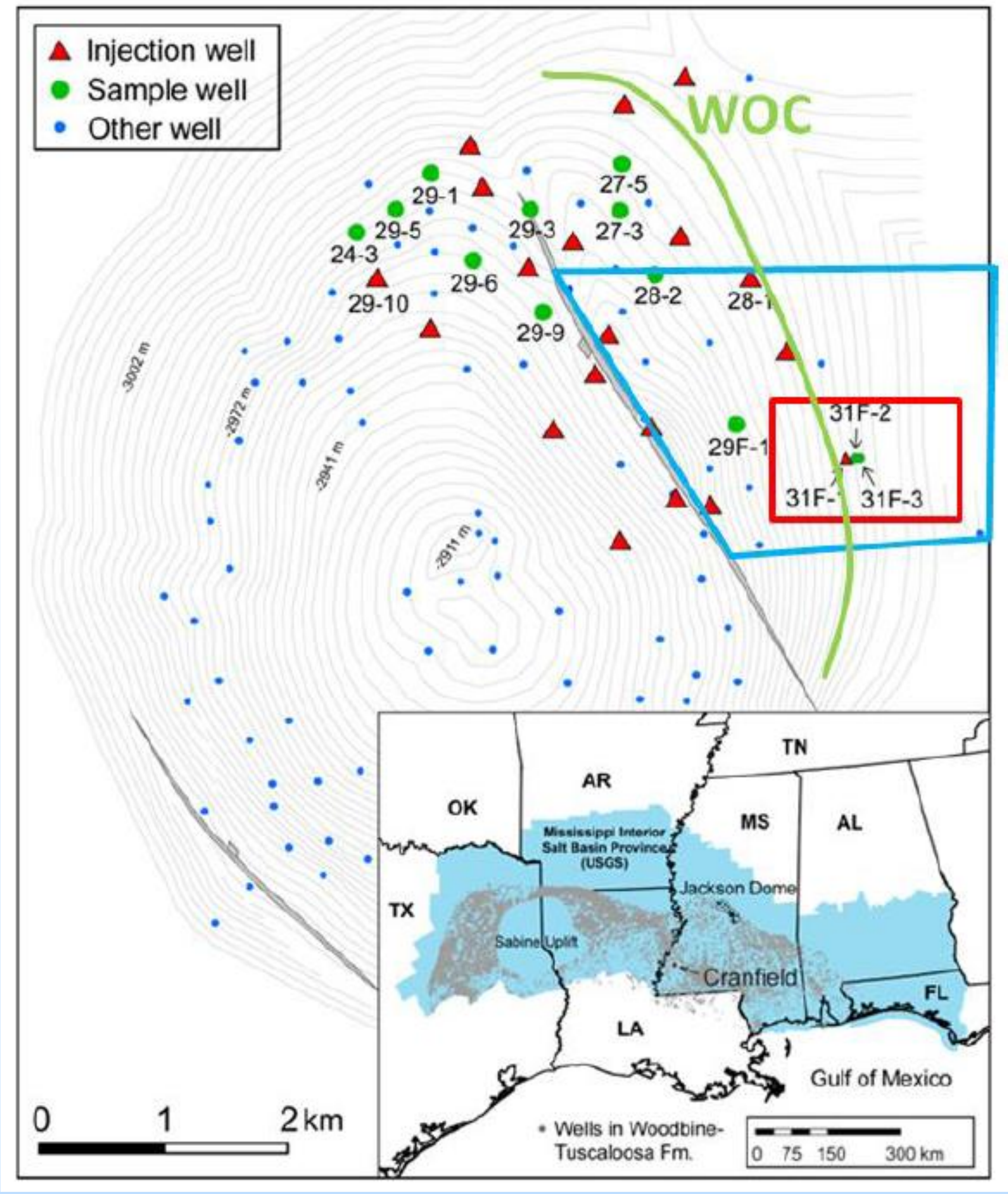
- **Regional setting** (Gulf Coast Wedge)
- **Location**
- **Tuscaloosa Formation** - depositional system
- **Confining system** (overburden)

Gulf Coast Wedge



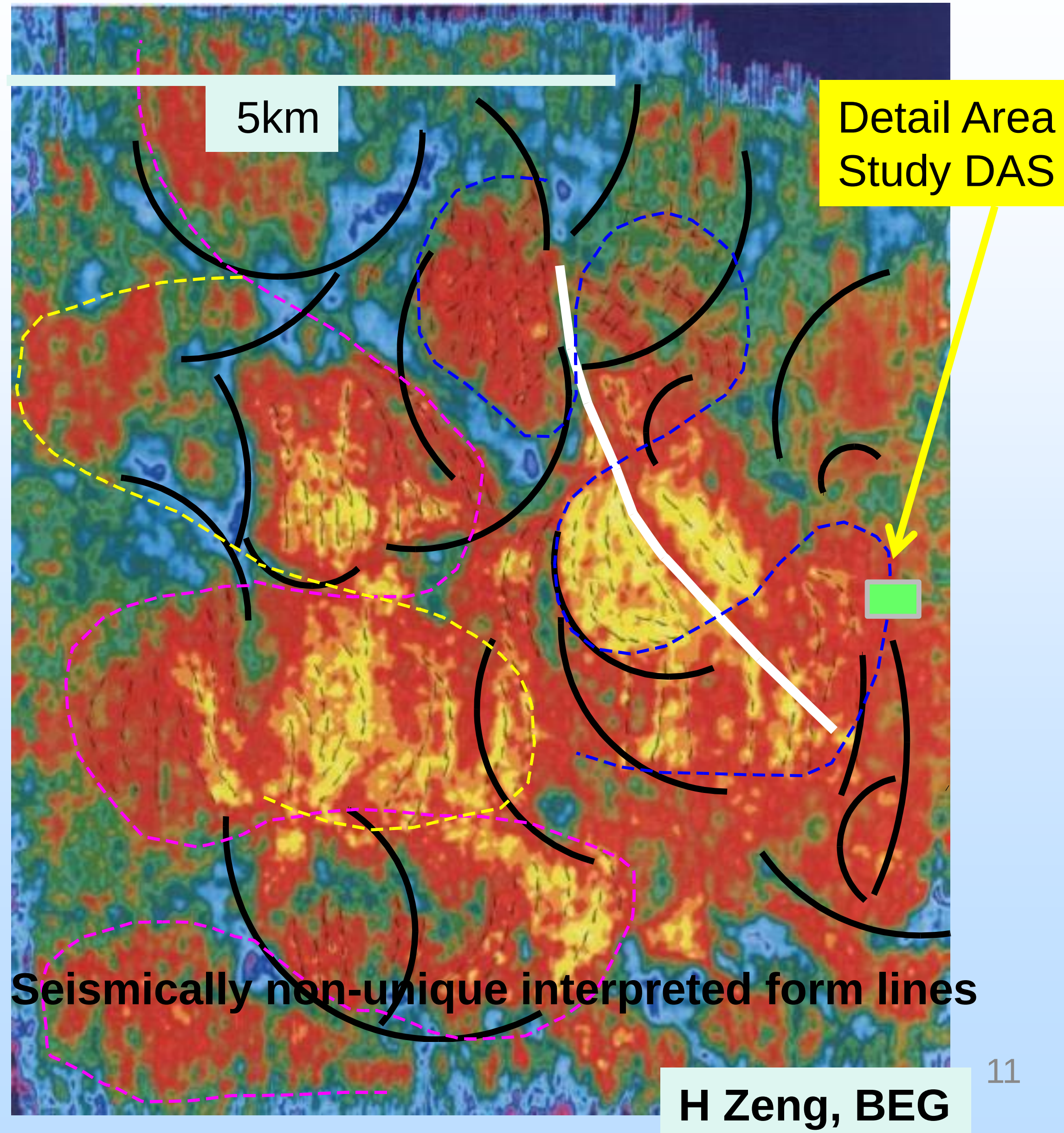
Galloway and others,2000

Location

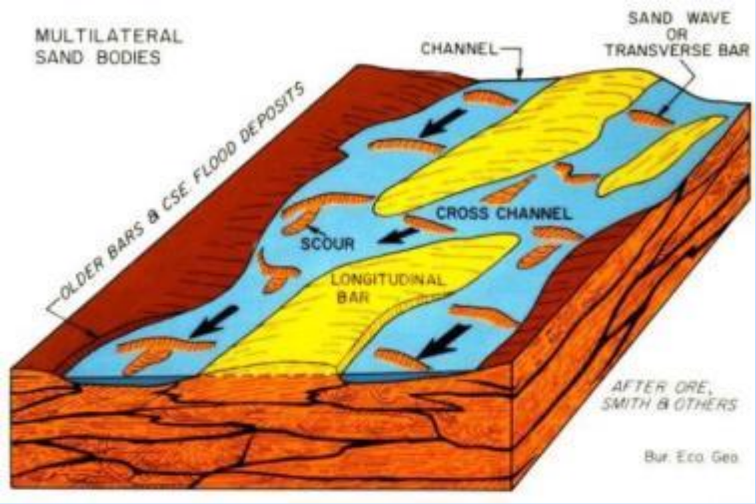


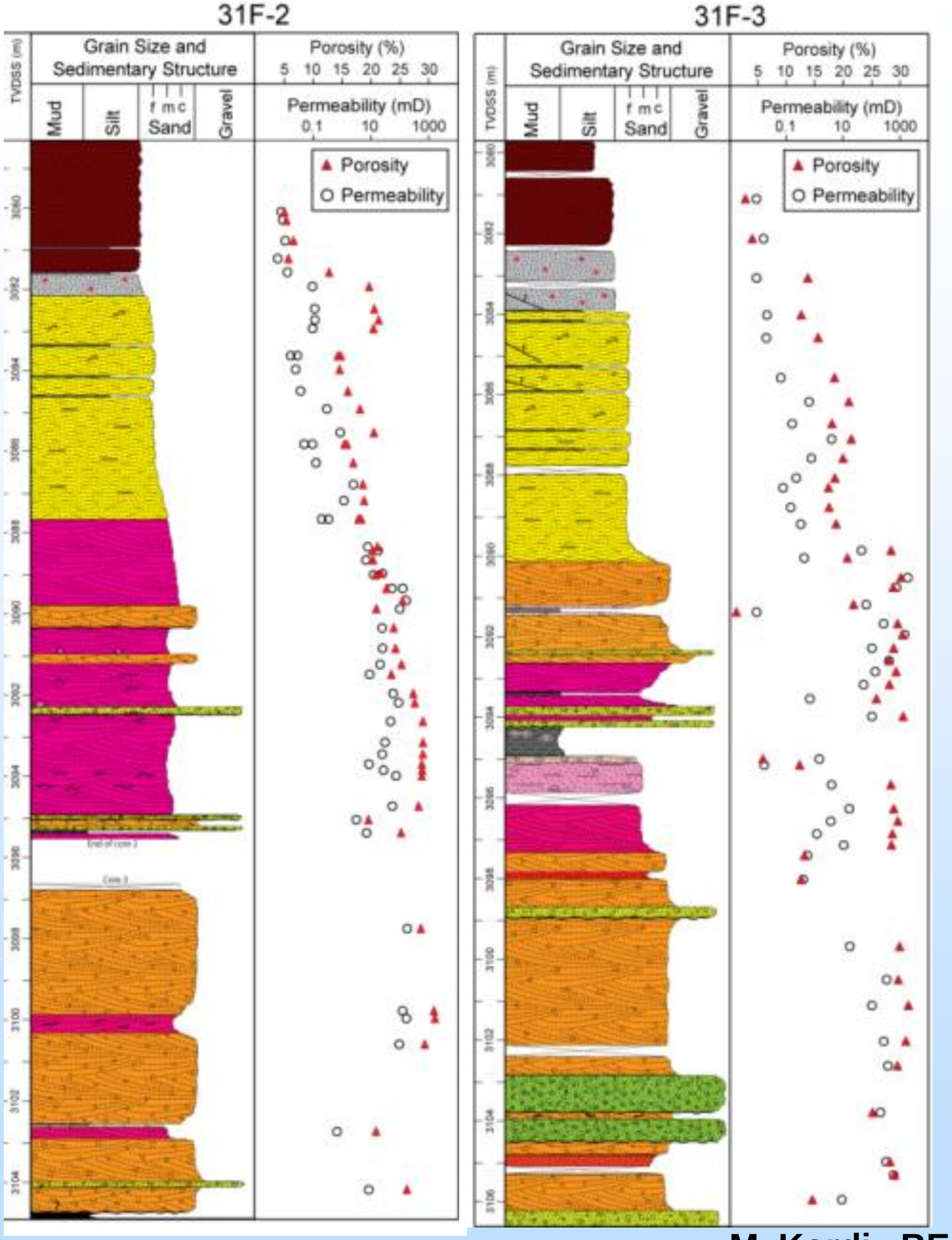
Injection well
Sample well
Other well
WOC
29-1
29-5
24-3
29-10
29-6
29-3
27-5
27-3
28-2
28-1
29-9
29F-1
31F-2
31F-1
31F-3
-3002 m
-2972 m
-2941 m
-2911 m
0
1
2 km
TN
AR
OK
MS
AL
TX
LA
FL
Mississippi Interior Salt Basin Province (USGS)
Jackson Dome
Sabine Uplift
Cranfield
Gulf of Mexico
Wells in Woodbine-Tuscaloosa Fm.
0 75 150 300 km

Lower Tuscaloosa sand and conglomerate fluvial depositional environment



Amalgamated Fluvial Channels - Heterogeneity

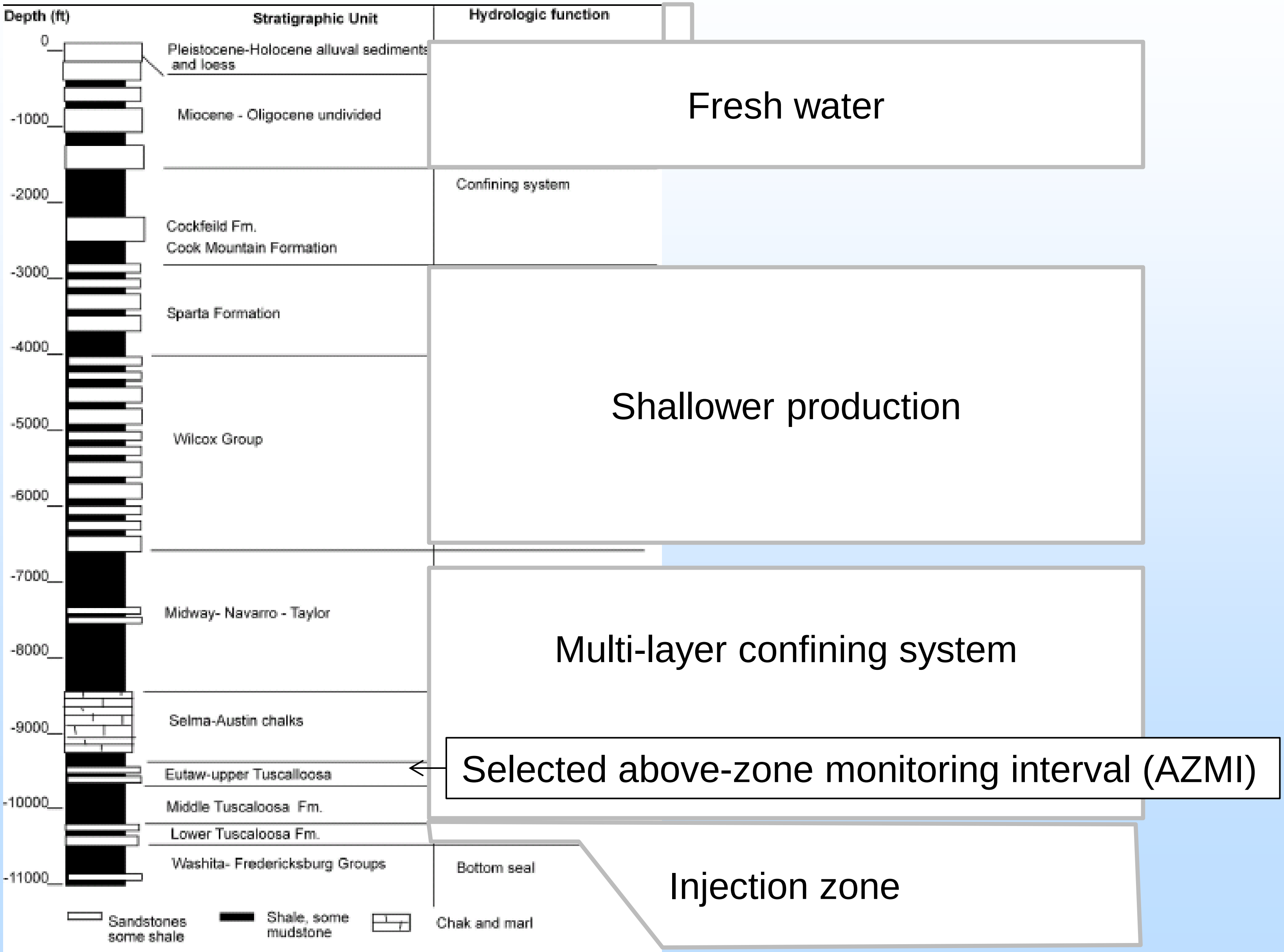




30-m apart

M. Kordi , BEG

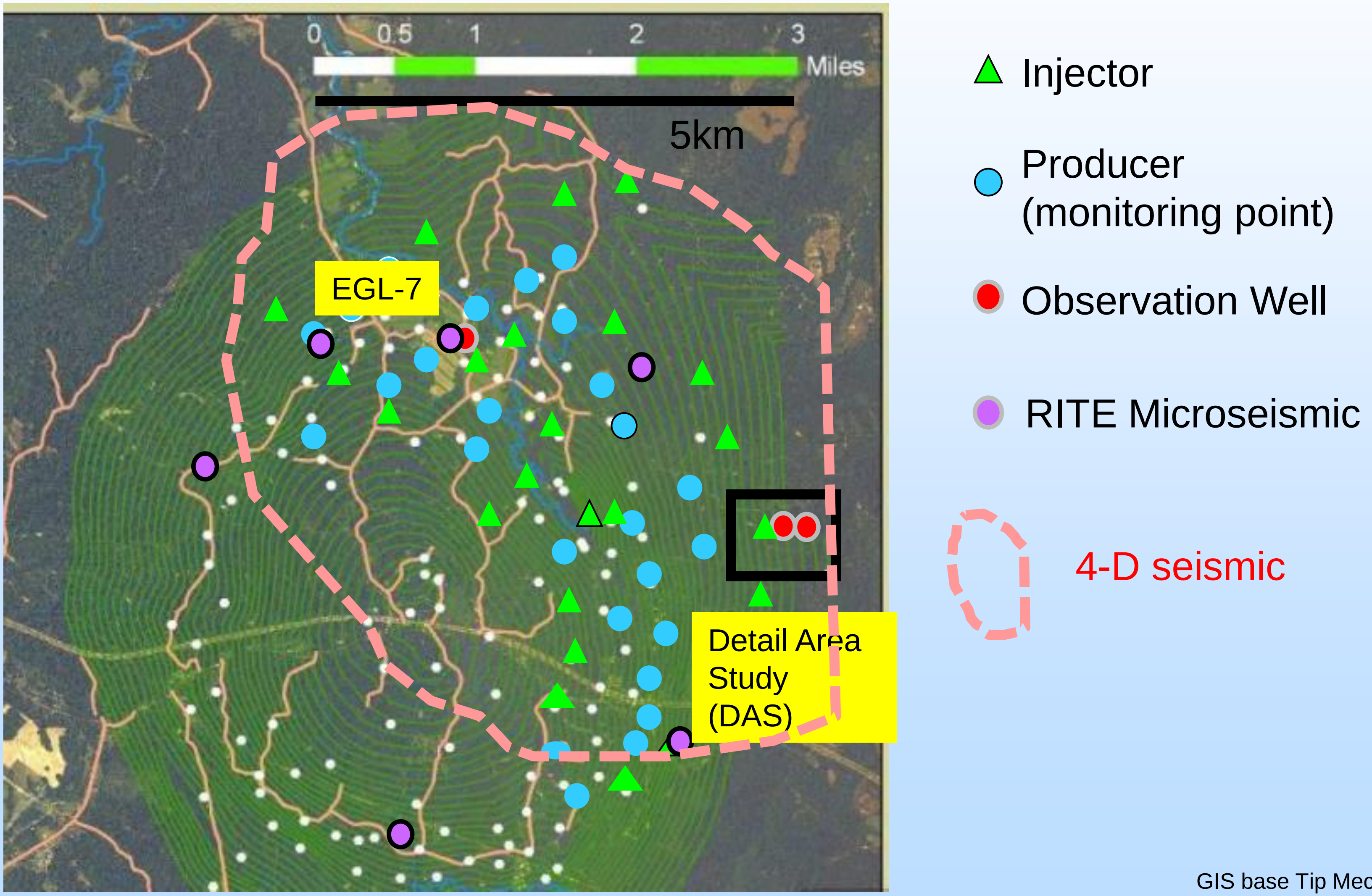
Characterization of Overburden



Presentation Outline

- SECARB Early Test Goals
- Site Characterization
- Monitoring and modeling response to injection in the deep subsurface
- Monitoring the shallow subsurface – what would response to leakage or migration look like?
- Remaining work

Monitoring response to injection in the deep subsurface

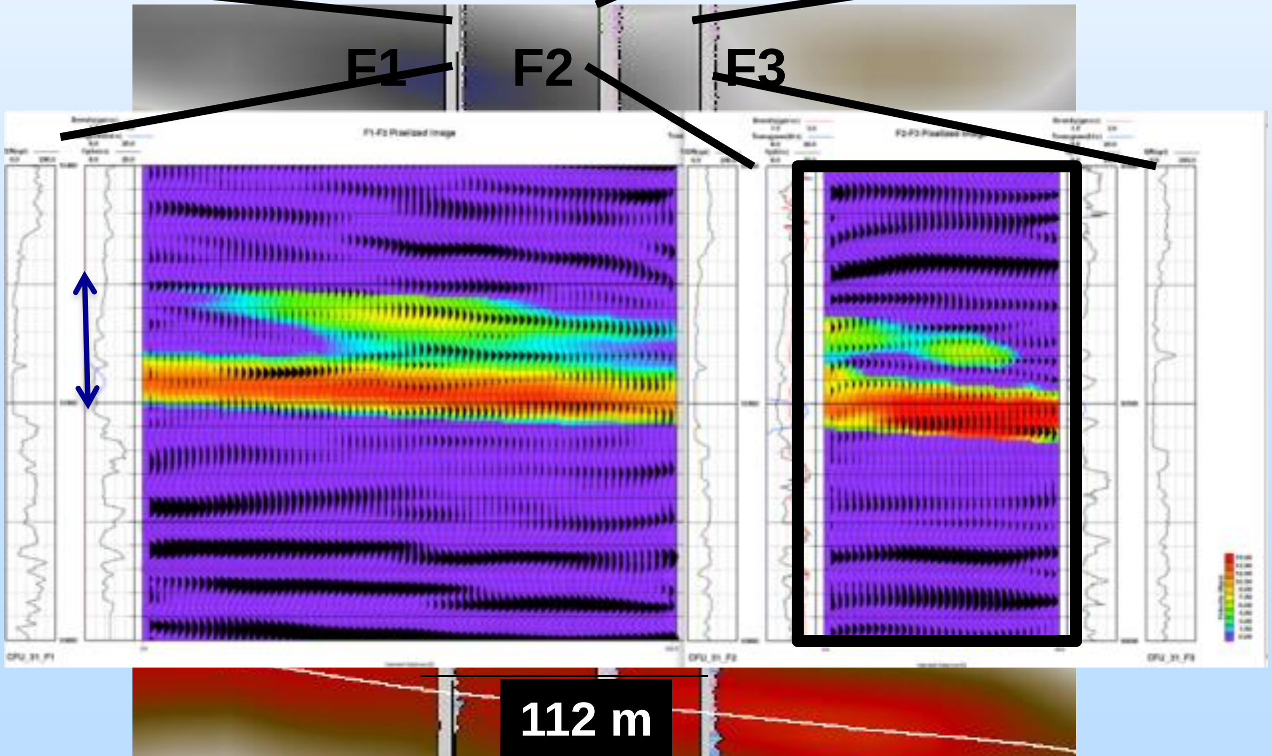


GIS base Tip Meckel, BEG

Detailed Area Study (DAS)

Closely spaced well array to examine flow in complex reservoir

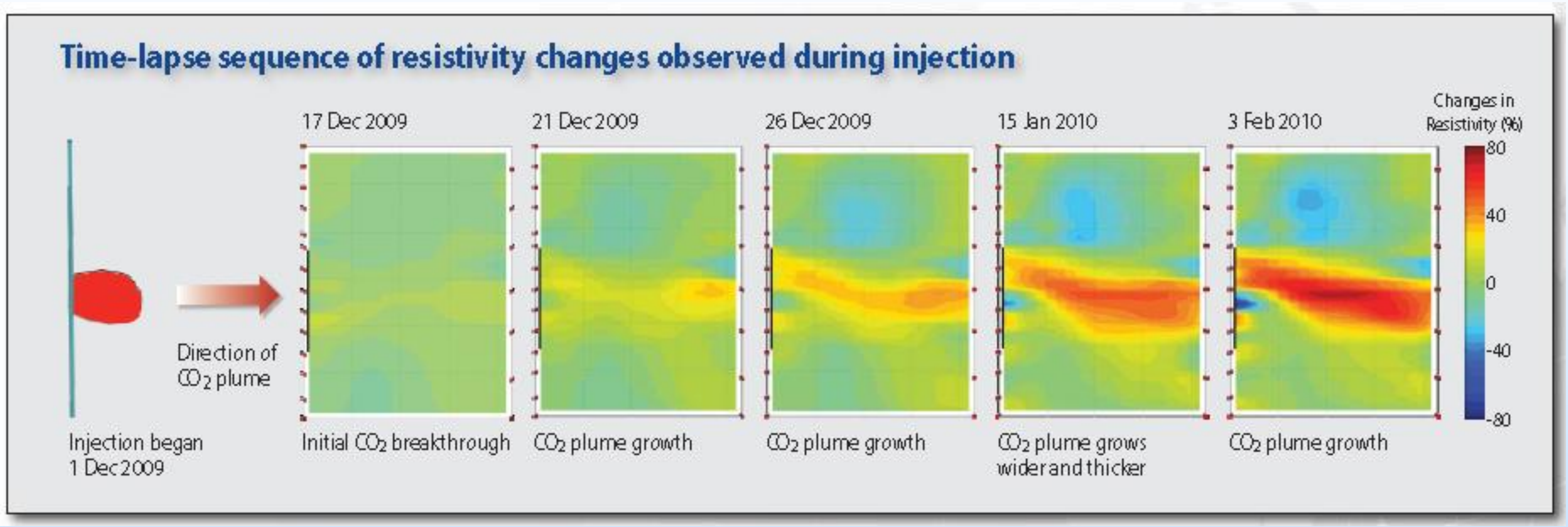
Tuscaloosa D-E reservoir



Petrel model Tip Meckel
Time-lapse cross well Schlumberger

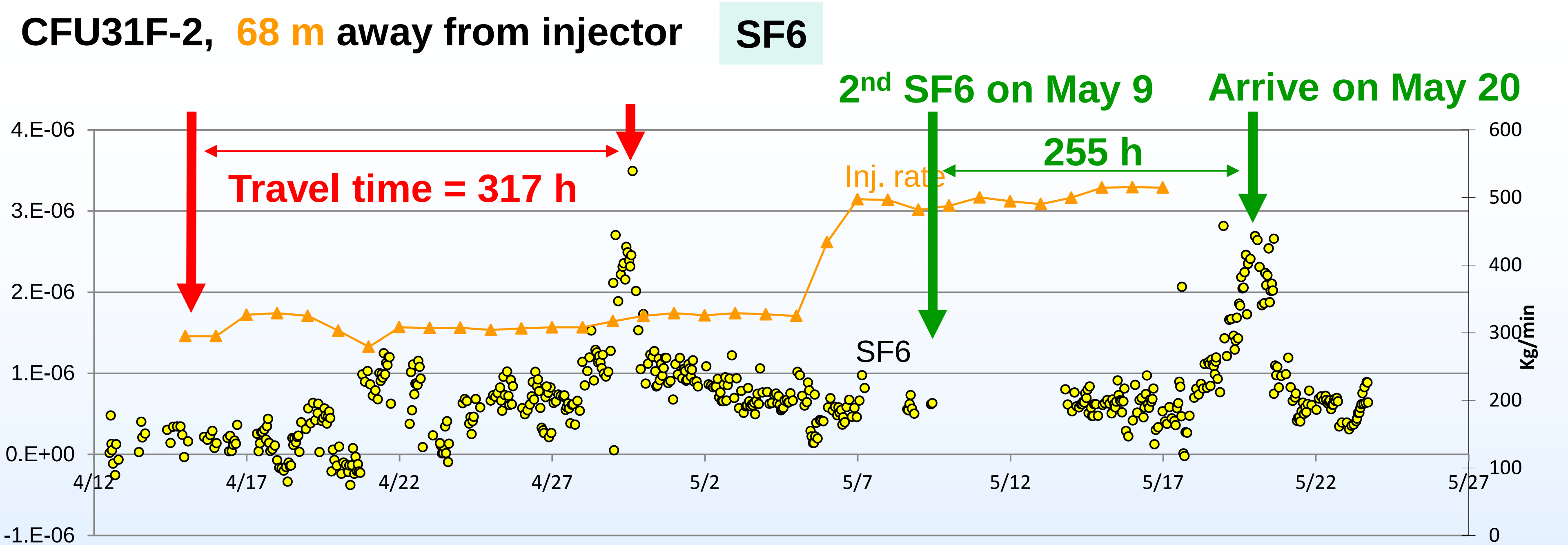
LLNL Electrical Resistance Tomography-changes in response with saturation

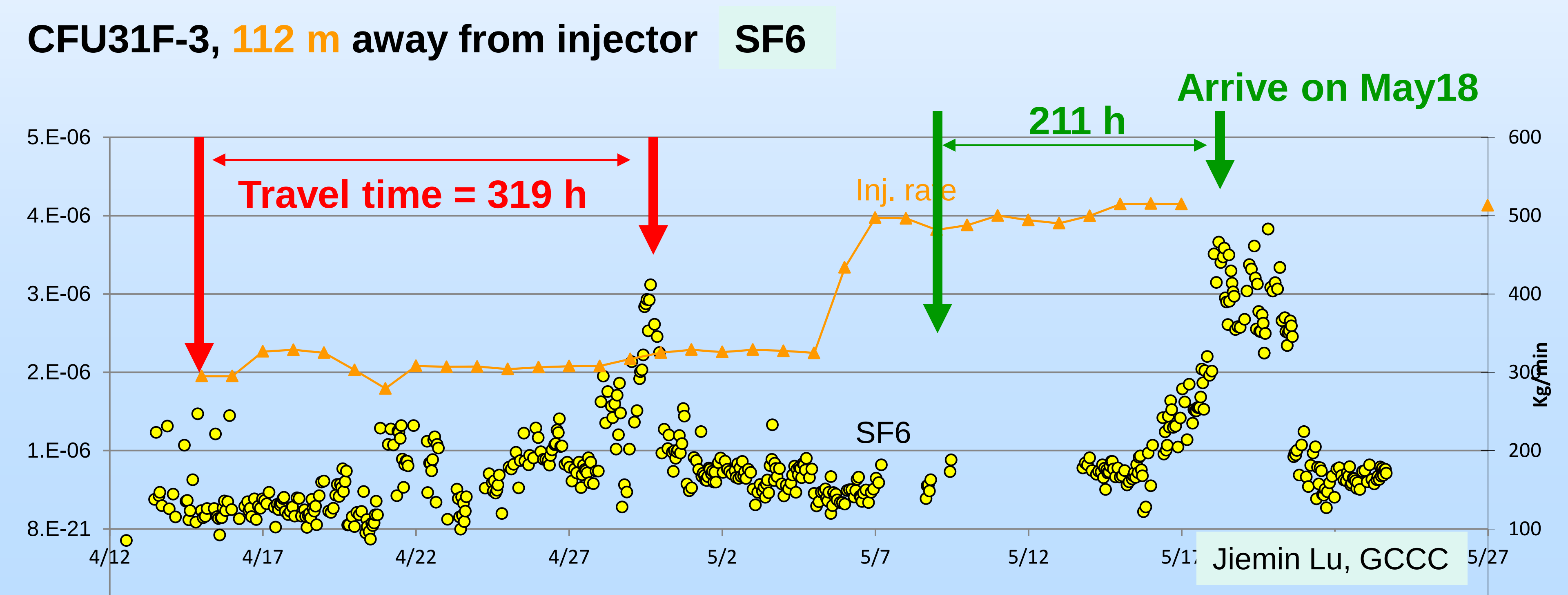
F1 **F2** **F3**



Lawrence Livermore National Laboratory

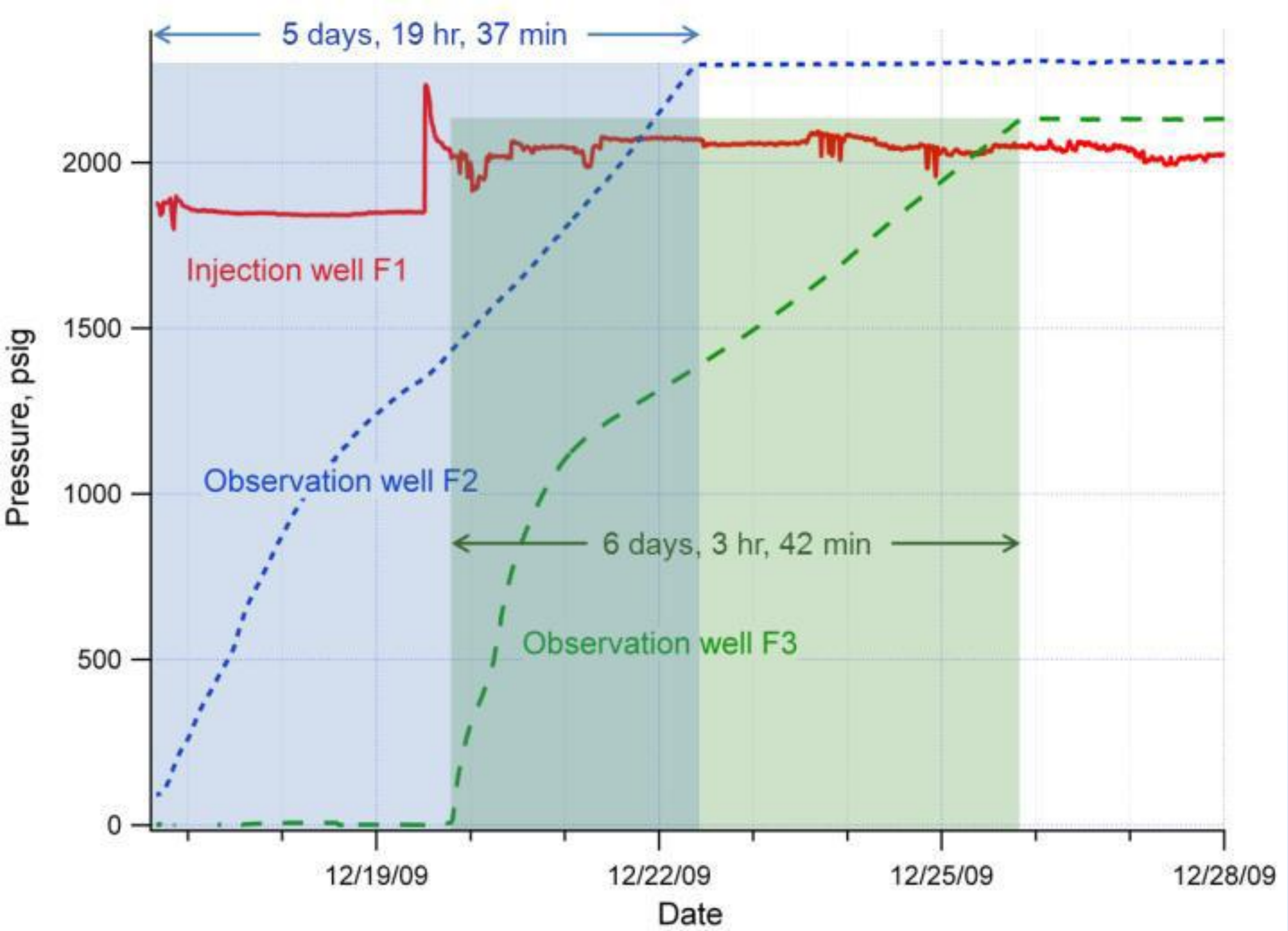
C. Carrigan, X Yang, LLNL
D. LaBrecque Multi-Phase Technologies





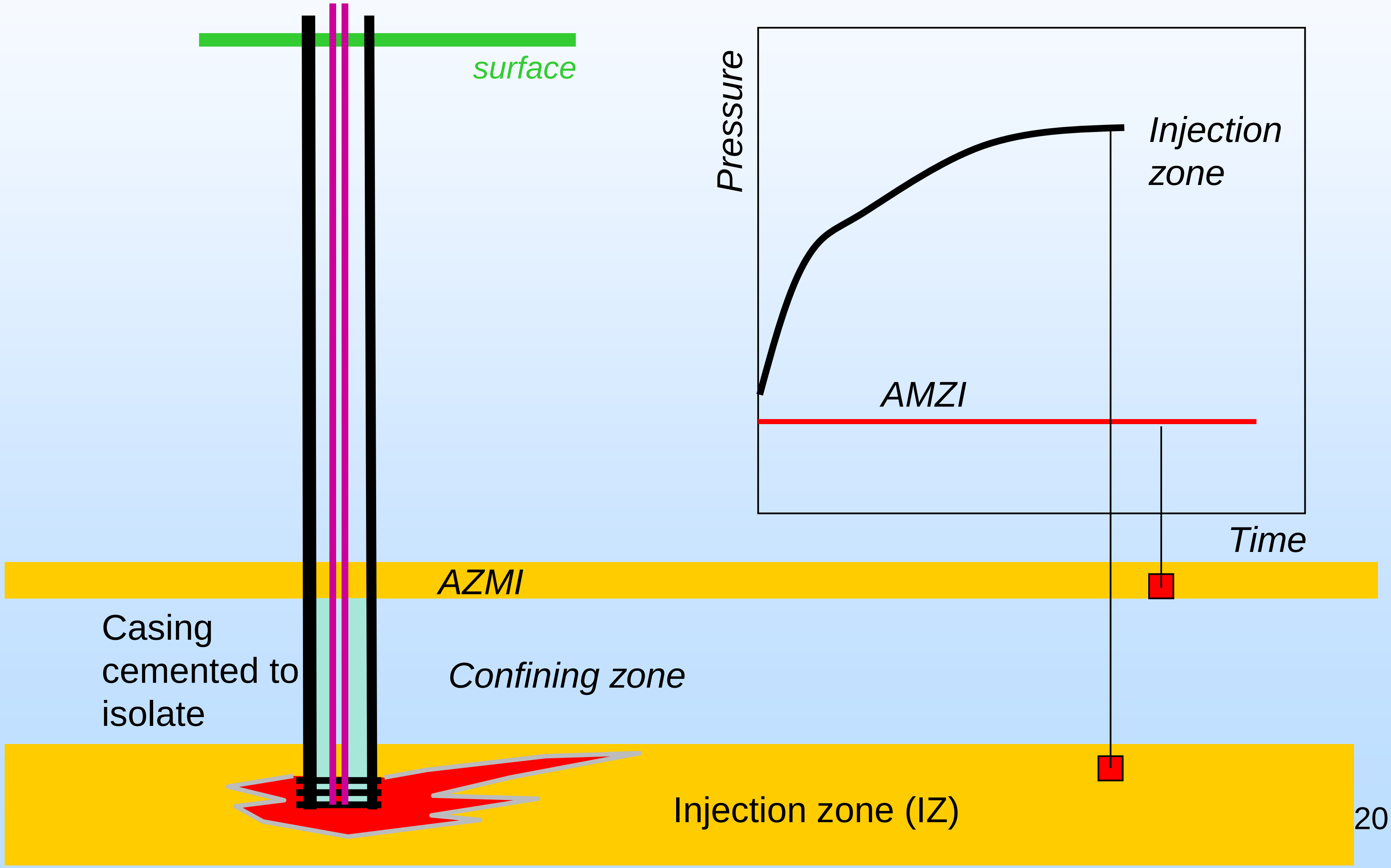
Jiemin Lu, GCCC

Wellhead pressure indicating breakthrough

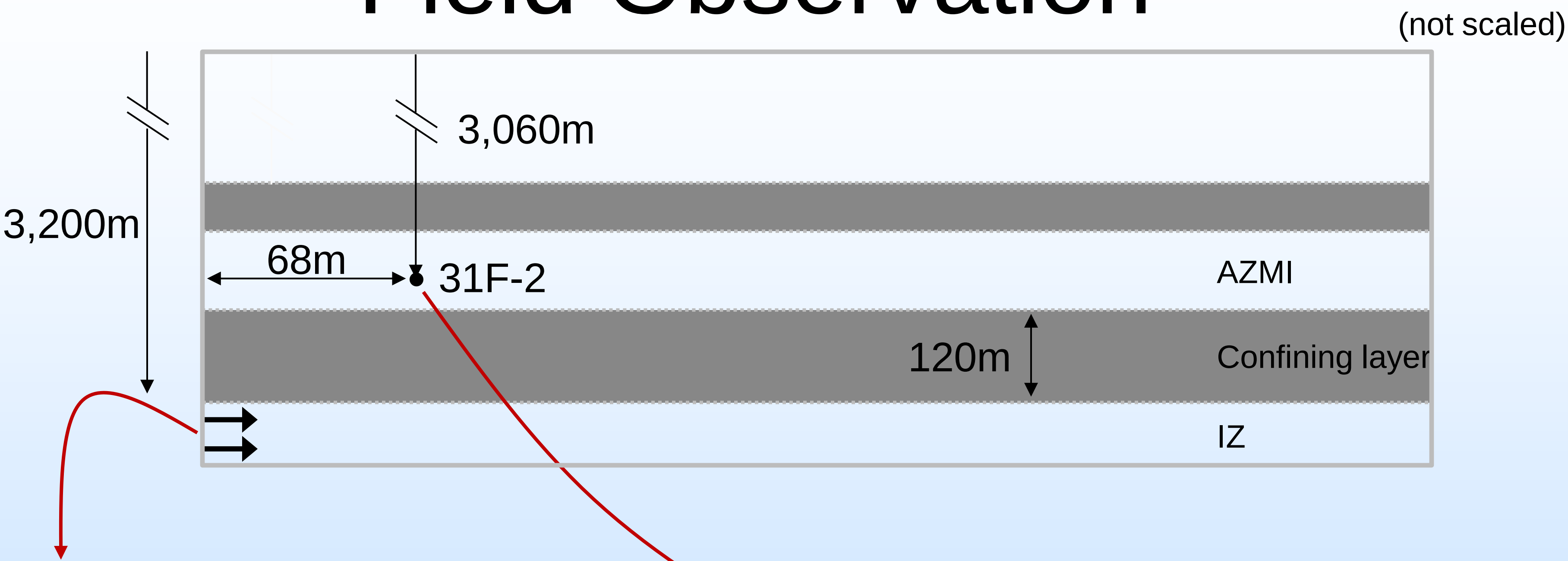


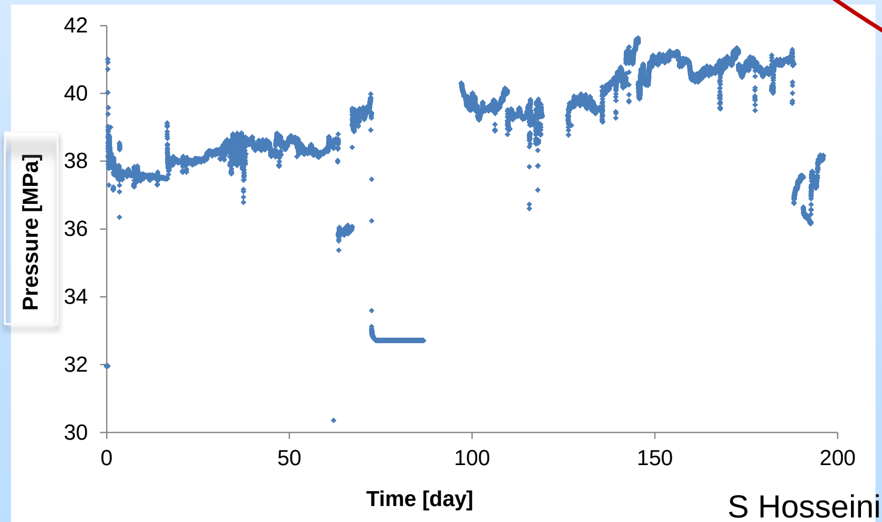
Seyyed Hosseini, BEG, Sandeep Verma Schlumberger

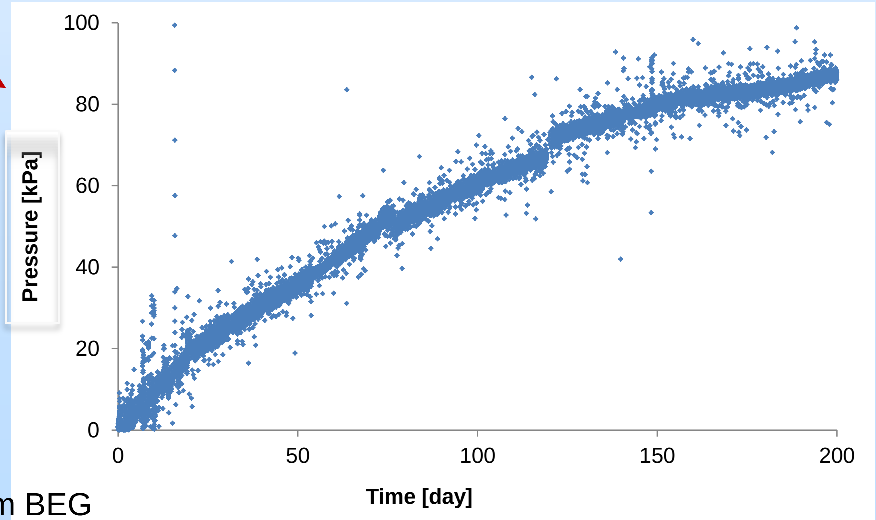
Pressure Monitoring in AZMI (Above zone monitoring interval)



Field Observation

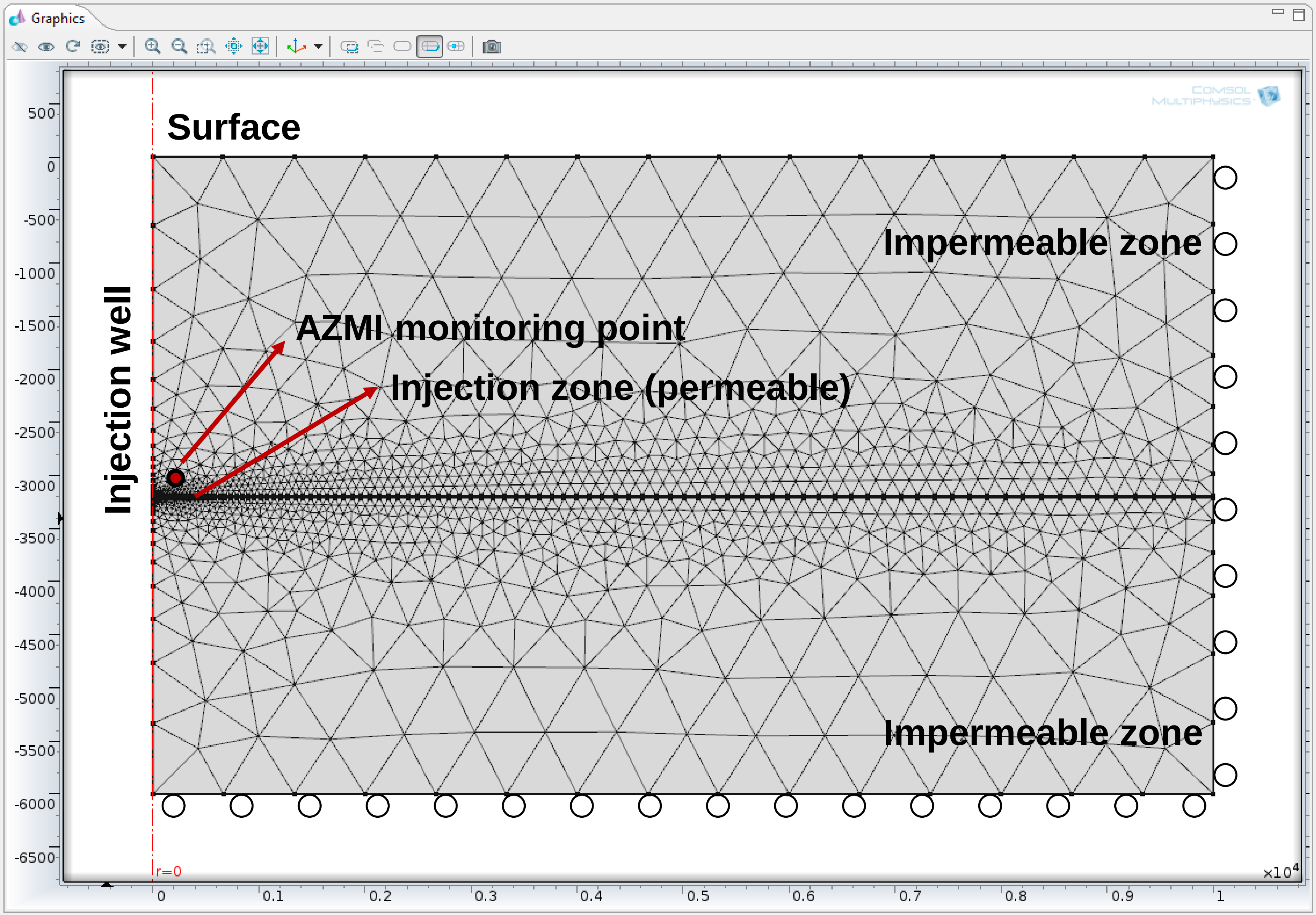






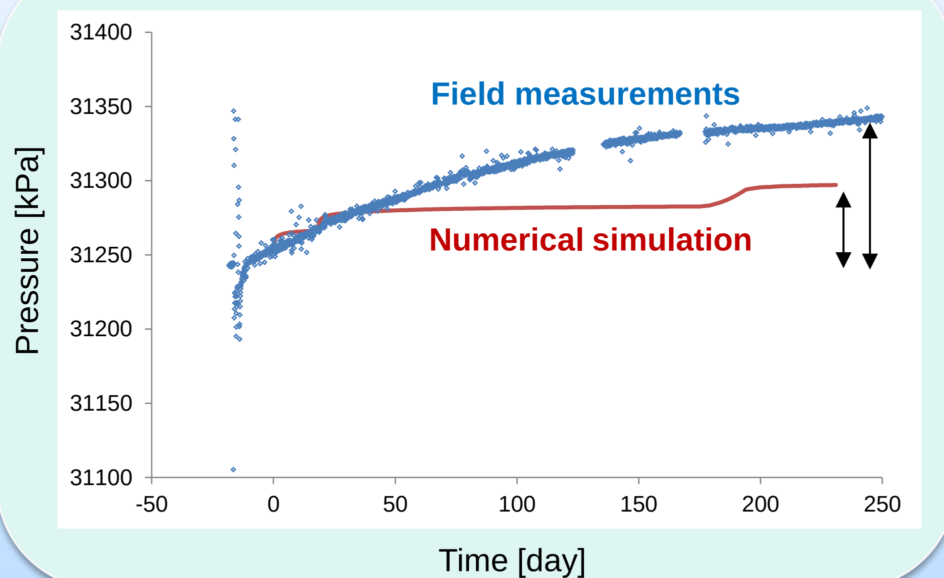
S Hosseini, S. Kim BEG

- COMSOL: simulation model

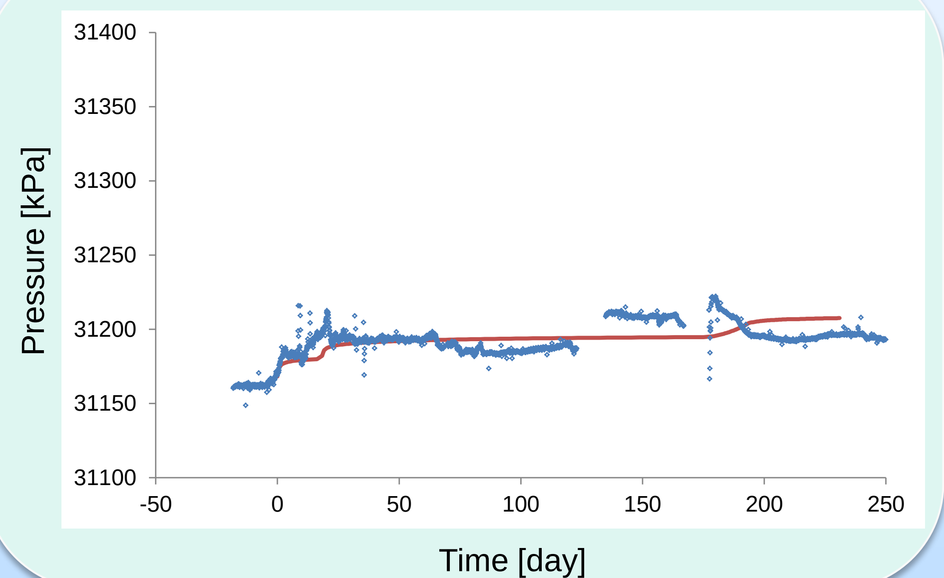


Matching pressure in AZMI

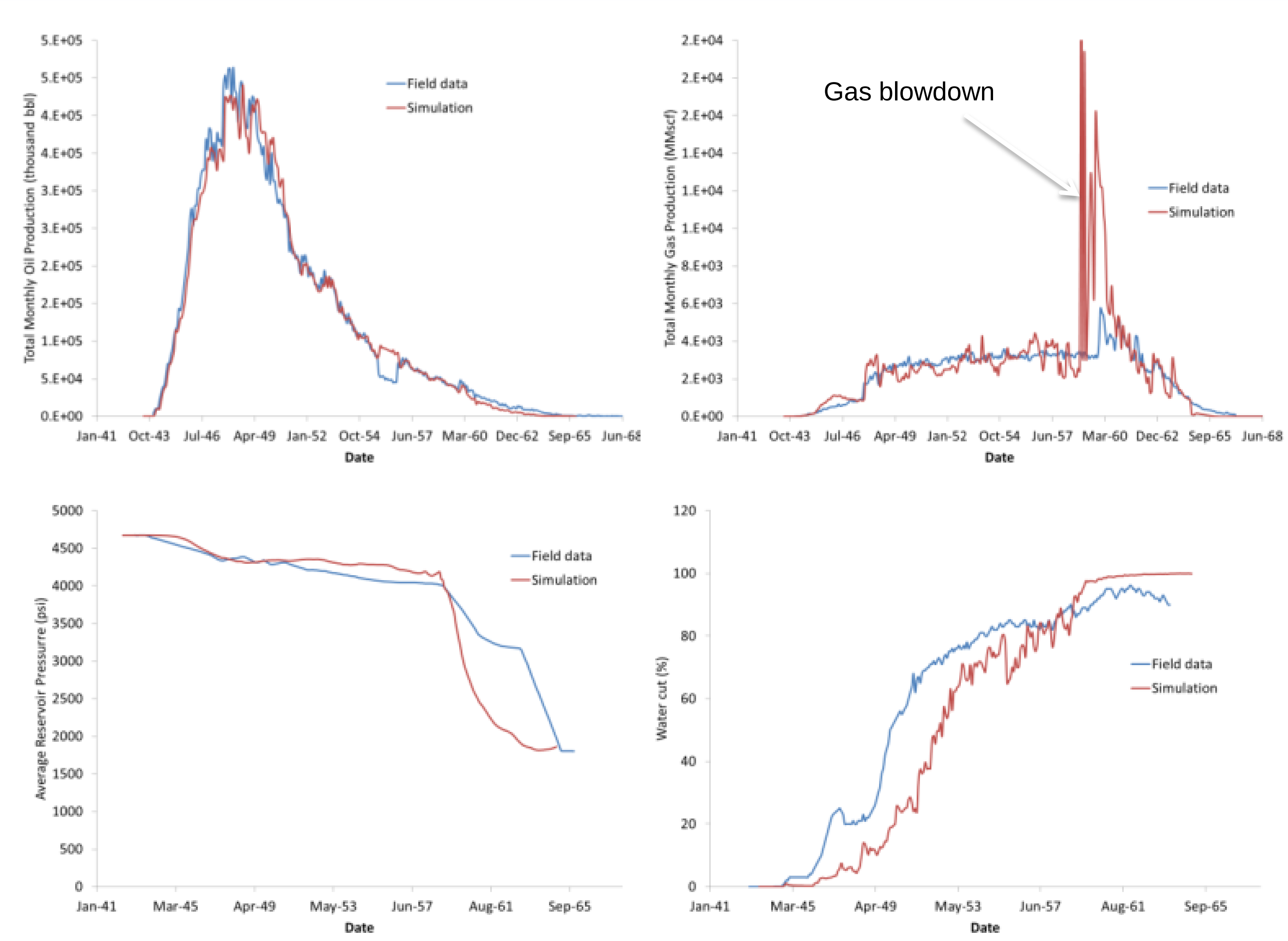
- 31 F2 Mon. Well: Pressure



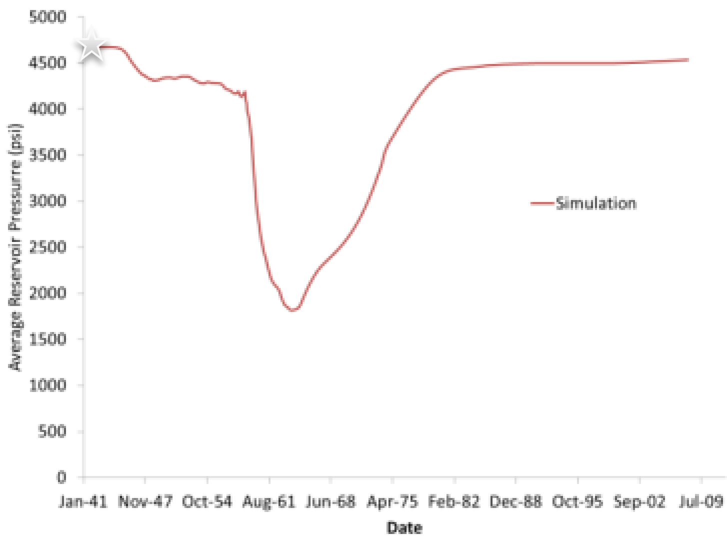
- 31 F3 Mon. Well: Pressure

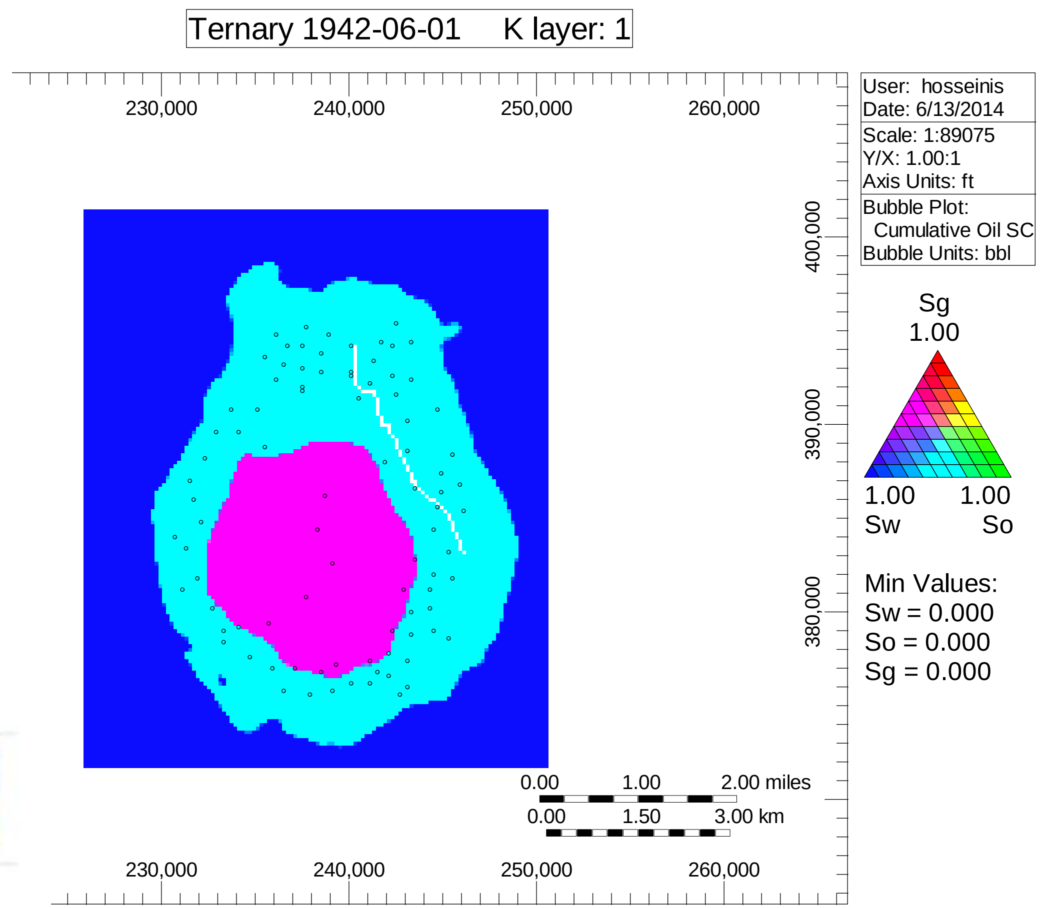


4 D seismic- Historic data history matching (1942-1967)



Ternary saturation map (1942)





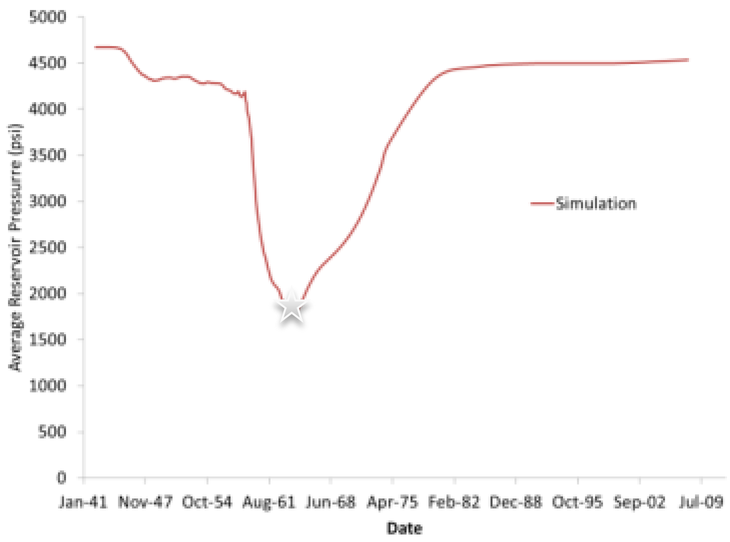
International Journal of Greenhouse Gas Control

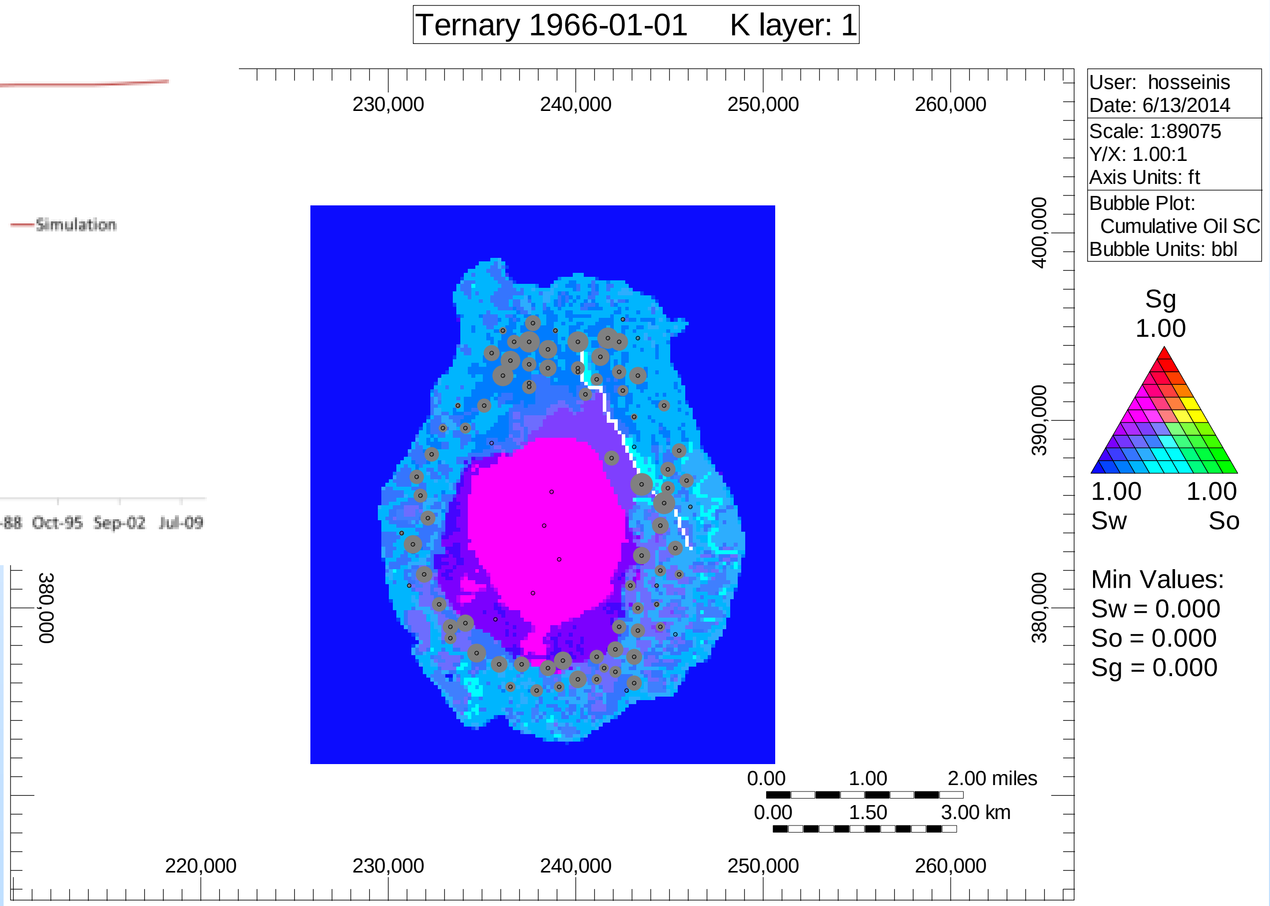
Volume 18, October 2013, Pages 449–462

Static and dynamic reservoir modeling for geological CO_2 sequestration at Cranfield, Mississippi, U.S.A.

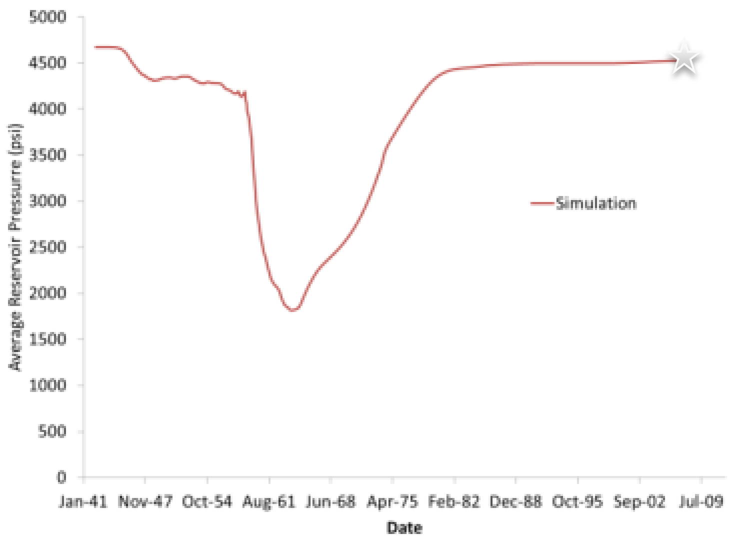
Seyyed Abolfazl Hosseini[a], Hamidreza Lashgari[b], Jong W. Choi[a], Jean-Philippe Nicot[a], Jiemin Lu[a], Susan D. Hovorka[a]

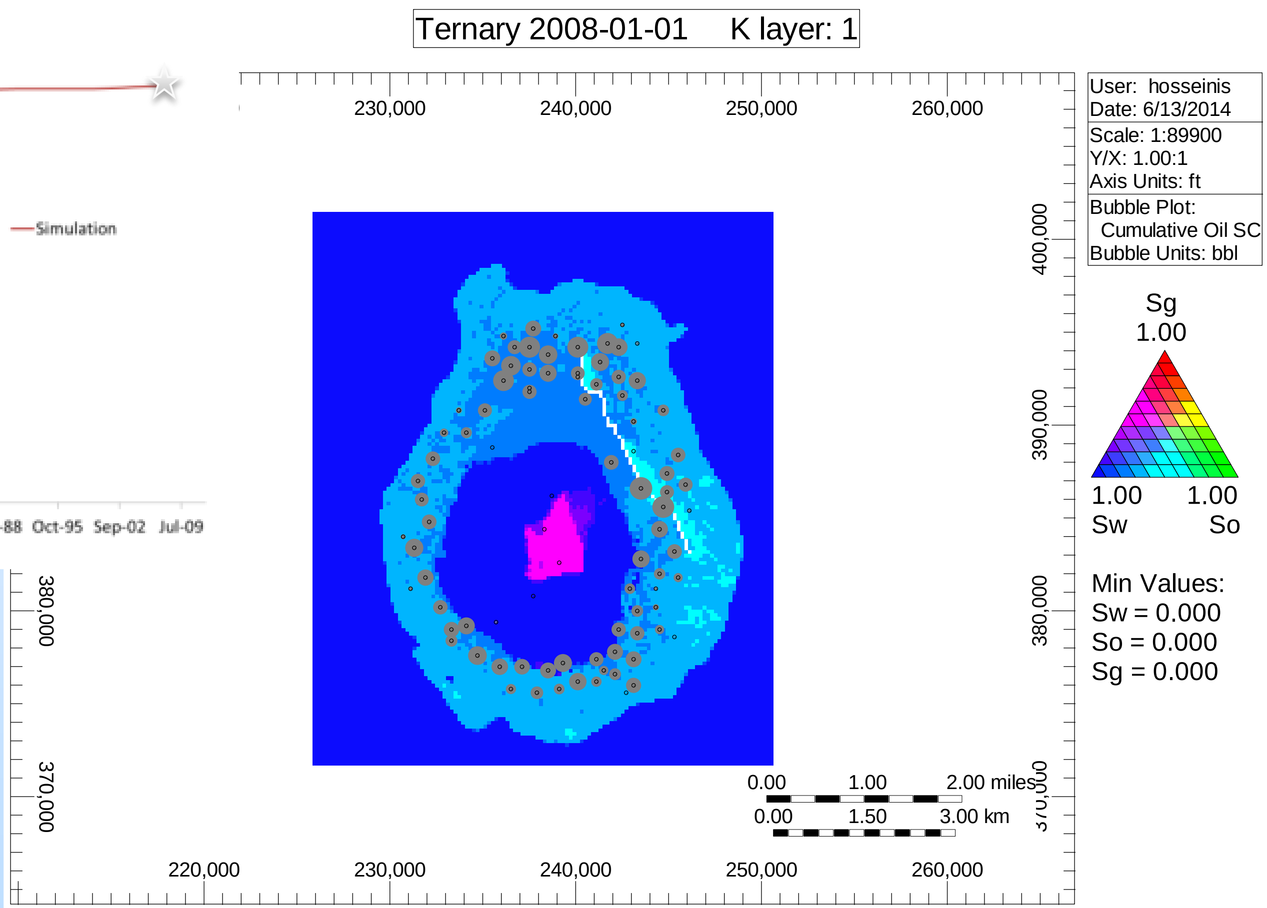
Ternary saturation map (1966)



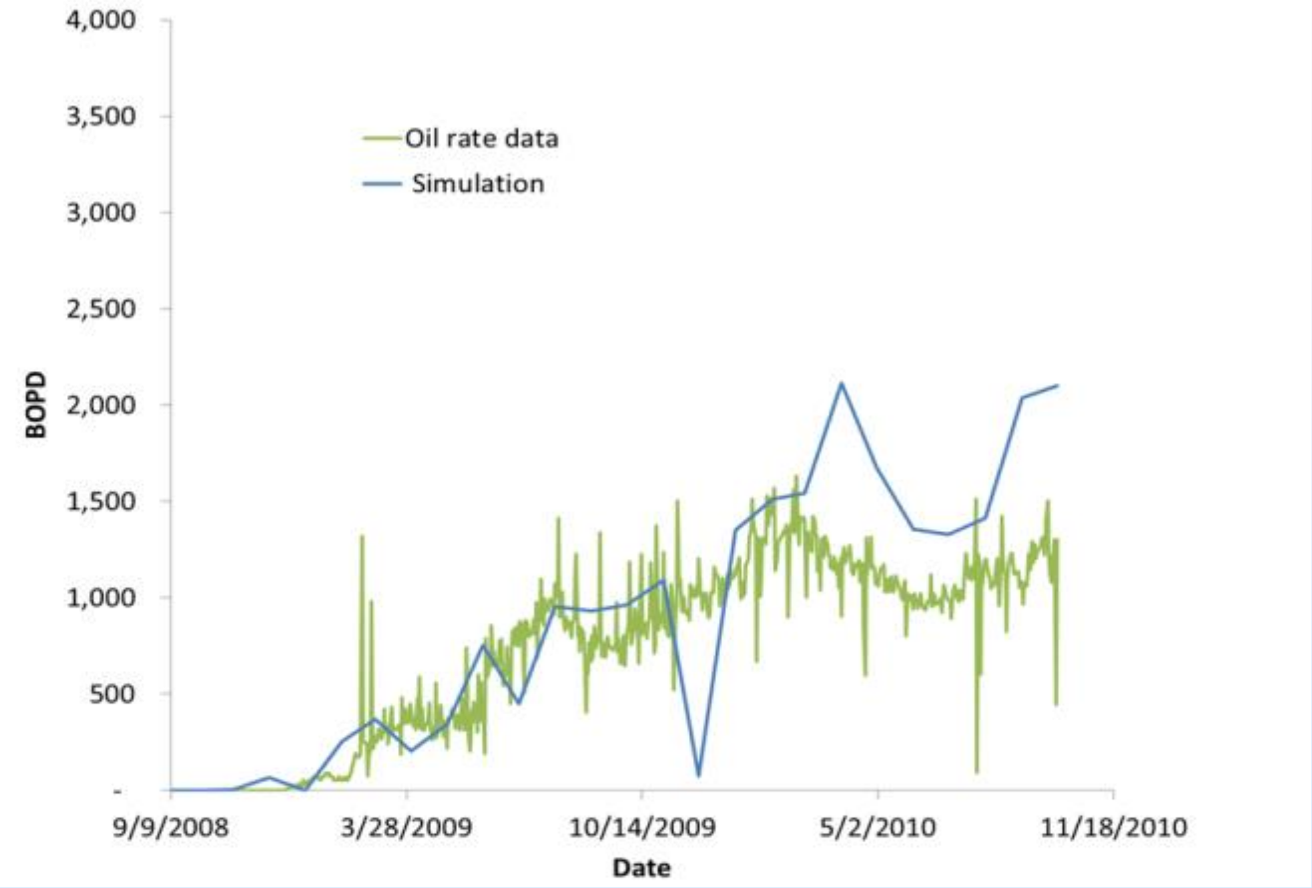


Ternary saturation map (2007)

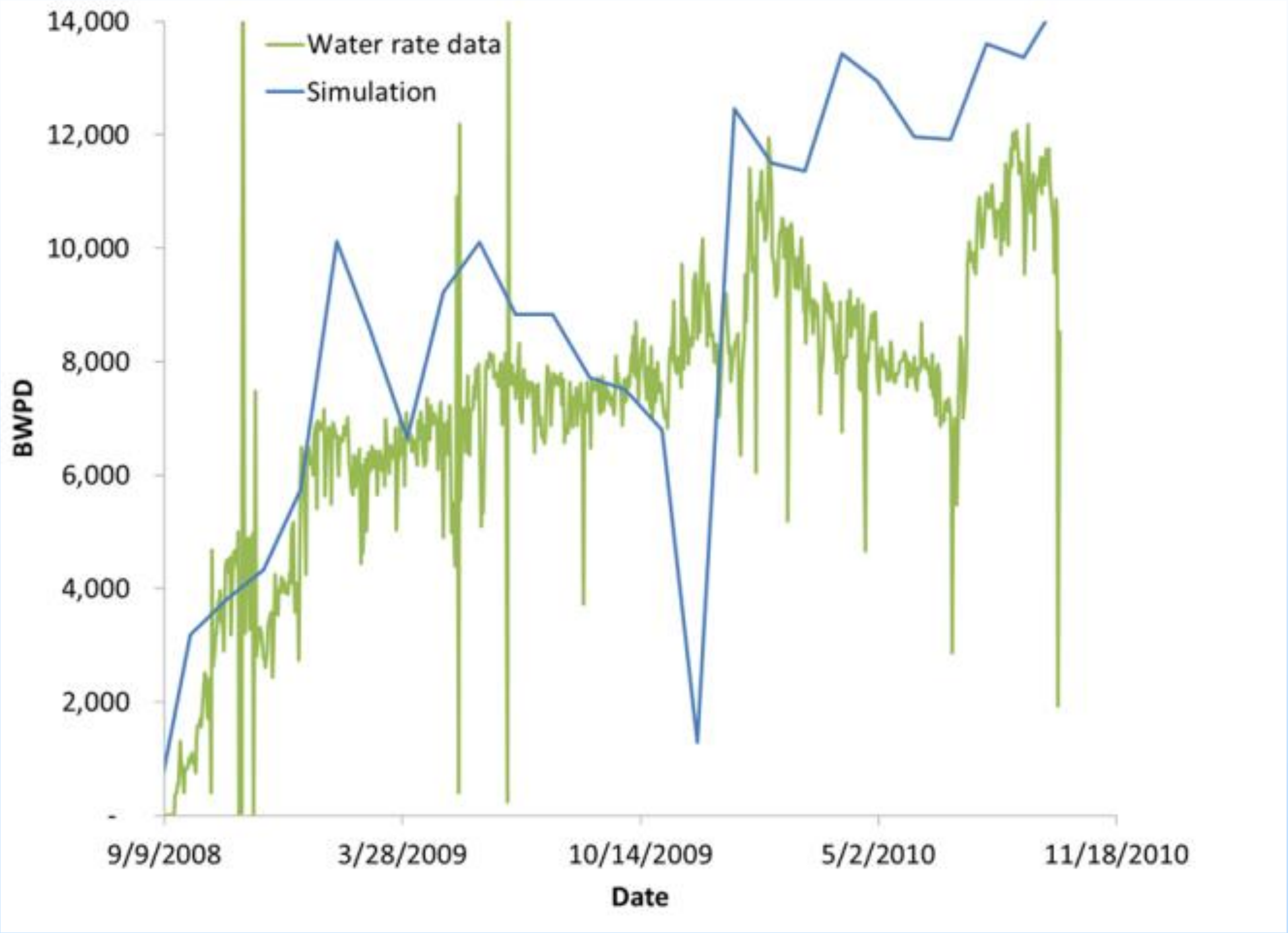




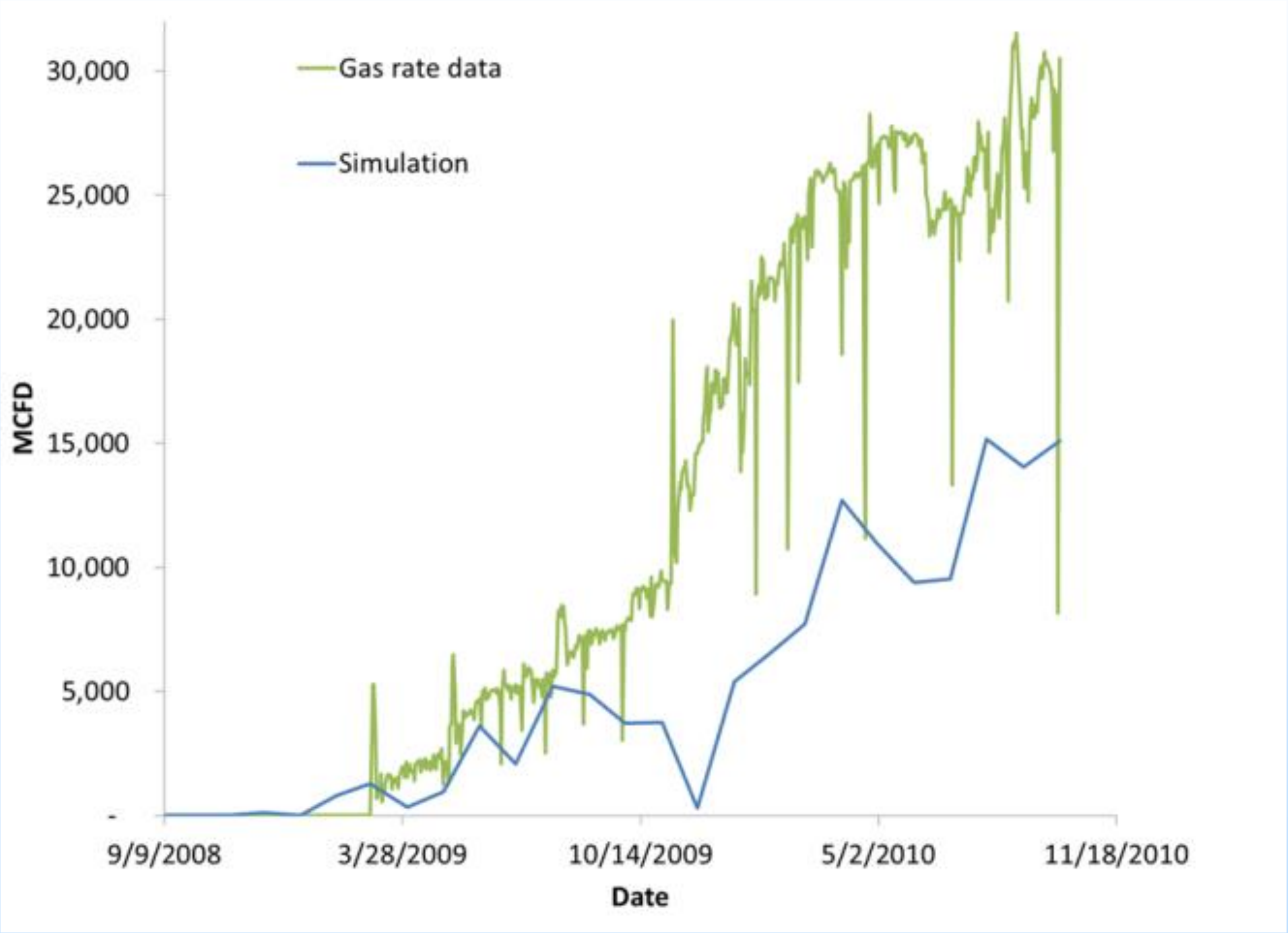
CO_2 Injection Simulation (2007-2010)



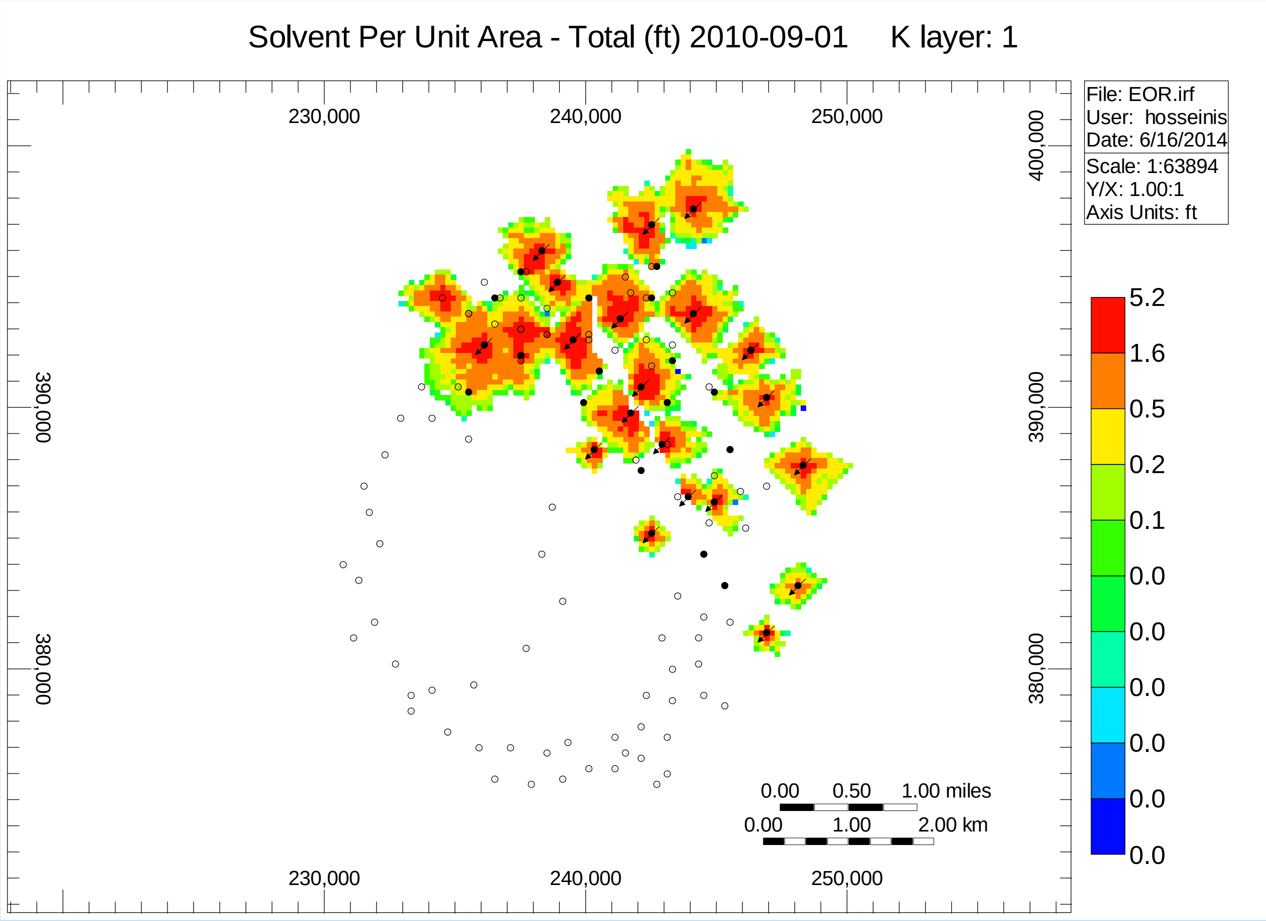
CO_2 Injection Simulation (2007-2010)



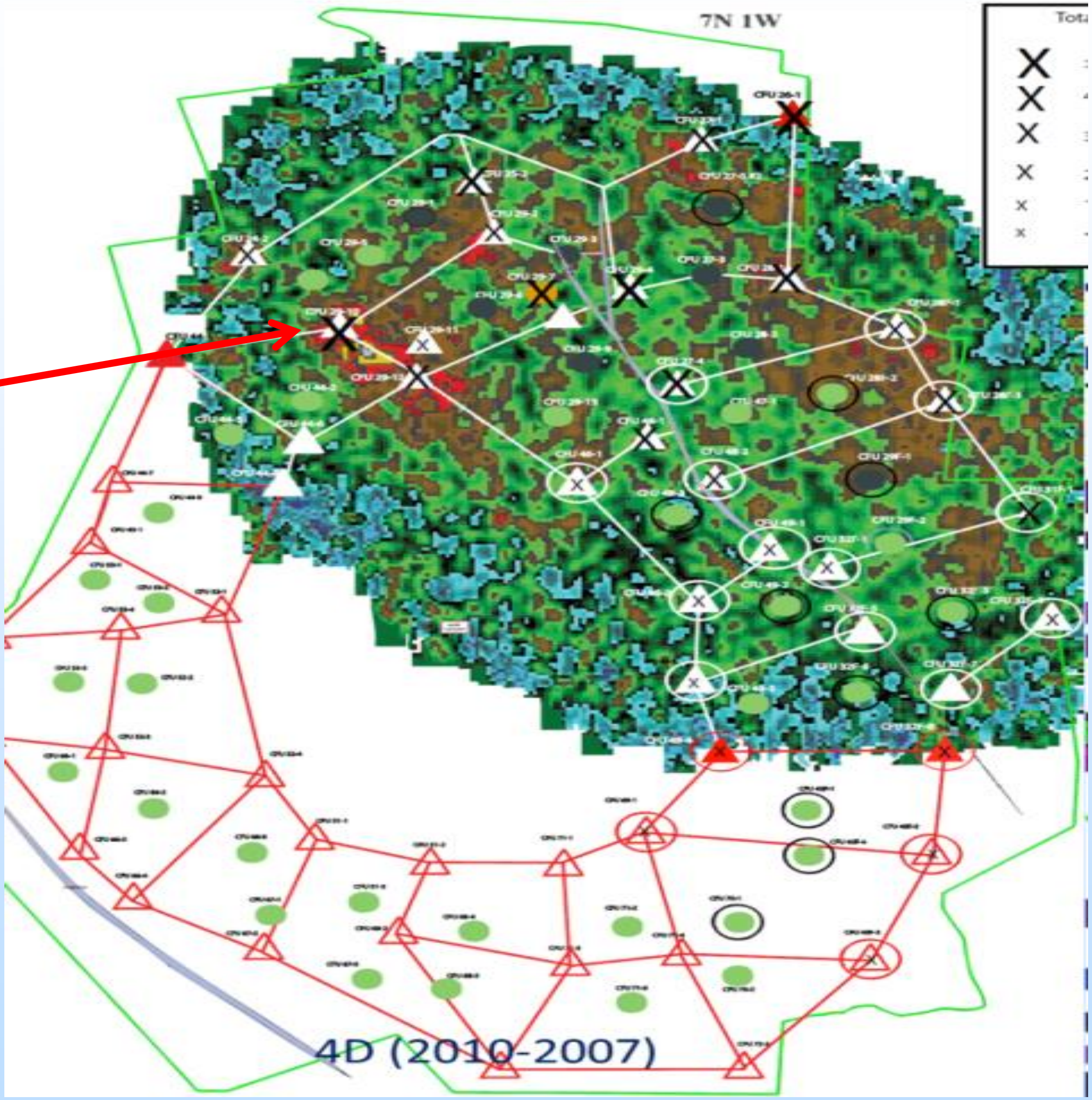
CO_2 Injection Simulation (2007-2010)



CO_2 Injection Simulation (2007-2010)



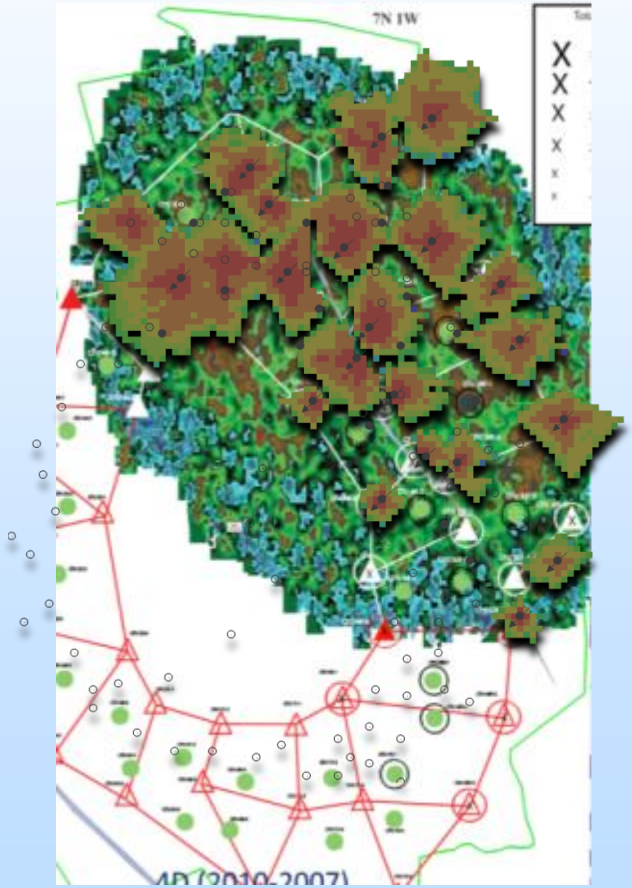
4-D Seismic difference (2010-2007)



Injection began July 15, 2008

Comparison to 4-D Seismic

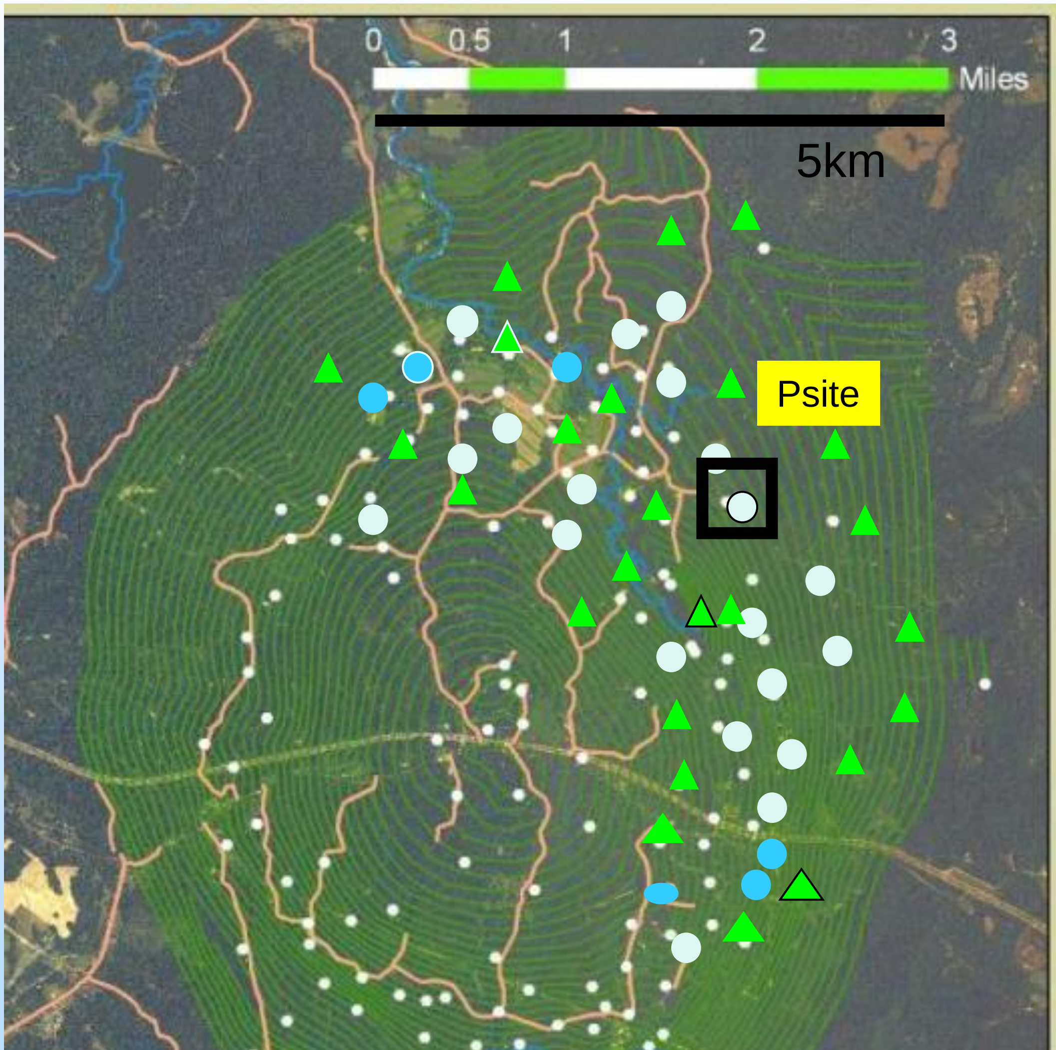
Red and brown areas are high gas saturation regions



Presentation Outline

- SECARB Early Test Goals
- Site Characterization
- Monitoring and modeling response to injection in the deep subsurface
- Monitoring the shallow subsurface – what would response to leakage or migration look like?
- Remaining work

Monitoring the shallow subsurface – what would response to leakage or migration look like?



Groundwater sampling point at each Injector

Plugged and abandoned well

Producer

Selected soil gas monitoring points

GIS base Tip Meckel, BE

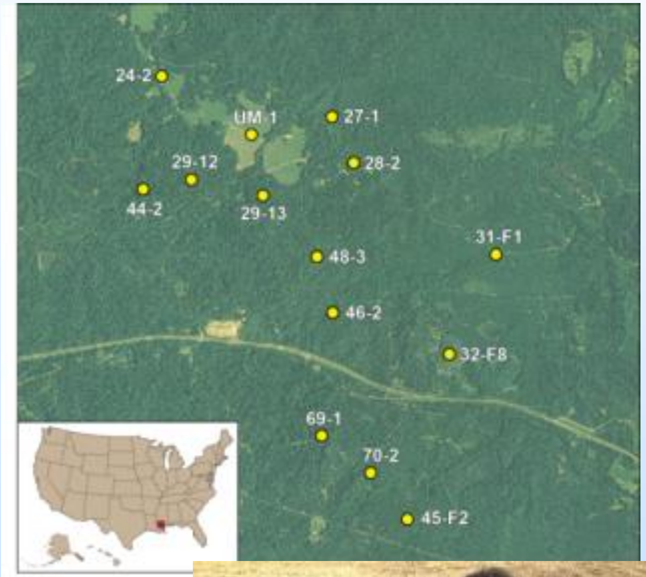
Groundwater at the Cranfield Site: Sampling

- More than 12 field campaigns since 2008
- ~ 130 groundwater samples collected for chemical analysis of

  Cations: Ag, Al, As, Ba, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Pb, Se, Zn
  Anions: F^-, Cl^-, SO_4^{2-}, Br^-, NO_3^-, PO_4^{3-}
  TOC, TIC, pH, Alkalinity, VOC, $\delta C13$

  On-site: pH, temperature, alkalinity, water level

- ~10 samples for noble gases
- ~20 groundwater samples for dissolved CH_4

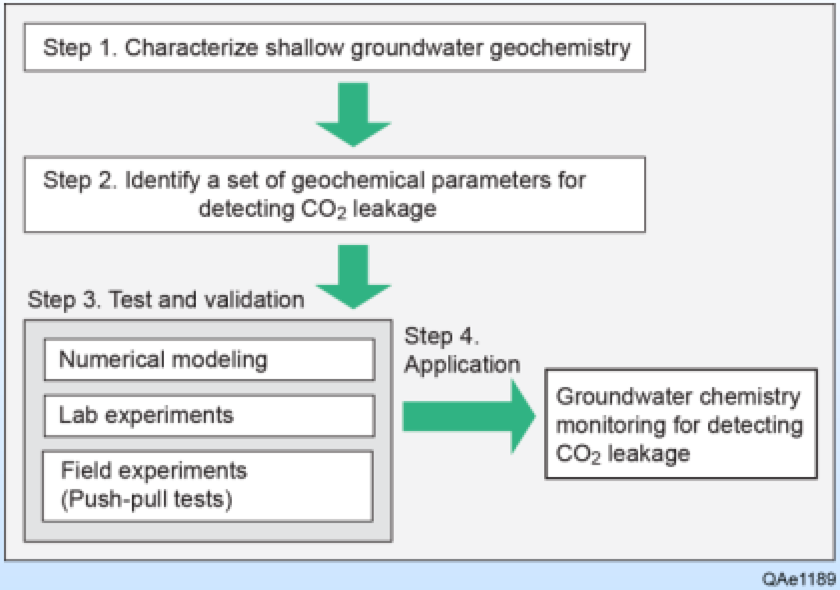


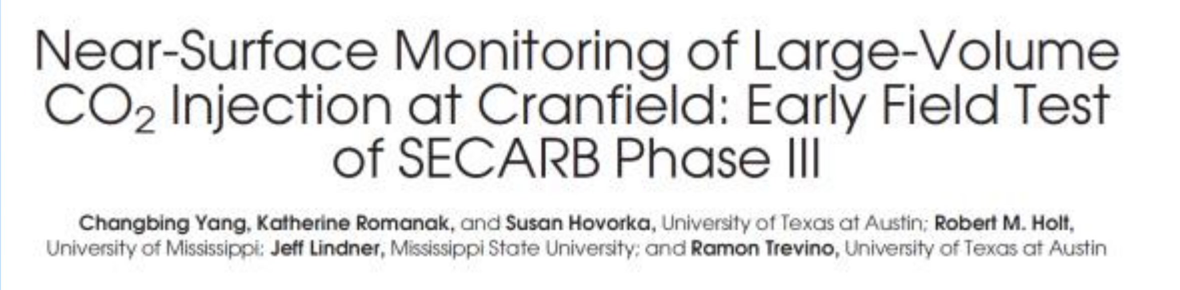
C. Yang, BEG

Groundwater at the Cranfield Site Sampling

- Results (prior to 2013) were summarized in the peer-reviewed paper

- No obvious change in groundwater chemistry was documented
- A step-wise working procedure for groundwater chemistry monitoring was proposed





Near-Surface Monitoring of Large-Volume CO_2 Injection at Cranfield: Early Field Test of SECARB Phase III

Changbing Yang, Katherine Romanak, and **Susan Hovorka,** University of Texas at Austin; **Robert M. Holt,** University of Mississippi; **Jeff Lindner,** Mississippi State University; and **Ramon Trevino,** University of Texas at Austin

C. Yang, BEG

Groundwater at the Cranfield Site Laboratory and Modelling

- Test response of groundwater chemistry to CO_2 leakage under laboratory conditions
  - Samples of sediments & groundwater collected
  - Bubbled with Ar for a week, then with CO_2 for ~half year

Pros: easy to do, little cost
Cons: Non-realistic conditions

- Modeled concentrations of major ions showed overall increasing trends, depending on mineralogy of the sediments, especially carbonate content.
- Modeling results suggested that reductions in groundwater pH were more significant in the carbonate-poor aquifers than in the carbonate-rich aquifers, resulting in potential groundwater acidification.
- Mobilization of trace metals was likely caused by mineral dissolution and release of surface complexes on clay mineral surfaces.

C. Yang, BEG

Environmental Science & Technology
Article
pubs.acs.org/est

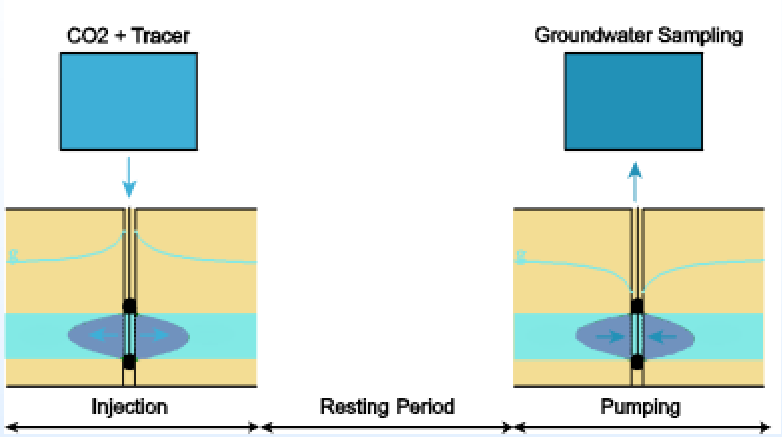
Inverse Modeling of Water-Rock-CO_2 Batch Experiments: Potential Impacts on Groundwater Resources at Carbon Sequestration Sites

Changbing Yang,[*,†] Zhenxue Dai,[‡] Katherine D. Romanak,[†] Susan D. Hovorka,[†] and Ramón H. Treviño[†]

[†]Bureau of Economic Geology, The University of Texas at Austin, 10100 Burnet Road, Austin, Texas 78758, United States
[‡]Earth and Environmental Sciences Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, United States

Groundwater at the Cranfield Site Single-Well Push-Pull Test

- Maximum concentrations of trace metals observed, such as As and Pb, are much less than the EPA contamination levels;
- Single well push-pull test appears to be a convenient field controlled-release test for assessing potential impacts of CO_2 leakage on drinking groundwater resources;



Results were summarized in the following paper

International Journal of Greenhouse Gas Control 18 (2013) 375–387

Contents lists available at ScienceDirect

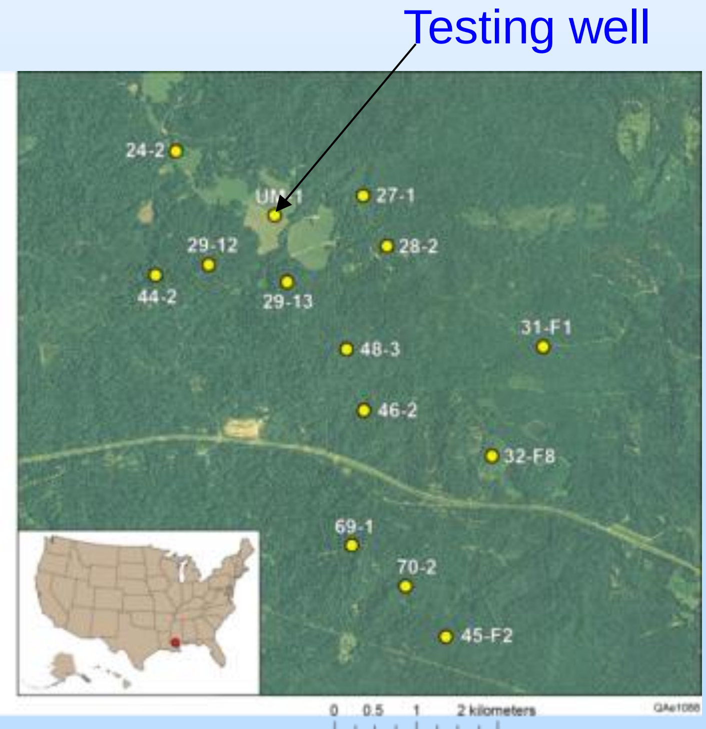
International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

Single-well push–pull test for assessing potential impacts of CO_2 leakage on groundwater quality in a shallow Gulf Coast aquifer in Cranfield, Mississippi

Changbing Yang[a,*], Patrick J. Mickler[a], Robert Reedy[a], Bridget R. Scanlon[a], Katherine D. Romanak[a], Jean-Philippe Nicot[a], Susan D. Hovorka[a], Ramon H. Trevino[a], Toti Larson[b]

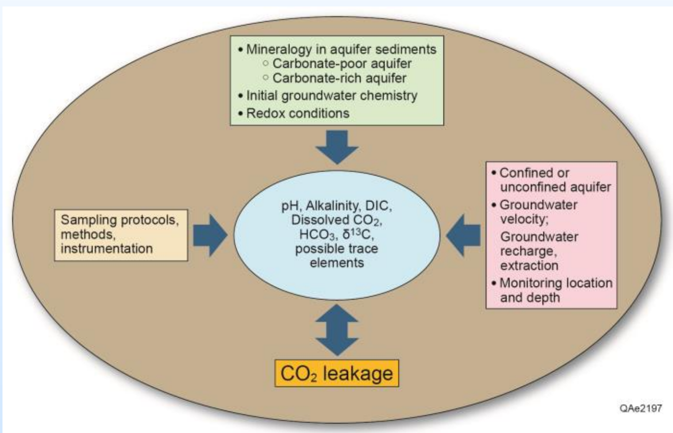
[a] Bureau of Economic Geology, The University of Texas at Austin, 10100 Burnet Road, Bldg 130, Austin, TX 78758, United States
[b] Department of Geological Sciences, The University of Texas at Austin, 2275 Speedway Stop C9000, Austin, TX 78712-1722, United States



C. Yang, BEG

Groundwater at the Cranfield Site Numerical Modelling

- To assess sensitivity of geochemical parameters to CO_2 leakage



Preliminary results were summarized in the following paper

Modeling and Analysis

Geochemical sensitivity to CO_2 leakage: detection in potable aquifers at carbon sequestration sites

Changbing Yang*, Susan D. Hovorka, Michael H. Young and Ramon Trevino

Article first published online: 31 JAN 2014
DOI: 10.1002/ghg.1406

© 2014 Society of Chemical Industry and John Wiley & Sons, Ltd

Issue

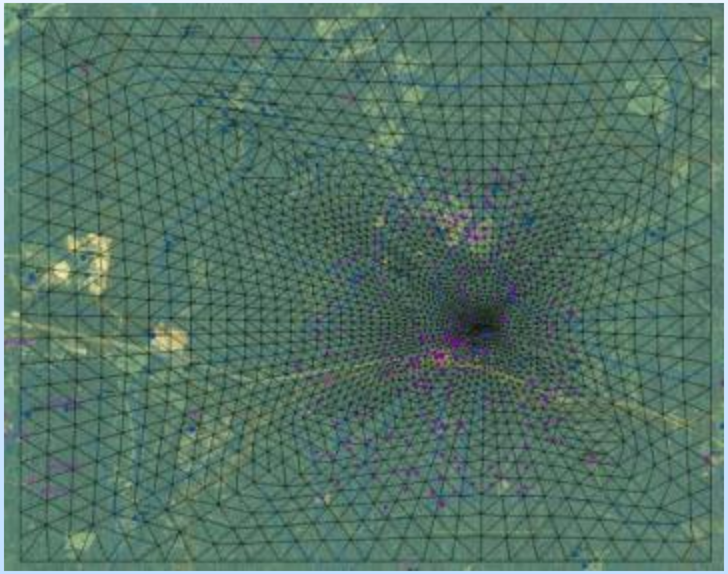
Greenhouse Gases: Science and Technology
Volume 4, Issue 3, pages 384–399, June 2014

- Dissolved CO_2 & DIC in groundwater are most sensitive to CO_2 leakage
- Alkalinity is moderately sensitive, with the best response in the presence of carbonates in the aquifer sediments while groundwater pH shows best response in the aquifer sediments with little carbonates.
- For monitoring purpose, dissolved CO_2 & DIC are better indicators than pH and alkalinity in potable aquifers at geological carbon sequestration sites.

C. Yang, BEG

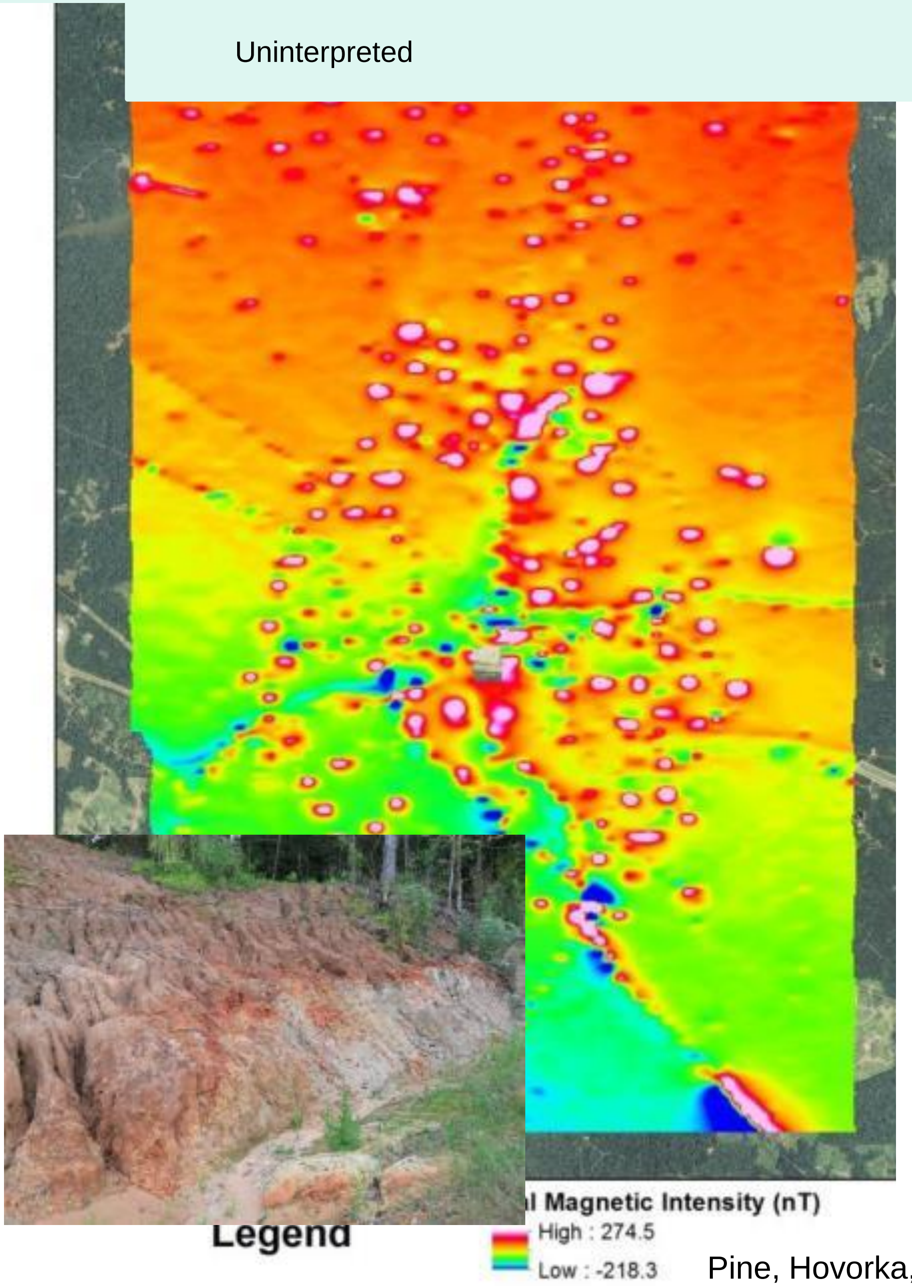
Groundwater at the Cranfield Site Next Steps

- Continue field campaigns for groundwater sampling
- Comprehensively analyze the field results on groundwater
- Compare our groundwater study at the Cranfield site to other sites, such as Weyburn,…
- Conduct reactive transport modeling
  - A preliminary model was completed in 2012 by QEA
  - The new model will focus on assessing
    - Impacts of natural groundwater flow on CO_2 leakage monitoring and change in groundwater quality
    - Heterogeneity
    - Monitoring well spacing

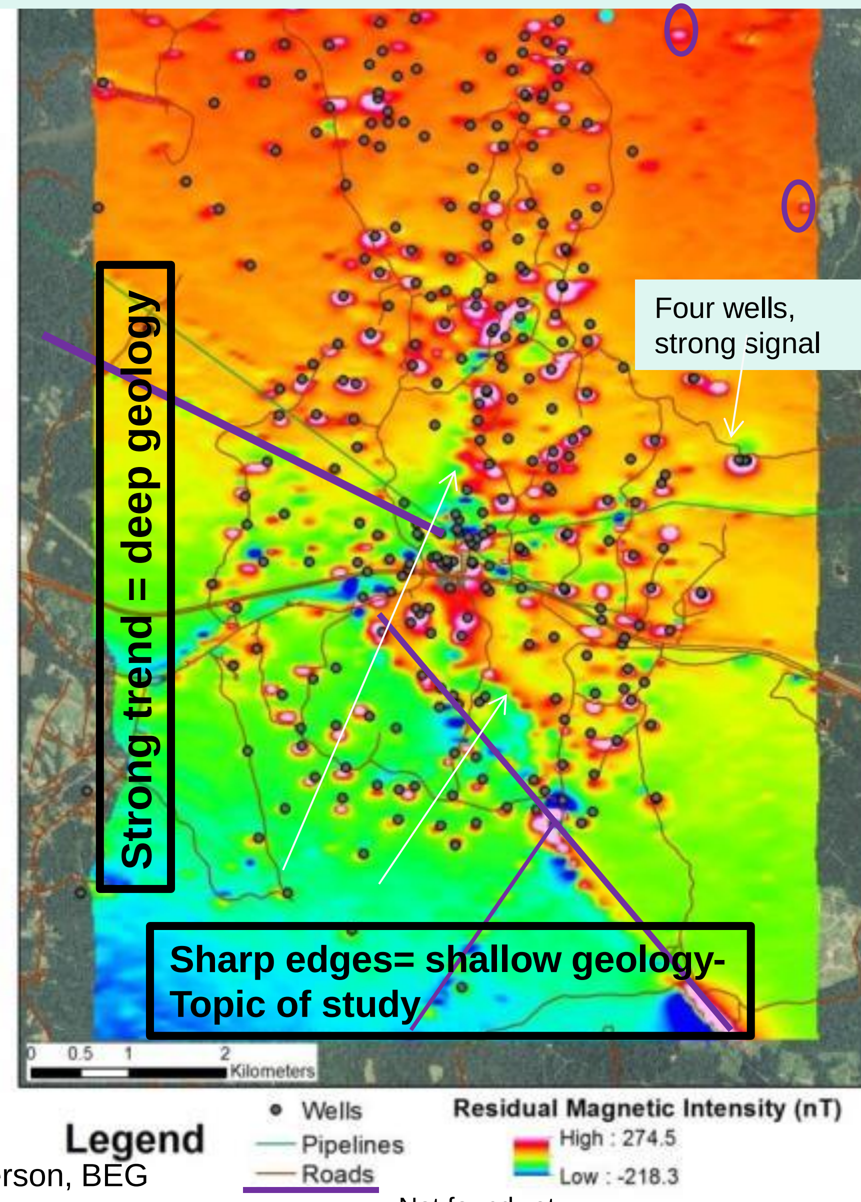


Airborne Magnetics for Characterization

Uninterpreted

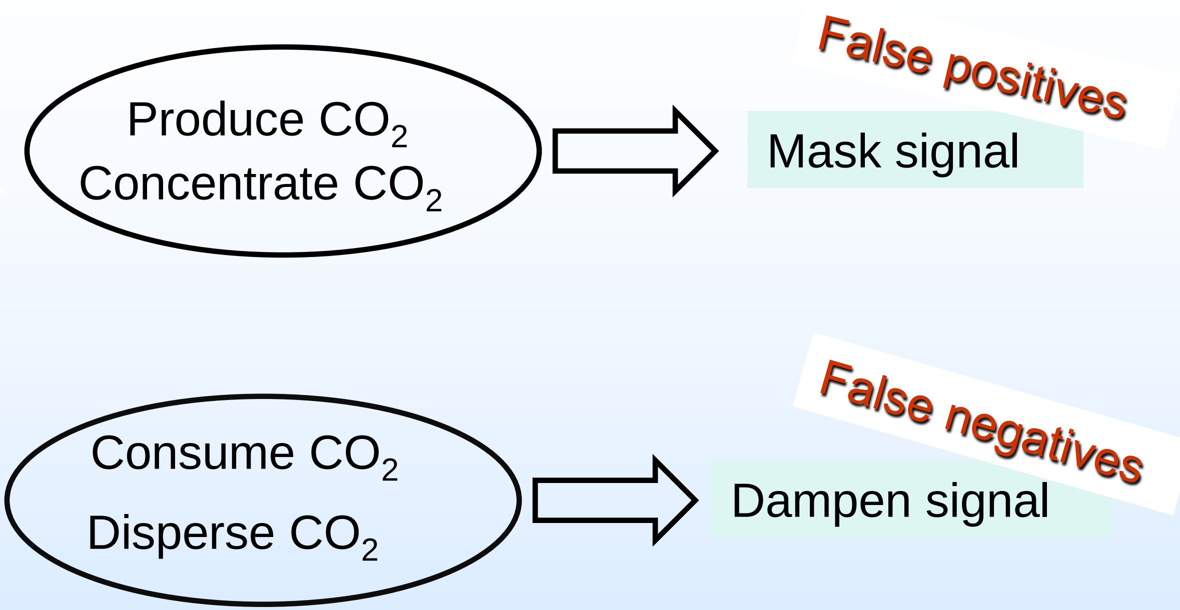


Identification of infrastructure and geologic variatblity



Pine, Hovorka, Anderson, BEG

Process-based Near-Surface Monitoring



Plant activity

Organics → CO_2

Soil carbonate

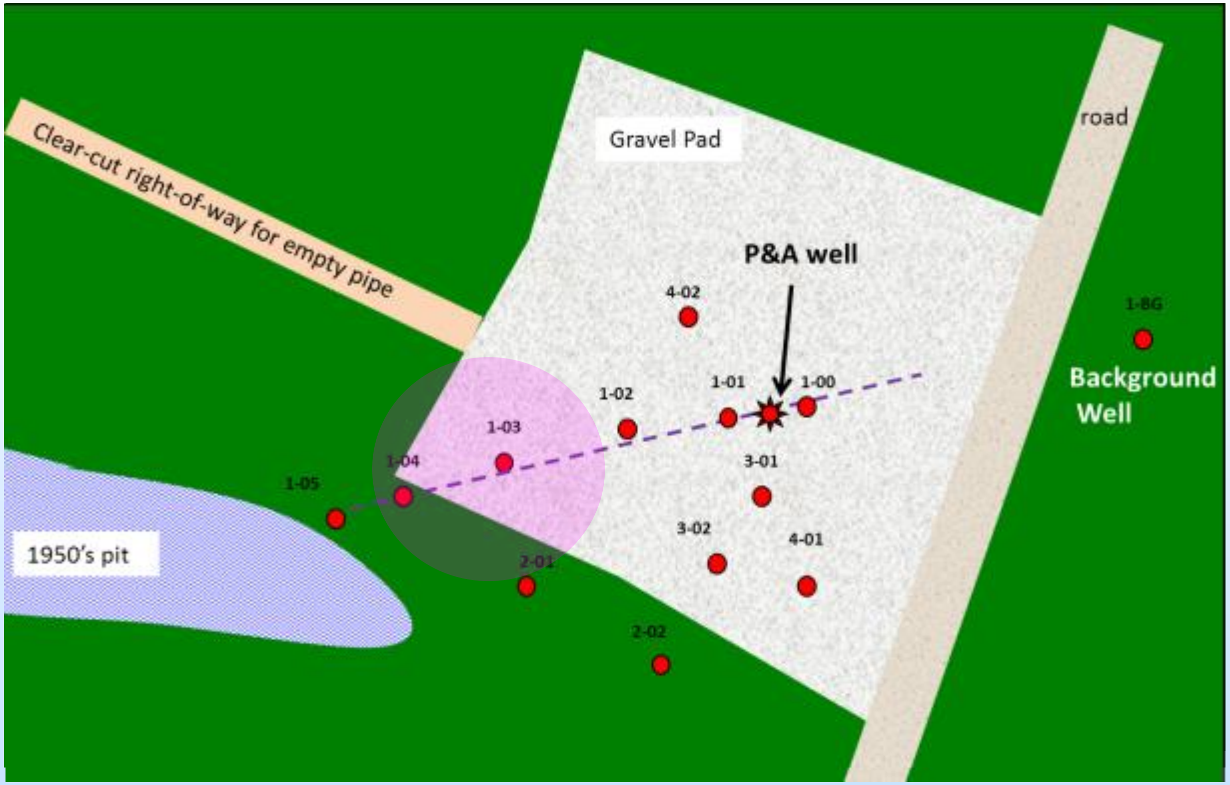
Soil moisture

Weather fronts

} Produce, consume, redistribute CO_2

Katherine Romanak BEG

“P-Site”



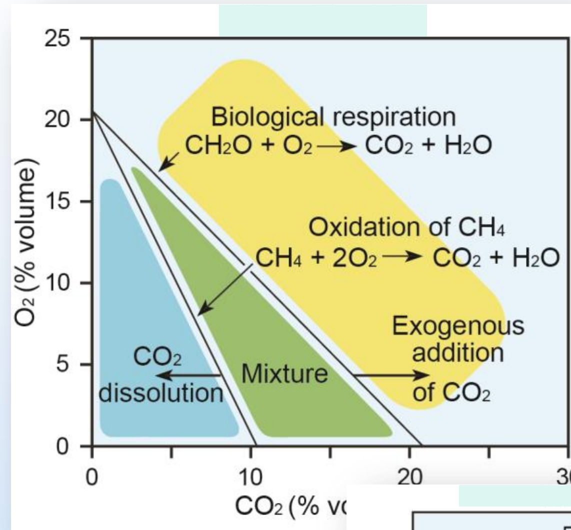
- Pad, Pit, Plants, P&A well
- Localized monitoring beginning Sept 2009
- 13 multi-depth soil gas sampling stations - 5 m depth
- Localized soil gas anomaly at 1-03
  - **$CH_4 \leq 50$ vol. %**
  - **$CO_2 \leq 45$ vol. %**

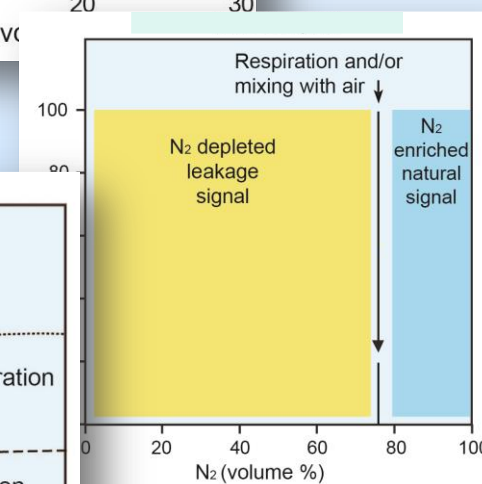
Katherine Romanak BEG

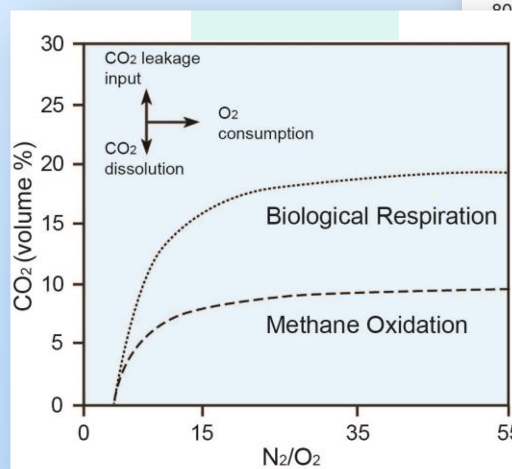
Process-Based Monitoring

- No need for years of background measurements.
- Promptly identifies leakage signal over background noise.
- Uses simple gas ratios

  (CO_2, CH_4, N_2, O_2)
- Can discern many CO_2 sources and sinks
  - Biologic respiration
  - CO_2 dissolution
  - Oxidation of CH_4 into CO_2 (Important at CCUS sites)
  - Influx air into sediments
  - CO_2 leakage







Katherine Romanak BEG

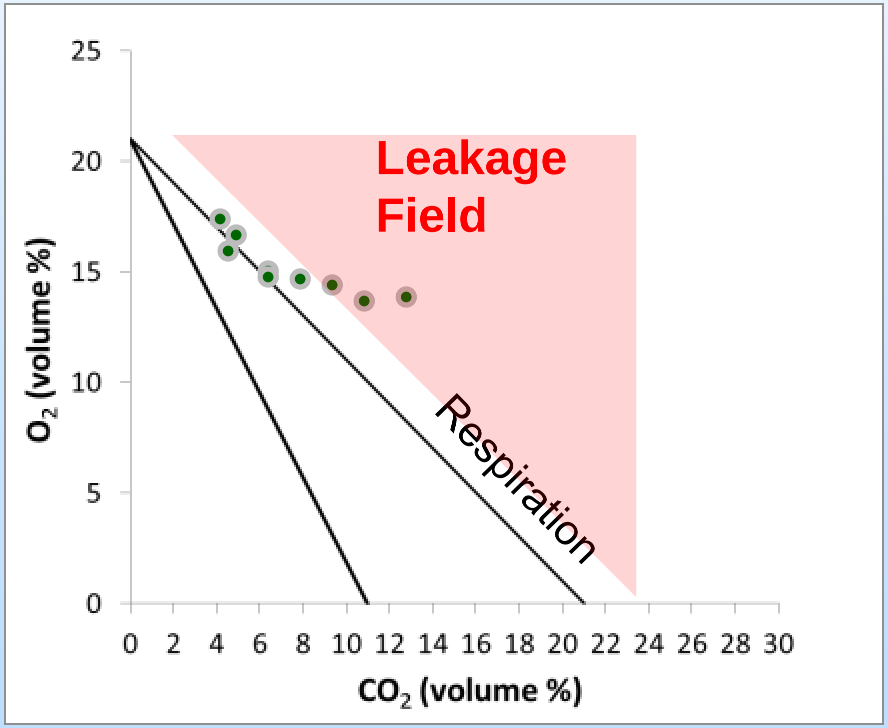
Process-Based Monitoring

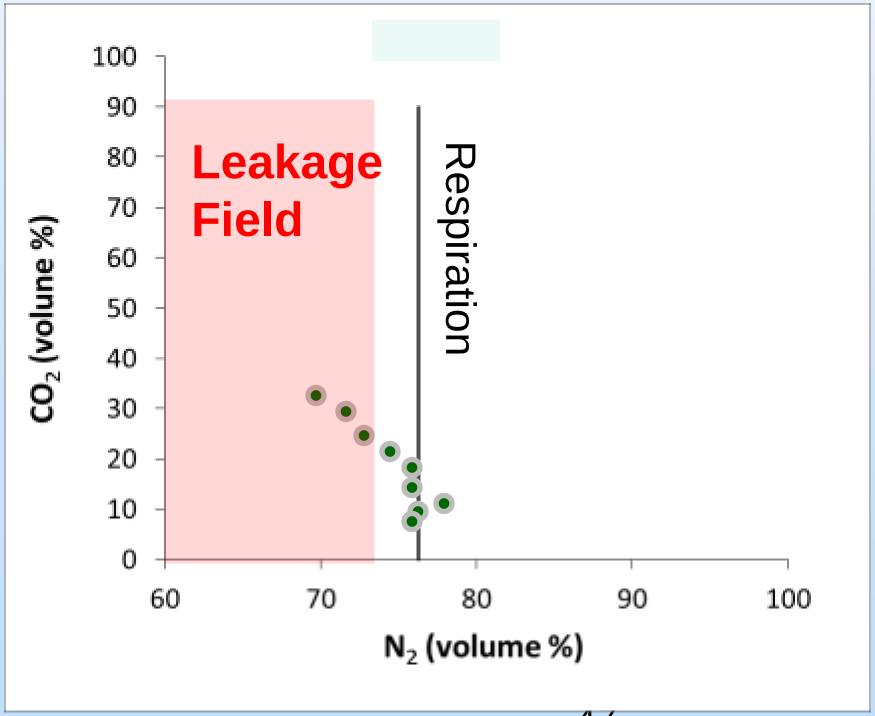
- Developed and tested at Cranfield
- Validated at ZERT Controlled-Release Field Laboratory
- Applied at the Kerr Farm, Weyburn-Midale Oilfield where landowners claimed leakage
- Used at Otway Project, Australia, and considered for use at QUEST and Gorgon
- Being developed for use in offshore marine environments
- Goal to collaborate with Mesa Photonics to develop continuous monitoring capabilities for upscaling

Romanak et al., in press, *Process-based soil gas leakage assessment at the Kerr Farm: comparison of results to leakage proxies at ZERT and Mt. Etna, in press International Journal Greenhouse Gas Control*

"User-Friendly" Data Collection

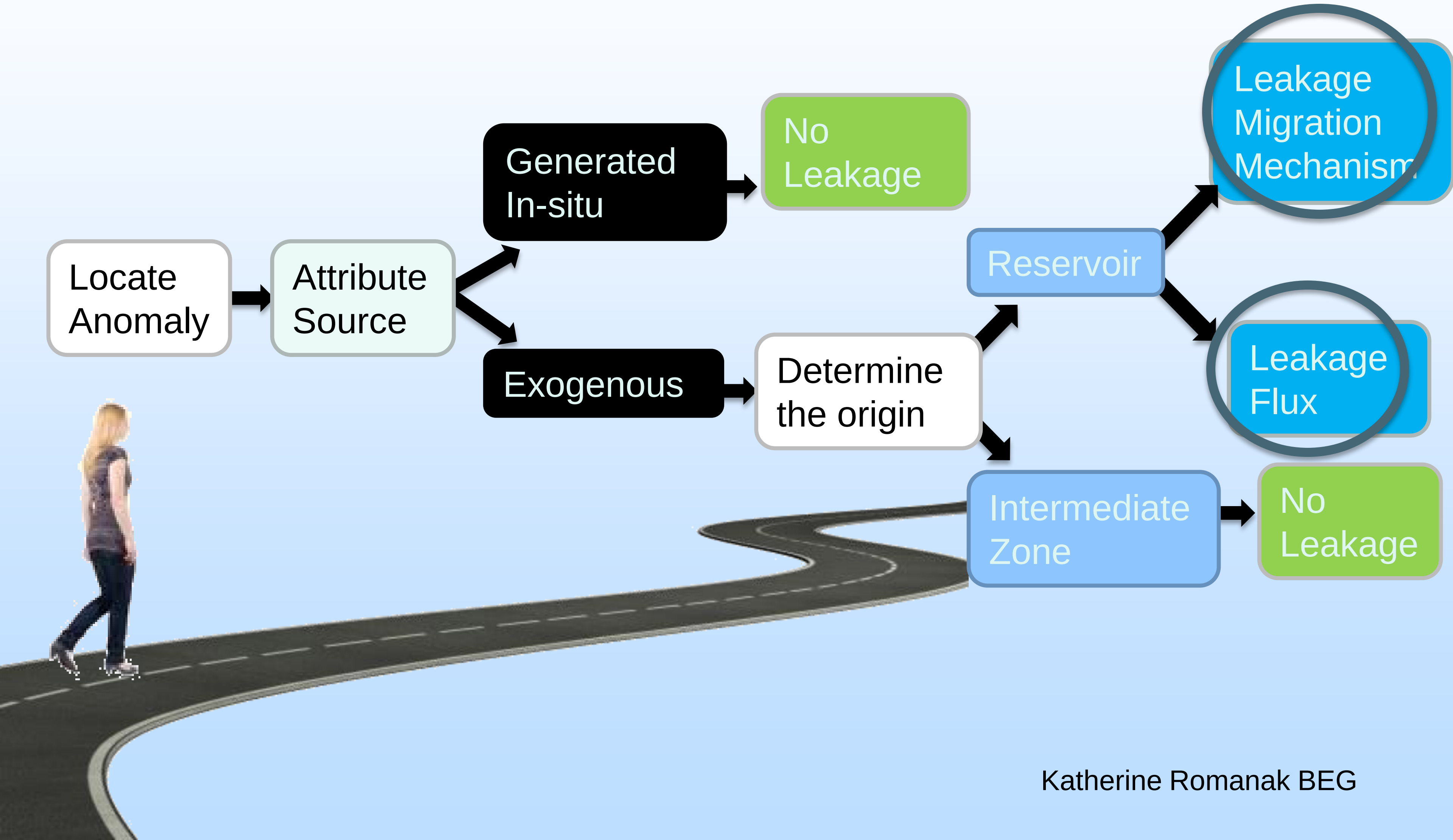
- Simple data reduction
- No complex correlations with weather
- Graphical analysis can be done instantly
- Continuous monitoring capability will give instant real-time leakage detection information.





Katherine Romanak BEG

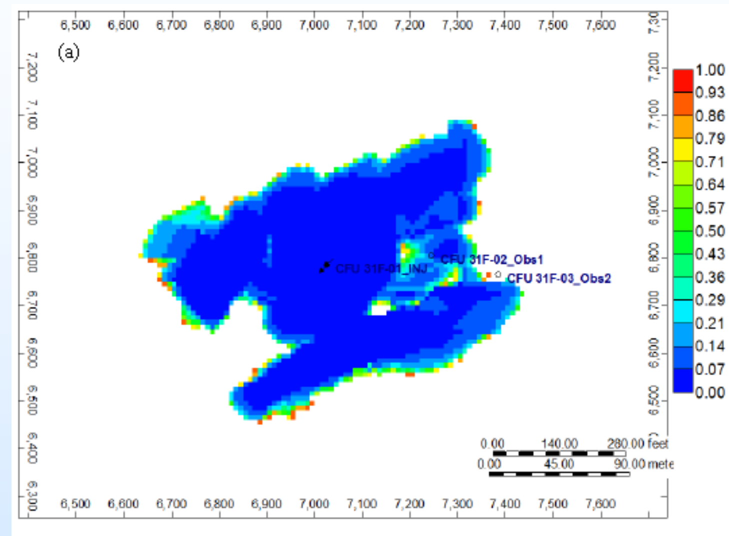
Near-Surface Leakage Assessment

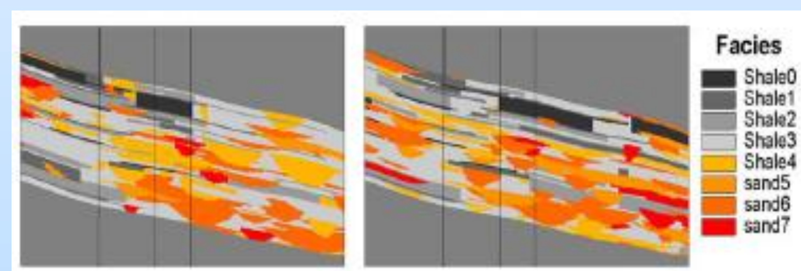


Katherine Romanak BEG

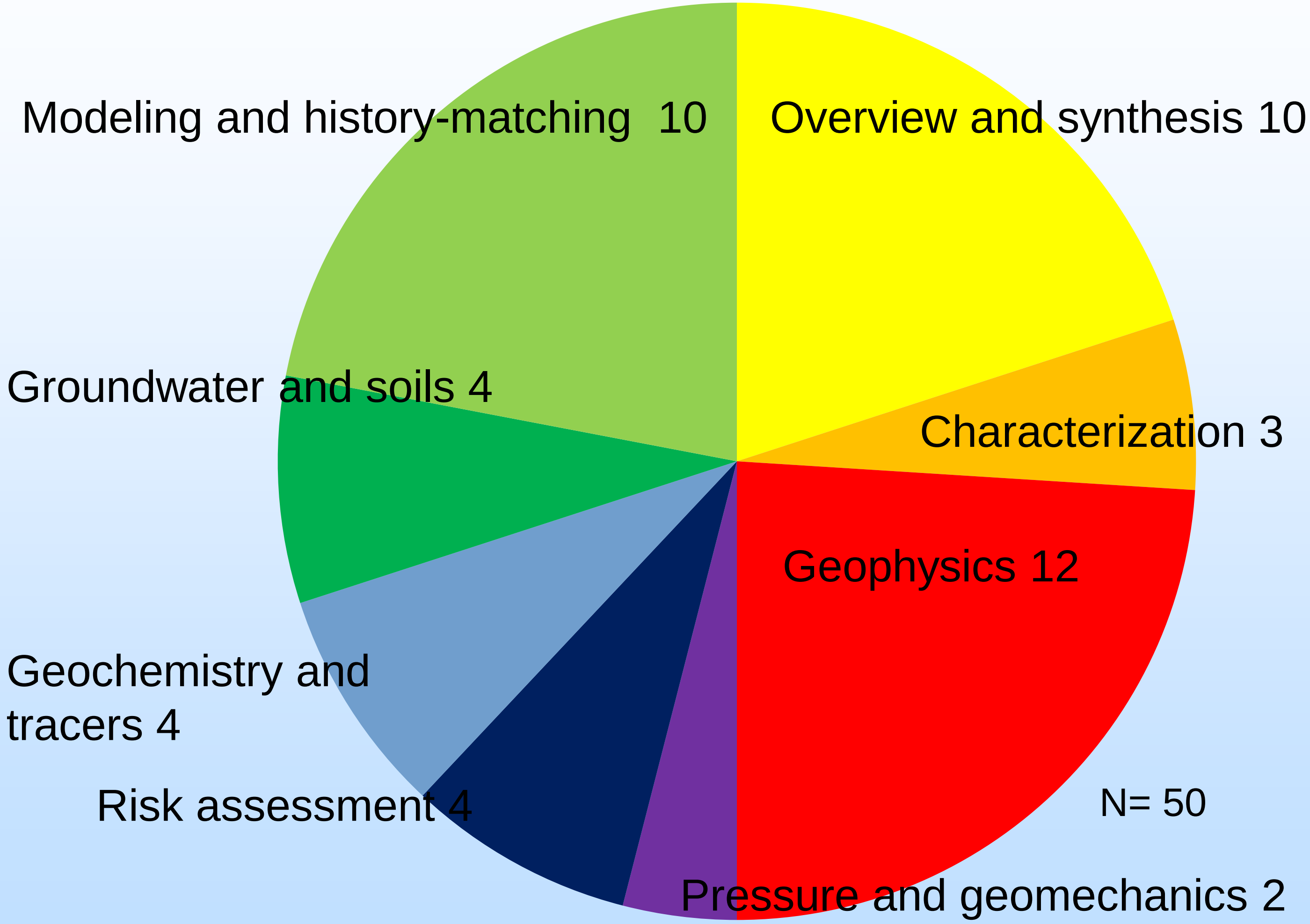
Accomplishments & Key Findings

- **Accomplishments to Date**
  - Monitored CO_2 injection since 2008
  - Injection through 23 wells, cumulative volume over 8 million metric tons
  - First US test of ERT for GS
  - Time lapse plume imaging with cross well seismic, VSP, RST, and surface 3-D
  - RITE microseismic – no detect
  - Groundwater sensitivity assessment push-pull
  - Recognized by Carbon Sequestration Leadership Forum (CSLF) in 2010 for research contributions
  - SIM-Seq inter-partnership model development test
  - Knowledge sharing to Anthropogenic Test and other U.S./International CCS projects
- **Key Findings**
  - Dense data allows assessment of fluid flow measurement and modeling uncertainty
  - Above zone pressure monitoring method viability
  - Process-based method viable





Publications



www.gulfcoastcarbon.org bookshelf

Future plans

- Knowledge sharing
  - Technical, public and policy
  - Closure issues
  - CCUS concept
- Analysis of data collected
  - Joint/comparative inversions
    - Whole plume inventory
    - Uncertainty methodologies
    - Airborne geophysics
- Continued data collection
  - Continue groundwater and soil gas observation
  - Final use of DAS obs. wells
    - CO_2 geothermal test
    - Pressure interference for leakage detection

extras

Extra slides and extra talking points on Goals FYI

Program Goals – Early Test (1)

Predict storage capacities within +/- 30%

- Well known based upon production history; Early Test advanced the understanding of efficiency of pore-volume occupancy (E factor).
- Success metrics: Measure saturation during multiphase plume evolution (completed). Increase predictive capabilities (modeling underway).

Evaluate protocols to demonstrate that 99% of CO_2 is retained

- Permanence of geologic system well understood prior to test because of retention of large volumes of hydrocarbon.
- Retention uncertainties lie in well performance. Early Test is evaluating methods to assess well performance.
- Success metrics: Measure changes above the injection zone along well, above zone monitoring interval (AZMI), and at surface (P-site) over long times (near complete)

Contribute to development of Best Practices Manuals

- Early Test researchers have contributed to Best Practices Manuals on MVA, characterization, risk and modeling. Assistance has been provided on related protocol development, including IOGCC (U.S.), Pew Center accounting study (U.S.), IPAC-CO_2 (Canada), and CO_2-Care (EU), FutureGen 2 (PNNL) review, BGS, IEAGHG networks, and others.

Program Goals – Early Test (2)

Goal 1 - Injectivity and Capacity

- **Advanced understanding of efficiency of pore-volume occupancy (E factor) by measuring saturation during multiphase plume evolution.**
- **Increase predictive capabilities through modeling.**

Goal 2 - Storage Permanence

- **Measure changes above the injection zone along well, above zone monitoring interval (AZMI), and at surface (P site) over long times (underway)**

Goal 3 - Areal Extent of Plume and Potential Leakage Pathways

- **Measured down-dip extent of plume via VSP and 4-D seismic to improve the uncertainty regarding the radial flow (down dip/out of pattern) in the 4-way closure.**
- **Increase predictive capabilities through modeling**

Goal 4 -Risk Assessment

- **Saline storage site is located in EOR field with operator owning CO_2.**
- **Completed certification framework assessment of leakage risk.**
- **Confirmed well performance as highest uncertainty and focus of monitoring research.**
- **Geomechanics and RITE/WESTCARB microsiesimic study**

Program Goals – Early Test (3)

Goal 5 - Develop Best Practices

- **Participated in developing BPMs for MVA, characterization,** risk and reservoir modeling.

Goal 6 - Public Outreach and Education

- **On-site outreach handled by Landmen.**
- **SSEB and Early Team focus on O&E in public and technical arenas.**
- **Hosted site visits, responses to local and trade media, Fact Sheets, and website postings of project information.**

Goal 7 - Improvement of Permitting Requirements

- **Permits obtained by site operator.**
- **Project team focus is on development of regulatory framework for GHG.**
- **Provided experience with monitoring instruments and well performance to decision makers.**

Southeast Regional Carbon Sequestration Partnership
Early Test at Cranfield
Status 2015

Susan Hovorka
Seyyed Hossieni
Changbing Yang
Gulf Coast Carbon Center
Bureau of Economic Geology
The University of Texas at Austin

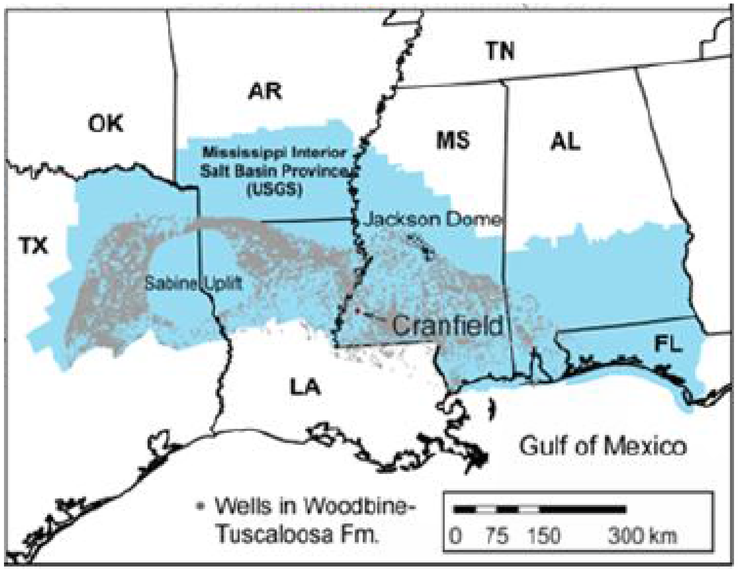
Introduction by Kimberly Sams Gray
Southern States Energy Board

U.S. Department of Energy
National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Transforming Technology through Integration and Collaboration
August 18-20, 2015

Acknowledgements

- This material is based upon work supported by the U.S. Department of Energy National Energy Technology Laboratory.
- Cost share and research support provided by SECARB/SSEB Carbon Management Partners.

SECARB Phase III



ELECTRIC POWER RESEARCH INSTITUTE

Anthropogenic Test

Capture: Alabama Power 's Plant Barry, Bucks, Alabama

Transportation: Denbury

Geo Storage: Denbury's Citronelle Field, Citronelle, Alabama

Early Test

Denbury Resources' Cranfield Field Near Natchez, Mississippi

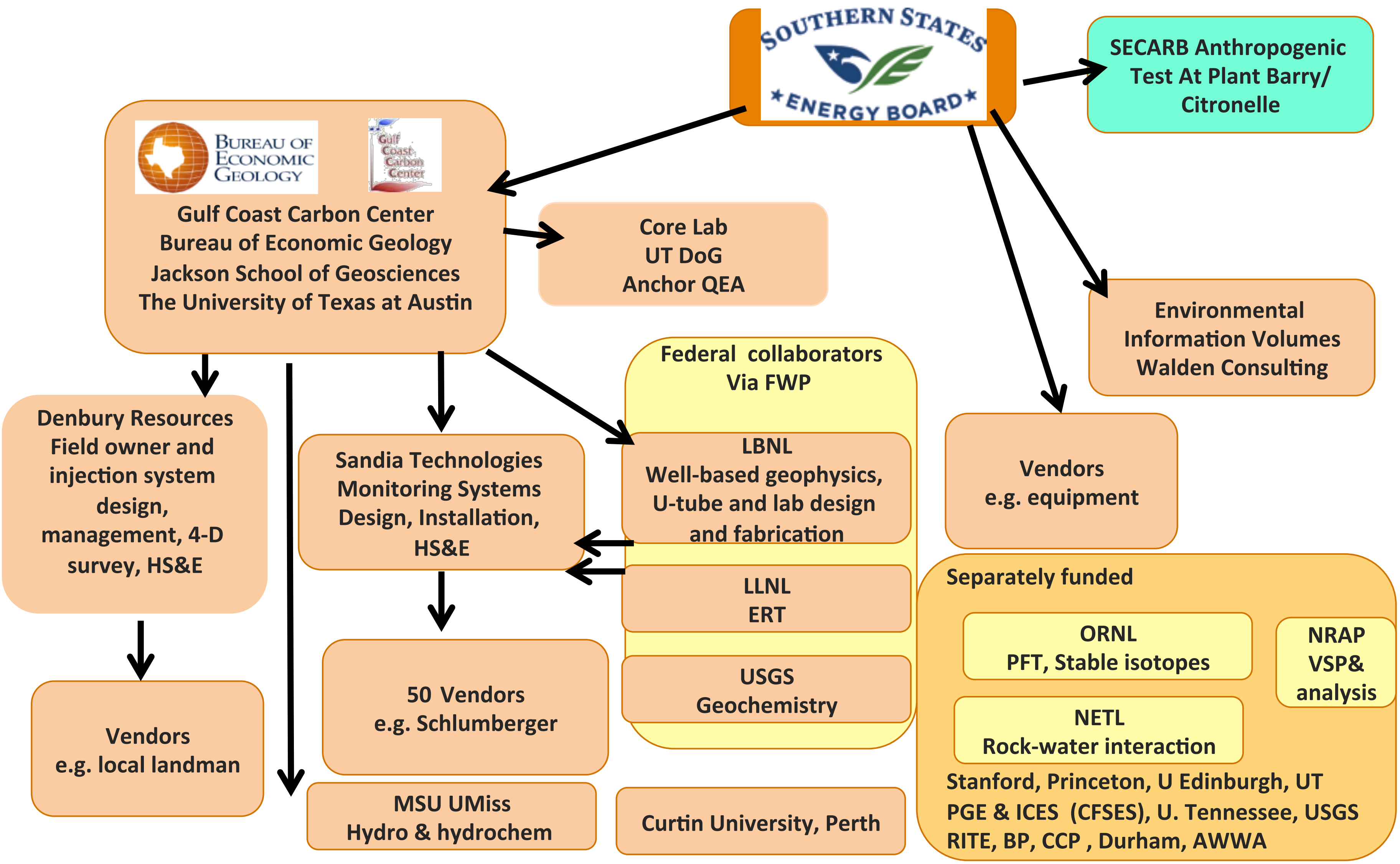
CO_2 Source: Denbury

CO_2 Transportation: Denbury

Saline MVA: GCCC

Gulf Coast Carbon Center

Cranfield Organization



Highlights

- Project status – fieldwork completed (Hovorka)
- Modeling status – history match to 4-D seismic (Hossieni)
- Assessing Impacts of CO_2 Leakage on Groundwater Quality and Monitoring Network Efficiency (Yang)

Fieldwork Completed!

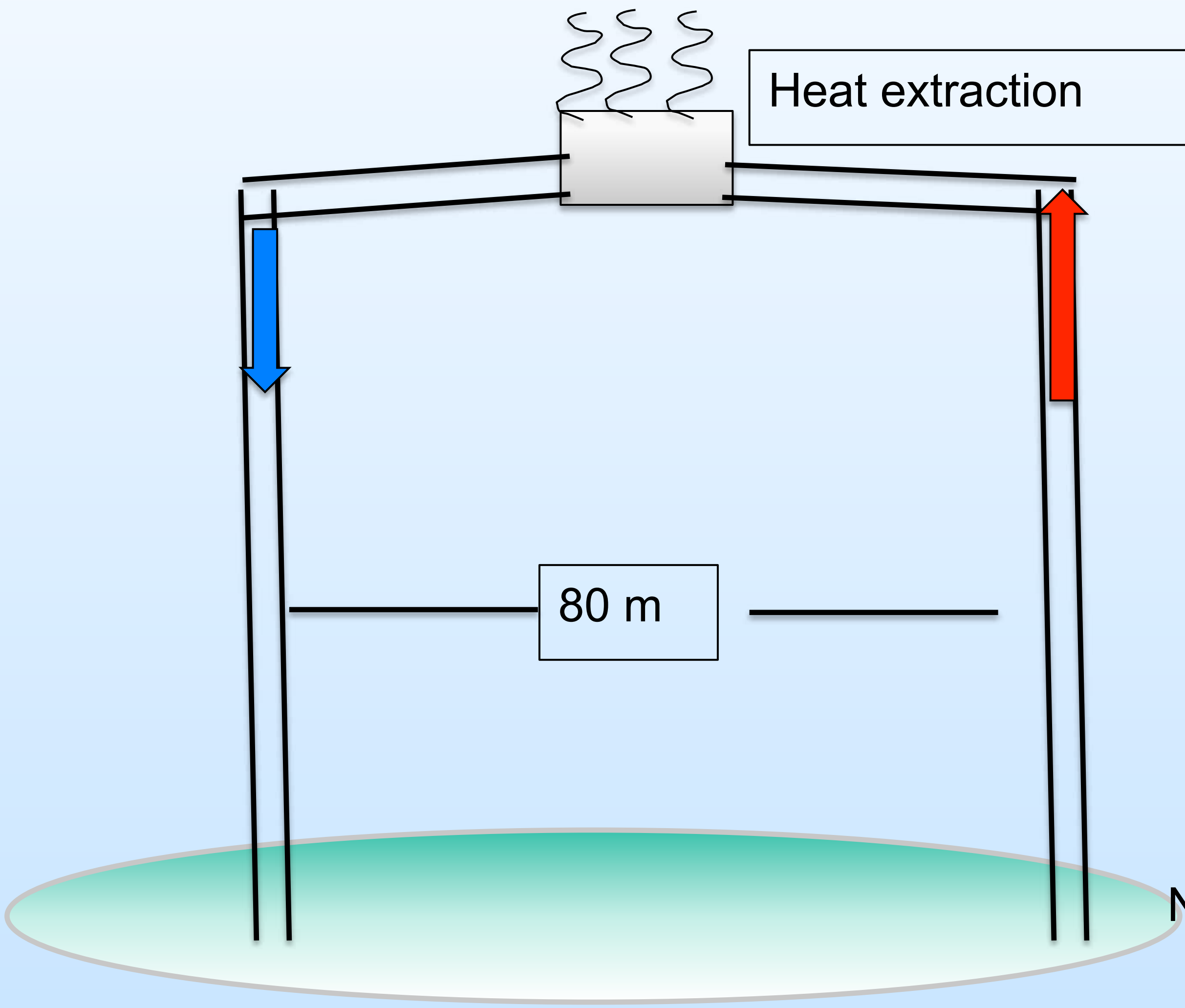
- Last stages of project:
  - Pulse testing (Sun) and thermosyphon (Freifeld, LBNL) completed in January 2015
  - Well integrity data collected (Duguid/Schlumberger/ Battelle)
  - P&A and final data collection completed in April, 2015
- This concludes field phase of Early Test
  - Denbury commercial EOR will continue
  - DOE program work will extract lessons learned and conduct technology transfer

Heat exchanger

Vent system

Photos by Lu

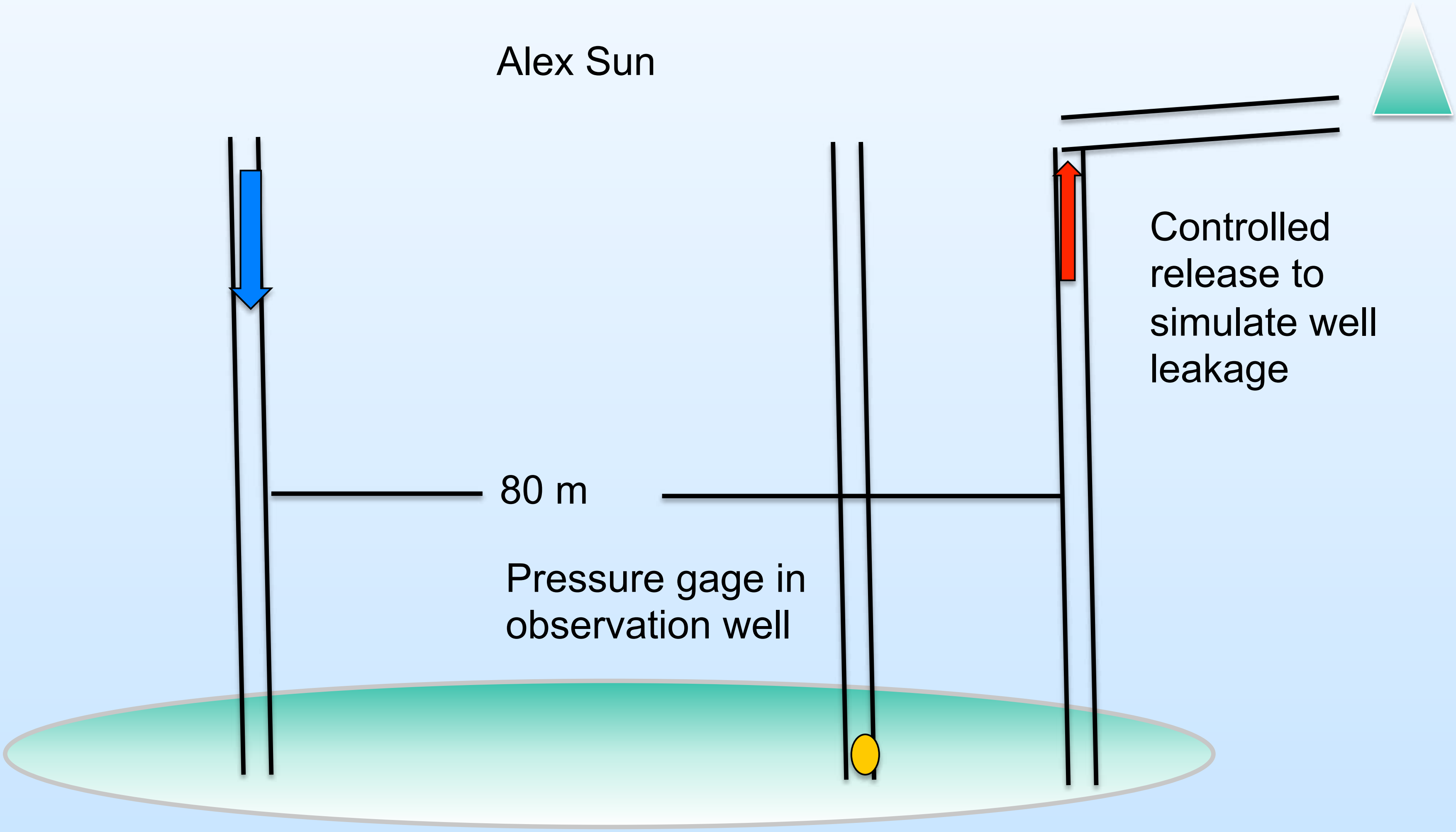
Thermosyphon
(Barry Freifeld)



DOE program combining CCUS and geothermal; LBNL lead

Harmonic Pulse testing for Leakage (PIDAS)

Alex Sun



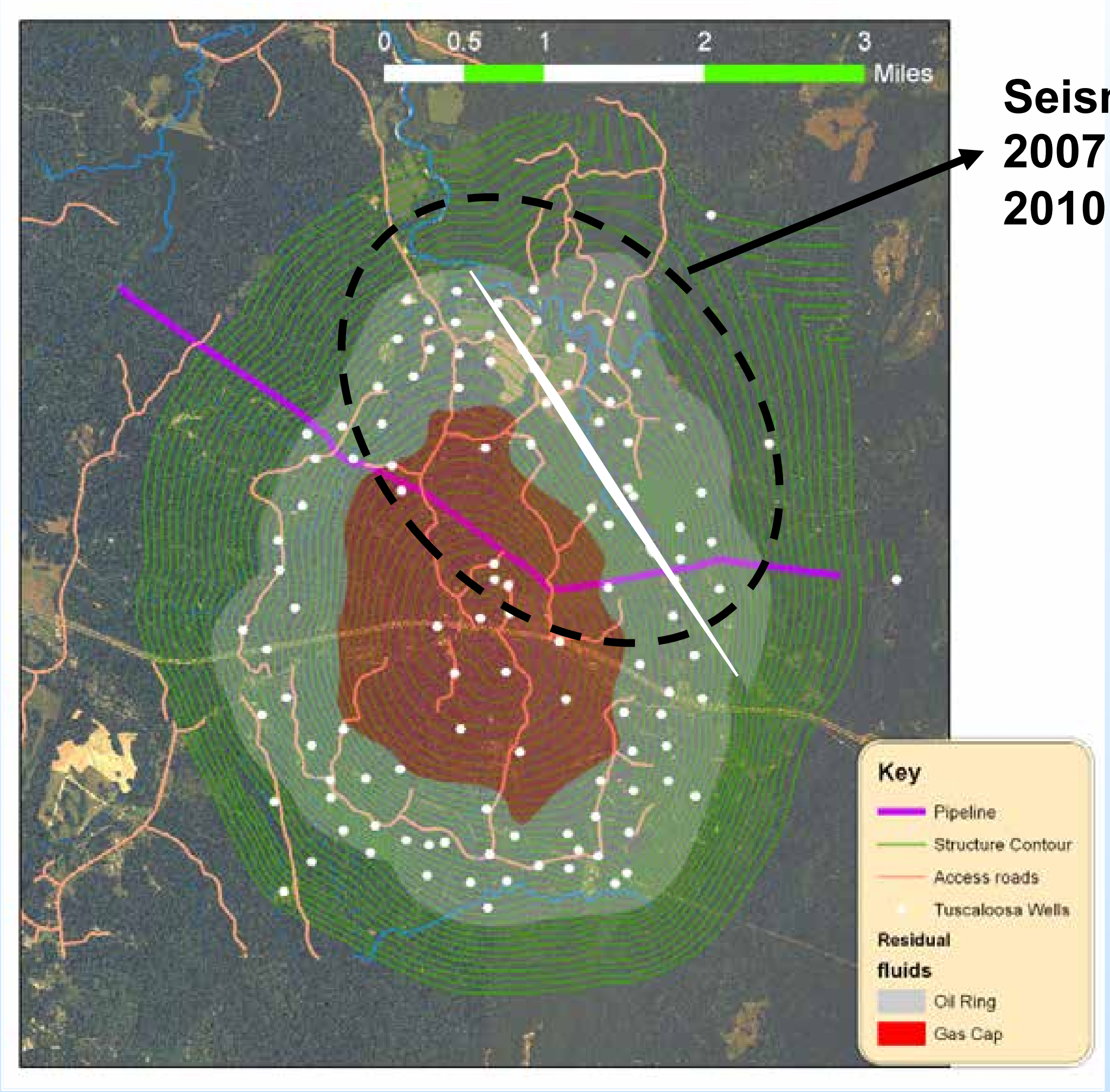
Plugging Procedure Overview

- Final Repeat RST
- “Kill” F2 and F3 wells
- Remove packers
- Squeeze Tuscaloosa perforations, test
- Logging, Sonic, USIT, gyro
- Schlumberger sidewall cores
- Fluid sampling and hydro tests in AZMI
- Squeeze AZMI perforations
- Cement and abandon according to MO&G Board rules

Next steps

- Analysis of data collected – value and best practices to commercial CCUS monitoring
  - Publications
- Technology transfer
  - Current commercial projects
  - International collaborators

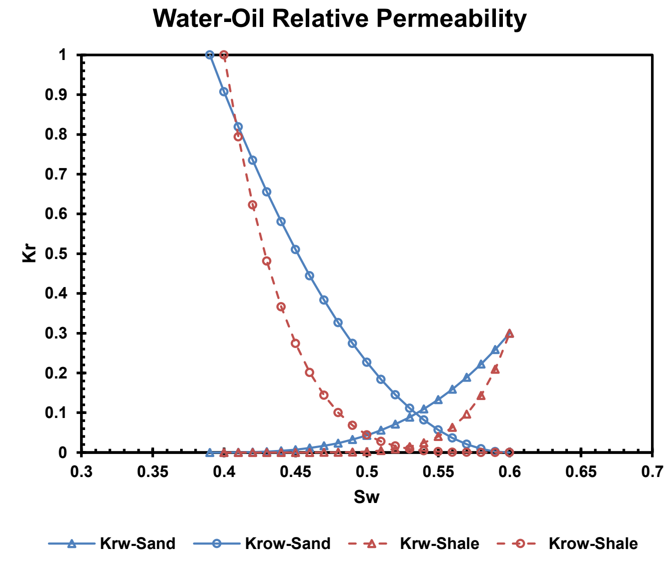
History matching and reservoir simulation



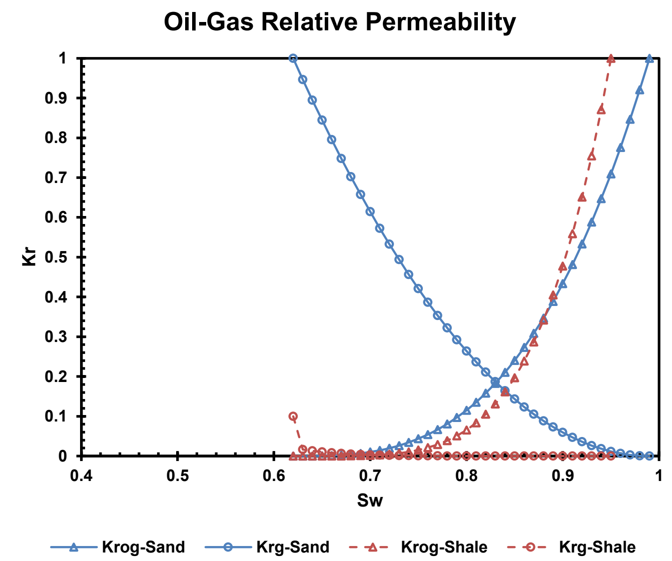
Seismic Surveys
2007 Baseline
2010 Repeat

Simulation parameters

Parameter	Value
Pressure	32 MPa
Temperature	125 C
Thickness	24 m
Depth	3060-3193 m
Historical production	1943-1966
CO_2-EOR	2008-2011



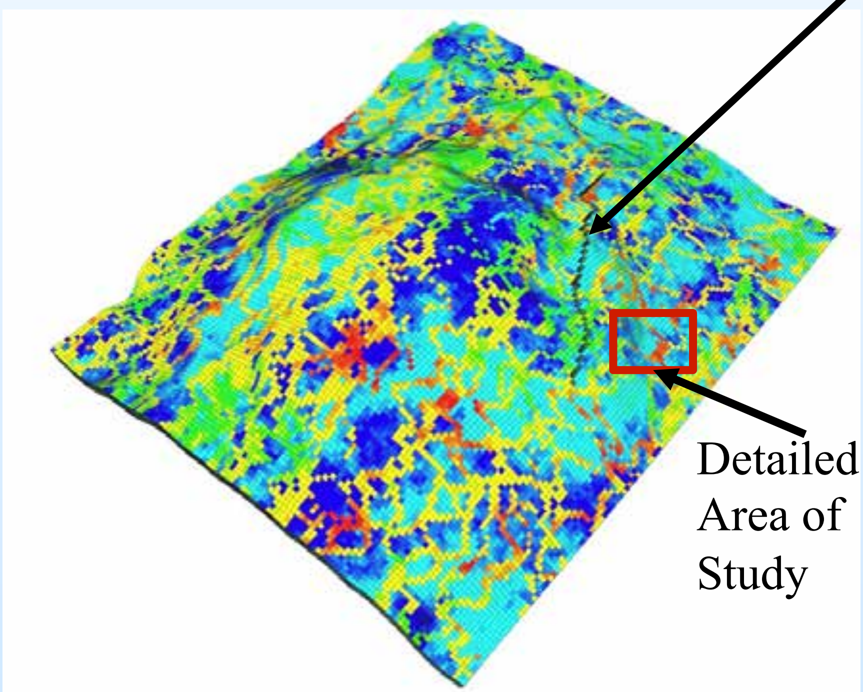
Parameter	Value
Reservoir Simulator	CMG
Number of grids	124 ×149×20
Grid size	61×61×1.2 m
Total number of grids	369,520
Boundary condition	Active aquifer
Facies	Sand/shale
Geochemistry	neglected



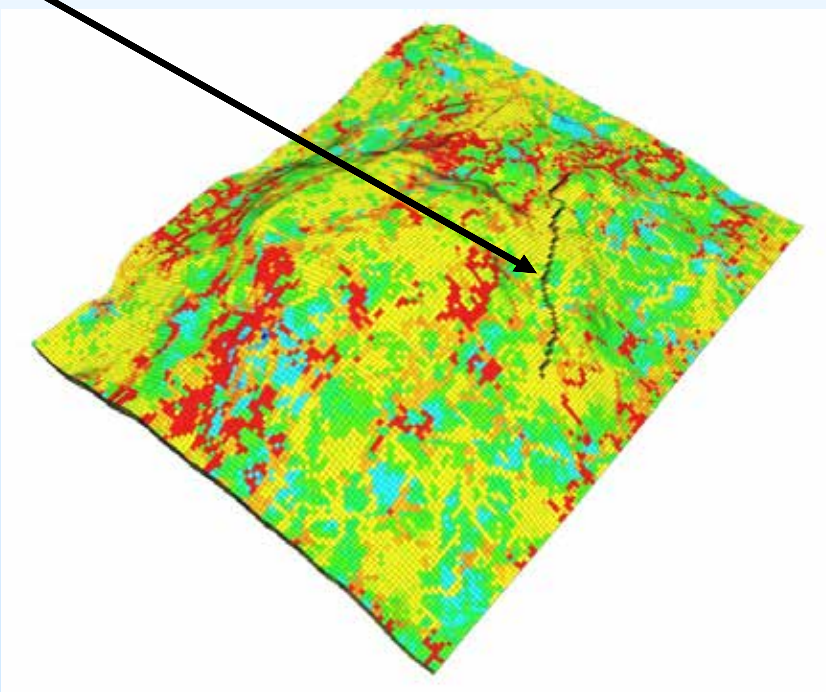
Static model development

Permeability range is 0.01-4400 md and porosity range is 0.0002- 0.45.

sealing fault



Porosity map



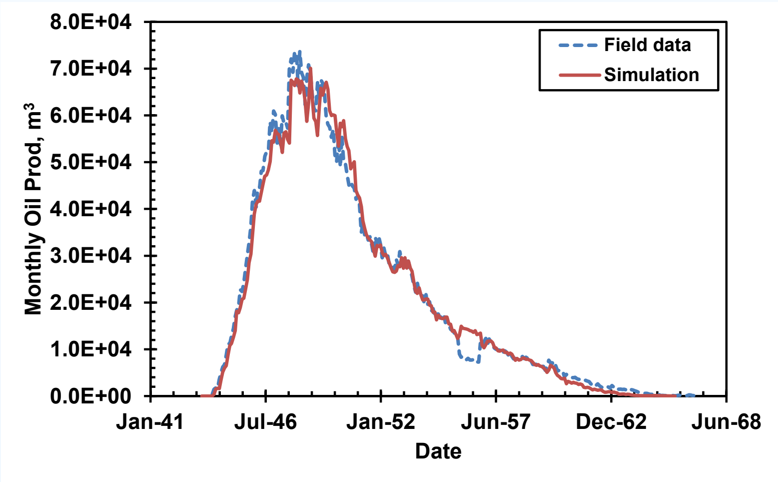
Permeability map (log scale)

Hosseini, S. A., Lashgari, H., Choi, Jong-Won, Nicot, J. -P., Lu, Jiemin, and Hovorka, S. D., 2013, Static and dynamic reservoir modeling for geological CO2 sequestration at Cranfield, Mississippi, U.S.A.: International Journal of Greenhouse Gas Control, v. 18, p. 449-462.

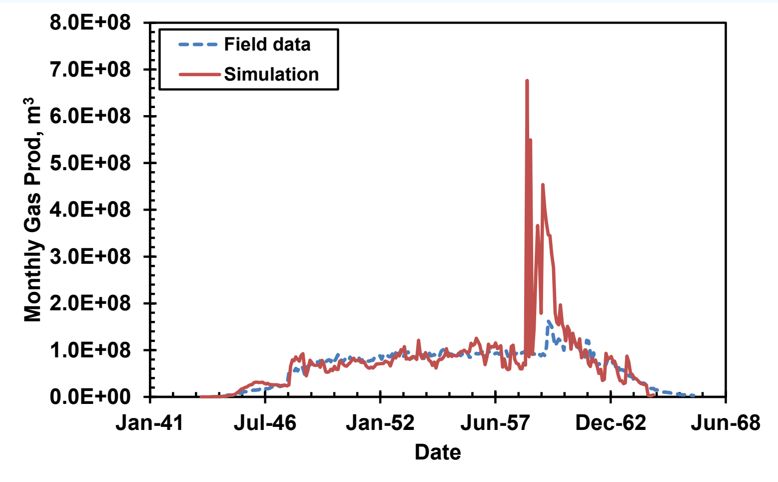
BUREAU OF ECONOMIC GEOLOGY

Gulf Coast Carbon Center

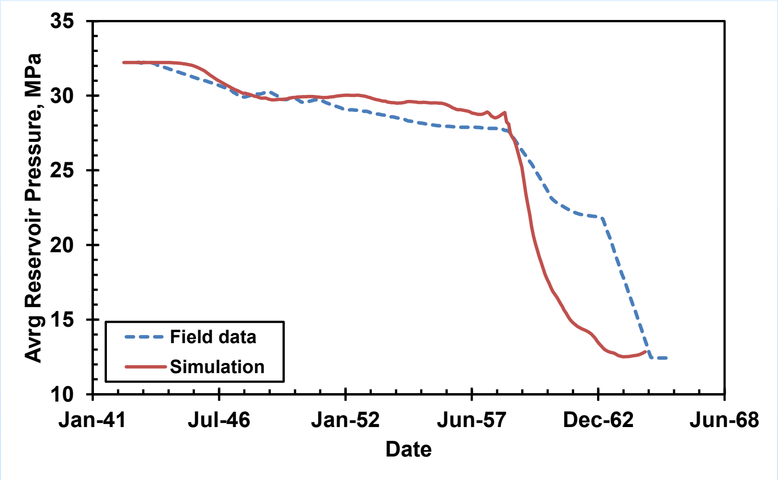
History Matching of Historic Production



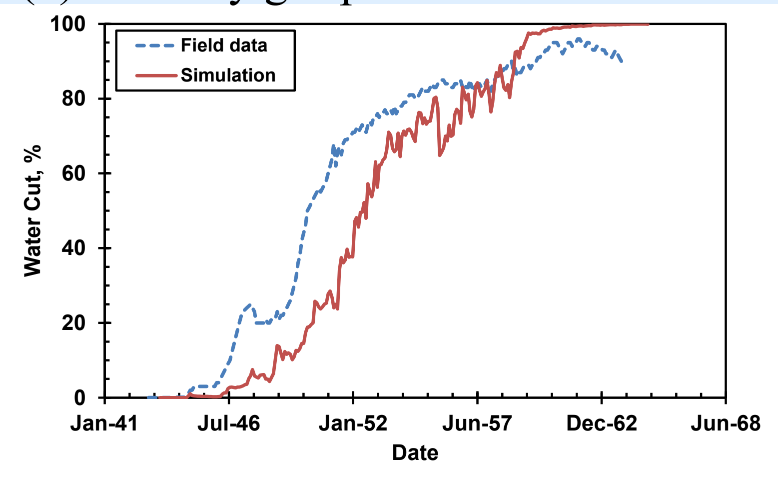
(a) Monthly oil production rate



(b) Monthly gas production rate

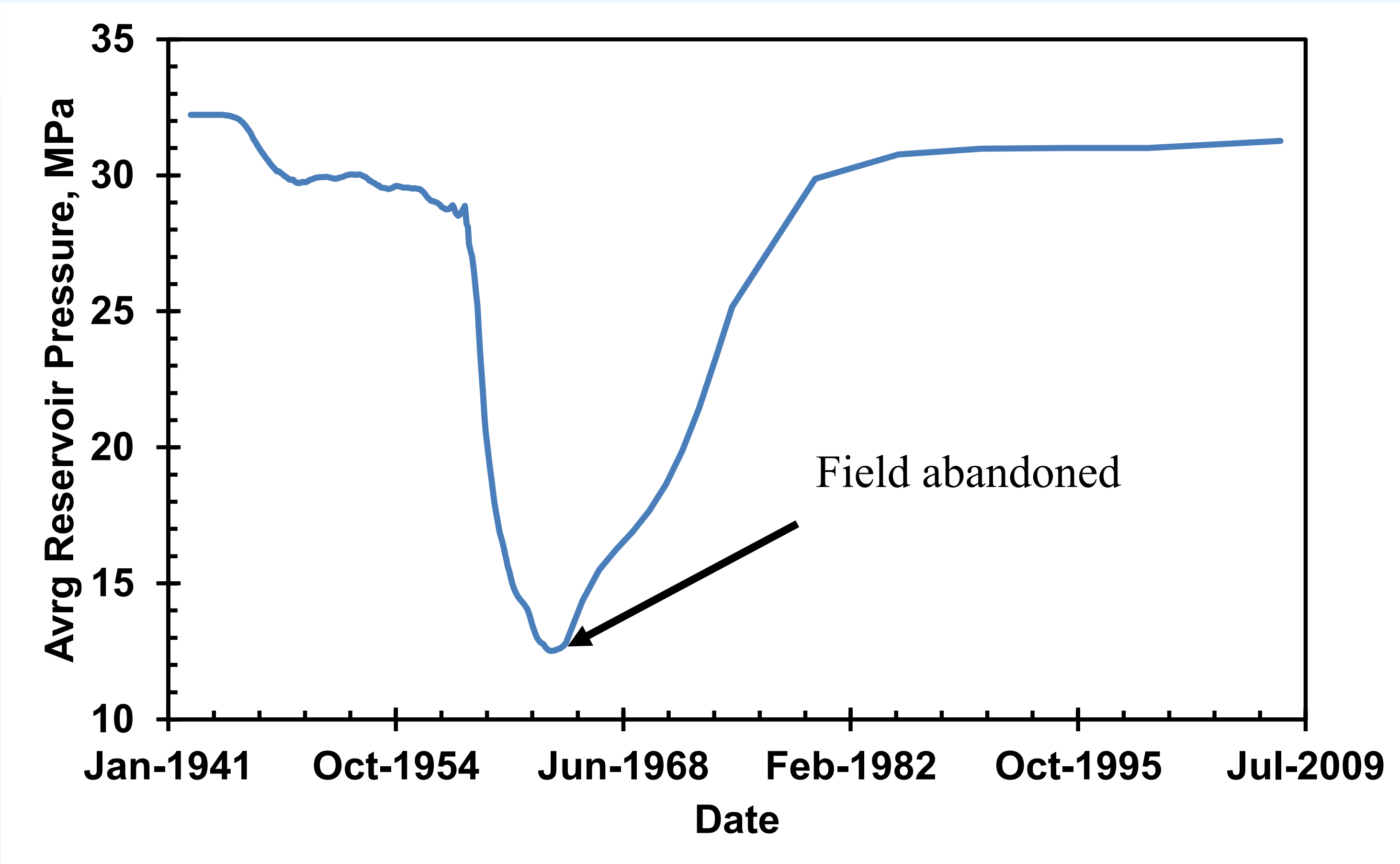


(c) Average reservoir pressure

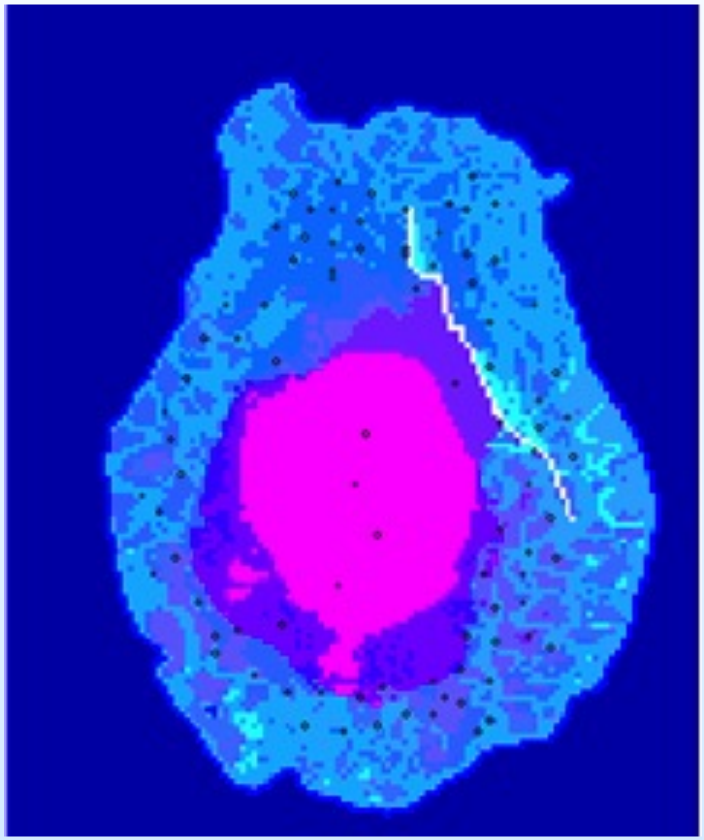


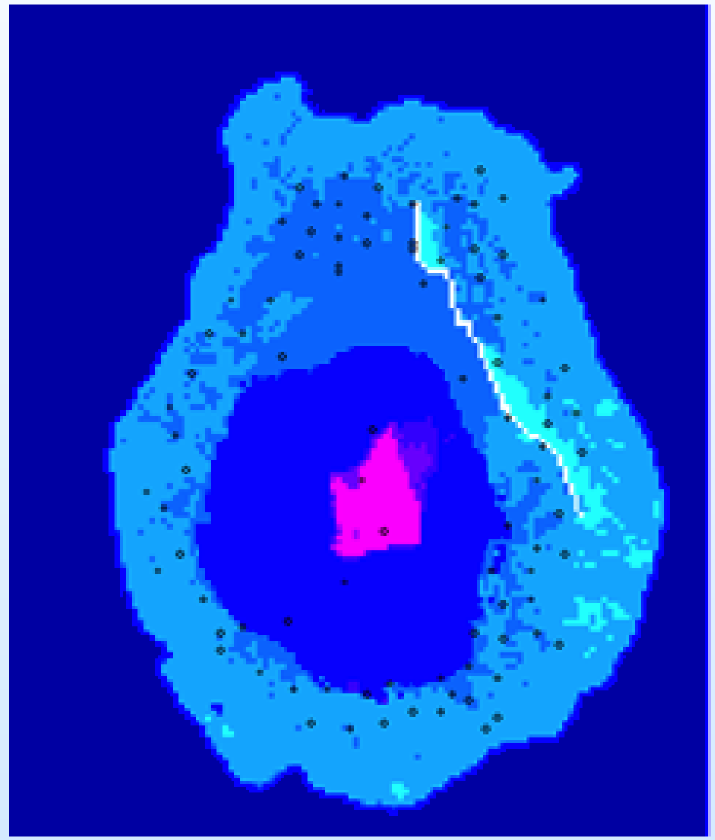
(d) Water cut

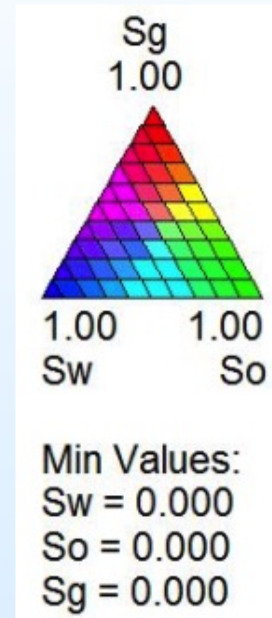
Pressure restores 1966-2008



Saturation distribution





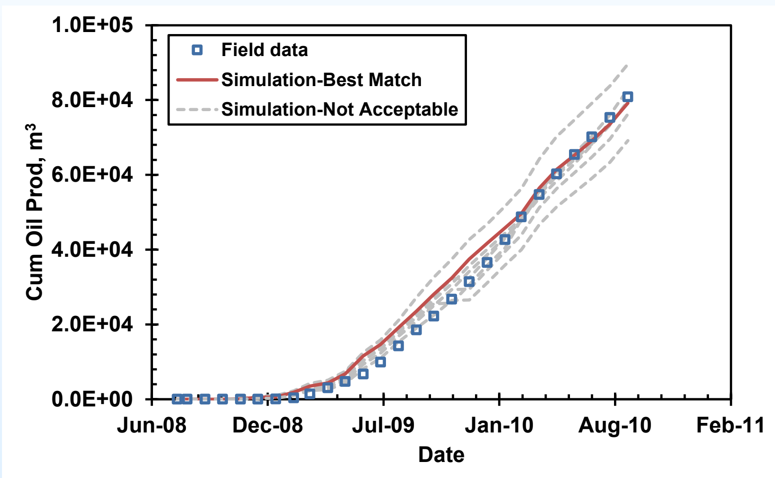


1966 **2008**

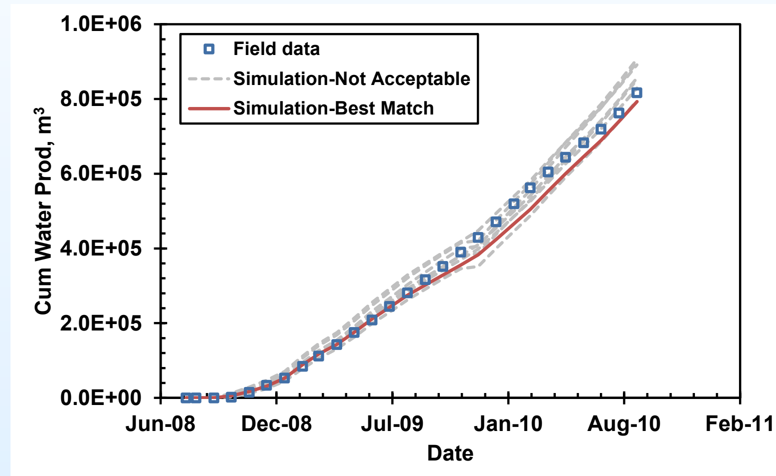
BUREAU OF ECONOMIC GEOLOGY

Gulf Coast Carbon Center

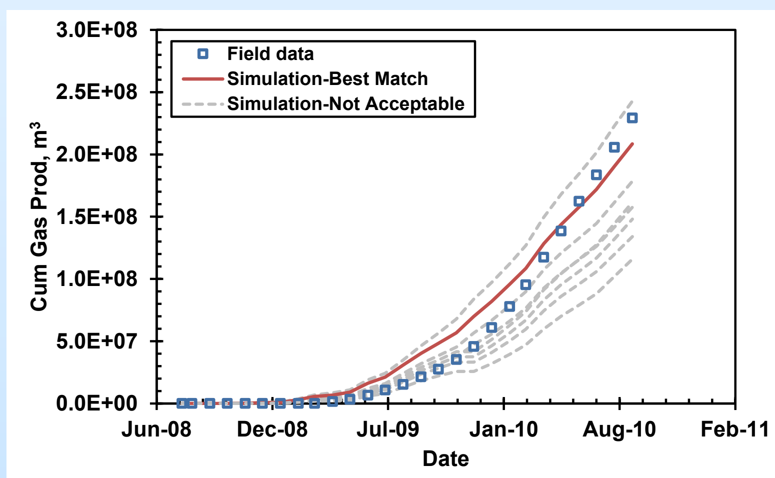
History matching of CO_2-EOR



(a) Cumulative oil production

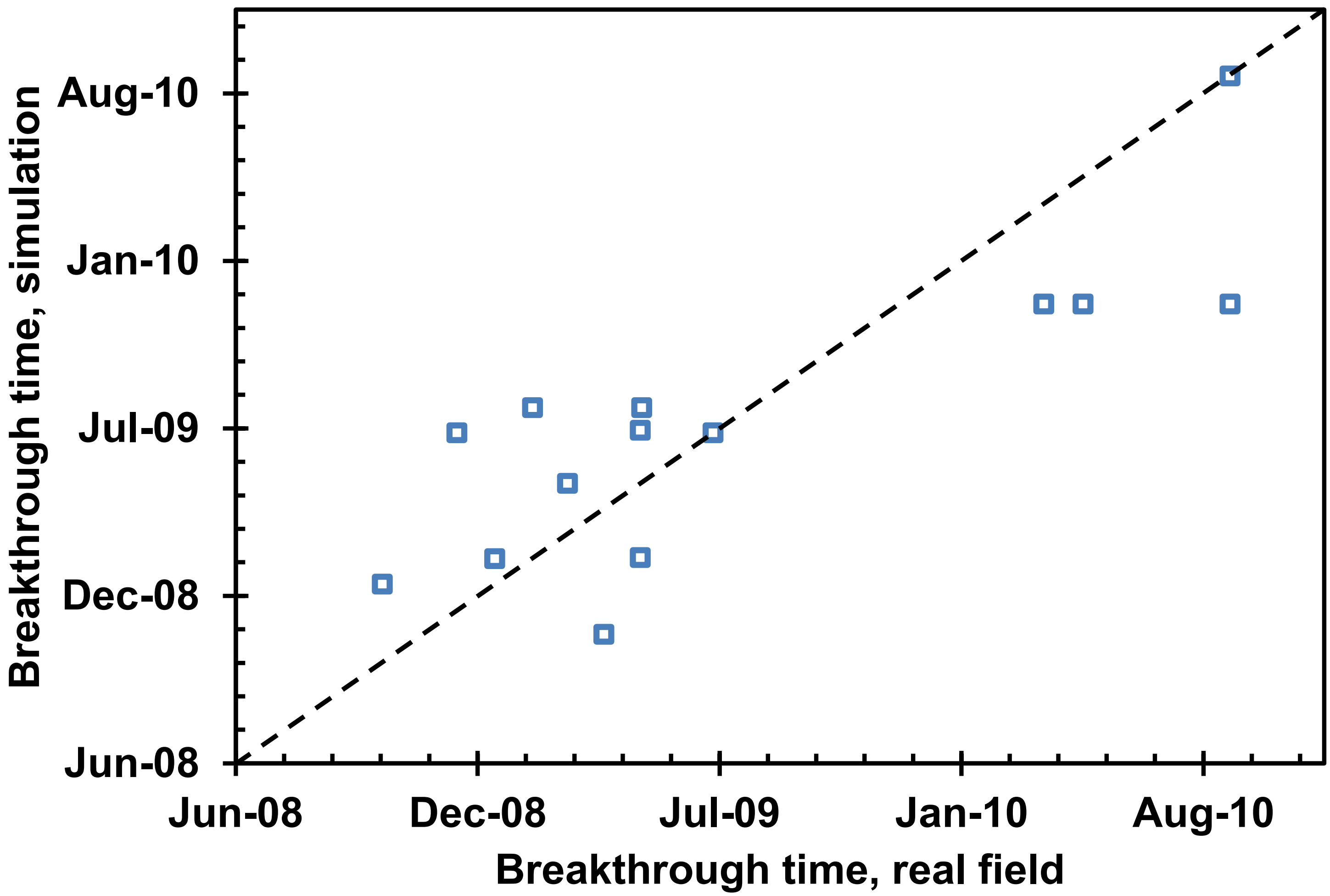


(b) Cumulative water production

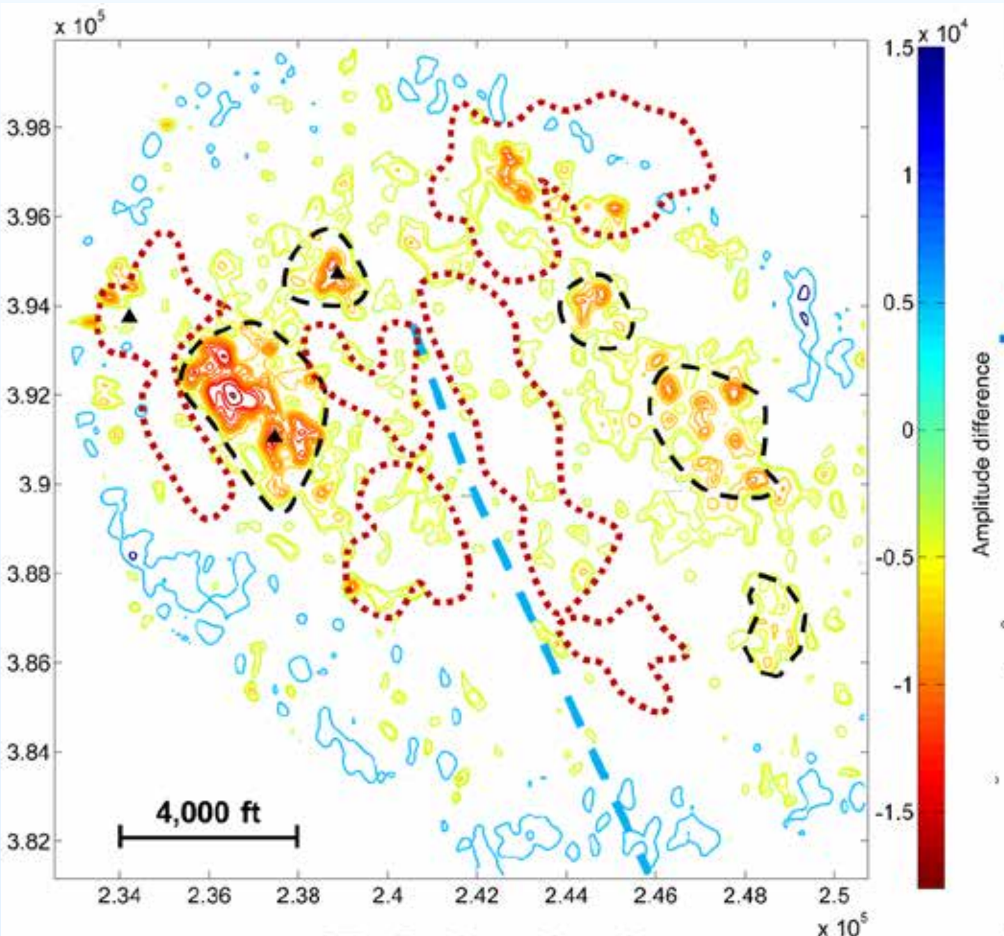


(c) Cumulative gas production

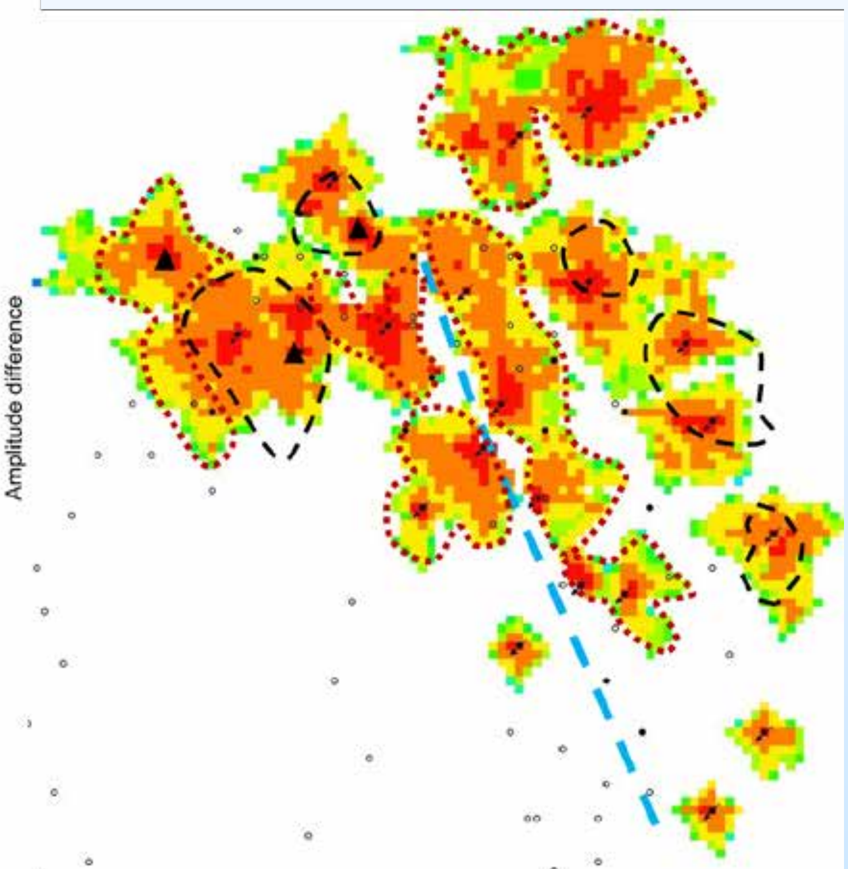
Performance of fluid flow model



4D seismic vs fluid flow simulation



4D Seismic data



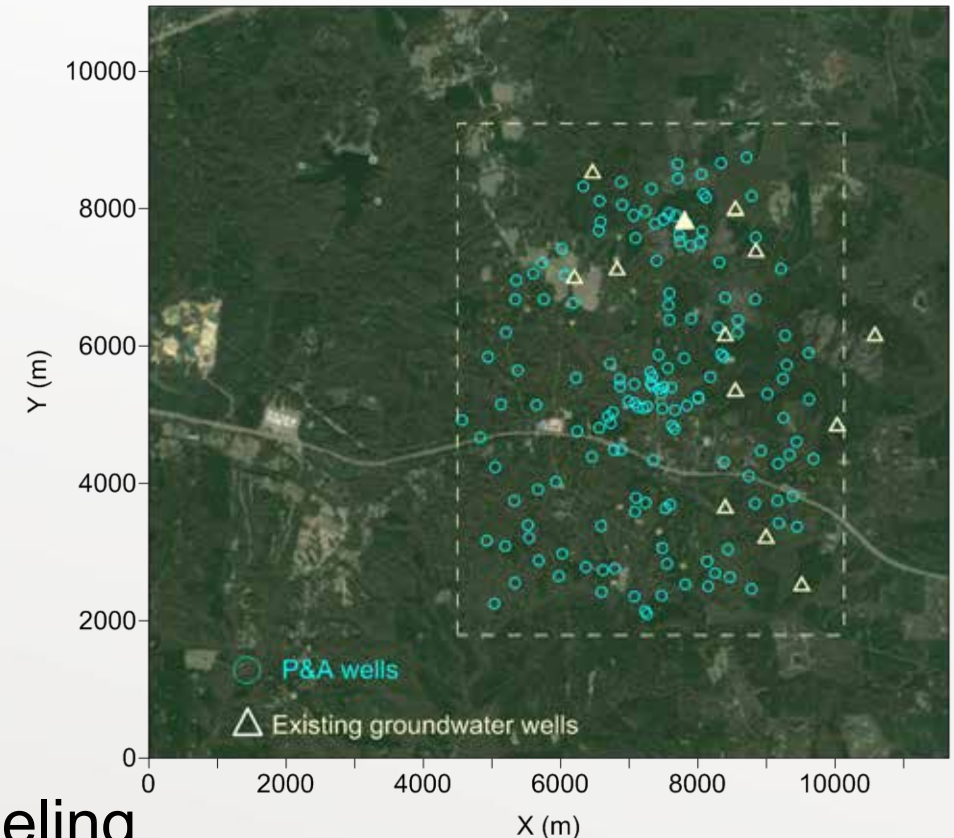
Simulation results

Future Modeling

- Investigate residual gas distribution in more detail (adjust bubble point, better match for blowdown)
- Extending forecast simulation
- Investigating effect of development strategies on reservoir response
  - Continue CO_2-EOR
  - Transition into pure storage
- Post injection simulations

- Field campaigns for groundwater sampling
- Lab experiments of water-rock-CO_2 interactions
- Single-well push-pull test

No CO_2 leakage signals have been detected.



Objectives

Use reactive transport modeling
- Assess impacts of CO_2 leakage on groundwater chemistry
- Evaluate monitoring network efficiency

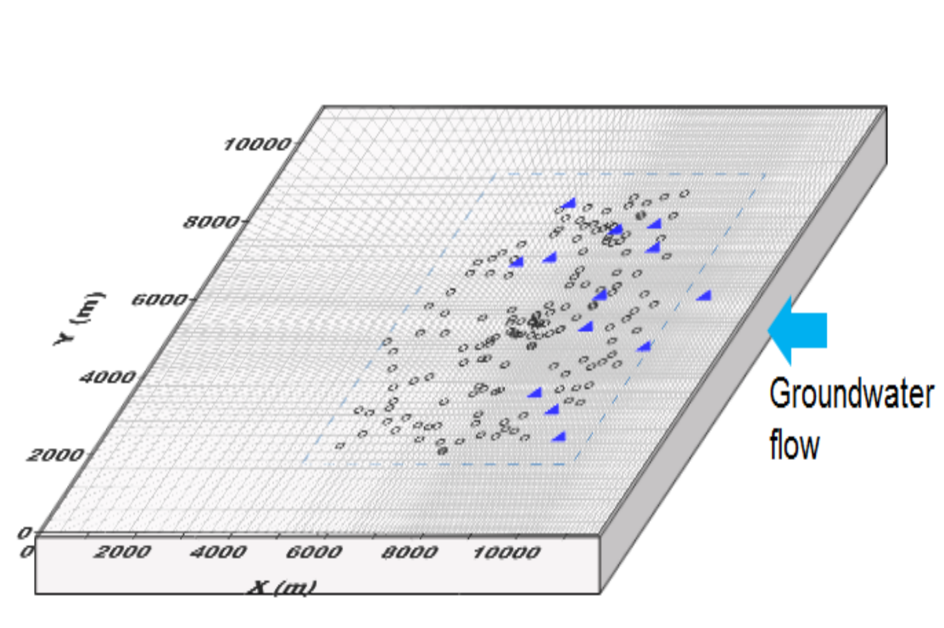
Yang, C.; S. D. Hovorka; R. H. Treviño; J. Delgado-Alonso, Integrated Framework for Assessing Impacts of CO2 Leakage on Groundwater Quality and Monitoring-Network Efficiency: Case Study at a CO2 Enhanced Oil Recovery Site. Environ Sci Tech 49: 8887-8898 (2015).
Yang, C; R. H. Treviño; S. D. Hovorka; J. Delgado-Alonso, Semi-analytical approach to reactive transport of CO_2 leakage into aquifers at carbon sequestration sites, Greenhouse Gas: Science and Technology, accepted.

THE UNIVERSITY OF TEXAS AT AUSTIN

WHAT STARTS HERE CHANGES THE WORLD

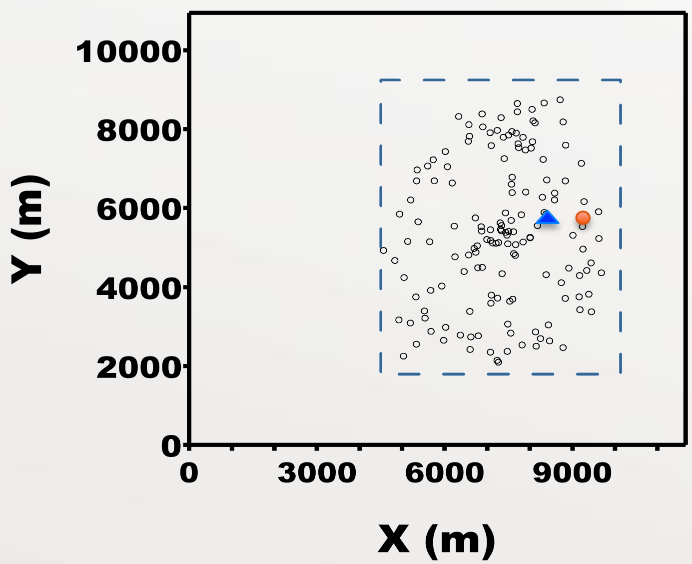
Regional-Scale Reactive Transport Modeling (RSRTM)

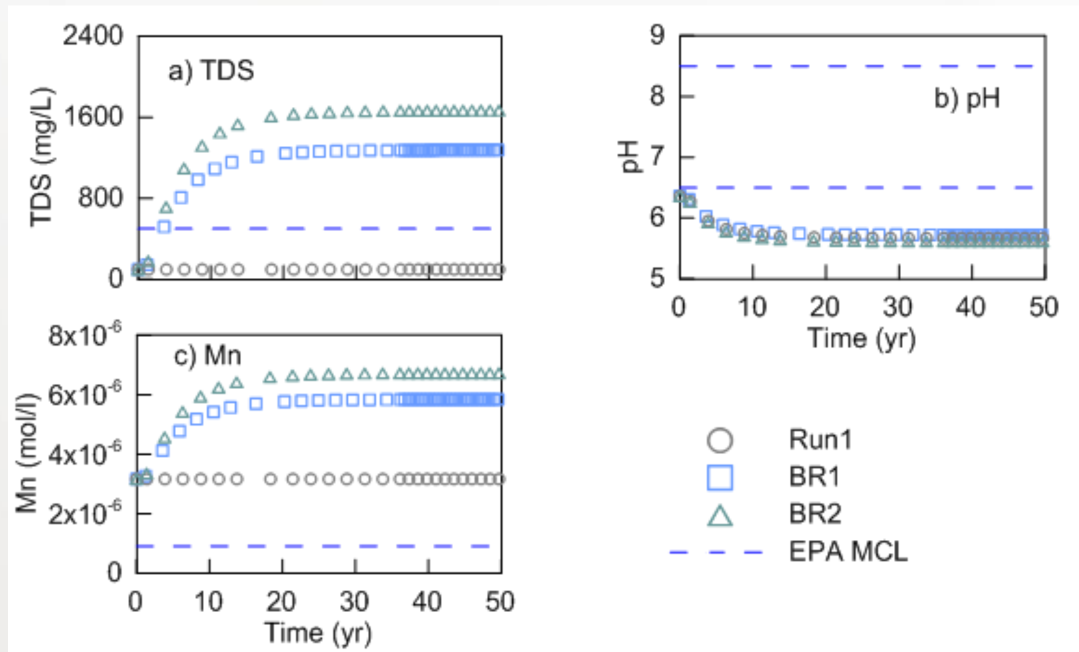
- Aquifer simplification (shallow, confined, homogeneous, groundwater flows from right to left);
- Geochemical interactions of water-rock-CO_2 tested and validated with laboratory experiments & the field test



- CO_2 as dissolved phase in either fresh groundwater or brine
- CO_2 leakage rate from 0.9 to 100 metric ton/yr

Potential impacts of CO_2 leakage on groundwater chemistry





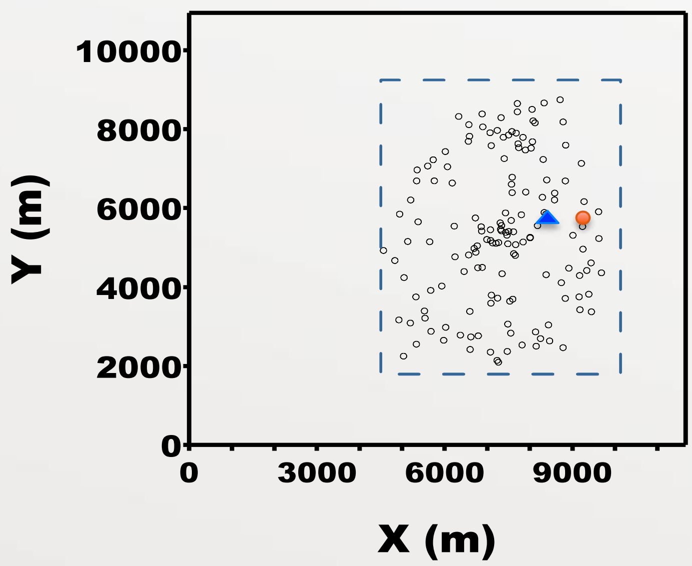
Leakage rate
metric ton/yr

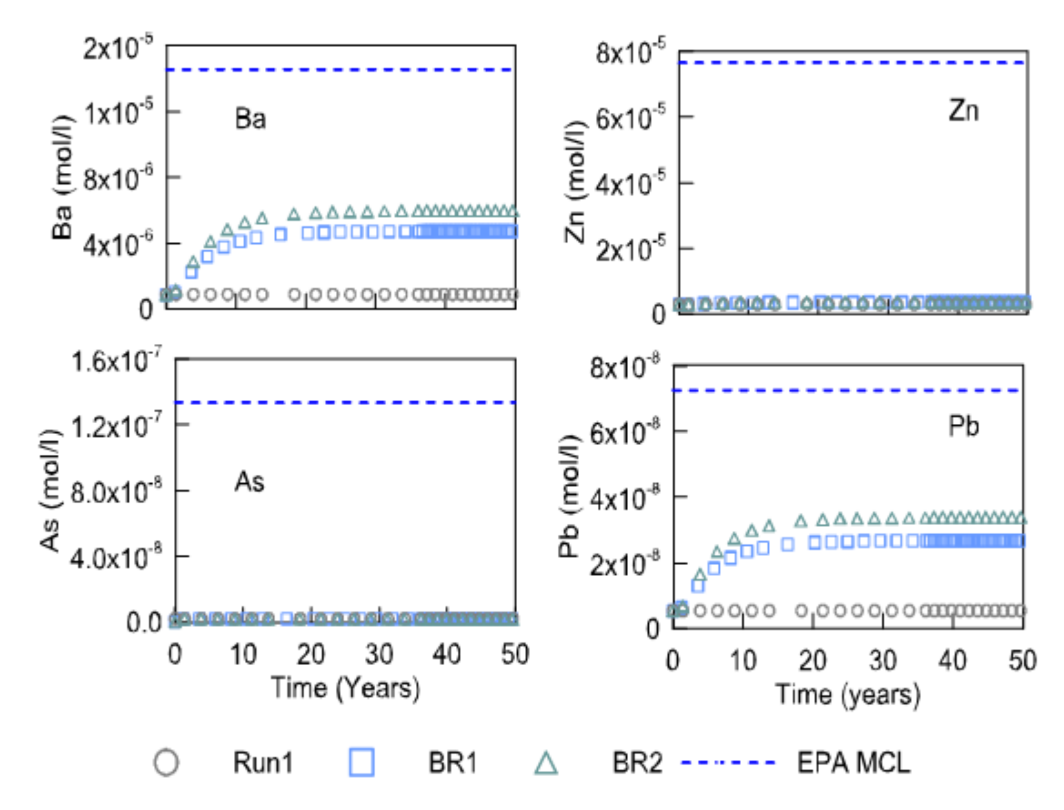
Run1: 50.3
BR1: 37.3
BR2: 50.3

J=0.5%

- TDS exceeds the EPA MCL if brine is leaked;
- pH degradation
- Mn is a concern

Potential impacts of CO_2 leakage on groundwater chemistry





Leakage rate
metric ton/yr

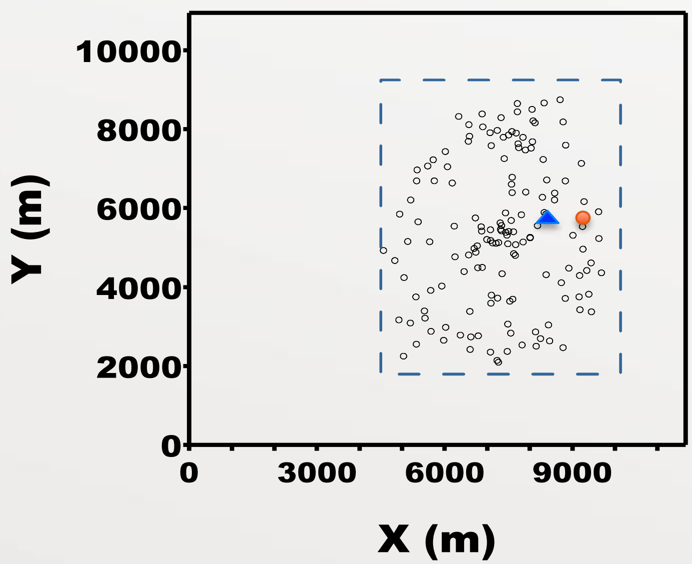
Run1: 50.3
BR1: 37.3
BR2: 50.3

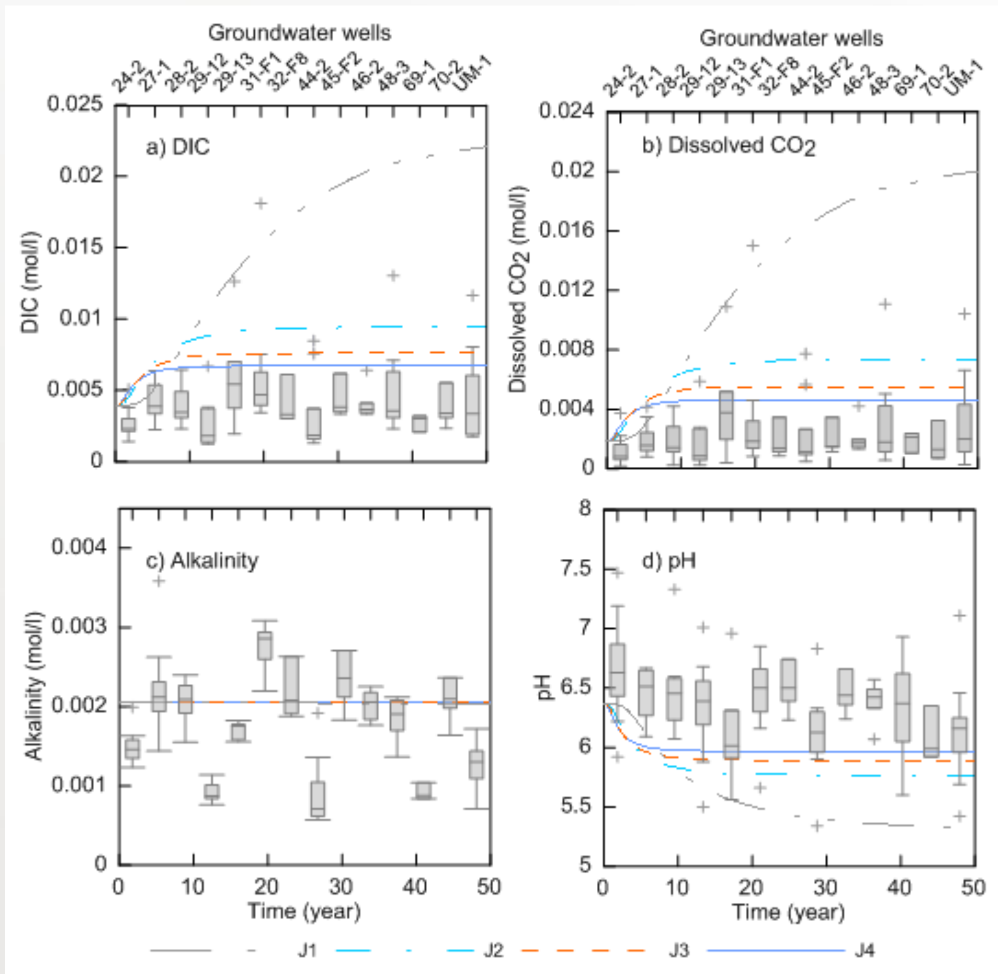
J=0.5%

- Simulated conc. < EPA MCL
- Ba and Pb increase caused by brine leakage

THE UNIVERSITY OF TEXAS AT AUSTIN
WHAT STARTS HERE CHANGES THE WORLD

Potential impacts of CO_2 leakage on groundwater chemistry



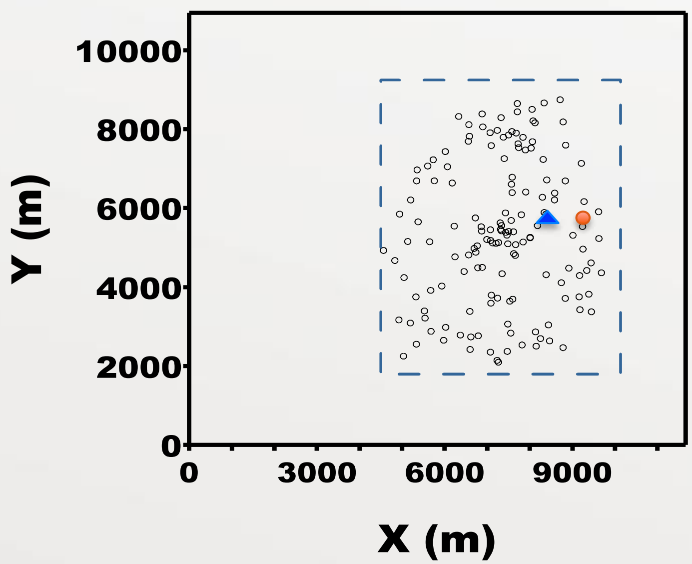


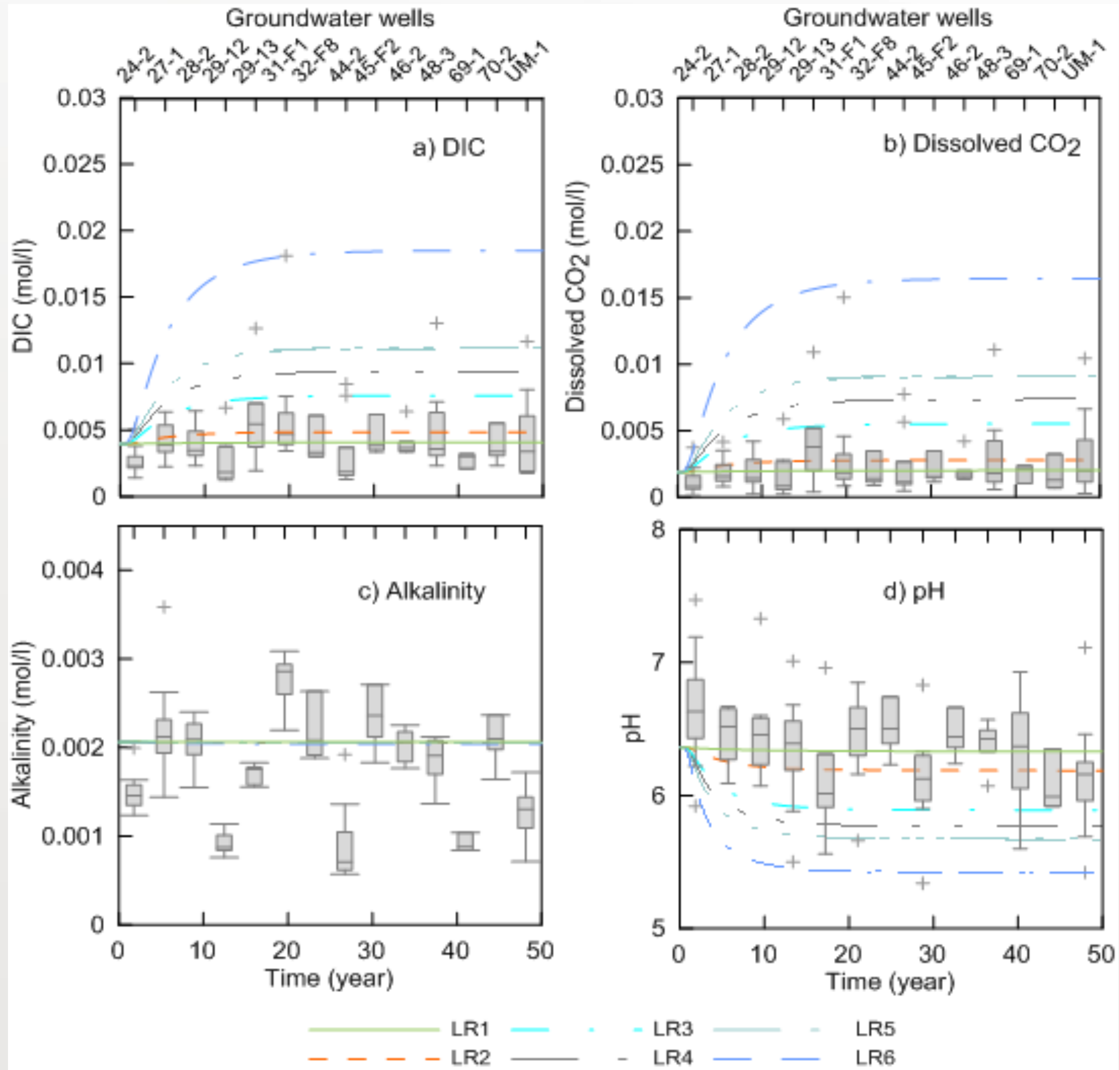
Regional hydraulic gradient

J1: 0.1%
J2: 0.5% (in the shallow aquifer)
J3: 0.8%
J4: 1.0%

Leakage rate: 37.7 metric ton/yr

Potential impacts of CO_2 leakage on groundwater chemistry





Leakage rate: metric ton/yr

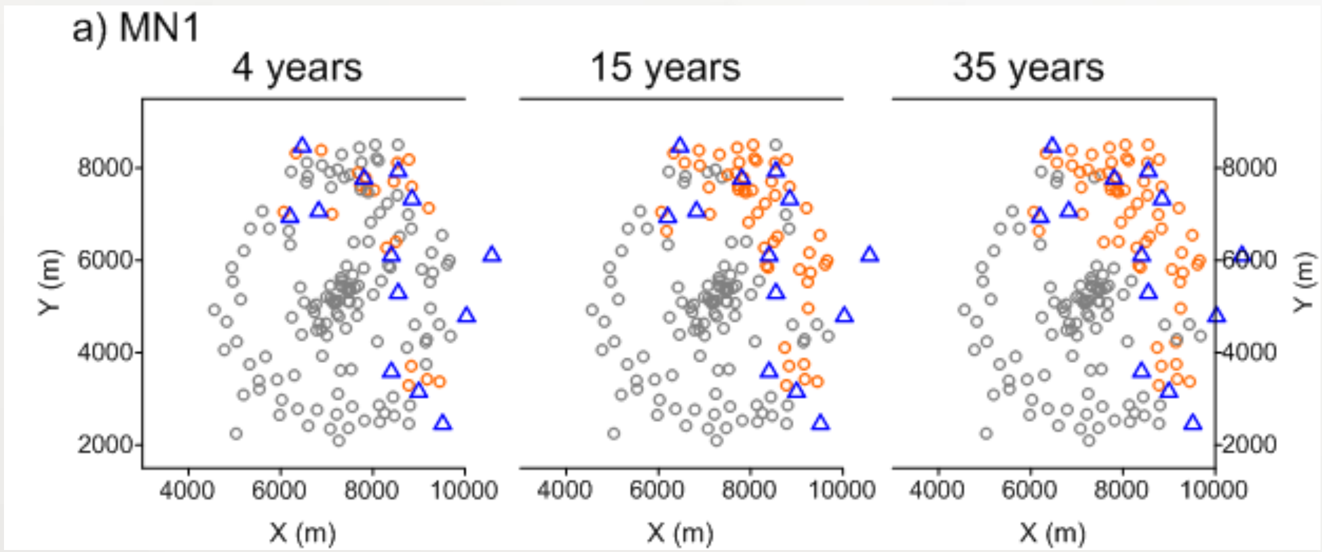
LR1: 0.94
LR2: 6.28
LR3: 25.1
LR4: 37.7
LR5: 50.3
LR6: 100

J=0.5%

Monitoring Network Efficiency

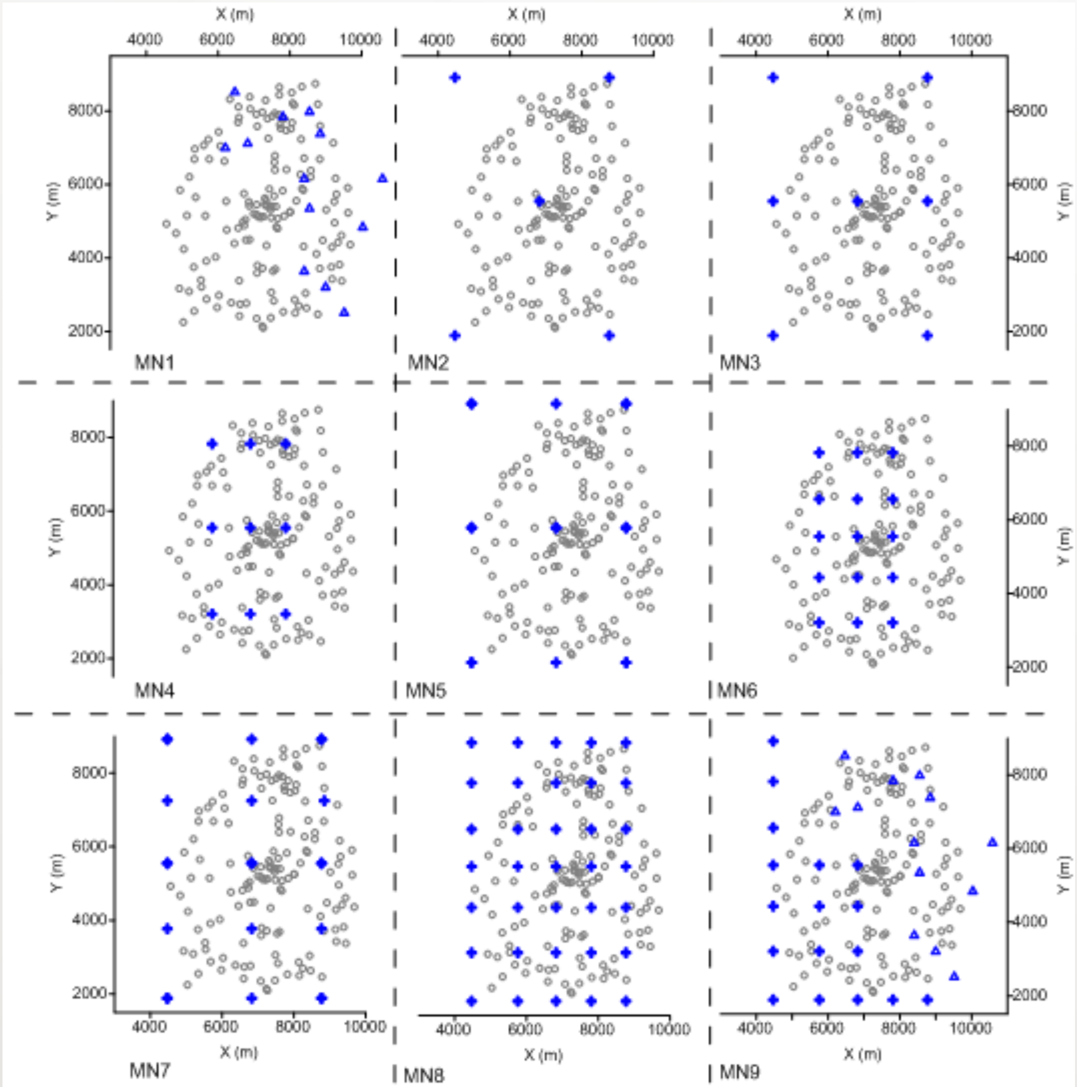
$$ME=W\uparrow d\ /W\uparrow T$$

- 20/151=0.13 by 4 years
- 50/151=0.33 by 15 years
- 58/151=0.38 by 35 years



CO_2 leakage from a P&A well is detected by a monitoring net work if change in DIC, dissolved CO_2, or pH in any one of wells of the monitoring network is higher than one standard deviation of the groundwater chemistry data collected in the shallow aquifer over the last 6 years.

Monitoring Network Efficiency



Unit: wells/km^2

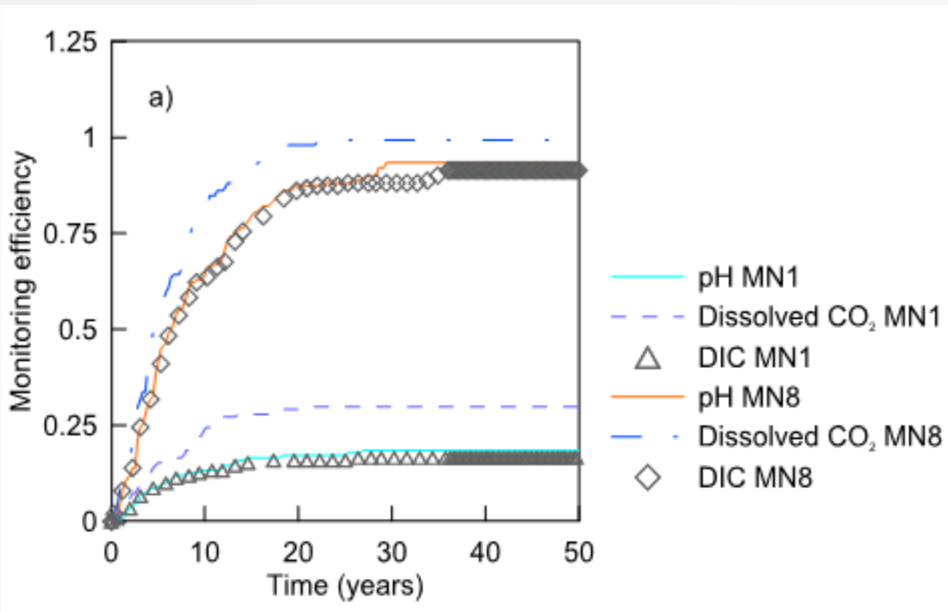
MN1: 0.322
MN2: 0.124
MN3: 0.173
MN4: 0.223
MN5: 0.223
MN6: 0.371
MN7: 0.371
MN8: 0.866
MN9: 0.742

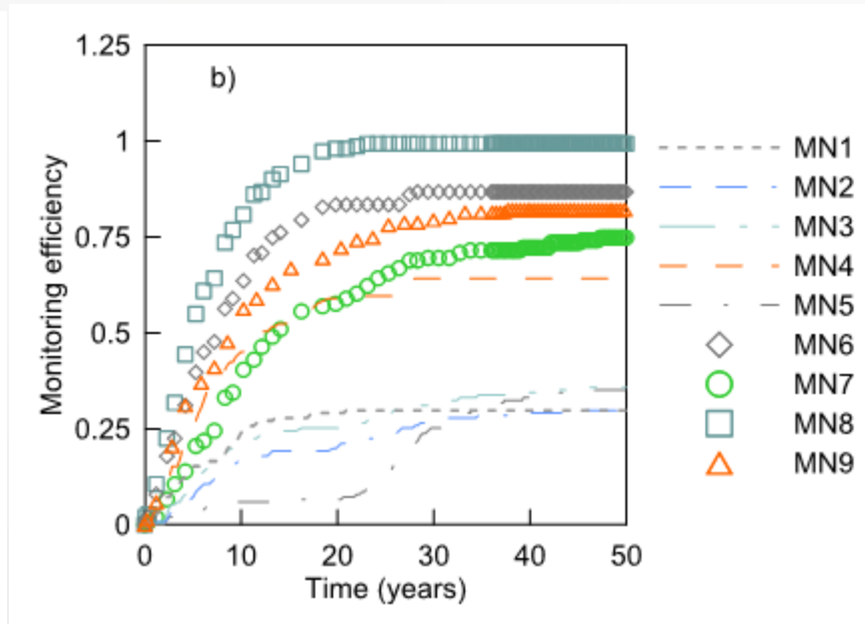
THE UNIVERSITY OF TEXAS AT AUSTIN

WHAT STARTS HERE CHANGES THE WORLD

Monitoring Network Efficiency

Leakage rate=37.7 metric ton/yr; J= 0.5%



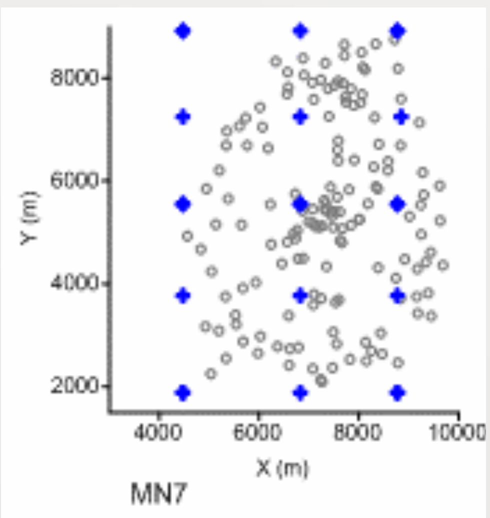


Comparison of ME for a) with pH, dissolved CO_2 and DIC as indicators for the two monitoring networks, MN1 and MN8

- Comparison of ME with dissolved CO_2 as indicator for the 9 monitoring networks
- Well densities for MN4 and MN5 are 0.223 wells/km2; ME of MN4 is ~2 times of ME of MN5, suggesting well locations are important

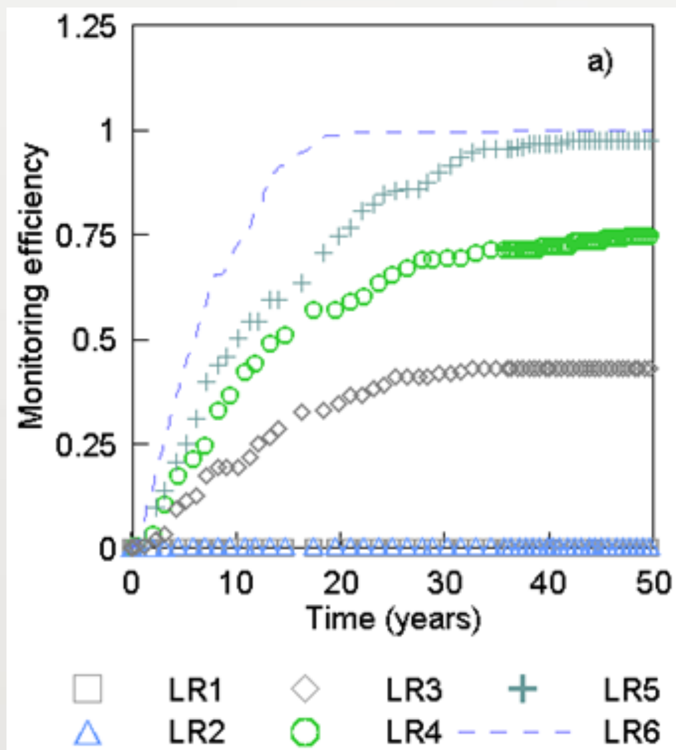
Monitoring Network Efficiency

Monitoring efficiency of MN7 with dissolved CO_2 as an indicator



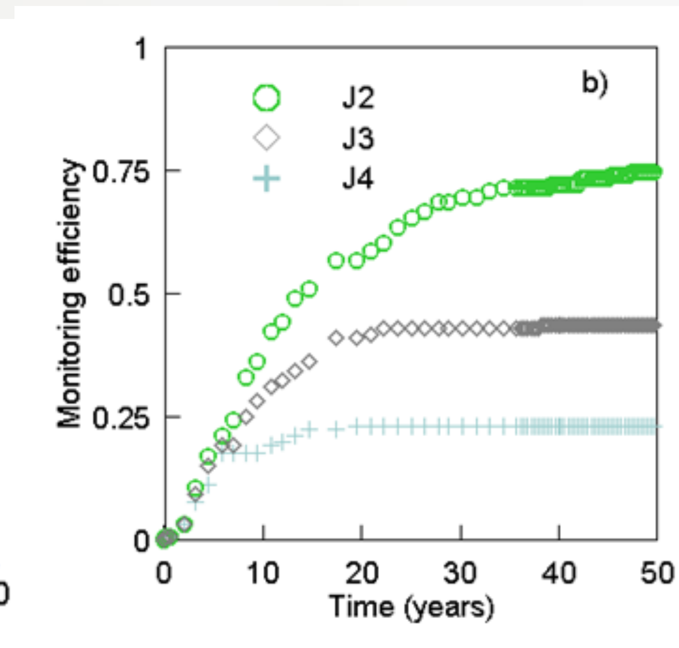
Leakage rate: metric ton/yr

LR1: 0.94, LR2: 6.28
LR3: 25.1, LR4: 37.7
LR5: 50.3, LR6: 100



Regional hydraulic gradient

J2: 0.5% , J3: 0.8%
J4: 1.0%



Summary

- Model outcome: No obvious degradation in groundwater quality (except degradation in pH) if only CO_2 is leaked. Salinization would be problematic if brine+CO_2 are leaked.
- Dissolved CO_2 appears to be a better indicator than DIC, pH, alkalinity for CO_2 leakage detection at the CO_2-EOR site, however, dependent on regional hydraulic gradient, leakage rate.
- Monitoring network efficiency depends on regional hydraulic gradient, leakage rate, flow direction, and also aquifer heterogeneity. Impact of dispersion coefficient could be neglected.

Summary

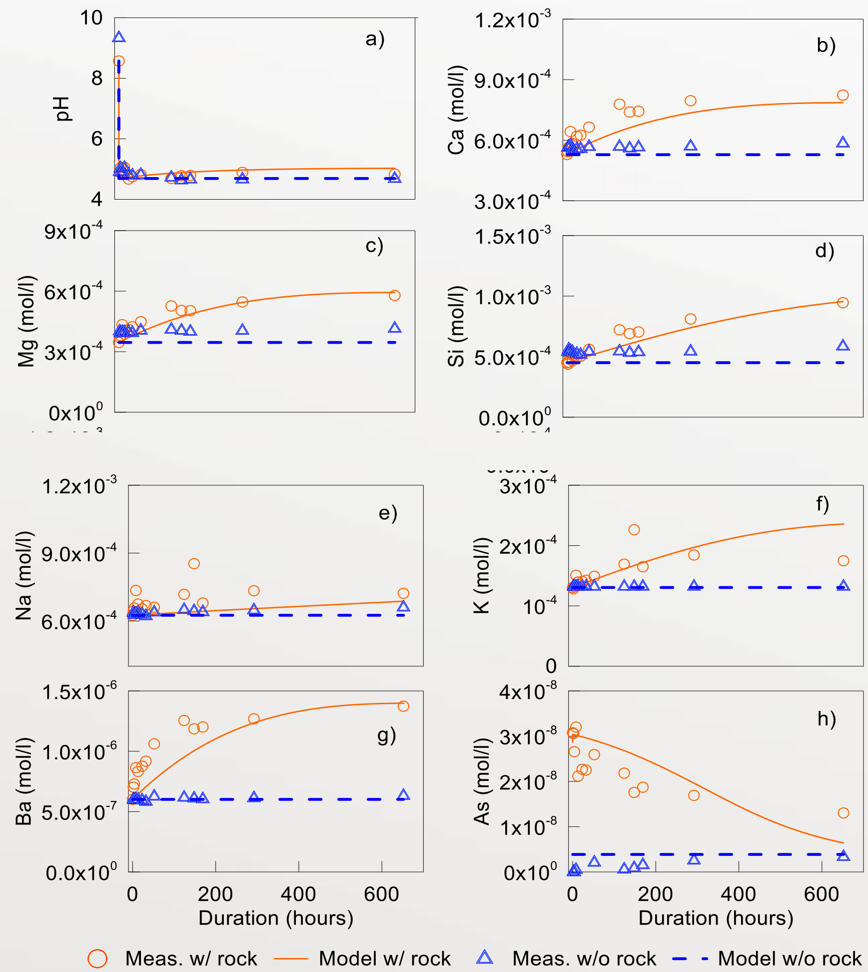
- The existing groundwater wells can monitor CO_2 leakage from up to 60 P&A wells and MN8, the ideal monitoring network which consists of 35 water wells can detect CO_2 leakage from almost all P&A wells.
- Site characterization + lab experiments + single-well PPTs + RTM could be enough for risk assessment.

Thanks!

Gulf Coast Carbon Center
Bureau of Economic Geology
NETL
Denbury
Southern States Energy Board
SECARB Southeast Regional Carbon Sequestration Partnership

Model calibration with laboratory and field tests

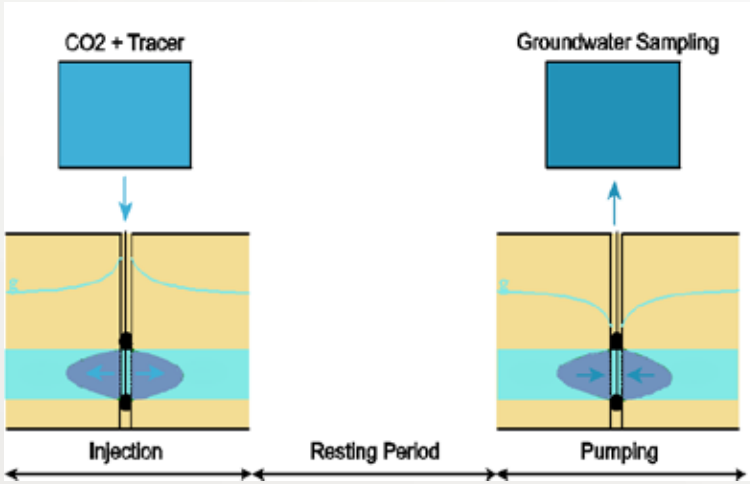
To understand responses of groundwater chemistry to CO_2 leakage under laboratory conditions

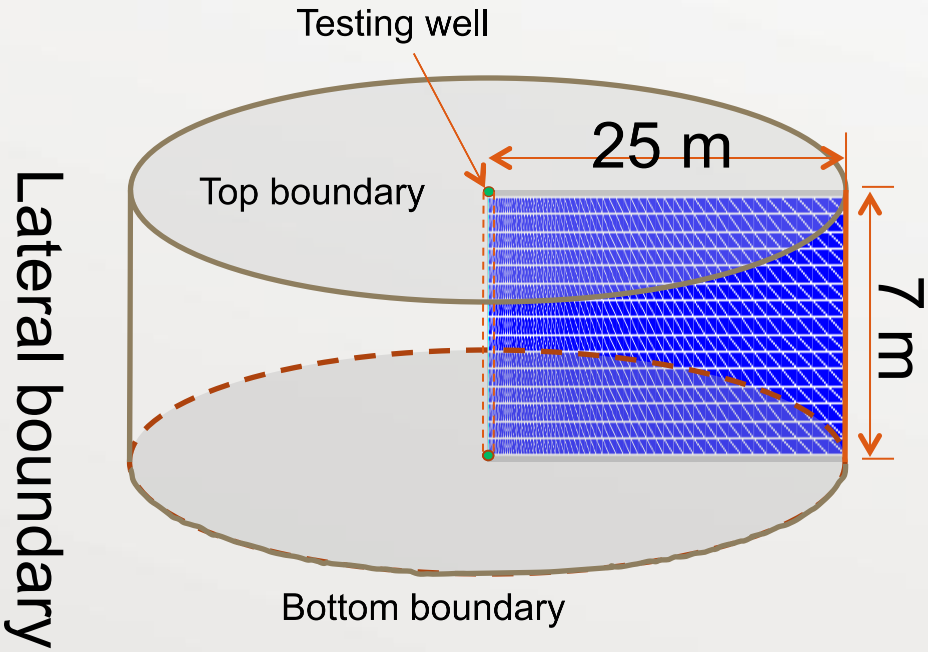


- 106 g of sedimentary samples and 420 ml groundwater from the Cranfield shallow aquifer
- bubbled with Ar for a week, then with CO_2 for ~half year

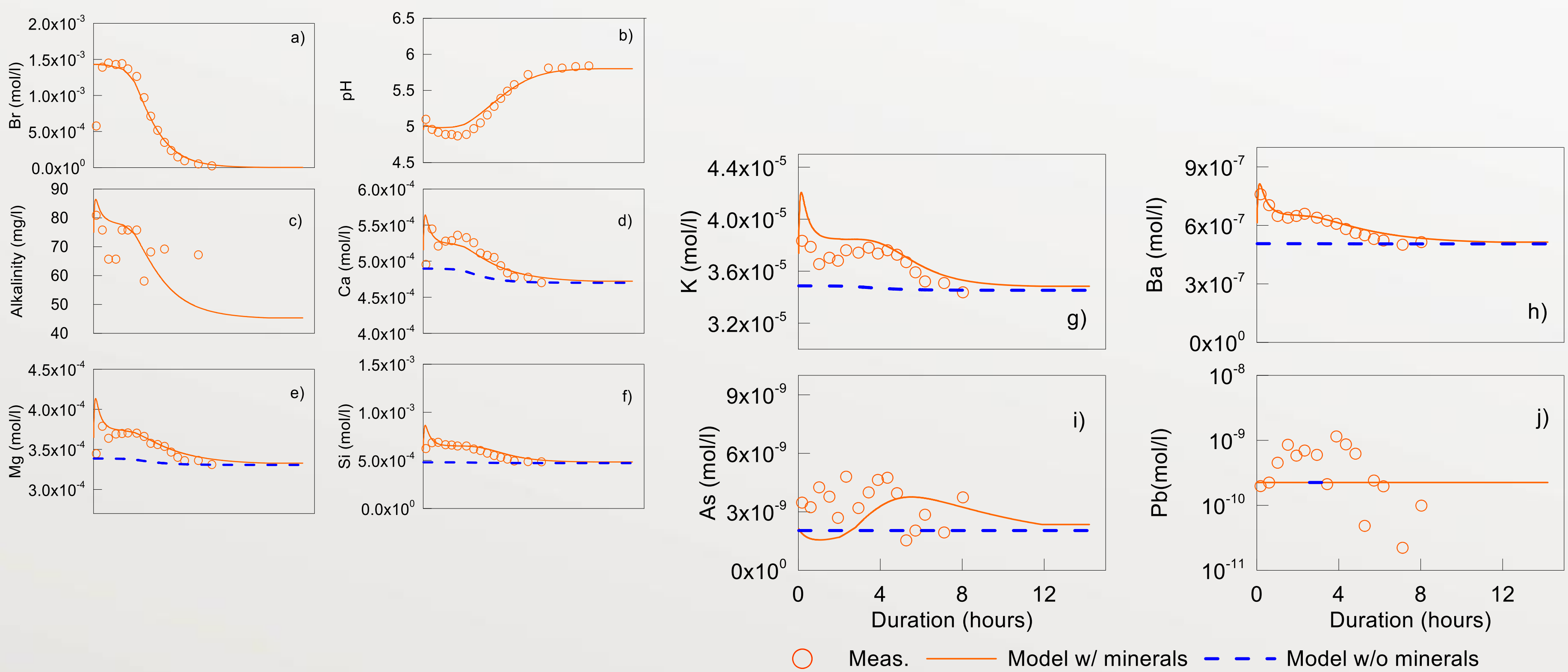
Model calibration with laboratory and field tests

Single well push-pull test





Model calibration with laboratory and field tests



Southeast Regional Carbon Sequestration Partnership

Citronelle Project

Carbon Storage R&D Project Review Meeting

Pittsburgh, PA

August 18, 2015

Gerald R. Hill, Ph.D.
Senior Technical Advisor
Southern States Energy Board

Presentation Outline

- **Jerry Hill, SSEB**
  - SECARB Overview
- **Jerrad Thomas, Southern Company**
  - Capture Unit Overview
  - Capture R&D Accomplishments
- **Rob Trautz, EPRI**
  - Storage Overview
  - Storage R&D Accomplishments

SECARB Phase III

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Anthropogenic Test

Capture: Alabama Power 's Plant Barry, Bucks, Alabama

Transportation: Denbury

Geo Storage: Denbury's Citronelle Field, Citronelle, Alabama

Early Test

Denbury Resources' Cranfield Field Near Natchez, Mississippi

CO_2 Source: Denbury

CO_2 Transportation: Denbury

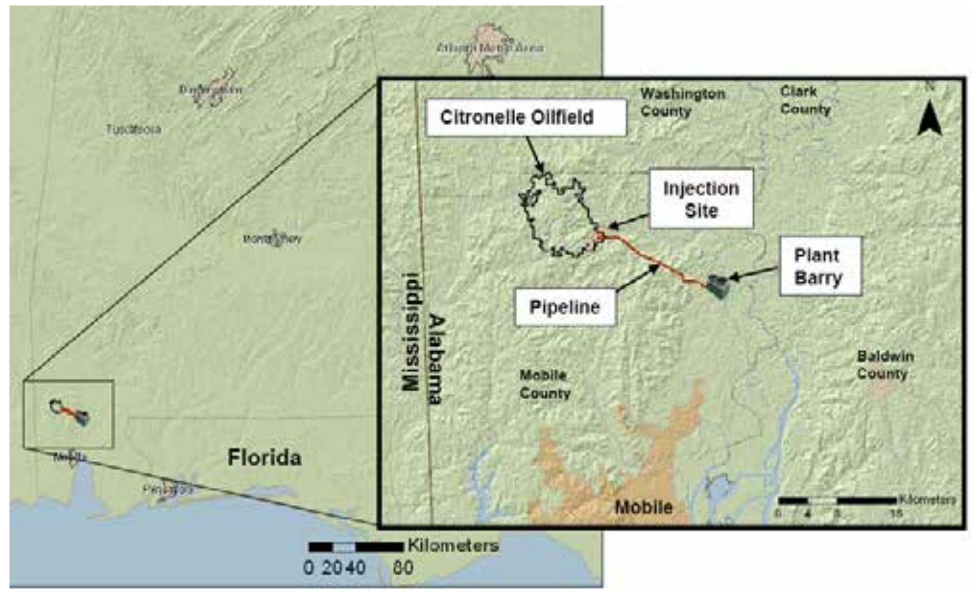
Saline MVA: GCCC

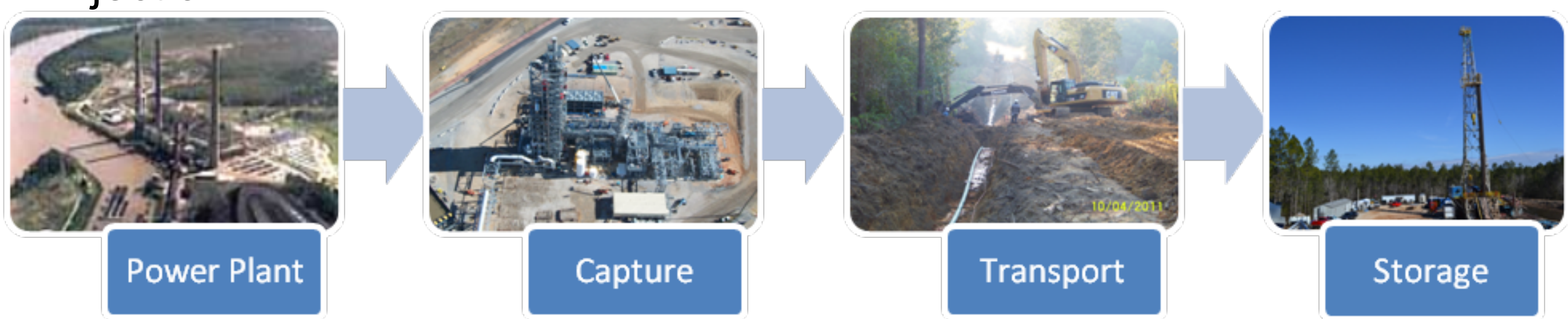
Gulf Coast Carbon Center

SECARB Southeast Regional Carbon Sequestration Partnership · NETL · Southern States Energy Board · Bureau of Economic Geology · Gulf Coast Carbon Center · EPRI · Advanced Resources International, Inc. · Southern Company · Denbury

SECARB Phase III Anthropogenic Test

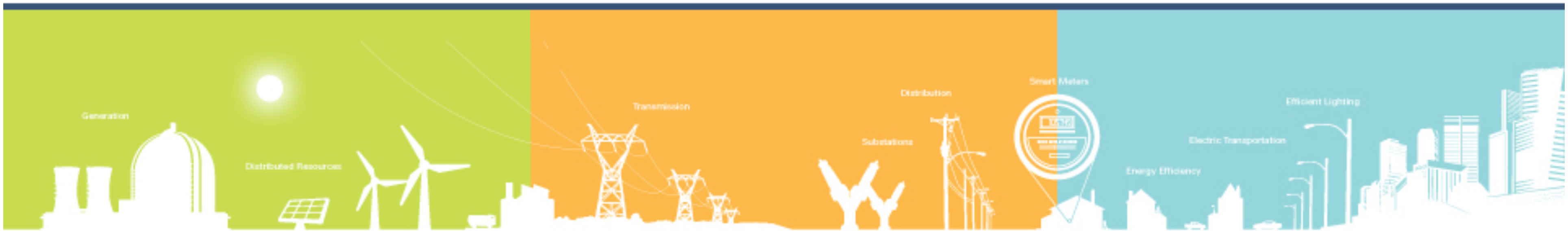
- Carbon capture from Plant Barry (equivalent to 25MW of electricity).
- 12 mile CO_2 pipeline constructed by Denbury Resources.
- CO_2 injection into ~9.400 ft. deep saline formation (Paluxy) above Citronelle Field
- Monitoring of CO_2 storage during injection and 3years post-injection.





Plant Barry 25 MW Demo

Jerrad Thomas | Research Engineer
Southern Company Services, Inc.



SOUTHERN COMPANY

Carbon Capture and Storage Projects

National Carbon Capture Center

- U.S. DOE facility operated by Southern Company.
- Accelerates commercialization of technologies.
- Coal or natural gas constituents tests.
- Enables coal-based power plants to achieve near-zero emissions

25-MW CCS Demo at Plant Barry

- 90% CO_2 capture.
- Capture, compression, transport, sequestration.
- ~115,000 tons sequestered, ~240,000 tons captured.
- Largest CCS facility on a fossil-fueled power plant in the U.S.

Kemper County IGCC project

- 582 megawatts of power.
- State-of-the-art coal gasification design.
- Will use a four-billion-ton reserve of Mississippi lignite.
- Affordable, abundant, but little-used natural resource.
- Will capture at least 65% of its CO_2 emissions for EOR use.
- Will reduce nitrogen oxide, sulfur dioxide and mercury.

SOUTHERN COMPANY

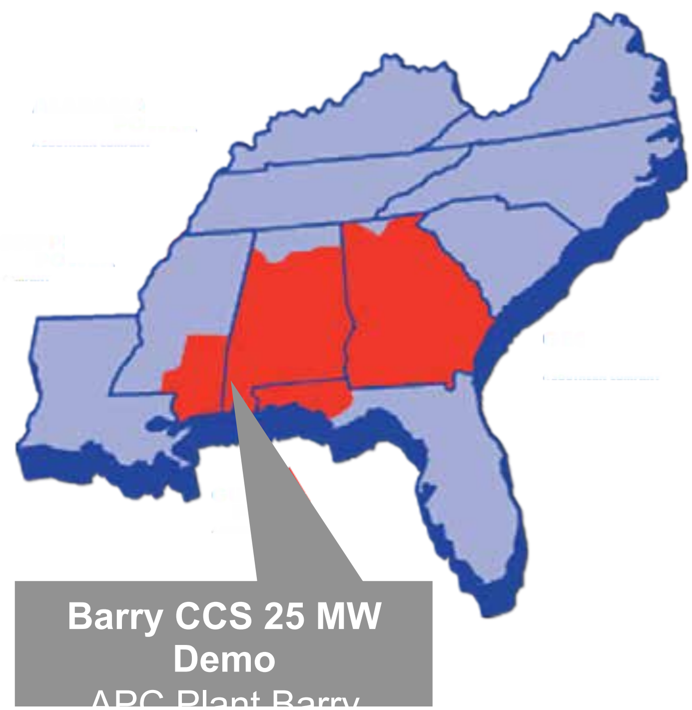
Project Overview

- Located just north of Mobile, Alabama at Alabama Power Plant Barry

- Largest CO_2 capture project on a coal-fired power plant in the United States

- First CO_2 pipeline permitted and constructed in the State of Alabama

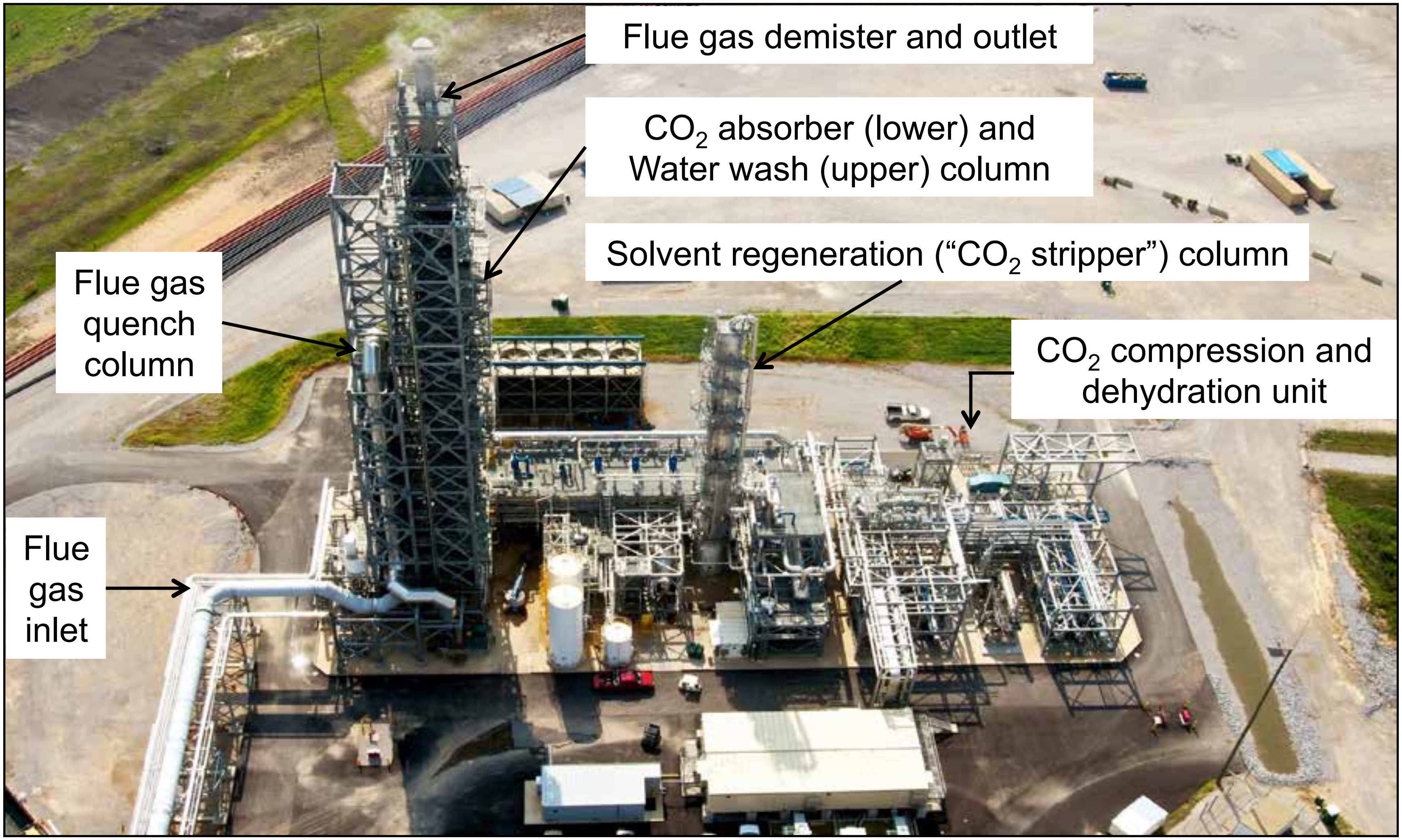
- First integration of a CO_2 capture plant on a coal plant with pipeline transportation and injection for geologic storage



Information and Goals

- CO2 Capture and Compression
  - SCS/MHI collaboration with partners
  - KM-CDR capture technology
- Transportation and Sequestration
  - DOE SECARB Phase III "Anthropogenic Test"
  - 100-300 kMton of CO2 will be injected into a saline formation over 2-3 years
  - 12 mile CO2 pipeline to Denbury Resources, Inc. injection site into Citronelle Dome
- Objectives/Goals
  - Advance saline sequestration technology through large field test
  - Characterize CCS operations to support larger scale development and deployment
  - Continue outreach and education to ensure seamless deployment

CO2 Capture Plant



SOUTHERN COMPANY

Plant Performance

- Gas In for CO_2 Capture Plant: June, 2011
- Commissioning of CO_2 Compressor: August, 2011
- Commissioning of CO_2 Pipeline: March, 2012
- CO_2 Injection: August, 2012
  (America's Largest Integrated CCS from a Coal-fired Power Plant)

Items		Results
Total Operation Time	**hrs**	**>10,000**
Total Amount of Captured CO_2	**metric tons**	**>220,000**
Total Amount of Injected CO_2	**metric tons**	**114,000**
CO_2 Capture Rate	**metric tons per day**	**500**
CO_2 Removal Efficiency	**%**	**90**
CO2 Stream Purity	**%**	**99.9+**
Steam Consumption	**ton-steam/ton-CO_2**	**0.98**

SOUTHERN COMPANY

Project Test Items

Item	Main Results
Baseline mass and heat balance	Verified that **steam consumption was lower than expectation** under the design condition (CO_2 removal efficiency: 90%, CO_2 capture rate: 500MTPD).
Emissions and waste streams monitoring	Successfully demonstrated **amine emission reduction** technologies under the various SO_3 concentration condition (2013)
Parametric test for all process systems	Verified **operation performance** under several controlled operating parameters changes. (2011-2012) Demonstrated several improved technologies for the cost reduction. (e.g. MHI Proprietary spray distributor) (2013)
Performance optimization	Achieved **0.95 ton-steam/ton-CO_2** by optimizing steam consumption. (2011)
High impurities loading test	Verified that the **amine emission increased** as a result of **higher SO_3 loading**. (Oct. 2011) Verified that the impurities were removed from the solvent by **reclaiming** operation. (2012, 2013)

SOUTHERN COMPANY

(1) Amine Emission Evaluation

- Amine emissions increased significantly with a small amount of SO3.
- MHI's amine emission reduction system decreases amine emissions down to less than 1/10 of the conventional system

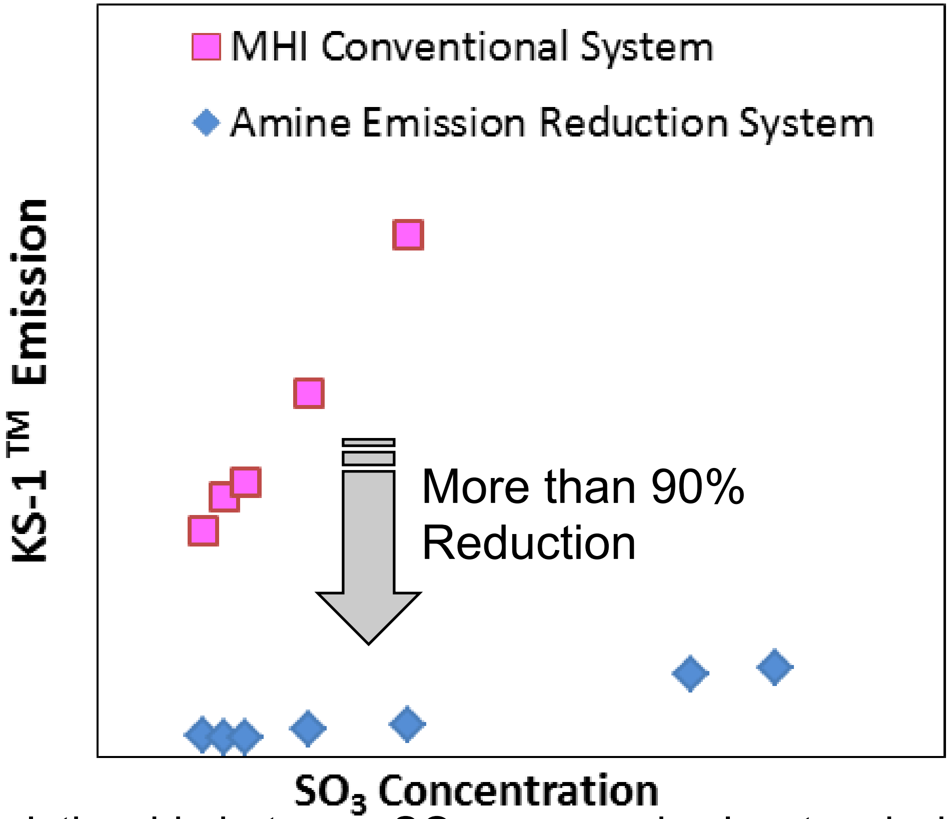


Fig. Relationship between SO_3 conc. and solvent emission

(2) Improved Technology

- Proprietary spray type distributor developed by MHI to reduce weight of tower internals
- Keeping the same performance as the trough type distributor approximately 50% cost reduction of tower internals was achieved

Fig. Trough Type Distributer

Fig. Spray Type Distributer
(MHI Proprietary)

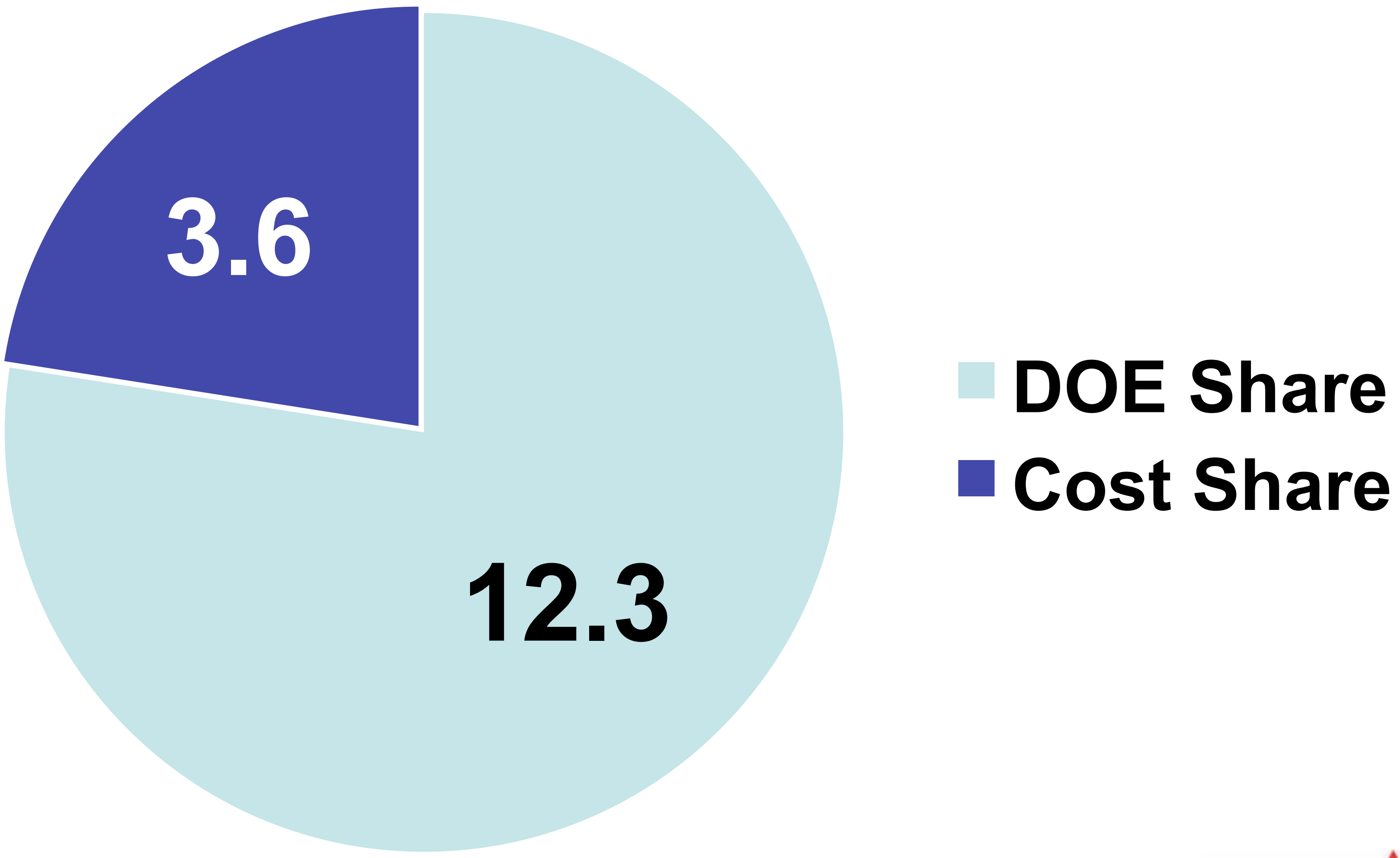
High Efficiency System

Project Scope

- Integrate a 25 MW ***waste heat recovery*** technology termed Mitsubishi High Efficiency System (HES) into 25 MW CCS plant and Plant Barry, Unit 5
- Recover low grade waste heat in flue gas and CO_2 to preheat condensate ***replacing LP steam***
- Evaluate improvements in the energy performance and emissions profile of the integrated plants
- Employ 0.5MW mini ESP to test effect of HES on SO3 and trace metals emissions

SOUTHERN COMPANY

Total Project Budget ($MM)



Flue Gas Cooler captures SO_3

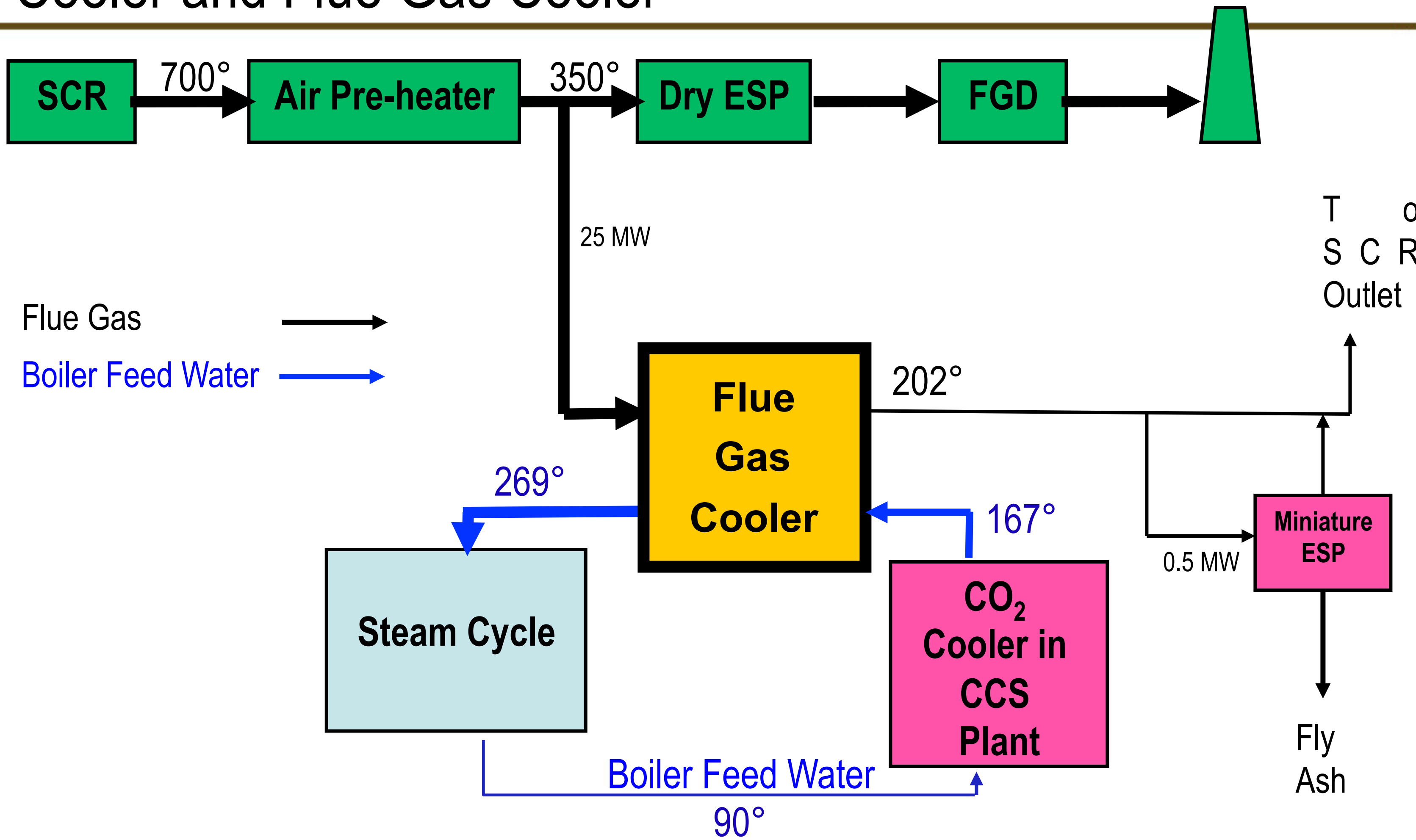
- Operates downstream of the APH
- Mechanism for removal of SO_3 from flue gas
  - SO_3 (g) + H_2O (g) --> H_2SO_4 (g)
  - H_2SO_4 (g) --> H_2SO_4 (l)
  - H_2SO_4 (l) condenses on fly ash in flue gas and a protective layer of ash on tube bundles
- Flue Gas Cooler tube skin temperature < SO_3 dewpoint
  - Alkaline species in fly ash (Ca, Na) neutralize H_2SO_4
  - Silicates, etc. physically adsorb H_2SO_4

SOUTHERN COMPANY

Other benefits of Flue Gas Cooler

- Improve removal of Hg, Se, SO_3 across the ESP
- Reduce AQCS cost
  - Improve ESP performance
  - Improve FGD performance
  - Improve CCS performance
- Potential to simplify boiler/steam turbine cycles
- Improve plant heat rate

PROJECT = Boiler feed water will be heated with CO_2 Cooler and Flue Gas Cooler



BP3 completes March 2016

BP1
- FEED and Target Cost Estimate
- Permitting

BP2
- Engineering, Procurement, Construction

BP3
- Operations
- Field Testing Analysis

WORK IN PROGRESS

SOUTHERN COMPANY

Remaining project work

Complete Constructi on — **Dec 2014**

Commission — **May 2015**

Operations and Testing — **June 2015 – Nov 2015**

- Verify efficiency
- Estimate reduction in FGD water use
- Measure corrosion, erosion
- Test water quality
- Measure SO_3, trace metal removal

SOUTHERN COMPANY

Thank You!

For more information please contact:

Jerrad Thomas – Southern Company Services

Project Manager for CCUS and Research Engineer

Email: JERRTHOM@southernco.com

Tel: 205-257-2425

SECARB Phase III Citronelle Project (Anthropogenic Test) in Alabama

Rob Trautz, Princ. Tech. Leader, EPRI

Carbon Storage R&D Project Review Meeting

18-August-2015

© 2015 Electric Power Research Institute, Inc. All rights reserved.

Acknowledgement

This presentation is based upon work supported by the Department of Energy National Energy Technology Laboratory under **DE-FC26-05NT42590** and was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

NETL

SECARB
Southeast Regional Carbon Sequestration Partnership

SOUTHERN COMPANY
Energy to Serve Your World℠

SOUTHERN STATES ENERGY BOARD

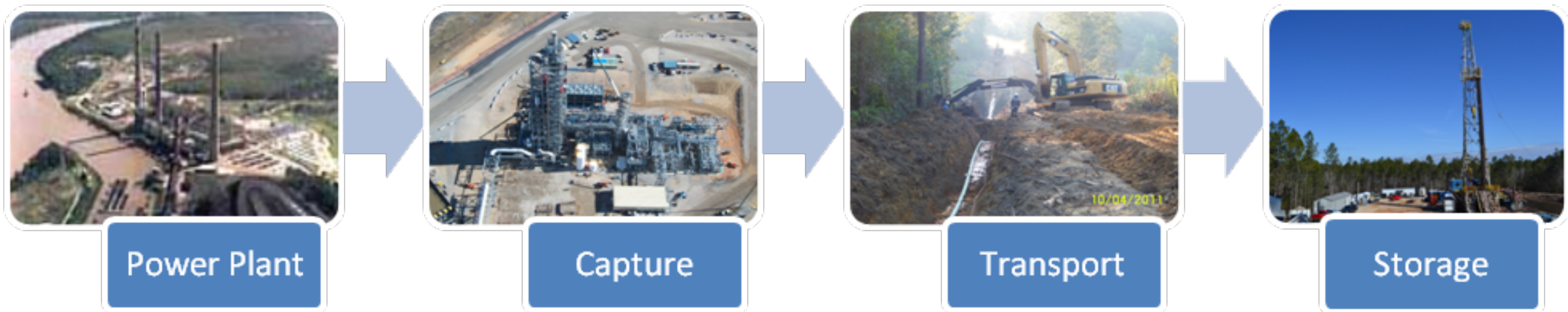
EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Denbury

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Advanced Resources International, Inc.

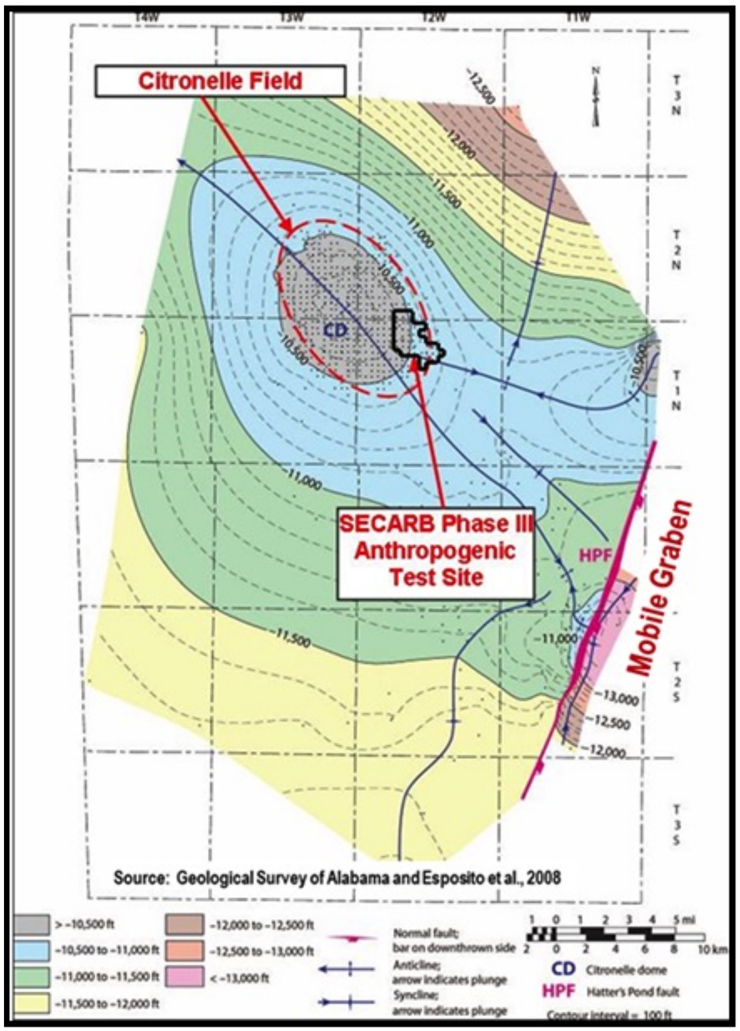
Storage Project Objectives



1. Test the CO_2 flow, trapping and storage mechanisms of the Paluxy Formation
2. Demonstrate how a saline reservoir's architecture can be used to maximize CO_2 storage and minimize the areal extent of the CO_2 plume
3. Test the adaptation of commercially available oil field tools and techniques for monitoring CO_2 storage
4. Test experimental CO_2 monitoring activities, where such technologies hold promise for future commercialization
5. Begin to understand the coordination required to successfully integrate all four components (capture, transport, injection and monitoring) of the project
6. Document the permitting process for all aspects of a CCS project

Largest demonstration of CO_2 capture, transportation, injection, monitoring and storage from a coal-fired electric generating unit in the United States

Storage Site Overview—Citronelle Oilfield



System	Series	Stratigraphic Unit		Major Sub Units	Potential Reservoirs and Confining Zones
Tertiary	Plio-Pliocene			Citronelle Formation	Freshwater Aquifer
	Miocene	Undifferentiated			Freshwater Aquifer
	Oligocene			Chickasawhay Fm.	Base of USDW
		Vicksburg Group		Bucatunna Clay	Local Confining Unit
	Eocene	Jackson Group			Minor Saline Reservoir
		Claiborne Group		Talahatta Fm.	Saline Reservoir
		Wilcox Group		Hatchetigbee Sand	Saline Reservoir
	Paleocene			Bashi Marl	
				Salt Mountain LS	
		Midway Group		Porters Creek Clay	Confining Unit
Cretaceous	Upper	Selma Group			Confining Unit
		Eutaw Formation			Minor Saline Reservoir
		Tuscaloosa Group	Upper Tusc.		Minor Saline Reservoir
			Mid. Tusc.	Marine Shale	Confining Unit
			Lower Tusc.	Pilot Sand Massive sand	Saline Reservoir
	Lower	Washita-Fredericksburg		Dantzler sand	Saline Reservoir
				Basal Shale	Primary Confining Unit
		Paluxy Formation		'Upper' 'Middle' 'Lower'	Injection Zone
		Mooringsport Formation			Confining Unit
		Ferry Lake Anhydrite			Confining Unit
		Donovan Sand		Rodessa Fm. Upper' 'Middle' 'Lower'	Oil Reservoir Minor Saline Reservoir Oil Reservoir

Advanced Resources International, Inc.

© 2015 Electric Power Research Institute, Inc. All rights reserved.

Storage Project Status

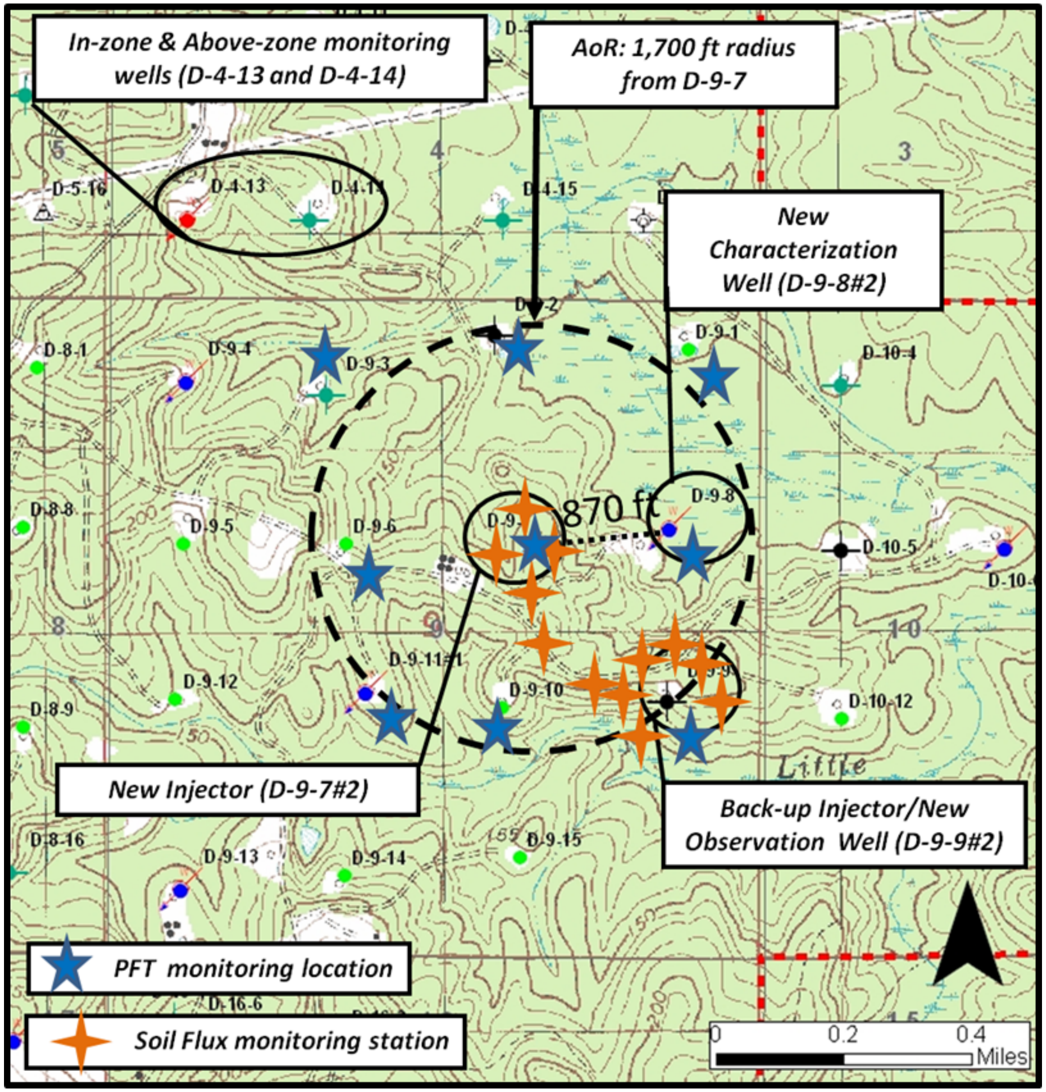
- Alabama Department of Environmental Management (ADEM) issued Class V permit, Nov. 2011
- ADEM granted permission to inject on August 8, 2012
  - Injection commenced on August 20, 2012
- Injection ended September 1, 2014
  - Approximately 114,104 metric tons of CO_2 injected
- A crosswell seismic survey acquired in June, 2014 captured a time-lapse image of the CO_2 plume
- Other testing and monitoring activities have indicated containment
- The project entered the *Post-Injection Site Care Period* on September 2, 2014
- *Site closure based on **demonstration of CO_2 containment and non-endangerment of USDW***

Advanced Resources International, Inc.
© 2015 Electric Power Research Institute, Inc. All rights reserved.
EPRI ELECTRIC POWER RESEARCH INSTITUTE

1. Monitoring & Modeling Lines of Evidence

© 2015 Electric Power Research Institute, Inc. All rights reserved.

Anthropogenic Test MVA Program

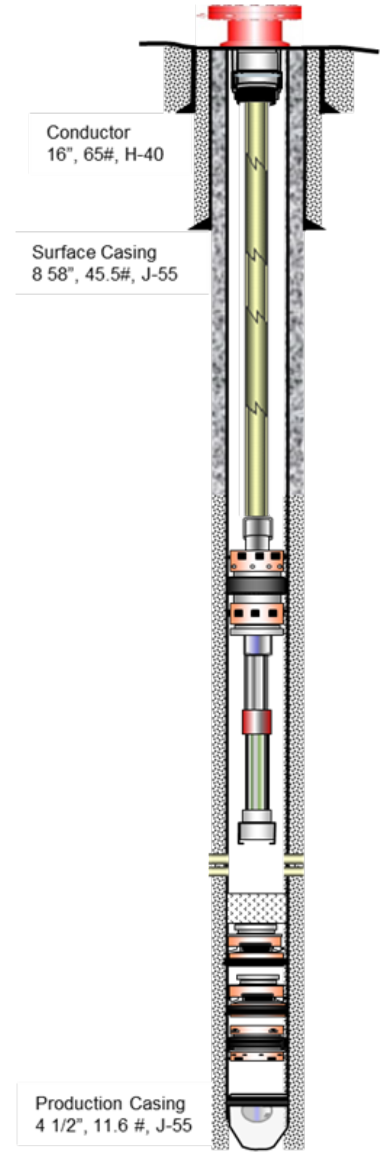


- Multiple lines of evidence to confirm CO_2 containment include:
  - Soil CO_2 flux
  - PFT monitoring
  - Crosswell Seismic and VSP surveys
  - PNC logging (above zone saturation)
  - Pressure monitoring
- Assure non-endangerment of USDWs
  - Monitoring geochemistry of multiple aquifers
- Monitoring results are used to inform the reservoir simulation

© 2015 Electric Power Research Institute, Inc. All rights reserved.

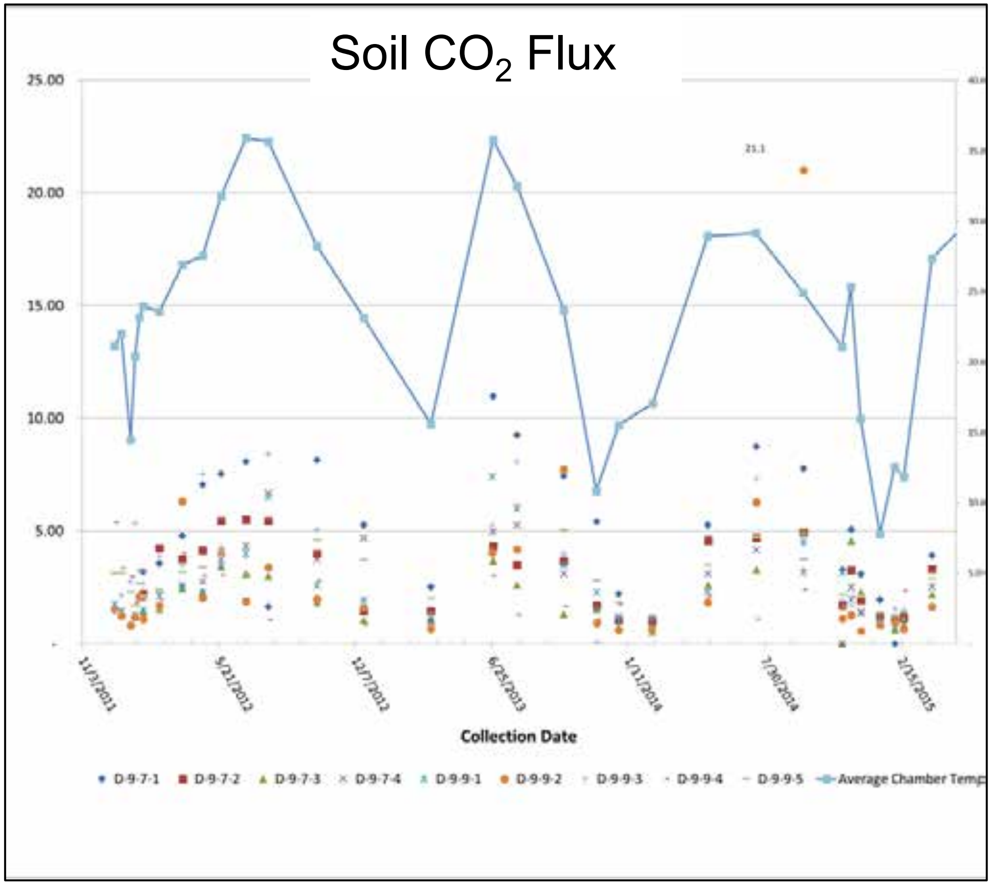
MVA Elements and Frequency

MVA Method	Frequency				
	Continuous	Monthly	Quarterly	Annual	Milestone *(Baseline, Injection, Post)*
Shallow					
Soil flux		■			
Groundwater sampling (USDW)			■		
PFT survey				■	
Deep					
CO2 volume, pressure & composition	■				
Reservoir fluid sampling				■	
Injection, temperature & spinner logs				■	
Pulse neutron logs				■	
Crosswell seismic					■
Vertical seismic profile (VSP)					■
Experimental					
Distributed Temperature Sensing (DTS)		■			
Comparative fluid sampling methods				■	
MBM VSP				■	
Distributed Acoustic Sensing (DAS)				■	
MBM VSP & OVSP Seismic				■	



© 2015 Electric Power Research Institute, Inc. All rights reserved.

CO_2 Containment—Soil CO_2 Flux and Tracer Monitoring



Tracer Results

Well	Innoculation	Jun-13	Nov-13	Mar-15
D-9-1	ND	ND	ND	ND
D-9-2	ND	ND	ND	ND
D-9-3	ND	ND	ND	ND
D-9-6	ND	ND	ND	ND
D-9-7	ND	ND	ND	ND
D-9-8	*Invalid Data*	ND	ND	ND
D-9-9	ND	ND	ND	ND
D-9-9	ND	ND	ND	ND
D-9-10	*Invalid Data*	ND	ND	ND
D-9-11	ND	ND	ND	ND

PRAXAIR

Soil CO_2 results appear to vary as a function of mean temperature and tracer surveys have been non-detect

Advanced Resources International, Inc.
© 2015 Electric Power Research Institute, Inc. All rights reserved.
EPRI ELECTRIC POWER RESEARCH INSTITUTE

Deep Monitoring—Time-Lapse Crosswell Seismic

Schlumberger

- Crosswell seismic surveys allow for high-resolution mapping of the acoustic travel time (velocity) and seismic reflectors between a pair of wells
- When CO_2 displaces water in the formation, it changes the acoustic impedance of the rock
  - Acoustic wave decreases and its direct travel time increases
- Results from "repeat" surveys performed during or after CO_2 injection can be compared to a pre-injection "baseline" survey to image the extent of the CO_2 plume (referred to as "time-lapse imaging")
- Baseline and repeat 2-D crosswell seismic surveys were performed between the injection well and the observation well

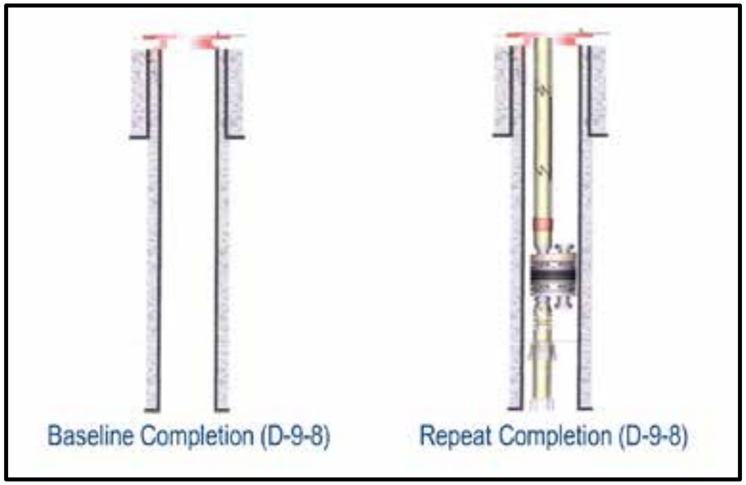
Advanced Resources International, Inc.

© 2015 Electric Power Research Institute, Inc. All rights reserved.

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Crosswell Survey Configuration and Parameters

- Pre-injection baseline survey acquired on January 19-26, 2012
- Repeat survey was acquired on June 14-23, 2014
- Source Type: Piezoelectric – deployed in D-9-7#2 well
- Receiver type: Hydrophone – 10 levels – deployed in D-9-8#2 well
- 842' between D-9-7#2 and D-9-8#2 at reservoir depth



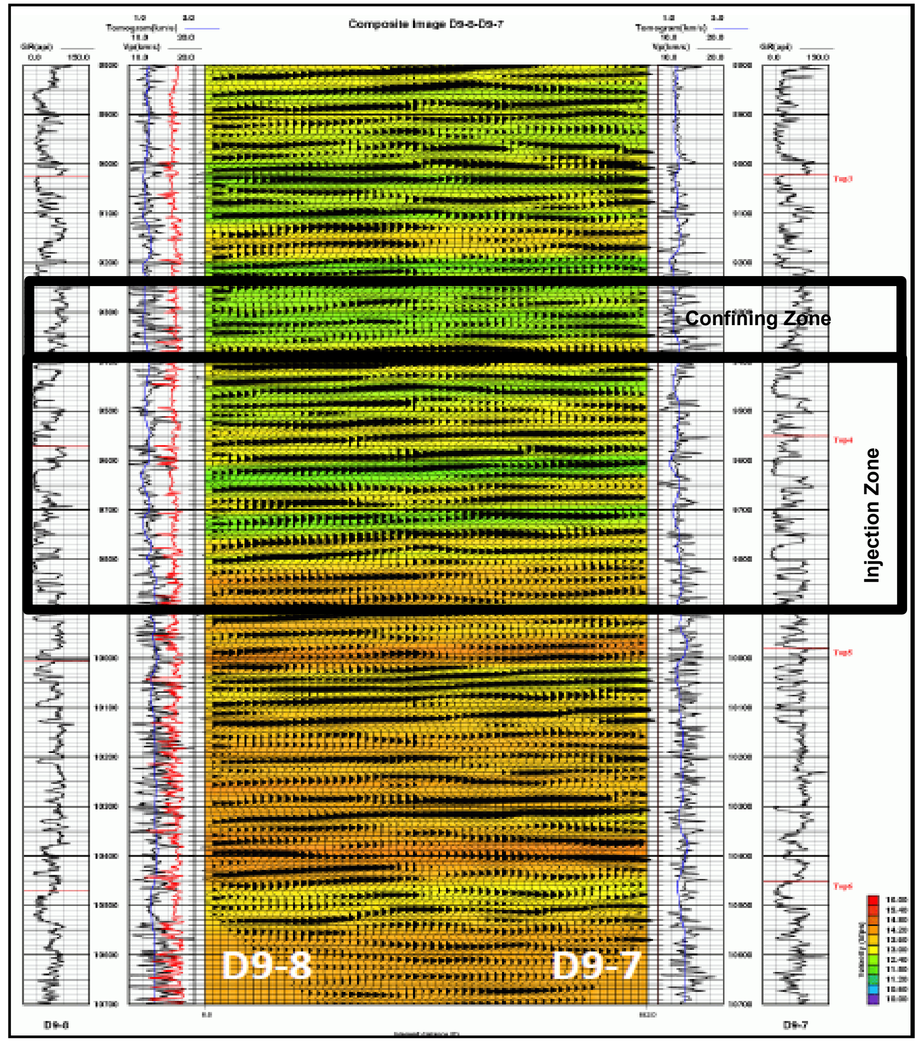
Schematic showing the open well completion in observation well D-9-8 during the baseline survey (left) and packer/tubing completion during the repeat (right)

Receivers were deployed in the open well during the baseline survey and inside the MBM tubing/packer assembly during the repeat survey, thus changing the data acquisition configuration

© 2015 Electric Power Research Institute, Inc. All rights reserved.

Baseline Survey Results

- Velocity tomograph and reflection image (right) provided a good representation of the reservoir and confining unit
  - ~10 feet vertical resolution
- No reservoir or confining unit discontinuities or small-scale faults were observed in the reflection data
- Layering observed in the Upper Paluxy will help disperse the CO_2 plume, thus minimizing its footprint
- Baseline velocity tomogram should be of sufficient quality for time-lapse CO_2 plume imaging



Composite image mapping the seismic reflections (squiggles) superimposed on top of the velocity tomogram (colored background)

© 2015 Electric Power Research Institute, Inc. All rights reserved.

Comparison of Baseline and Repeat Data Quality

- First arrivals and reflection data from the baseline survey have strong amplitudes and little noise, representing good quality data
- The first arrivals for the repeat survey are fairly "weak" probably due to signal attenuation caused by deploying the hydrophones inside the "stiff" production tubing and packer
- The reflection data that follow the first arrivals are noisy and of poor quality for the repeat survey

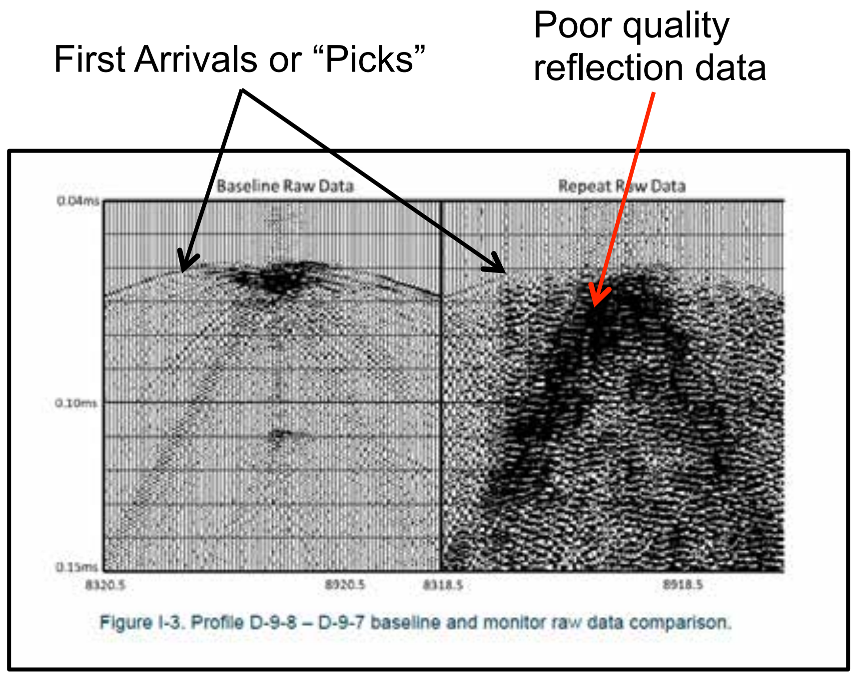


Figure I-3. Profile D-9-8 – D-9-7 baseline and monitor raw data comparison.

Side-by-side comparison of a baseline (left) and repeat (right) shot gather

There is a noticeable decrease in the signal-to-noise ratio (SNR) between the baseline and repeat surveys, which limits data interpretation

© 2015 Electric Power Research Institute, Inc. All rights reserved.

Comparison of Crosswell Reflectors

Baseline Tomogram

Strong, continuous reflectors

Repeat Tomogram

Weak and/or discontinuous reflectors

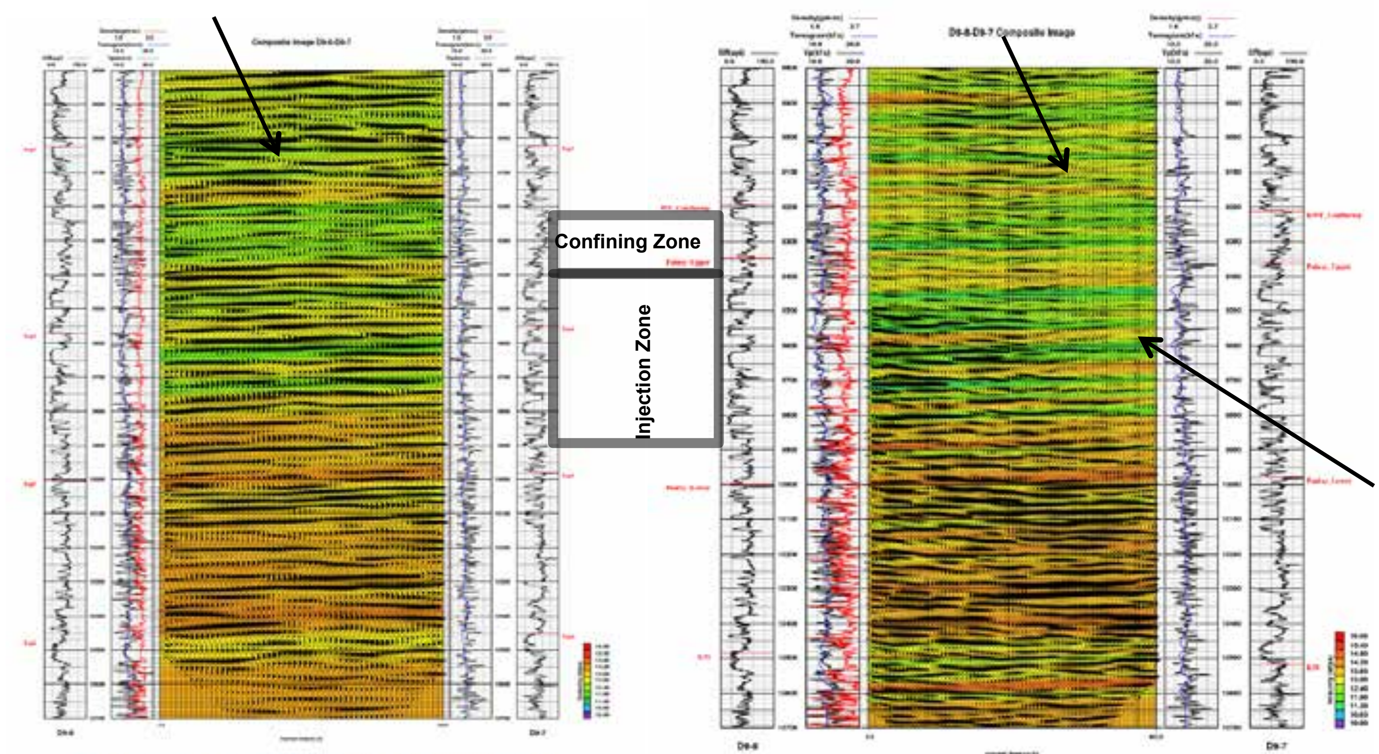


Figure I-4. Profile D-9-8 – D-9-7 baseline composite image

Figure I-5. Profile D-9-8 – D-9-7 monitor composite image

No reflector was detected at or near the top of the CO_2 where one should be present

Reflection data from the repeat survey are of poor quality and limited use. Likely cause is interference by tube waves moving up and down the well

Advanced Resources International, Inc.

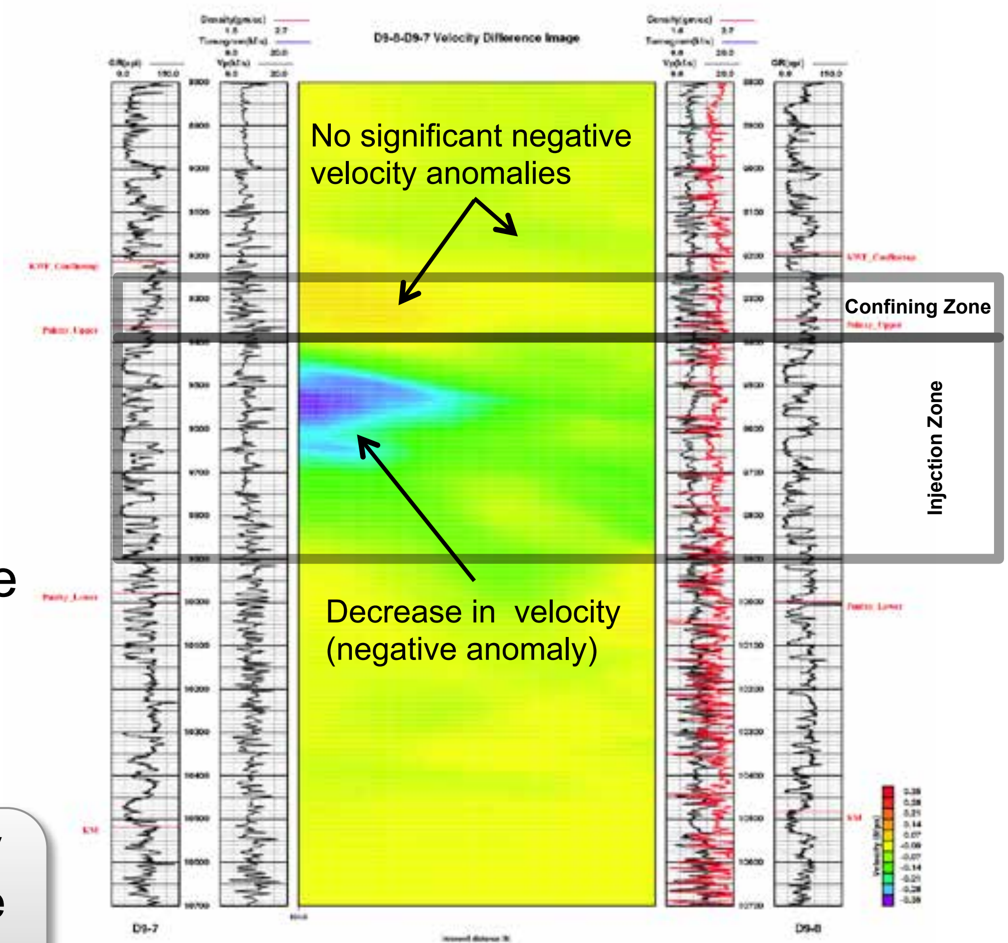
© 2015 Electric Power Research Institute, Inc. All rights reserved.

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Time-Lapse Differencing Using the Baseline and Repeat Velocity Tomograms

- First arrivals from repeat survey were of sufficient quality to produce a velocity difference image (right) showing regions where seismic velocity has changed over time
- Time-lapse difference image indicates a decrease in seismic velocity in the upper injection zone of up to 3%, suggesting an increase in CO_2 saturation

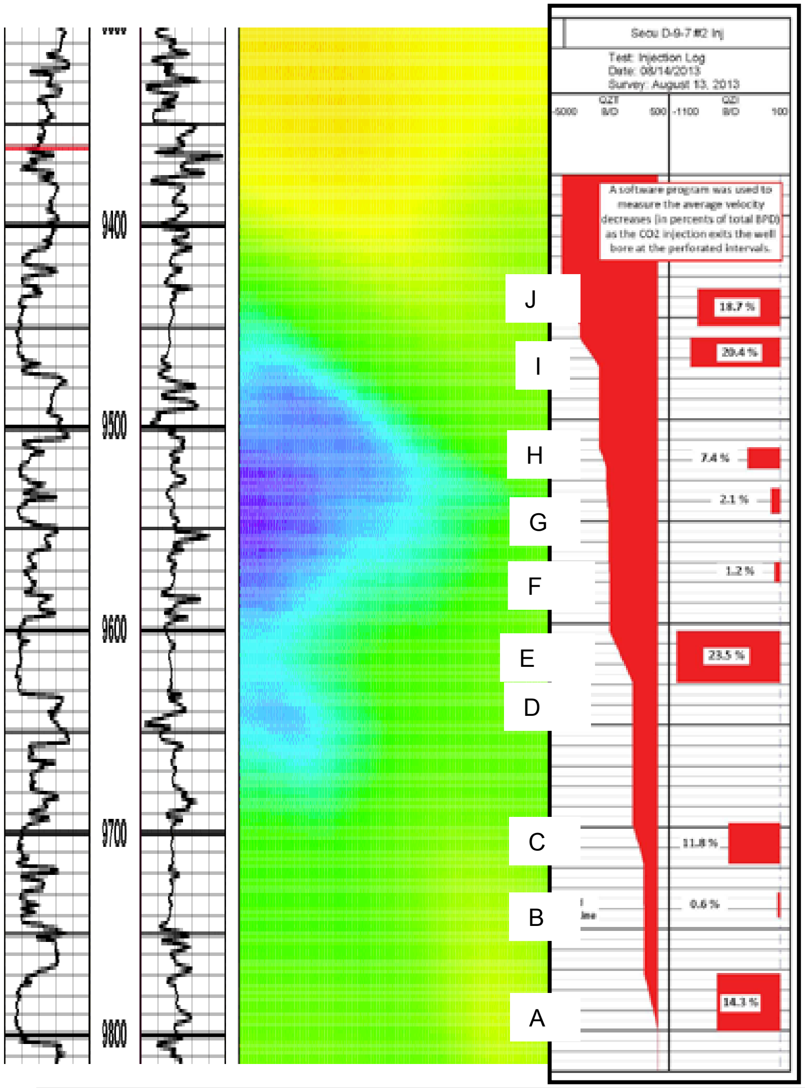
More importantly, no negative velocity anomalies are observed in or above the confining unit…implying no detectable leakage out of inj. zone



Pixelized difference tomography results without seismic reflection overlay showing positive velocity differences in warm colors and negative differences in cool colors

© 2015 Electric Power Research Institute, Inc. All rights reserved.

Plume Image Comparison with Spinner Surveys

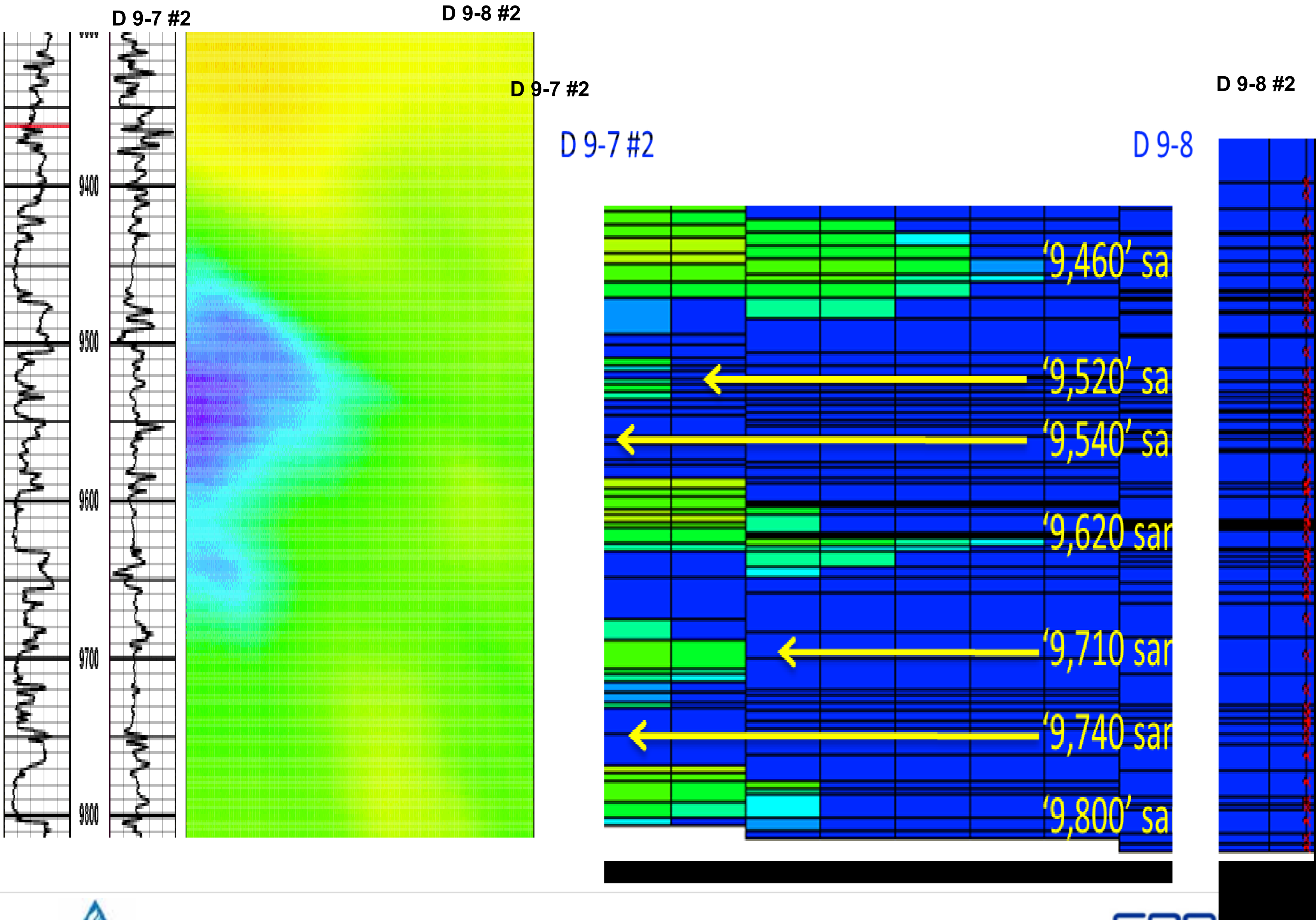


- Time-lapse image shows CO_2 plume located primarily in Paluxy sands F-H
- October 2013 spinner survey show these sands taking only 10% of the flow

Sand	Sand Unit Properties (ft)			Nov 2012	Aug 2013	Oct 2013
Unit	Bottom	Top	Thickness	Flow %	Flow %	Flow %
J	9,454	9,436	18	14.8	18.7	16.7
I	9,474	9,460	14	8.2	20.4	19.6
H	9,524	9,514	10	2.8	7.4	7.7
G	9,546	9,534	12	2.7	2.1	0.9
F	9,580	9,570	10	0.0	1.2	1.2
E	9,622	9,604	18	26.8	23.5	30.8
D	9,629	9,627	2	0.0	0.0	0.0
C	9,718	9,698	20	16.5	11.8	10.3
B	9,744	9,732	12	4.9	0.6	0.4
A	9,800	9,772	28	23.3	14.3	12.4

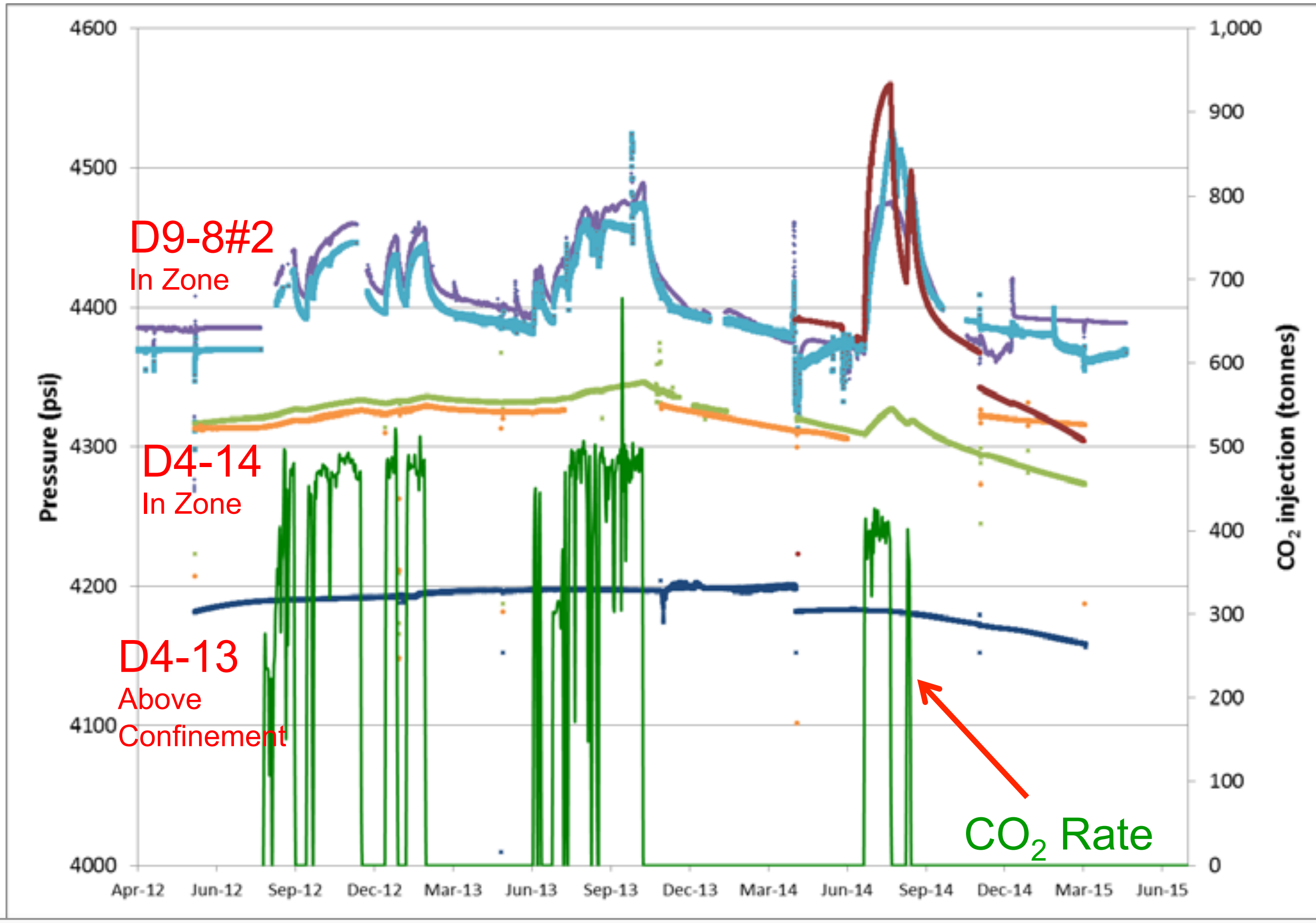
© 2015 Electric Power Research Institute, Inc. All rights reserved.

Plume Image Comparison with Simulation



Advanced Resources International, Inc.
© 2015 Electric Power Research Institute, Inc. All rights reserved.
EPRI RESEARCH INSTITUTE

Deep MVA – Pressure Response



Downhole pressure data is a primary input to the history match and plume model

© 2015 Electric Power Research Institute, Inc. All rights reserved.

Plan Next Steps

- Continue to use multiple lines of evidence to demonstrate CO_2 containment and non-endangerment during PISC
  - Continue shallow subsurface and surface monitoring activities
  - Conduct full VSP and crosswell seismic repeats
  - Additional water injection tests to monitor pressure transient times
- Engage regulators throughout project closure process
- Permit closure

Advanced Resources International, Inc.
© 2015 Electric Power Research Institute, Inc. All rights reserved.
ELECTRIC POWER RESEARCH INSTITUTE

Southeast Regional Carbon Sequestration Partnership

QUESTIONS

SECARB

NETL

SOUTHERN STATES ENERGY BOARD

Carbon Storage R&D Project Review Meeting
Pittsburgh, PA
August 18, 2015

THE UNIVERSITY OF TEXAS AT AUSTIN

WHAT STARTS HERE CHANGES THE WORLD

SECARB Early Test Retrospective

Susan Hovorka, Ramón Treviño, Tip Meckel,
Jacob Anderson, Seyyed Hosseini, Jiemin Lu, JP Nicot,
Katherine Romanak, Changbing Yang, Vanessa Nuñez-Lopez

BUREAU OF ECONOMIC GEOLOGY

TEXAS Geosciences
The University of Texas at Austin
Jackson School of Geosciences

GCCC GULF COAST CARBON CENTER

Early Test Research team

NETL

SECARB
Southeast Regional Carbon Sequestration Partnership

Southern States Energy Board

SECARB Anthropogenic
Test At Plant
Barry/Citronelle

Gulf Coast Carbon Center
Bureau of Economic Geology
Jackson School of Geosciences
The University of Texas at Austin

Core Lab
UT DoG
Anchor QEA

Environmental
Information Volumes
Walden Consulting

Vendors
e.g. equipment

Denbury Resources
Field owner and
injection system
design,
management, 4-D
survey, HS&E

Vendors
e.g. local landman

Sandia Technologies
Monitoring Systems
Design, Installation,
HS&E

50 Vendors
e.g. Schlumberger

MSU UMiss
Hydro & hydrochem

Federal collaborators
Via FWP

LBNL
Well-based geophysics,
U-tube and lab design
and fabrication

LLNL
ERT

USGS
Geochemistry

Curtin University, Perth

Separately funded

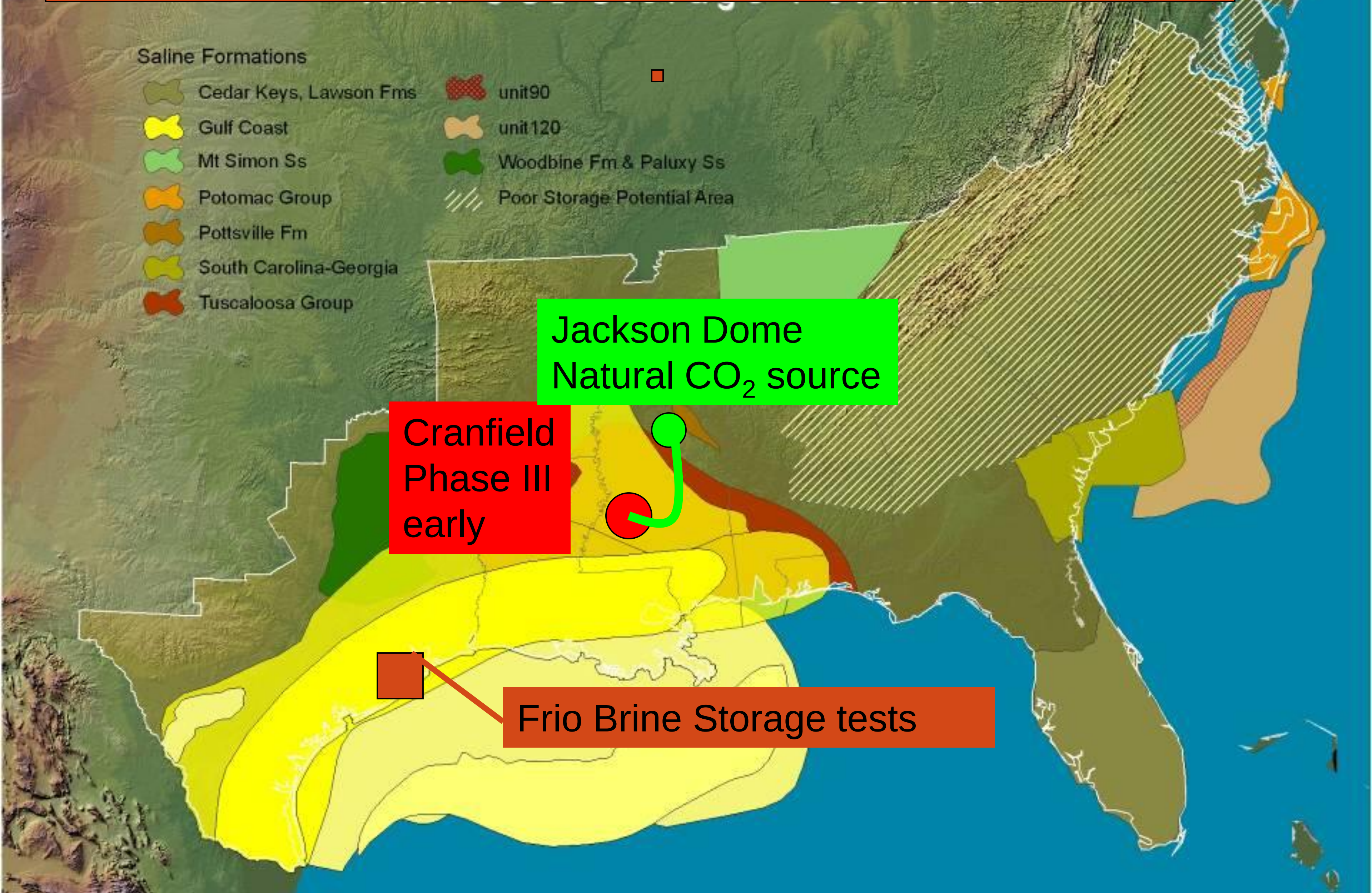
ORNL
PFT, Stable isotopes

NRAP
VSP&
analysis

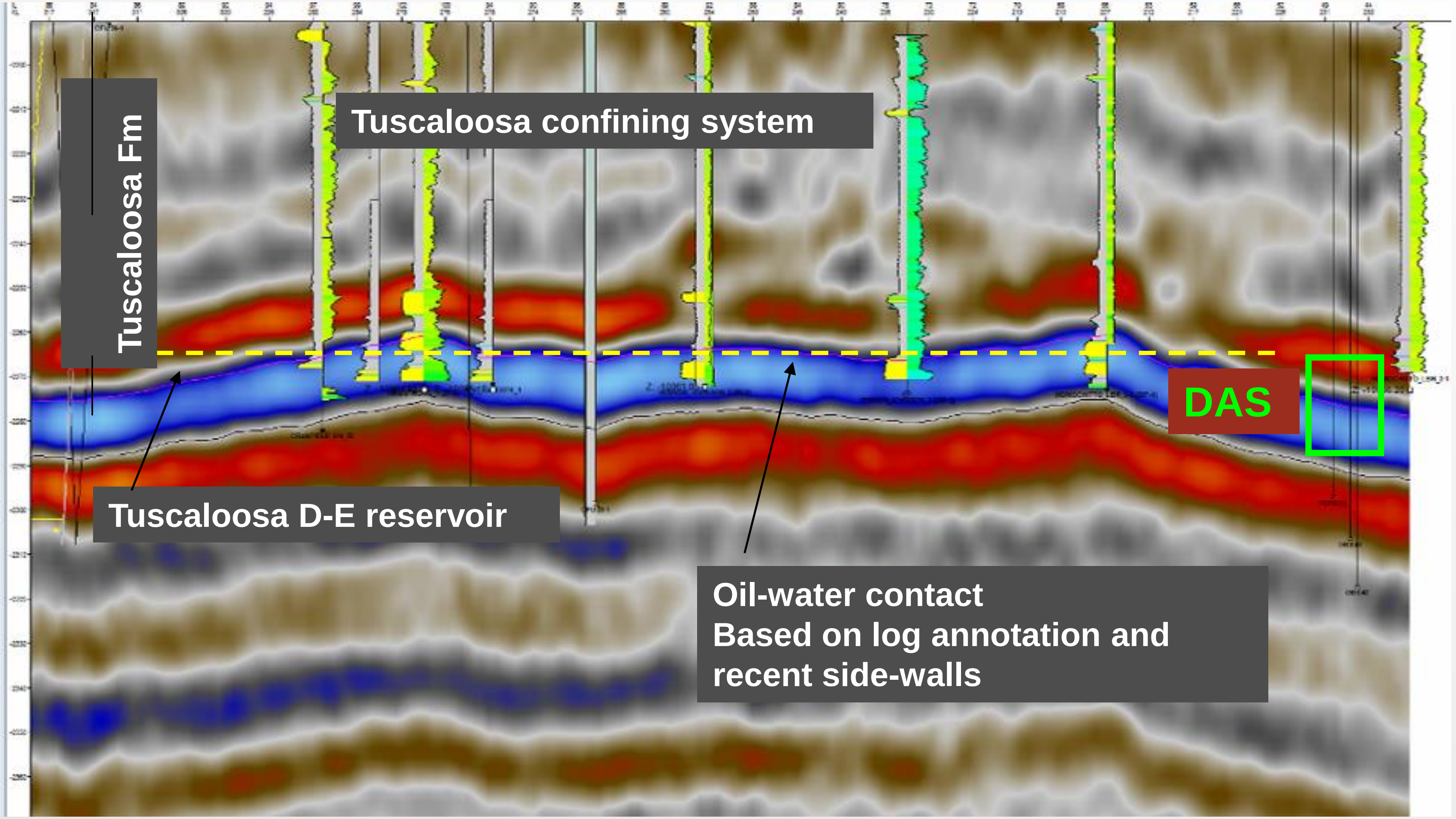
NETL
Rock-water interaction

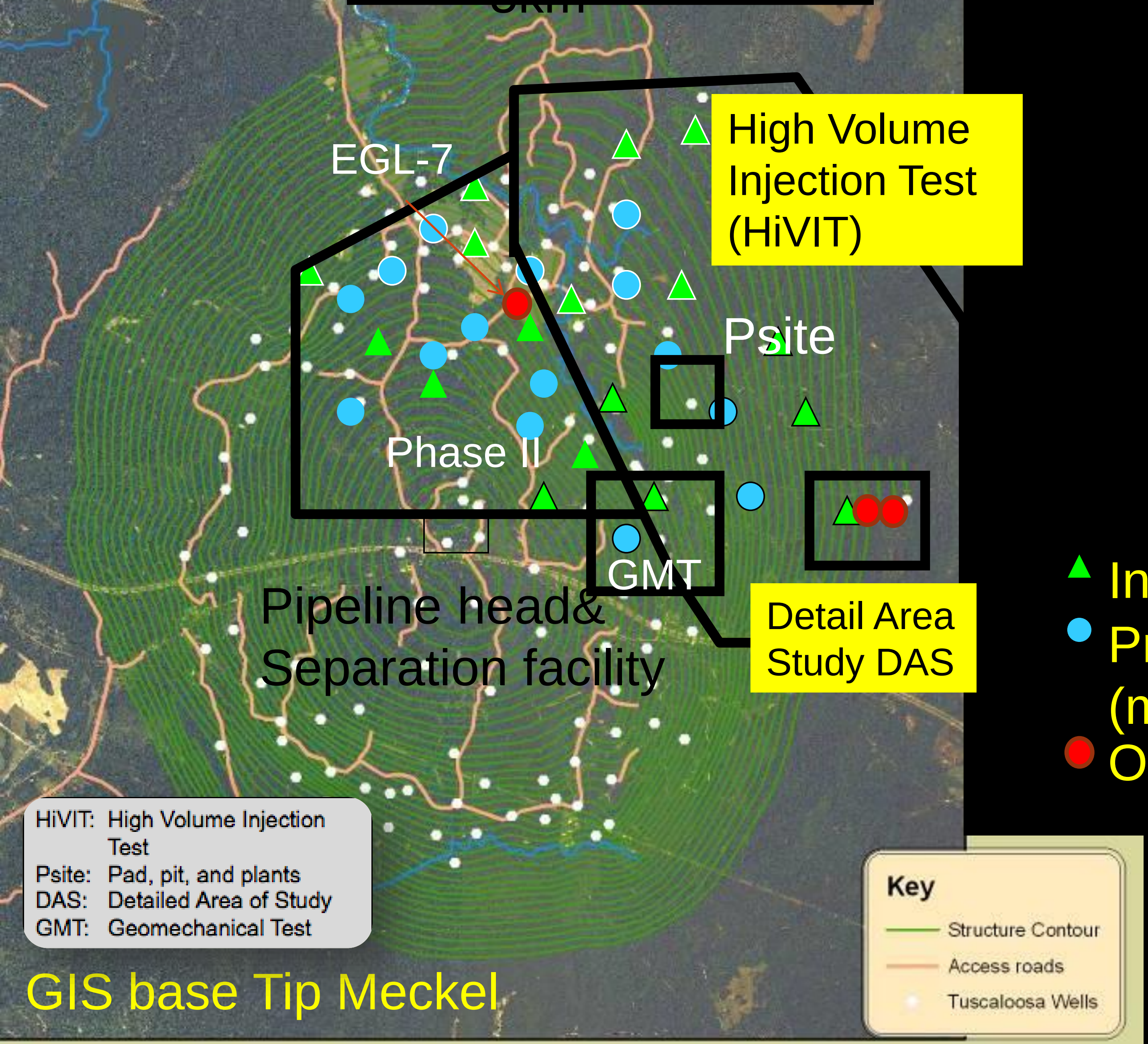
Stanford, Princeton, U Edinburgh, UT
PGE & ICES (CFSES), U. Tennessee, USGS
RITE, BP, CCP, Durham, AWWA

SECARB Test Site Location



Cranfield: geological location





- Injector
- Producer (monitoring point)
- Observation Well

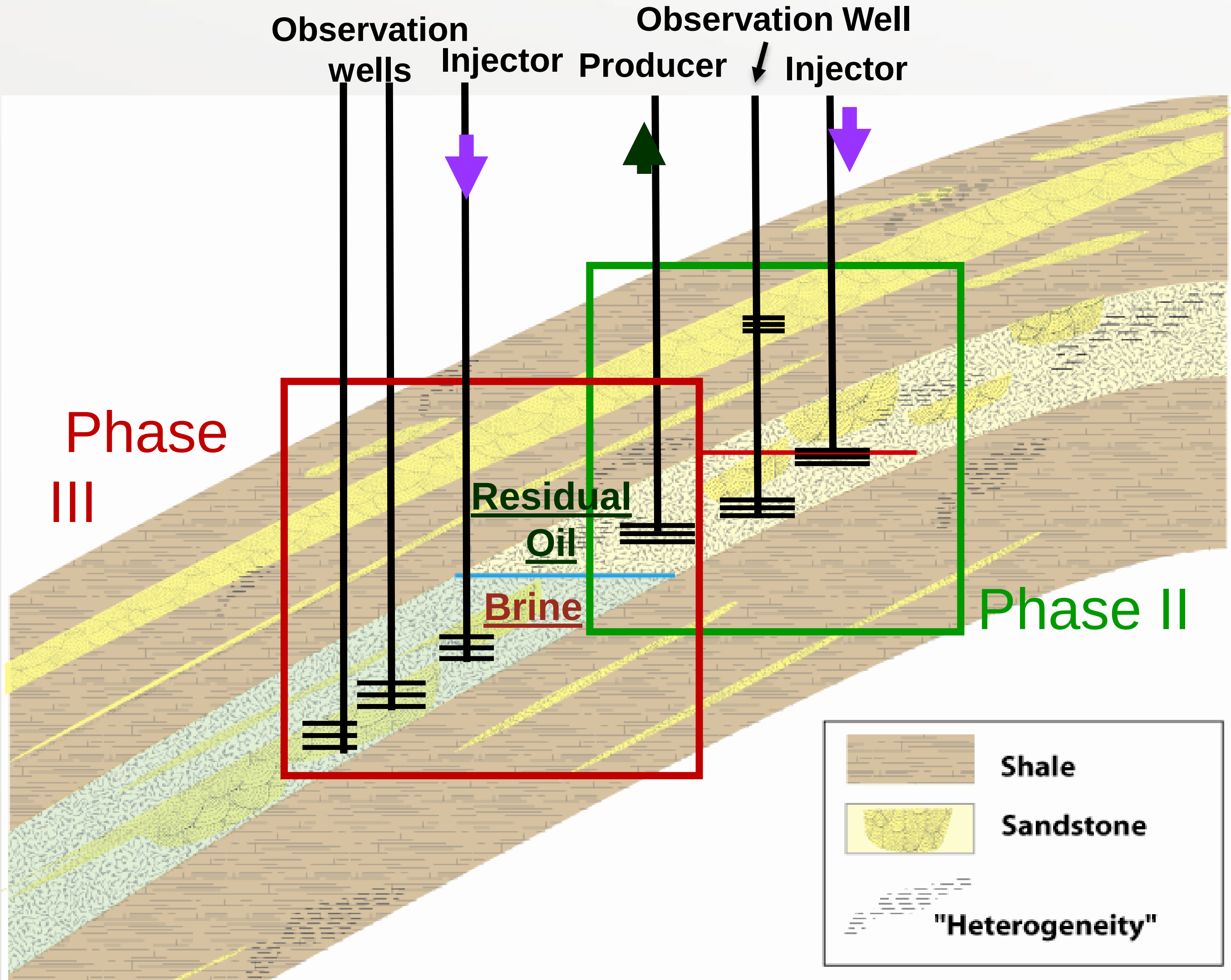
Bureau of Economic Geology

Gulf Coast Carbon Center

Overview

- > 1 Million metric tonne / yr injection
- Quick start up = "Early test" (bridge between pilot scale and SECARB's Plant Barry/Citronelle anthropogenic test)
- Of possible sites, Denbury's Cranfield field scheduled for 2008 CO_2 injection start was favorable:
  - Time to collect pre-injection data before injection
  - Build quickly to >1 MMT per year CO_2 injection rate (sufficient to assure project metrics were met & *exceeded*)
  - Experienced operator in CO_2 EOR – low risk of permitting delay: ***early results for RCSP program***
  - Field abandoned (40 years); pressure recovered and equilibrated

Favorable Characteristics of Cranfield for SECARB Early test



- Follow-on between Phase II and Phase III
- Phase III planned in water leg downdip of oil zone
- Provided RCSP experience with CO_2 EOR, (grew in importance)

Less than-ideal characteristics

- CO_2 from Jackson Dome (not anthropogenic)
- Field commercial EOR
  - operational aspects not under project's control
  - some data proprietary
- Research purpose only
  - Designed prior to EPA or international regulations
- Relatively complex geology both deep & near surface
- Modeling reservoir's injection response complicated
  - by oil presence
  - injection and withdrawal complexities – ***managed…***

Simplified by:

Focus on the DAS - ***brine only***

Early timing - ***production & recycle was minimal***

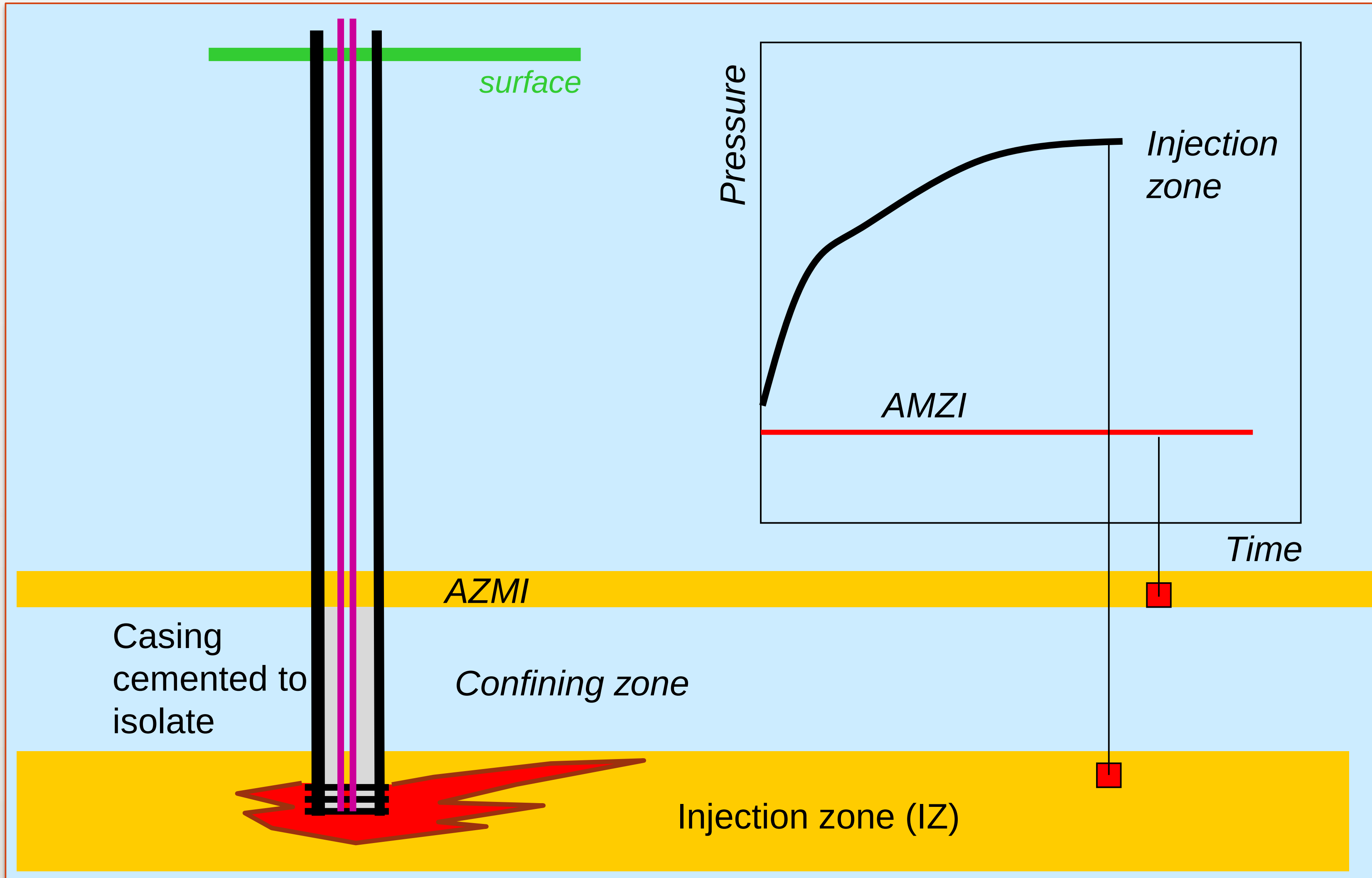
Developing the Experiment

- Year-long series of meetings (2007-2008)
  - designed plan
- Aligned general research objectives
  - well locations
  - selected team members
  - budget
- Designed detailed plans - major components
- Adapted to fast EOR field development
  - NEPA permitting (slow)
  - other timeline issues
    - equipment rental
    - procurement
    - cash flow (2009 “cash call”)

Project objectives

- Connect CO_2 plume development with pressure response
  - in far-field of reservoir ("in-zone")
- **A**bove-**Z**one **M**onitoring **I**nterval (**AZMI**) pressure response
  - first time in CCS
- Advance understanding of geomechanical response (deformation, microseismic)
- Advance understanding of
  - risk to groundwater / value of groundwater as a monitoring approach
  - soil gas methods as a monitoring approach

AZMI

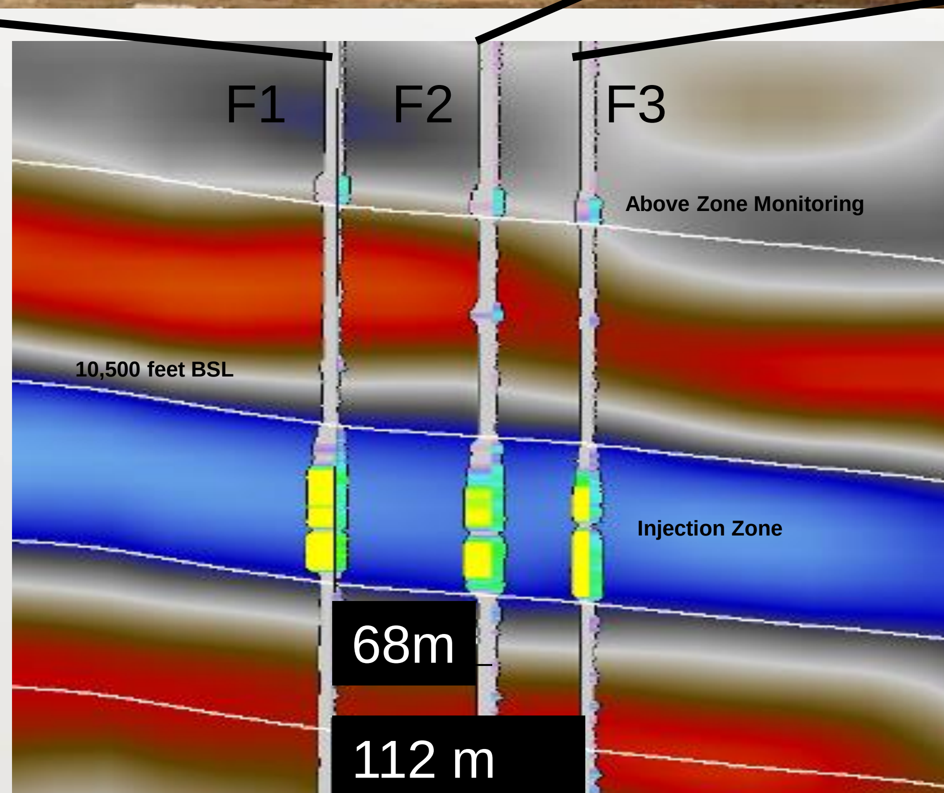

surface
Pressure
Injection zone
AMZI
Time
AZMI
Casing cemented to isolate
Confining zone
Injection zone (IZ)

Team contributions (2)

- LLNL
  - Multiphase geophysics
  - Cross-well EM fielding and interpretation
- USGS
  - reservoir fluid sampling & analyses
- Schlumberger Carbon Services
  - well logging
  - Cross well Seismic
  - AZMI fluid collection
- LBNL / NRAP
  - U-tube,
  - 3-D VSP
  - downhole fiber optic CASSM
- Oak Ridge NL
  - PFT and sampling
- University Edinburgh
  - Noble gasses
- Local landowners
  - access
- Walden Consulting
  - NEPA

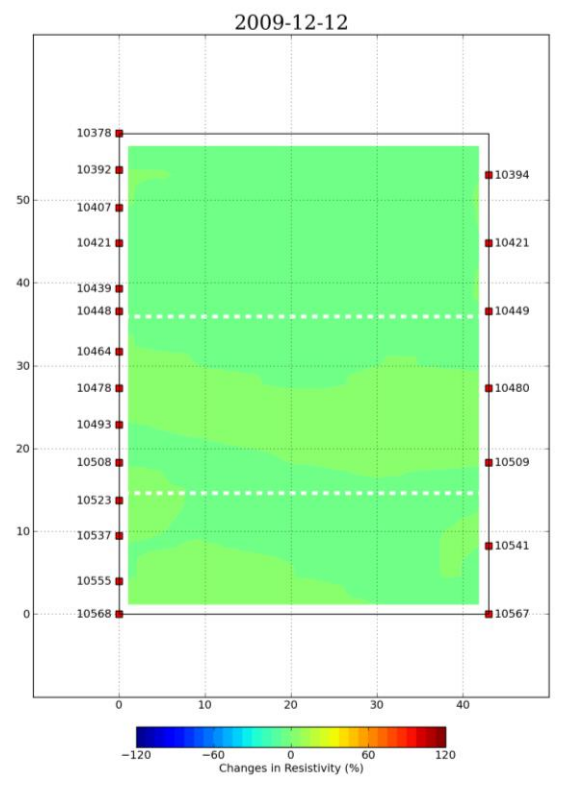
DAS Monitoring Site

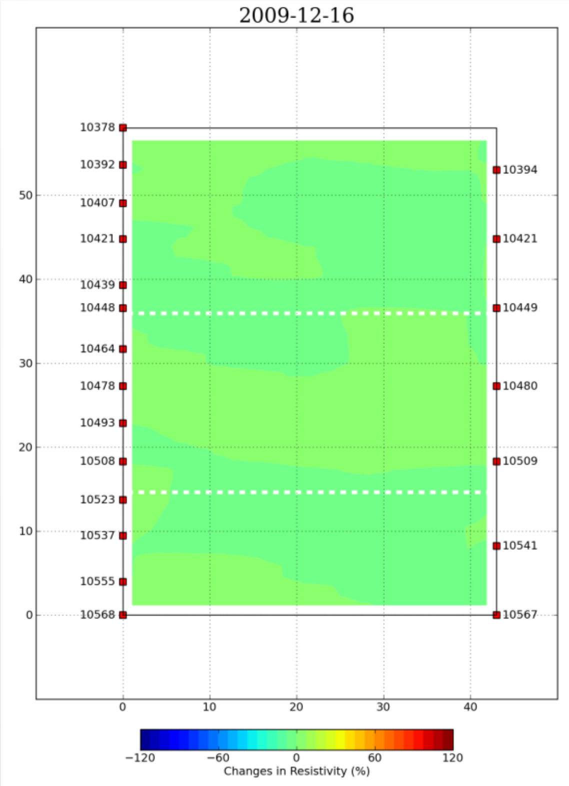
Closely spaced well array to examine flow in complex reservoir

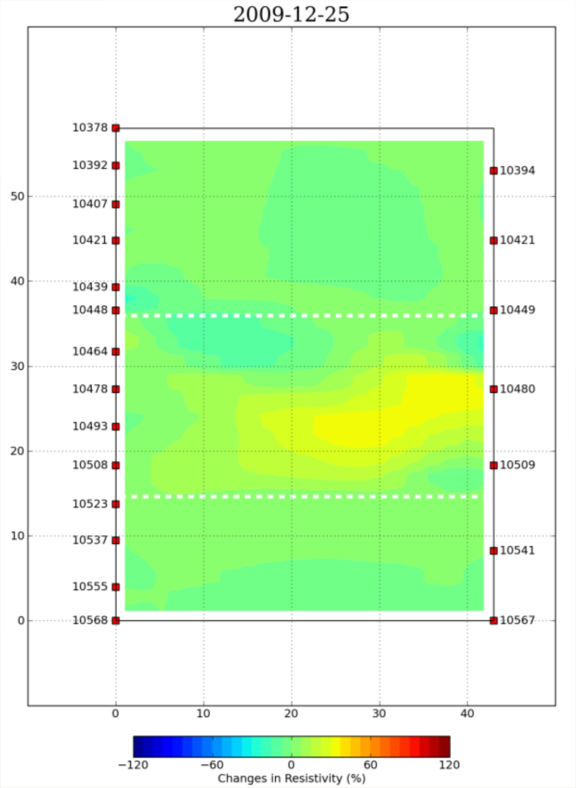


Petrel model Tip Meckel

Time Lapse Resistivity Changes



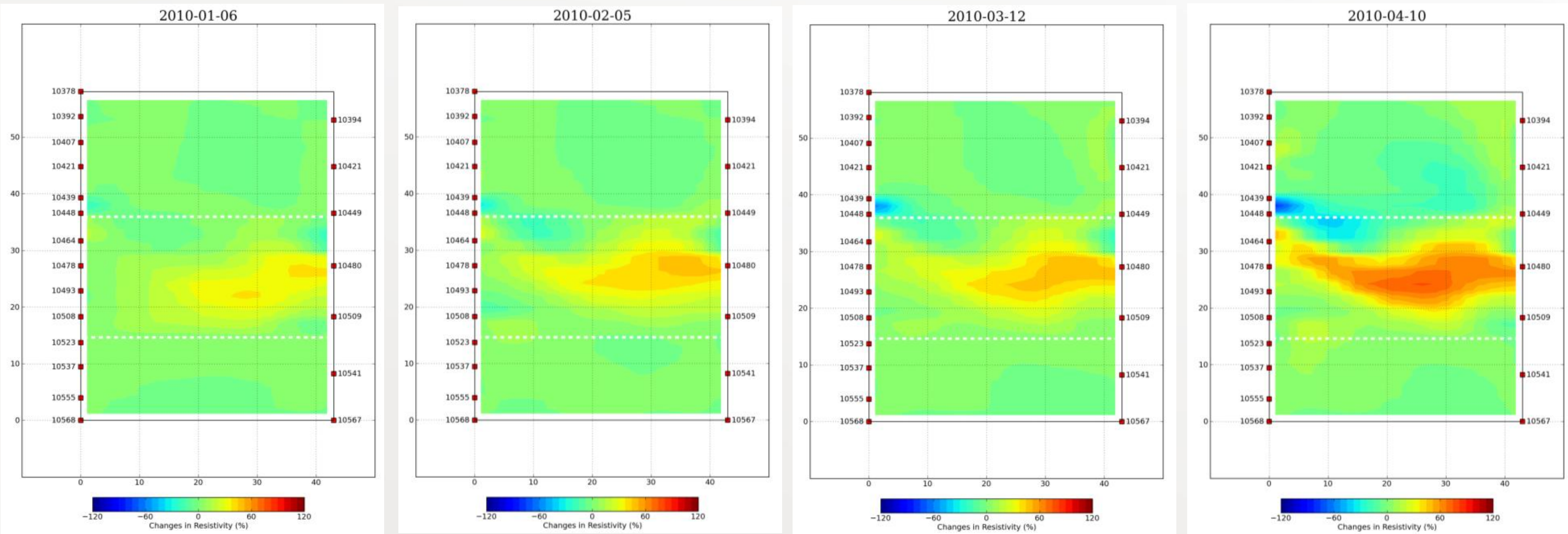




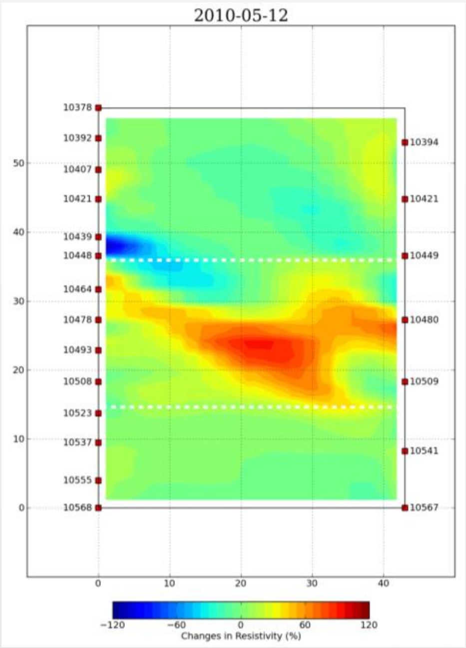
Initial CO_2 Breakthrough in F2

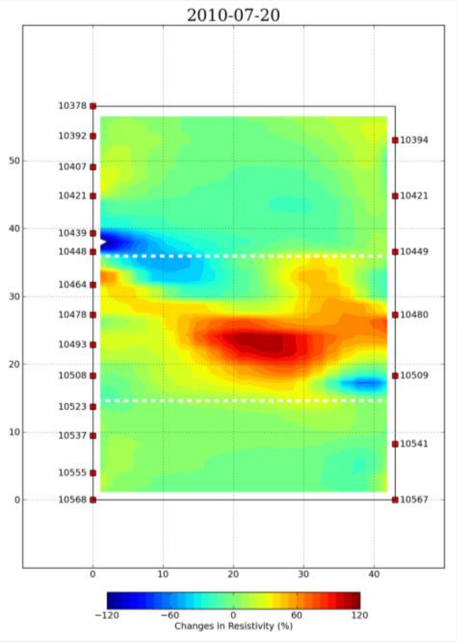
Initial CO_2 Breakthrough in F3

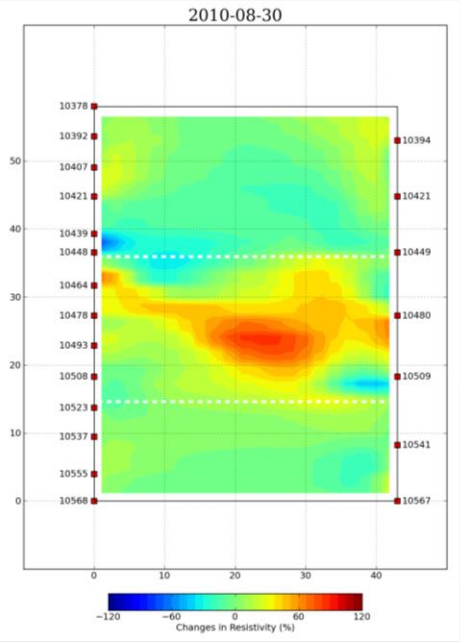
Time Lapse Resistivity Changes

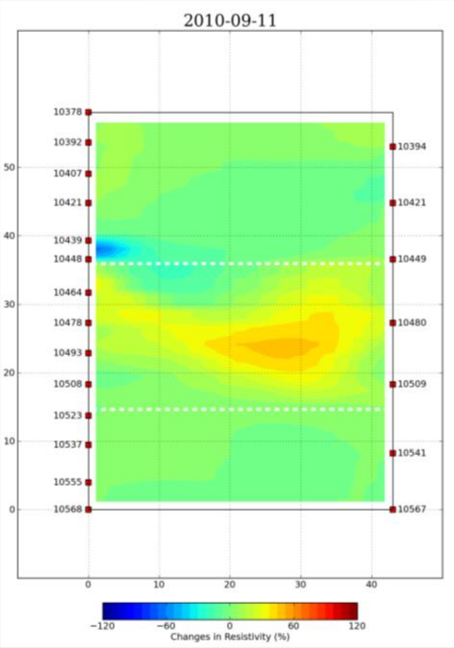


Time Lapse Resistivity Changes









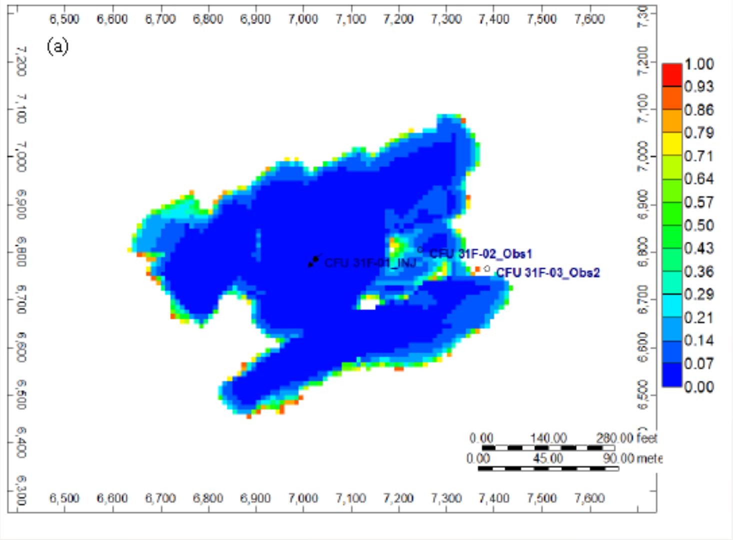
After Work-over in 9/2010

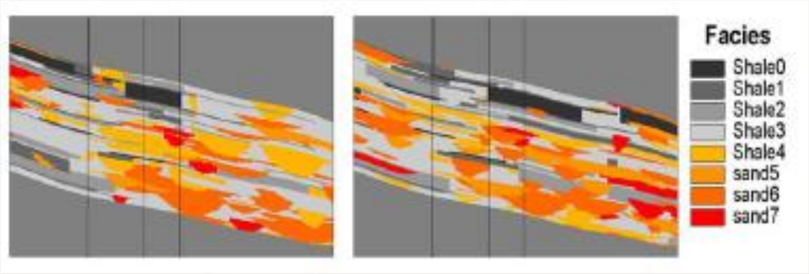
Contributions: Support Collaborators

- CFSES
  - rock samples for geomechanics
- NRAP
  - field site for 3D-VSP
- SIM SEQ
  - comparative modeling data set
- NETL
  - CO_2 EOR model data

Accomplishments

- Monitored CO_2 injection 2008 – 2015
- Injection through 23 wells, cumulative volume over 8 million metric tons
- First US test of ERT for GS (deepest)
- Time lapse plume imaging with cross well seismic, VSP, RST, & surface 3-D seismic
- RITE microseismic – none detected
- Groundwater sensitivity assessment (push-pull)
- Recognized by Carbon Sequestration Leadership Forum (CSLF) in 2010 for research contributions
- SIM-Seq inter-partnership model development test
- Knowledge sharing to Anthropogenic Test and other U.S./International CCS projects





GULF COAST CARBON CENTER

"Early Test's" Major Contributions

- Large volume injection bridged RCSP to current & future anthropogenic sources
- Value of AZMI pressure monitoring in demonstrating reservoir fluid retention
- Probabilistic monitoring helps history-match fluid response to injection in a complex reservoir
- Process-based soil gas method developed and demonstrated for the first time
- Demonstrated utility and site-specific limitations of groundwater monitoring

Ongoing (1)

- **Model additional scenarios incorporating uncertainties**
- Forward-model seismic response
- Compare Cranfield ERT to Ketzin
- Evaluate ERT for long-term viability (distinguish noise from signal)
- Determine time-dependent capacity through modeling
- Participate in ISO 265
- **Further optimize process-based soil-gas method**
- Further optimize groundwater uncertainties

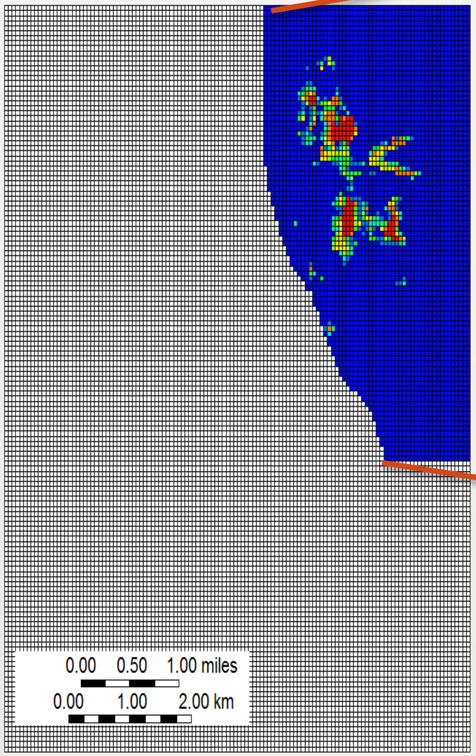
Ongoing (2)

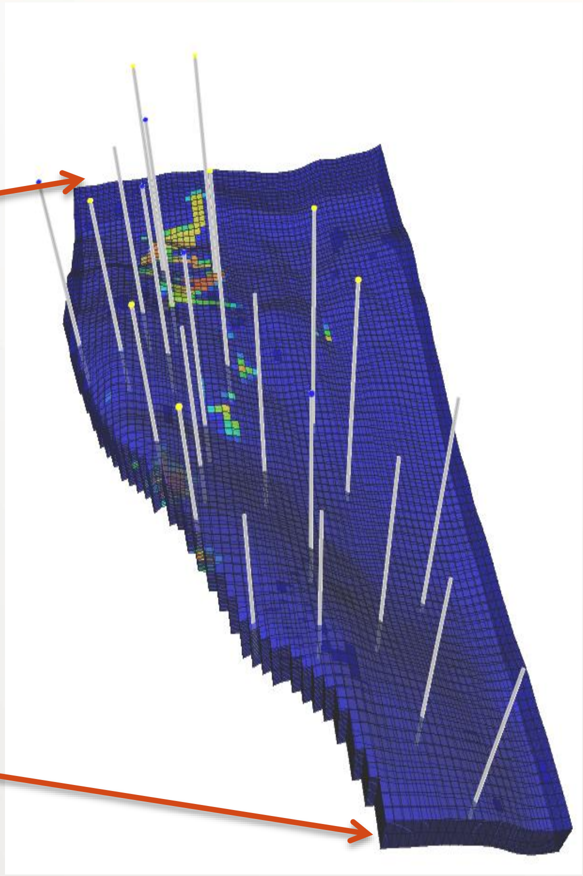
- Technology transfer
  - Deployment of monitoring strategies developed at SECARB "Early" test as well as other RCSP and international CCUS sites
  - Support for maturation of monitoring for EOR as well as saline sites through international standards, best practices, critical reviews

THE UNIVERSITY OF TEXAS AT AUSTIN

WHAT STARTS HERE CHANGES THE WORLD

Cranfield NE section model





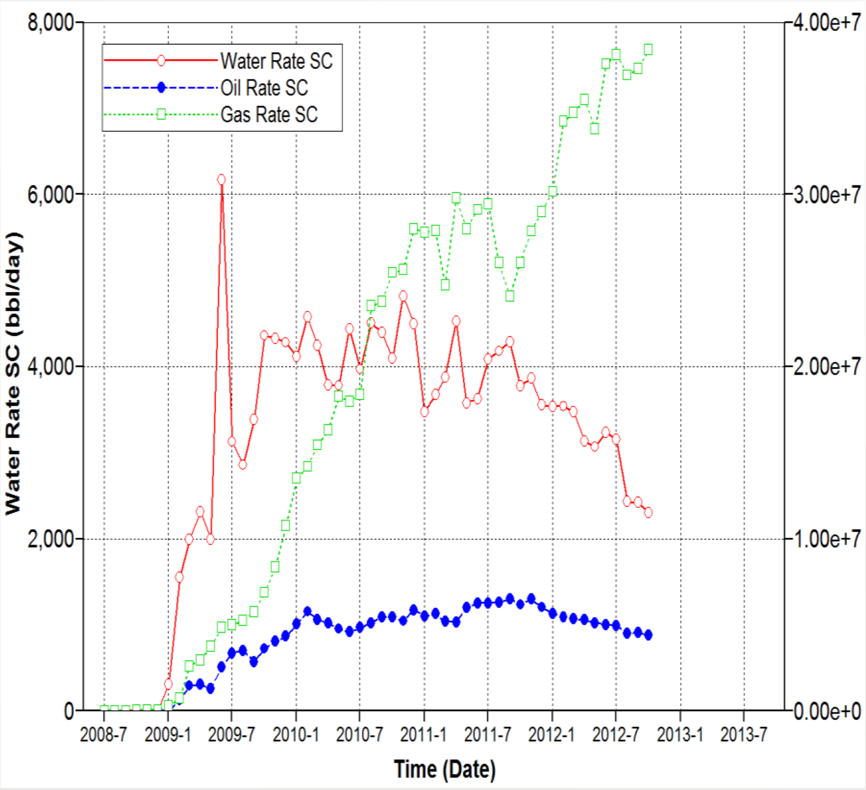
- Compositional simulation
- Total number of block = 82,500

- **CO_2 distribution:**
  - Super critical phase: **?%**
  - Dissolved in oil: **?%**
  - Dissolved in brine: **?%**

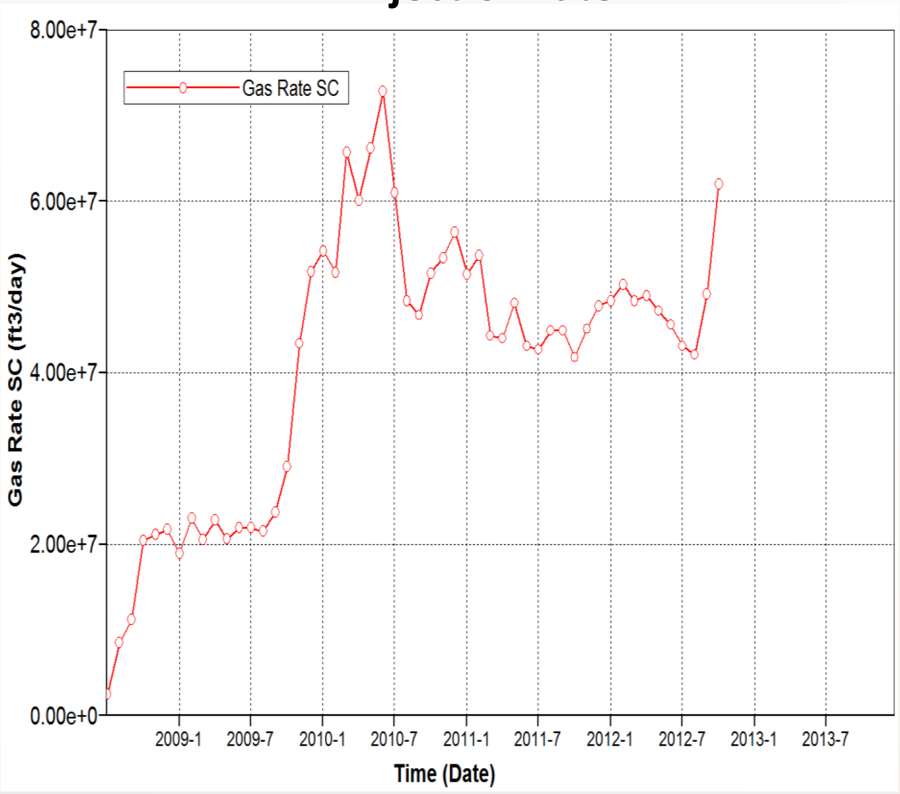
GCCC GULF COAST CARBON CENTER

Injection-Production data

Production rate



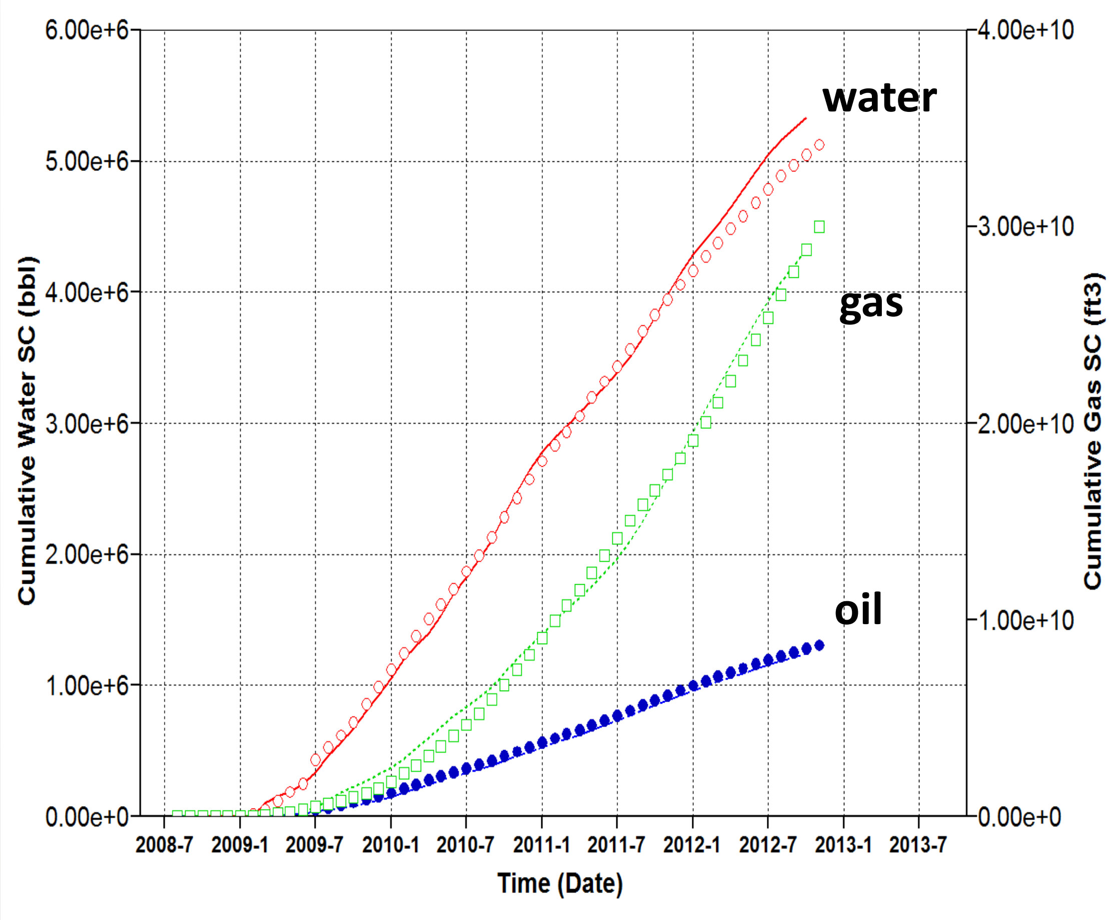
Injection rate



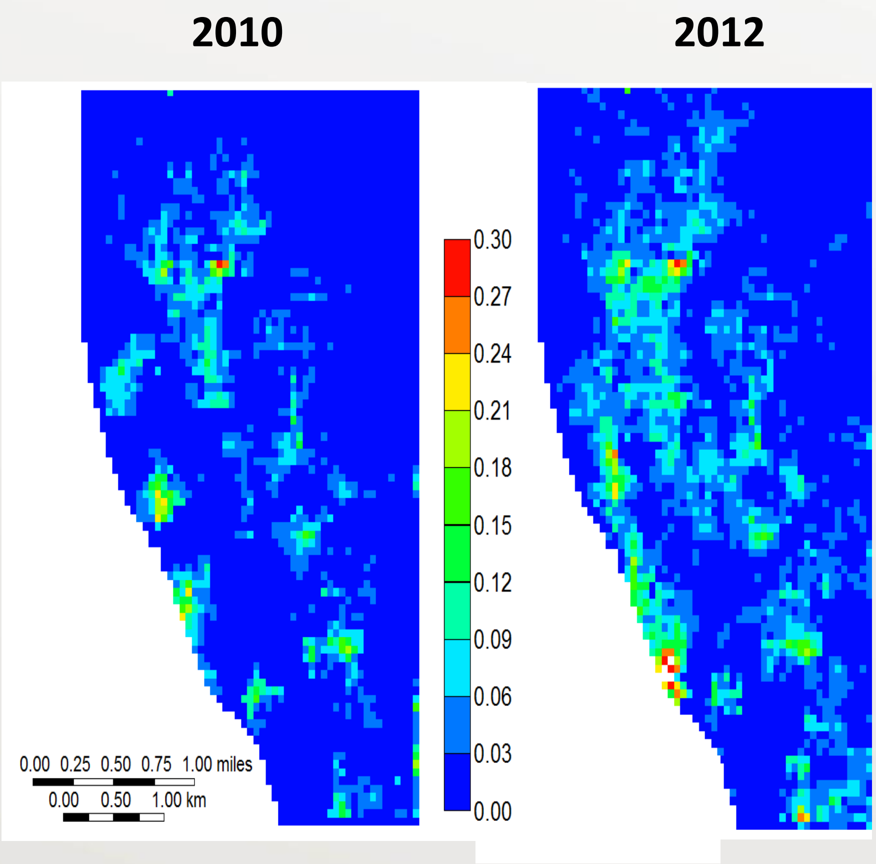
- **Available injection/production data:**
  - **Oil, gas, and water production rates**
  - **CO_2 injection rate**

- **Well constraints:**
  - **CO_2 injection rate, Oil production rate**
- **History match :**
  - **Gas and water production rates, breakthrough times**

History matching



Results and future plans



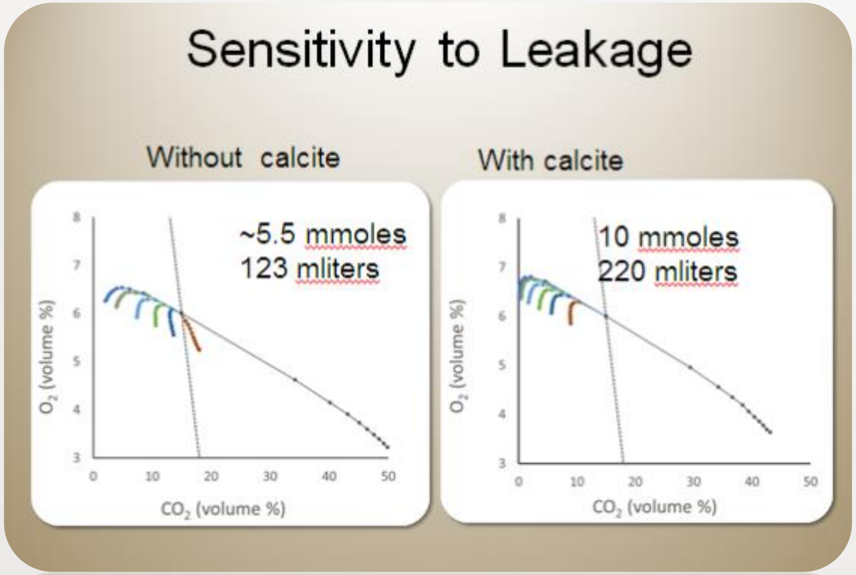
- **CO_2 distribution (2012):**
  - Super critical phase: **<u>56%</u>**
  - Dissolved in oil: **<u>26%</u>**
  - Dissolved in brine: **<u>18%</u>**
- **Running extended simulations and scenarios**
- **Compare with 4D seismic**

THE UNIVERSITY OF TEXAS AT AUSTIN

WHAT STARTS HERE CHANGES THE WORLD

Optimizing and Upscaling Process-Based Monitoring Technology

Understanding Complex Environments

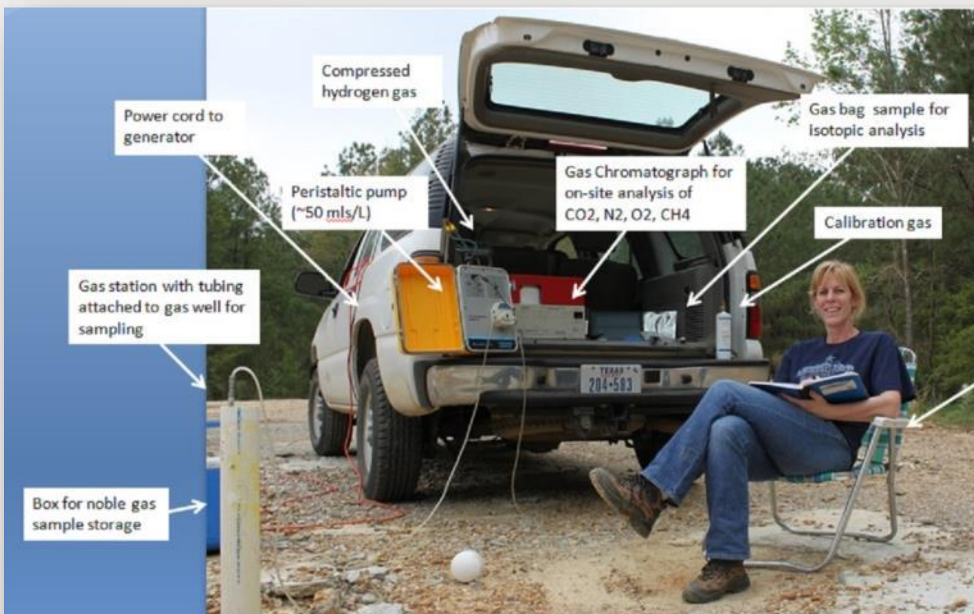


Testing and Developing Sensing Capabilities

- Continuous
- Real-time
- Smart

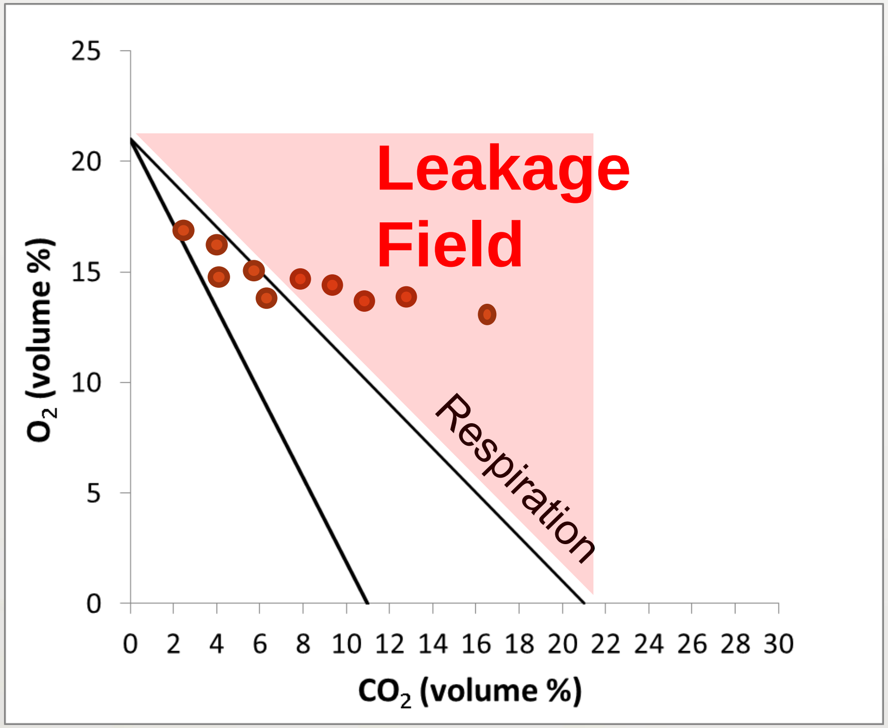
Current Method Shortfalls

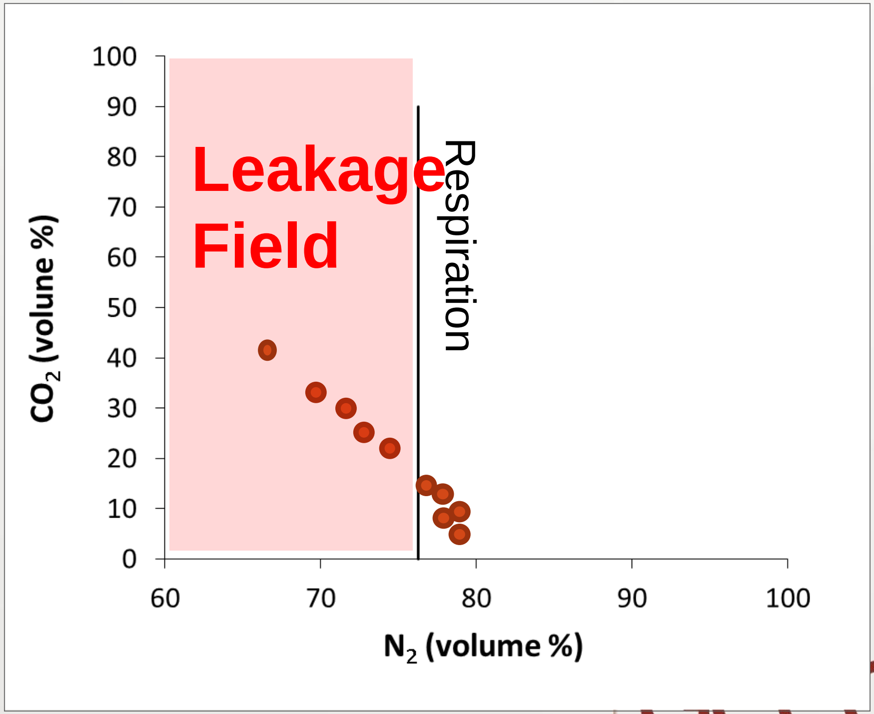
- Requires a manned gas chromatograph (GC)
- Time- and labor-intensive
- Requires consumable supplies
- No continuous real-time data



"User-Friendly" for Public Engagement

- Instant data reduction
- Reduces risk of false positives.
- Graphical analysis
- Continuous monitoring capability will give instant real-time leakage detection information.





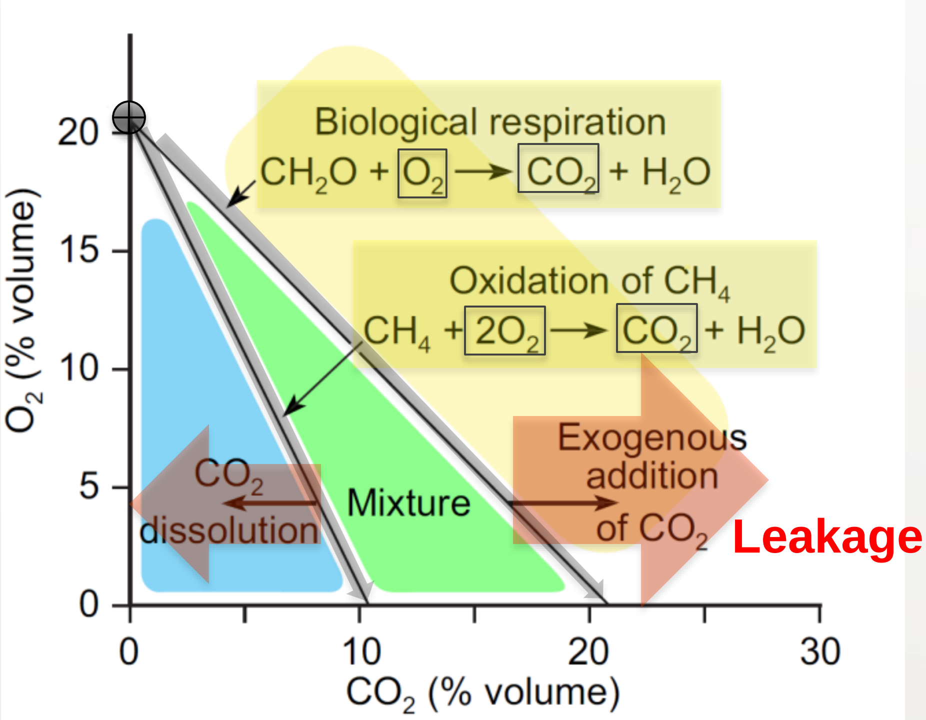
Katherine Romanak BEG

Extra Slides

Process-Based Gas Ratio - 1

O_2 vs. CO_2

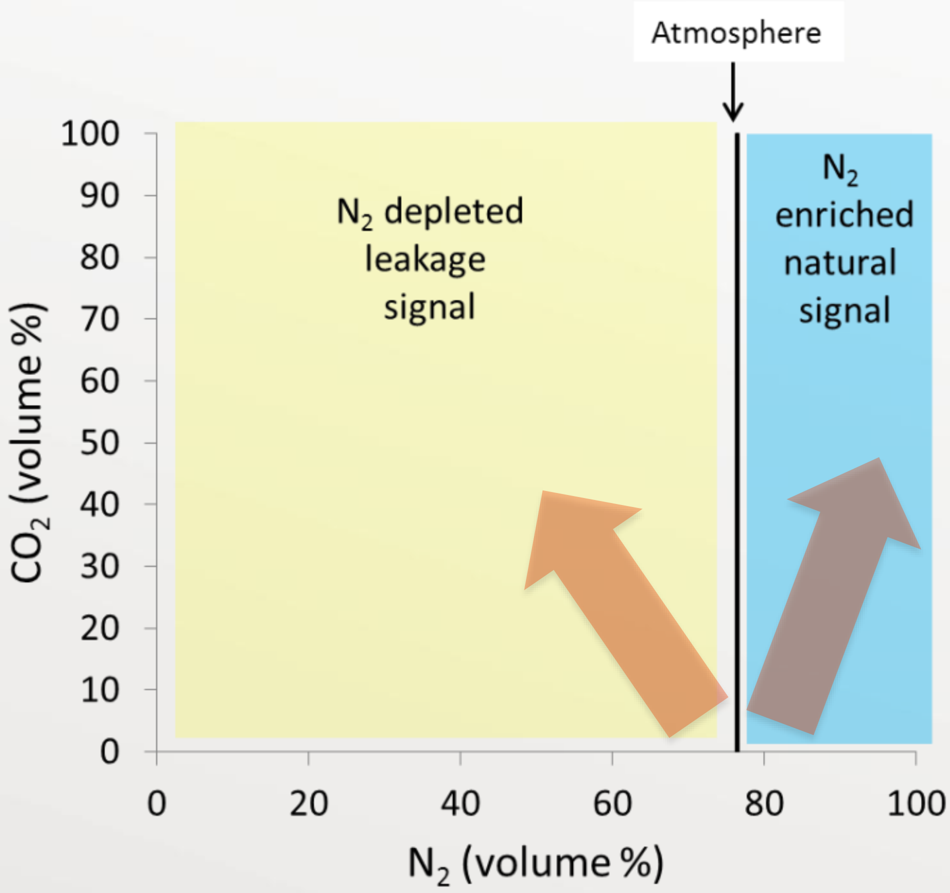
- Indicates natural processes that affect CO_2 concentrations
- Distinguishes among respiration, CH_4 oxidation and dissolution
- Gives an initial assessment of leakage



Process-Based Gas Ratio - 2

CO_2 vs. N_2

- Identifies whether gas has migrated from depth.
- Indicates whether CO_2 is being added through leakage or lost through dissolution.



SECARB Anthropogenic Test Lessons Learned

Project Number DE-FC26-05NT42590

Robert Trautz
Electric Power Research Institute

David Riestenberg and George Koperna Advanced Resources International. Inc.

U.S. Department of Energy
National Energy Technology Laboratory
Mastering the Subsurface Through Technology, Innovation and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting
August 16-18, 2016

Acknowledgement

This presentation is based upon work supported by the Department of Energy National Energy Technology Laboratory under **DE-FC26-05NT42590** and was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Presentation Outline

- Project Introduction and Status
- Permitting, Planning and Operations Lessons Learned
- Monitoring Lessons Learned

Project Objectives

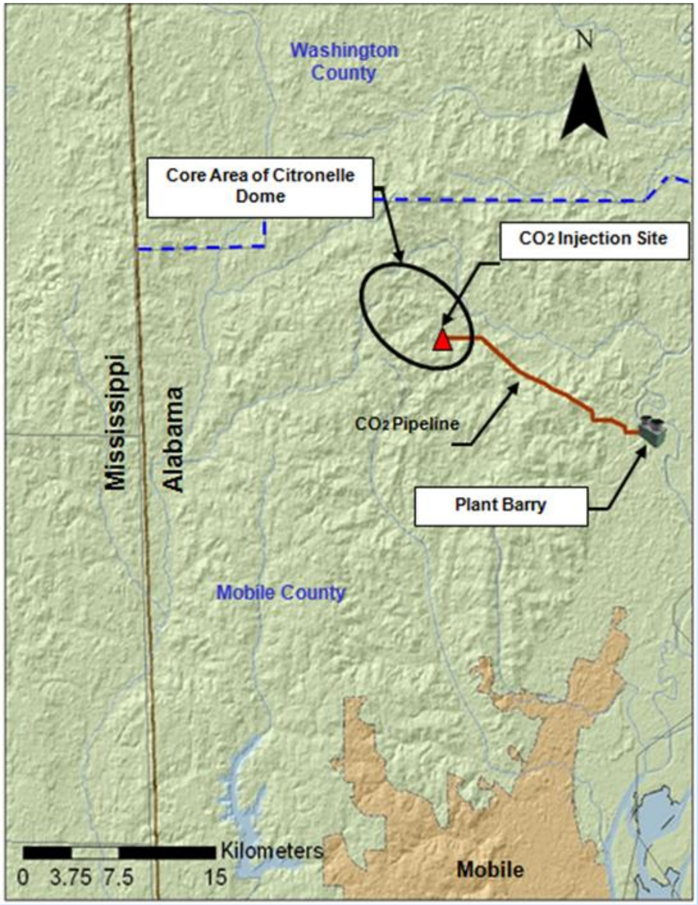
Baseline 1 year — APR 2011 to AUG 2012

Injection 2 years — SEPT 2012 to SEP 2014

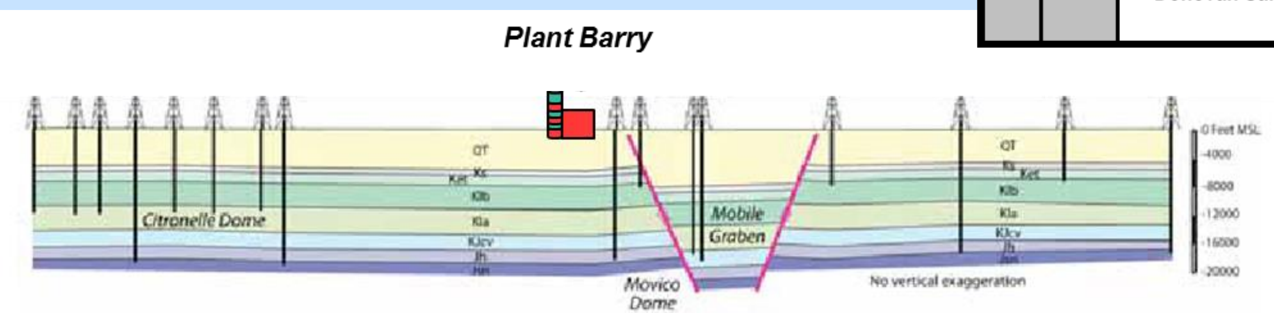
Post 3 years — SEP 2014 to SEPT 2017

1. Support the United States' largest prototype CO_2 capture and transportation demonstration with injection, monitoring and storage activities;
2. Test the CO_2 flow, trapping and storage mechanisms of the Paluxy;
3. Demonstrate how a saline reservoir's architecture can be used to maximize CO_2 storage and minimize the areal extent of the CO_2 plume;
4. Test the adaptation of commercially available oil field tools and techniques for monitoring CO_2 storage
5. Test experimental CO_2 monitoring activities, where such technologies hold promise for future commercialization;
6. Begin to understand the coordination required to successfully integrate all four components (capture, transport, injection and monitoring) of the project; and
7. Document the permitting process for all aspects of a CCS project.

Storage Site: The Citronelle Oilfield



System	Series	Stratigraphic Unit	Major Sub Units	Potential Reservoirs and Confining Zones
Tertiary	Plio-Pliocene		Citronelle Formation	Freshwater Aquifer
Tertiary	Miocene	Undifferentiated		Freshwater Aquifer
Tertiary	Oligocene		Chickasawhay Fm.	Base of USDW
Tertiary	Oligocene	Vicksburg Group	Bucatunna Clay	Local Confining Unit
Tertiary	Eocene	Jackson Group		Minor Saline Reservoir
Tertiary	Eocene	Claiborne Group	Talahatta Fm.	Saline Reservoir
Tertiary	Eocene	Wilcox Group	Hatchetigbee Sand Bashi Marl Salt Mountain LS	Saline Reservoir
Tertiary	Paleocene	Midway Group	Porters Creek Clay	Confining Unit
Cretaceous	Upper	Selma Group		Confining Unit
Cretaceous	Upper	Eutaw Formation		Minor Saline Reservoir
Cretaceous	Upper	Tuscaloosa Group	Upper Tusc.	Minor Saline Reservoir
Cretaceous	Upper	Tuscaloosa Group	Mid. Tusc. Marine Shale	Confining Unit
Cretaceous	Upper	Tuscaloosa Group	Lower Tusc. Pilot Sand Massive sand	Saline Reservoir
Cretaceous	Lower	Washita-Fredericksburg	Dantzler sand	Saline Reservoir
Cretaceous	Lower	Washita-Fredericksburg	Basal Shale	Primary Confining Unit
Cretaceous	Lower	Paluxy Formation	'Upper' 'Middle' 'Lower'	Injection Zone
Cretaceous	Lower	Mooringsport Formation		Confining Unit
Cretaceous	Lower	Ferry Lake Anhydrite		Confining Unit
Cretaceous	Lower	Donovan Sand	Rodessa Fm. Upper' 'Middle' 'Lower'	Oil Reservoir Minor Saline Reservoir Oil Reservoir



Structure map by GSA

Storage Project Status

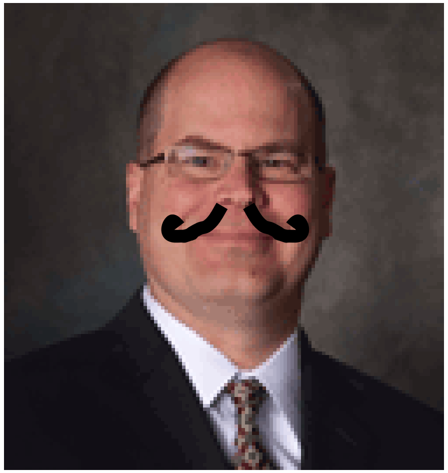
- Three deep wells drilled in 2011/2012
- Experimental Modular Borehole Monitoring System tool string run in early 2012
- Injection commenced on August 20, 2012
- Injection ended September 1, 2014
- 114,104 metric tons of CO_2 injection
- Entered the three year Post-Injection Site Care Period in September, 2014
- CO_2 breakthrough at the D-9-8#2 observation well in late 2015
- Testing and monitoring activities indicate containment

Permitting, Planning and Operations Lessons Learned

Or what we like to call …

The Good

The Bad



…And The Ugly

What went well?

- Integration of capture unit, pipeline and injection operations
  - Required transfer of CO_2 custody at plant gate from Alabama Power to Denbury
  - No outages due to “lack of communication”
  - All monitoring requirements met
- Receptiveness of UIC regulators, the Alabama Department of Environmental Management
  - First of its kind permitted as a Class V experimental well(s) by Alabama with elements that reflect Class VI well requirements

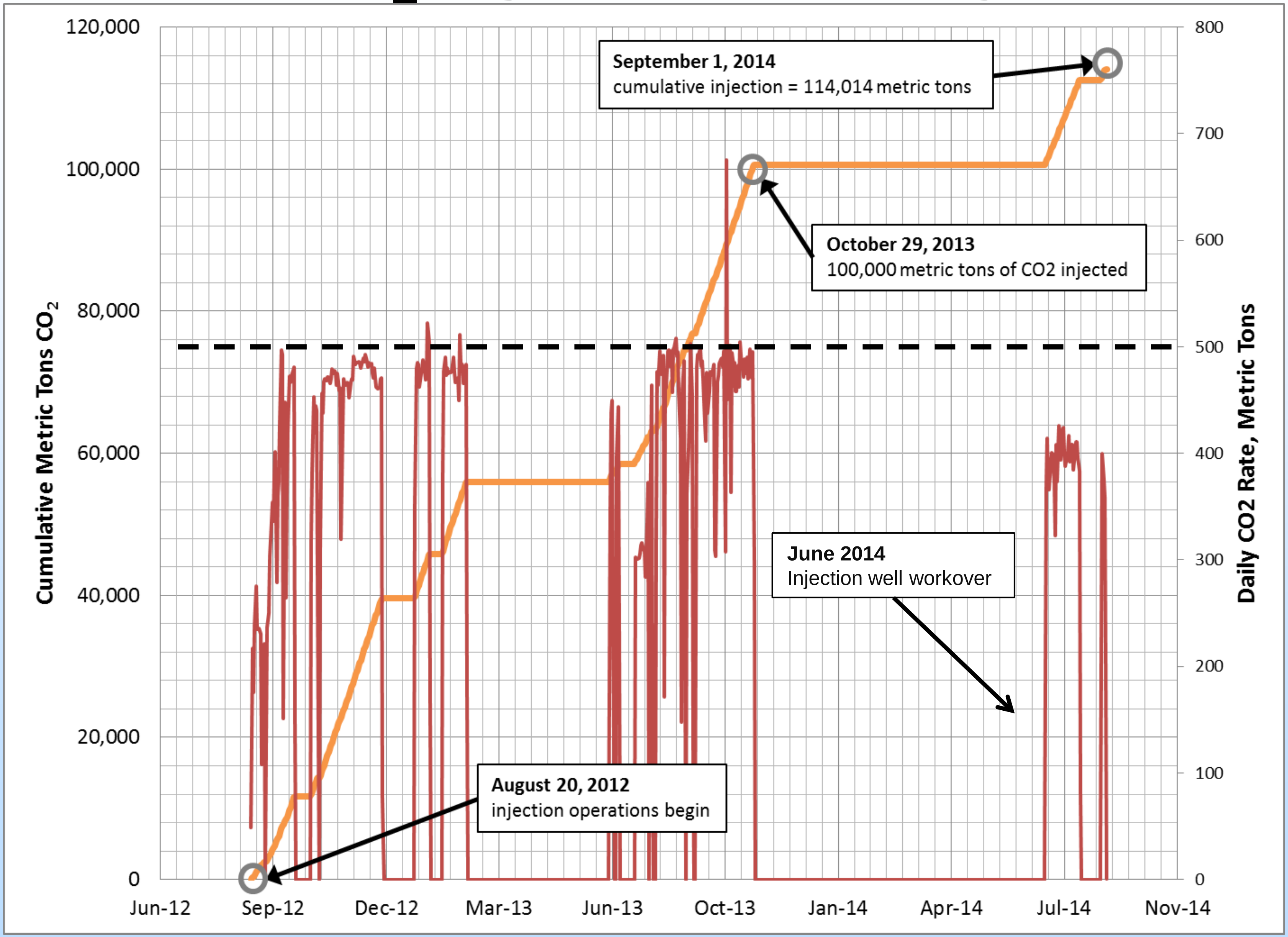
What Could Have Gone Better

- Amount of capture unit downtime was disappointing
  - ➢ Mostly a function of low dispatch of a coal-fired unit where the capture unit was drawing from a slip stream
  - ➢ Planned 300-400 kilotonnes of injection, realized 114 kilotonnes
- Pressure drop in pipeline during 2013-2014 capture unit outage
  - ➢ Iron (magnetite?) precipitate collected in pipeline, clogged pump filter on startup
  - ➢ Resulted in about 35 kilotonnes of non-injection in mid-2014

What Could Have Gone Better (2)

- Well workovers have been challenging!
  - ➢ In 2014 the injection well (D-9-7#2) was killed with a heavy mud so the tubing and packer could be pulled for a crosswell seismic survey resulting in injectivity damage
  - ➢ In July 2016 an attempt was made to pull the tubing-deployed monitoring tool string from the D-9-8#2 well. Despite multiple tubing cuts the tool string could not be completely removed and the well was ultimately plugged and abandoned.

CO_2 Injection History

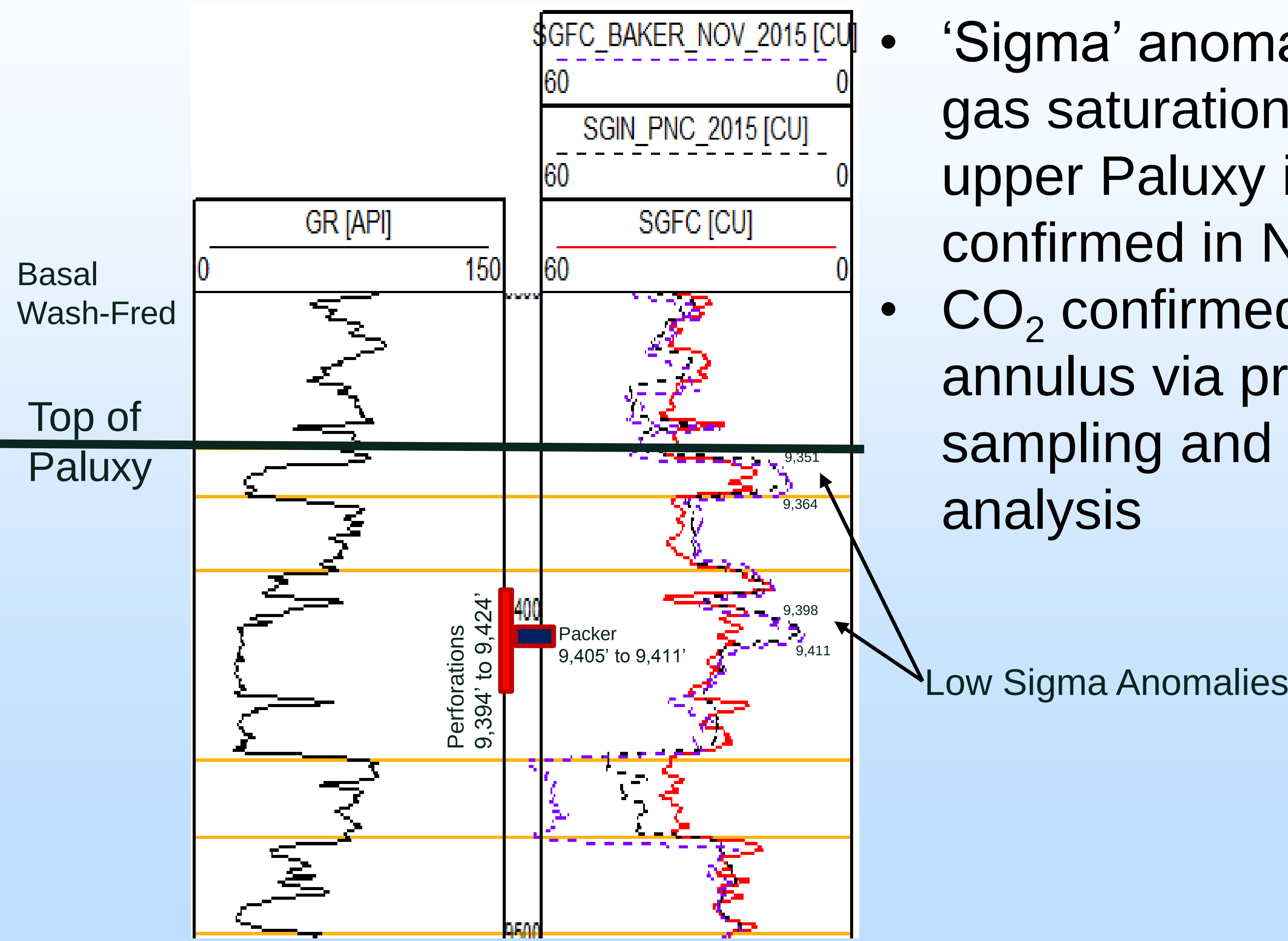


Monitoring Lessons Learned

What went well?

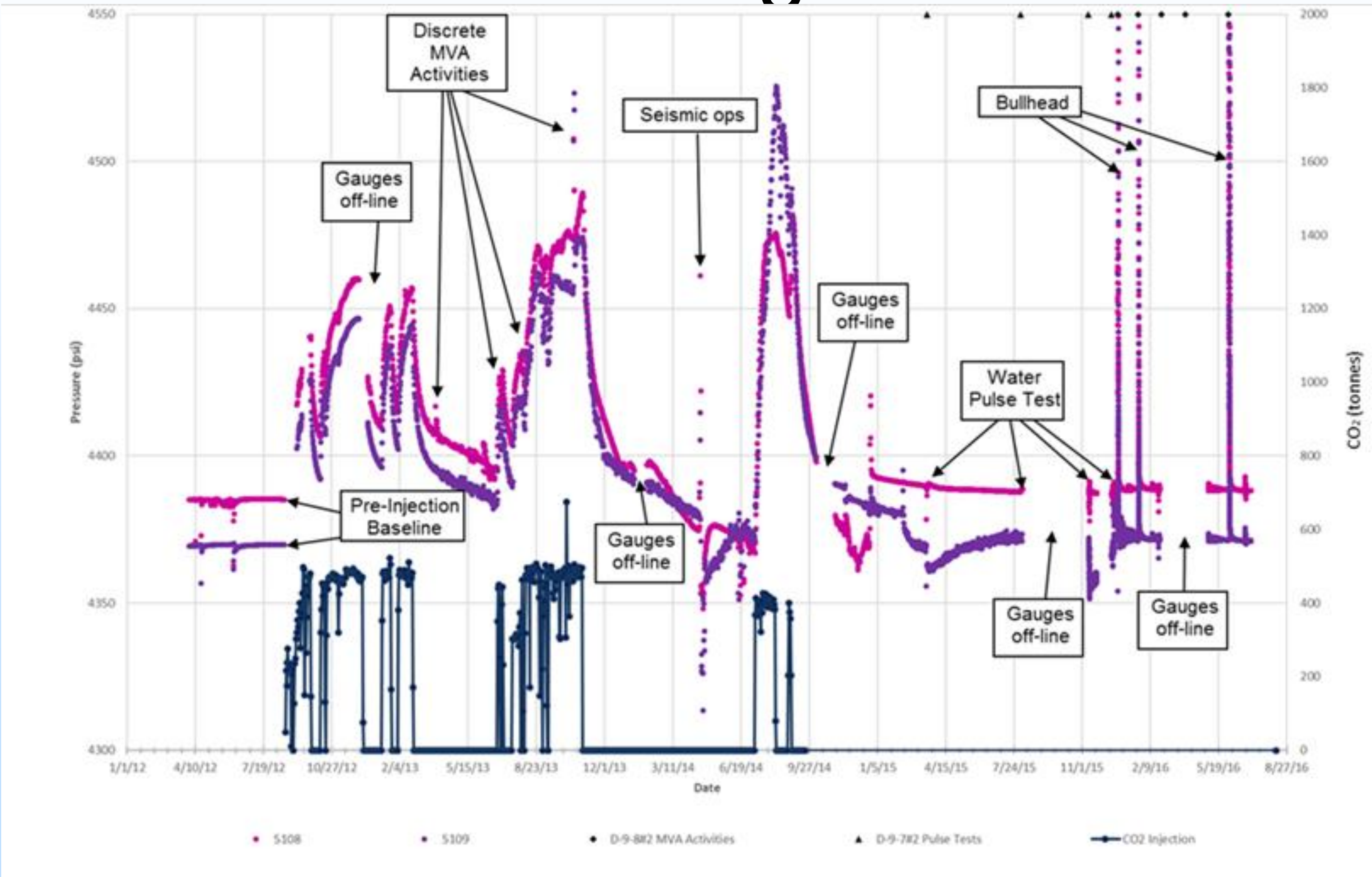
- Successful identification of CO_2 breakthrough with cased hole pulsed neutron log
- Pressure gauge data and frequent injection pauses/startups provide and opportunity for "cheap" pressure transient analysis
- Fiber optic arrays (DTS and DAS) worked better than expected
  - ➢ Temperature data utilized to diagnose a bad completion
  - ➢ high density acoustic dataset
  - ➢ time-lapse acoustic imaging appears promising

Cased Hole Pulsed Neutron Log Used to Identify CO_2 Breakthrough

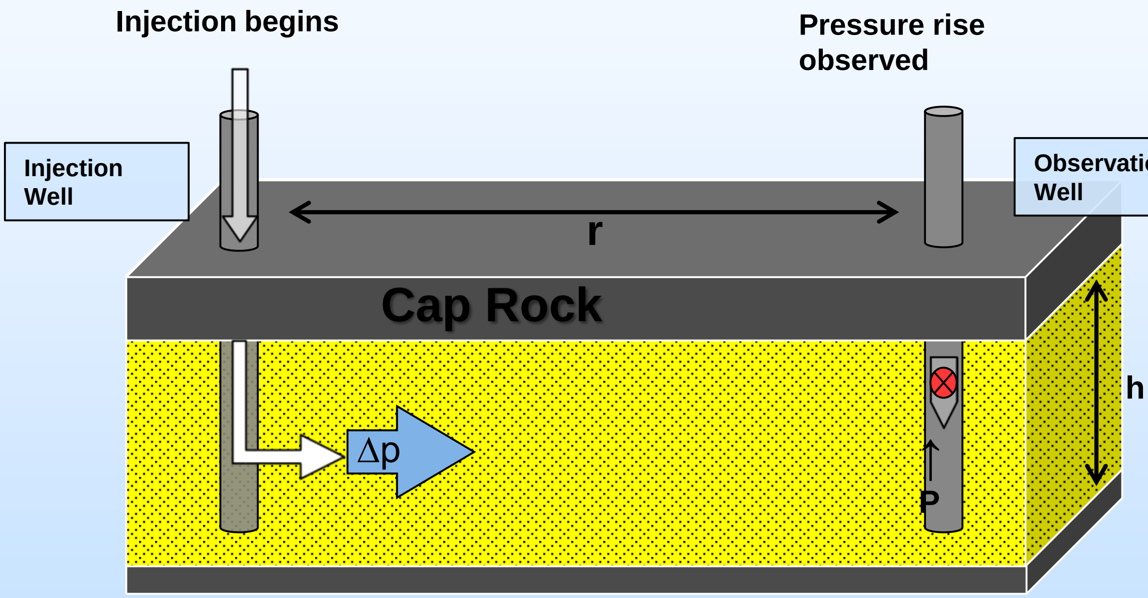


- 'Sigma' anomaly indicated gas saturation buildup in the upper Paluxy in Aug. 2015, confirmed in Nov. 2015
- CO_2 confirmed in casing annulus via pressure, tracer sampling and compositional analysis

Pressure Response at D-9-8#2 Monitoring Well

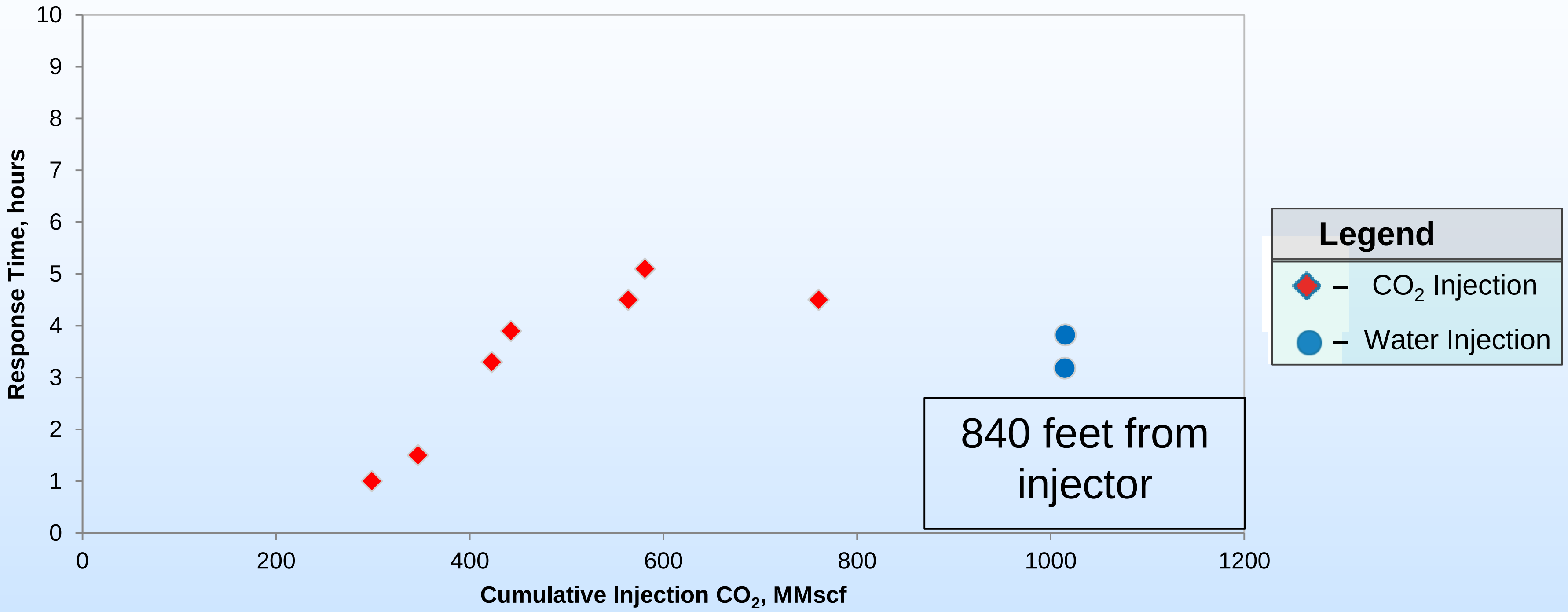


Injection Interruptions provided an opportunity for cheap pressure transient analysis



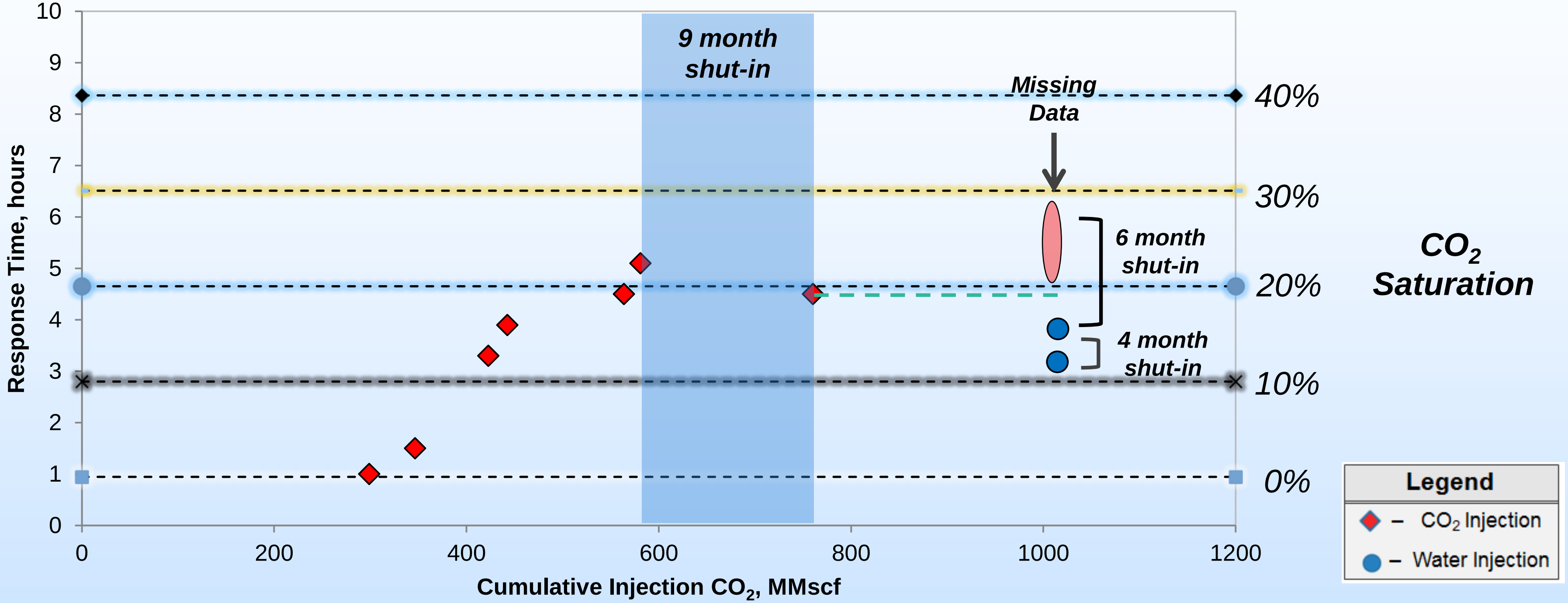
Time the pulse takes to reach the observation well is a function of reservoir characteristics

D-9-8#2 Pressure Response Times



- Red diamonds represent CO_2 injection starts
- Blue circles represents post-injection water pulse tests

D-9-8#2 Saturation Changes



Theoretical response times for a pressure transient to travel from the injector to the observation well were calculated as a function of CO_2 saturation in the reservoir. Assume:

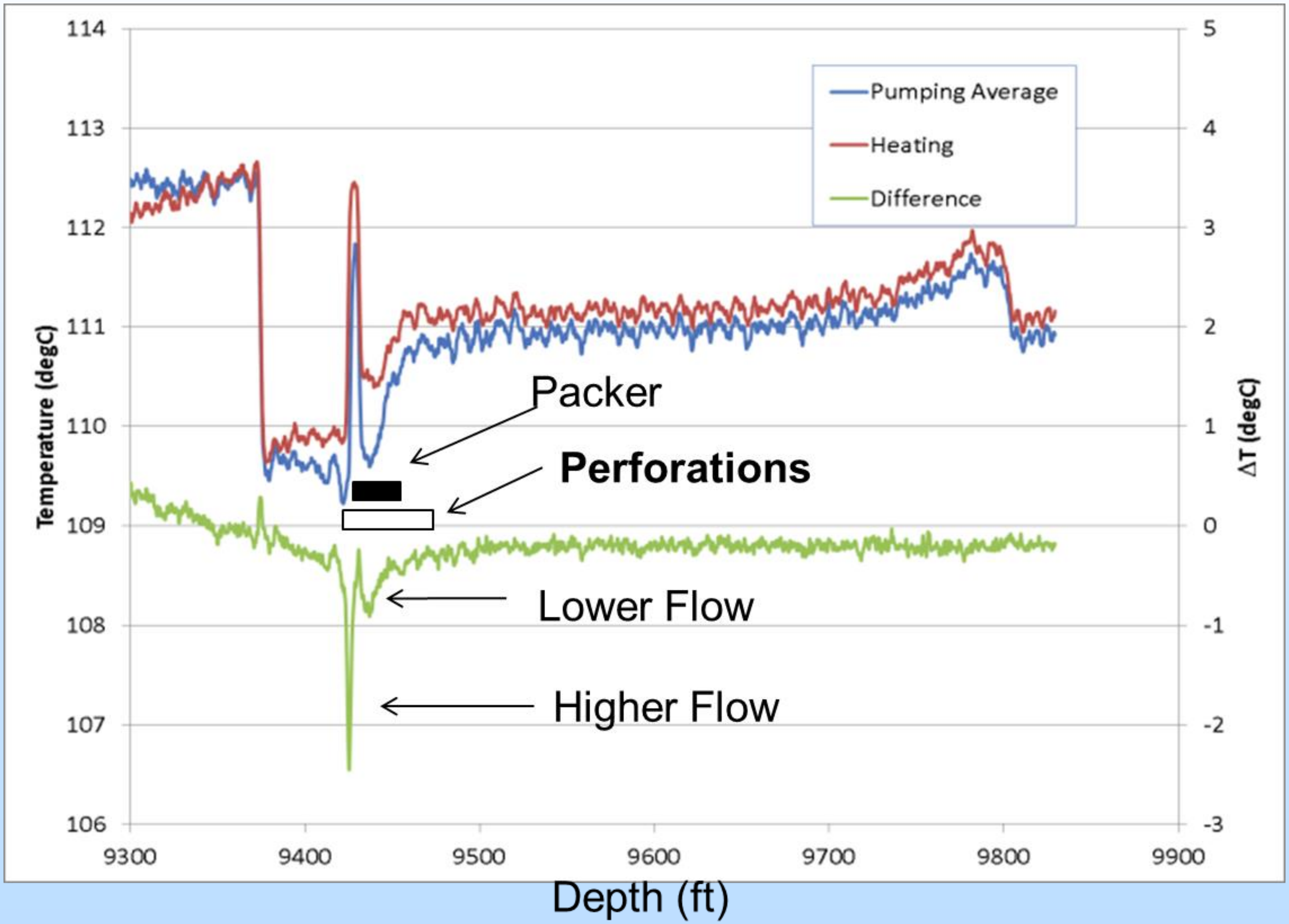
- Homogenous distribution of CO_2 in reservoir
- Fixed reservoir properties

Distributed Fiber Optic Arrays Provide a Lot of Bang for the Buck

- Distributed temperature FO proved its utility in identifying a bad completion in the D-9-8#2 (packer set in perforations)
- Distributed acoustic FO provided a high-density single mode array
  - Wave-form acquired using stacked VSP-DAS provides a good match with conventional geophone results
- ***For further information on distributed FO, please attend Rob's presentation at 2:15 this afternoon in the Geophysics 2 session.***

Heat Pulse with Annular Pump Test

Identify location of 30 ft perf. interval with respect to packer



Temperature Data:

Heating

Heating during Pumping (~1 hour average)

Difference

What would we do differently?

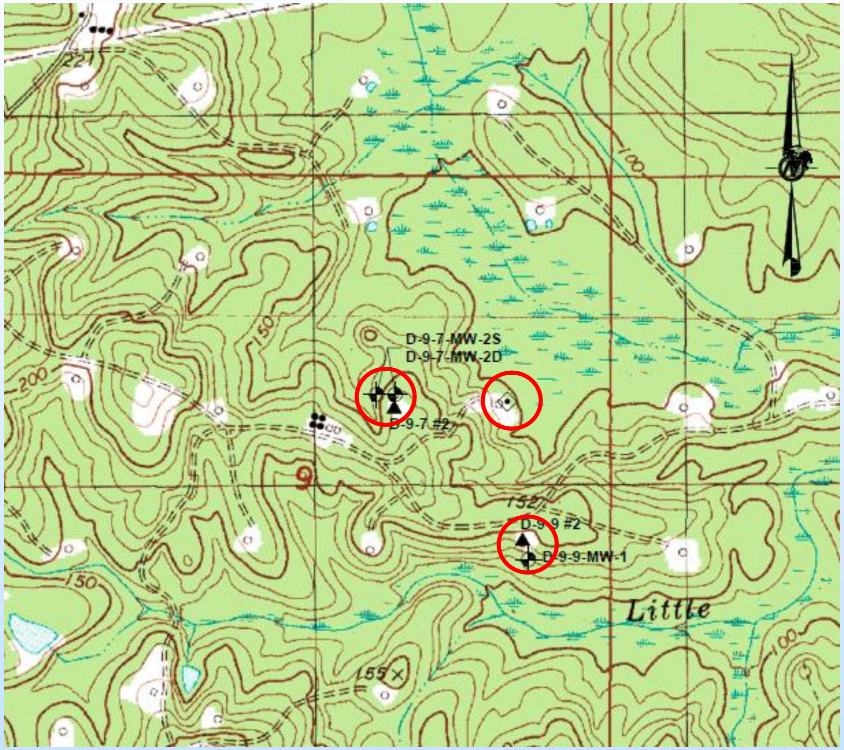
- Install USDW monitoring wells earlier, develop and sample for a longer period prior to injection
  - Large background data sets are required to avoid false positive/negatives in statistical results.
  - Monitoring well geochemistry can vary as wells are developed.

Citronelle Groundwater Sampling Program

- Three dedicated groundwater sampling wells and one water supply well

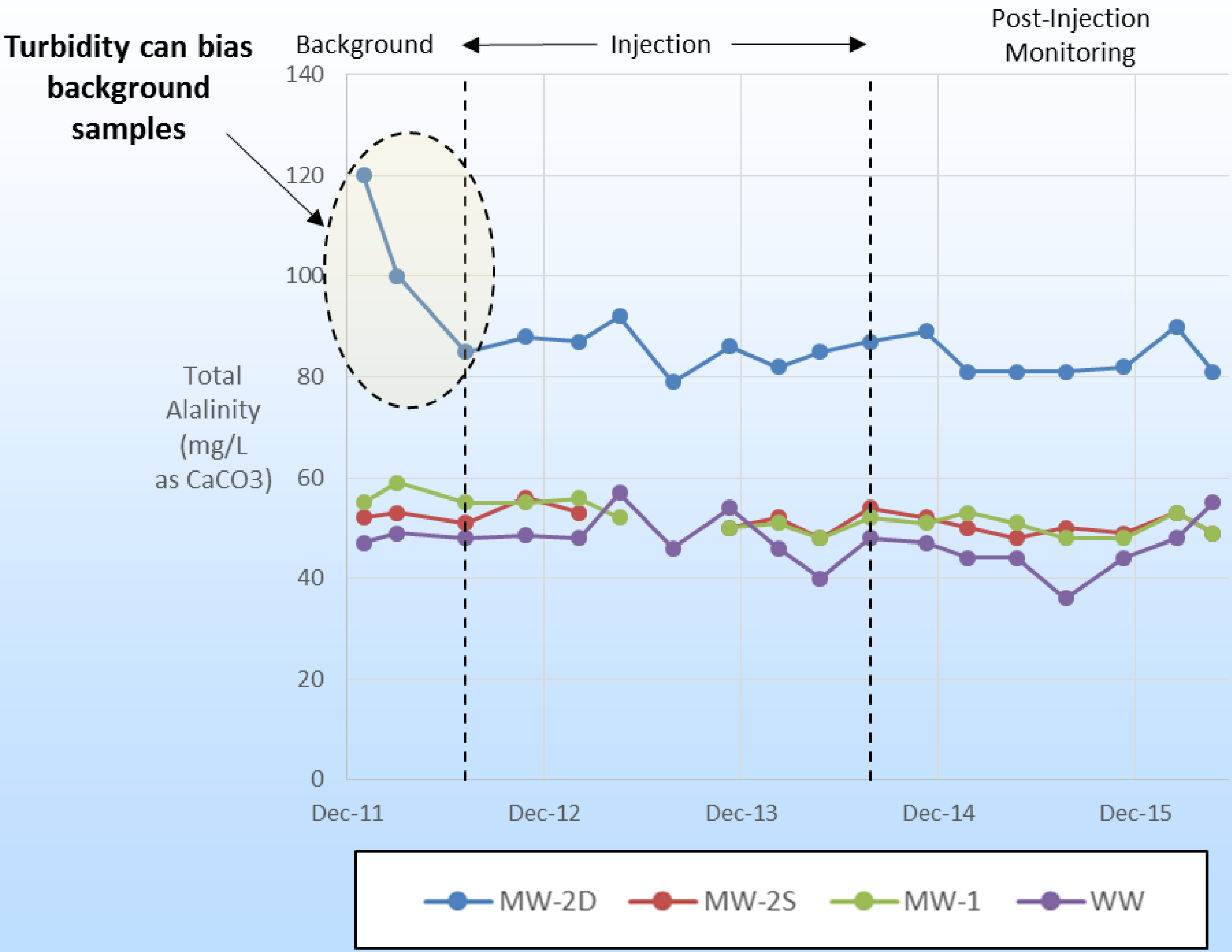
Well	Depth (ft)	Elev. (ft)
D9-9 MW-1	169.6	-20.23
D9-7 MW-2S	170.8	-5.24
D9-7 MW-2D	501.0	-335.6
D9-8 WW	143	--

- Three background sampling events prior to CO_2 injection
- Fifteen quarterly sampling events since injection started
- 17 metals, alkalinity, TDS, TIC, pH…etc.

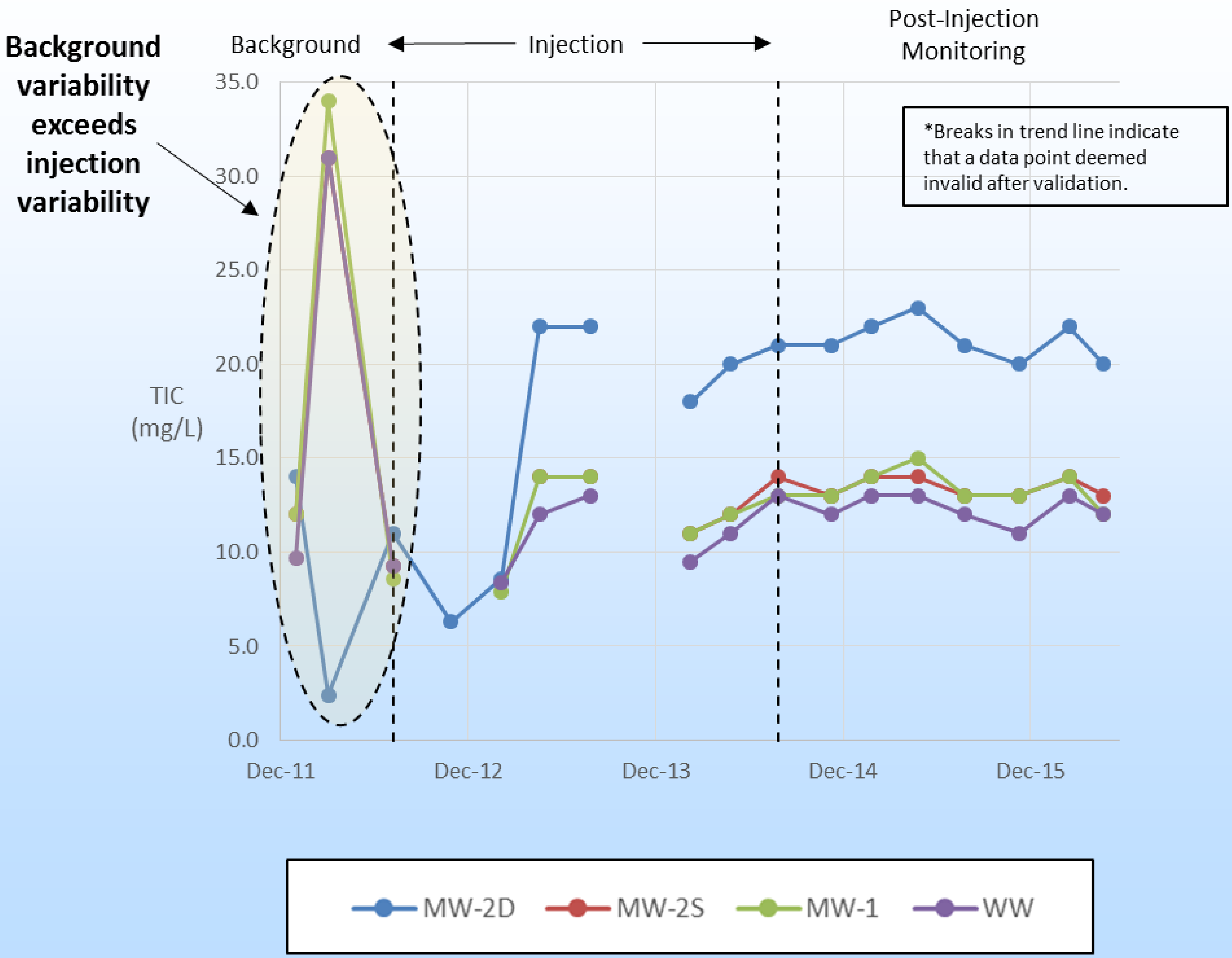


Groundwater sampling locations (circled)

Total Alkalinity



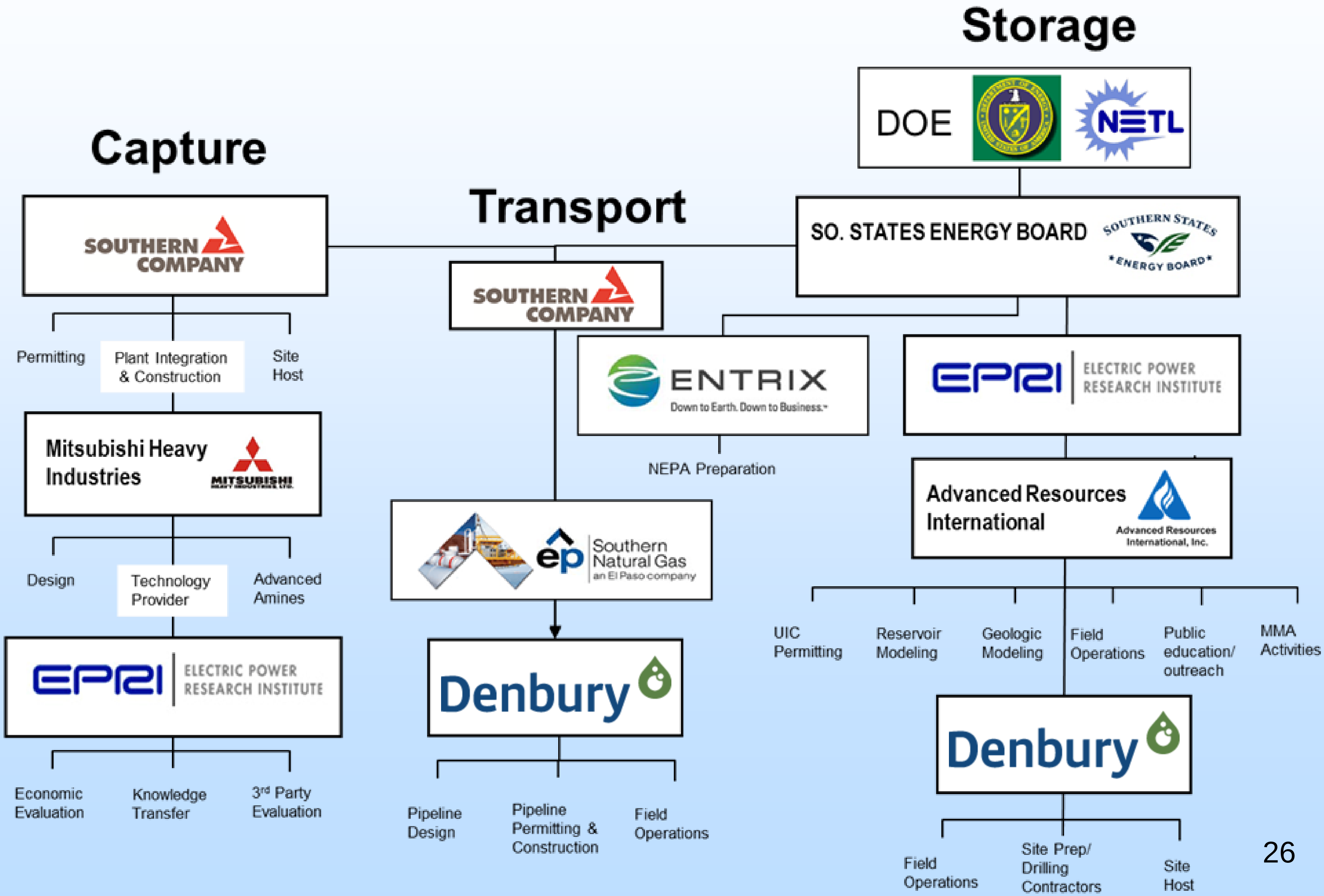
Total Inorganic Carbon (TIC)



Project Closure

- Complete post-injection monitoring
  - Partial repeat of baseline VSP
  - Continue quarterly groundwater sampling
- Demonstration of CO_2 containment within the injection zone and non-endangerment of USDWs using modeling and monitoring results
  - Close out UIC permit
- Temporary abandonment of remaining project wells and transfer of test site to Denbury

Thank You From The SECARB Team



SECARB "Early Test" at Cranfield

DE-FC26-05NT42590

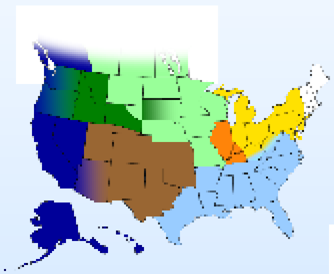
Susan D. Hovorka

Gulf Coast Carbon Center

Bureau of Economic geology

Jackson School of Geoscience

The University of Texas at Austin



Mastering the Subsurface through Technology Innovation, Partnerships and Collaboration: Carbon Storage and Oil and Natural Gas Technologies Review Meeting, August 1–3, 2017, Pittsburgh, Pennsylvania

Team Structure

SECARB
Southeast Regional Carbon Sequestration Partnership

Bureau of Economic Geology
Gulf Coast Carbon Center

Gulf Coast Carbon Center
Bureau of Economic Geology
Jackson School of Geosciences
The University of Texas at Austin

Southern States Energy Board

SECARB Anthropogenic Test At Plant Barry/Citronelle

Denbury Resources
Field owner and injection system design, management, 4-D survey, HS&E

Vendors
e.g. well drilling, landmen

Sandia Technologies
Monitoring Systems Design, Installation, HS&E

50 Vendors
e.g. Schlumberger

Core Lab
UT DoG
Anchor QEA

MSU & UMiss
Hydro & hydrochem

Curtin University
3-D Seismic processing

Federal collaborators
Via FWP

LBNL
Well-based geophysics, U-tube and lab design and fabrication

LLNL
ERT

USGS
Geochemistry

Separately funded

NRAP
VSP deployment & analysis

NETL
Rock-water interaction

Model comparisons
LBNL SIM SEQ study

IPARS Modeling
CFSES M. Wheeler

4-D Seismic analysis
K. Spikes UT DoGS

Rock Mechanics
CFSES Sandia NL

Microseismic deployment
RITE, Japan

Groundwater controlled release
AWWA

Recent progress- Knowledge Transfer to Industry

Separately-funded work monitoring large scale commercial projects based on SECARB early test experience

Air Products Port Arthur industrial capture from SMRI at 1 MMT/year transported to Denbury's Hastings Field.

Petra Nova and NRG /Hillcorp/JX capture up to 1.6 MMT/ year and use for EOR at West Ranch field

Commercialization of Monitoring

	Mass balance	soil gas	groundwater chem	AZMI chem	AZMI pressure	3D seismic	VSP	ERT	EM	gravity	u-tube	IZ chem	tracers
Frio	x	x	x	x			x		x		x	x	x
SECARB Early test at Cranfield	x	x	x	x	x	x	x	x		x	x	x	x
Industrial capture Air Products -Hastings	x	x	x		x	x	x						
Clean Coal Power initiative Petra Nova/ West Ranch	x	x	x	x	x								

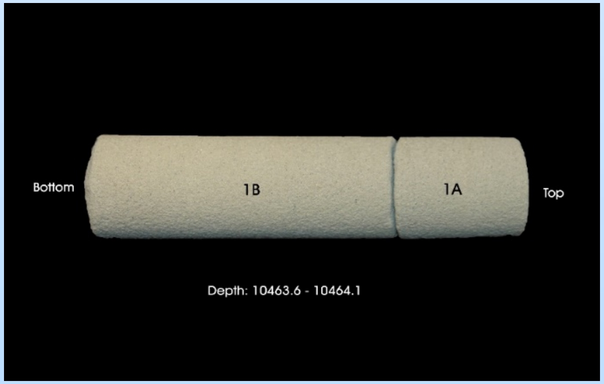
Synergies

Field data collection
Microseismic --RITE
CO_2 Geothermal-- LBNL
PIDAS – Sun
CCP-BP gravity
Microbes – U KY
NRAP 3-D VSP
Borehole seismic – Groundmetrics
Nobles
U. Edinburgh
Fluid Chem--Ohio State
Well integrity -Schlum/Battelle

Modeling efforts
SIMSEQ –LBNL 15 teams
CFSES – UT/ SNL
IPARS --Wheeler
NRAP
NCNO
LBNL
CCP3
UT- LBNL Zhang
LLNL (yesterday)

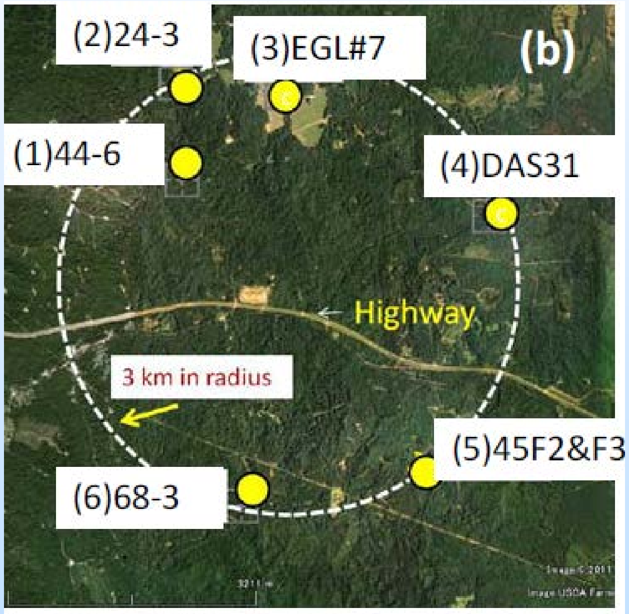
119 history match efforts

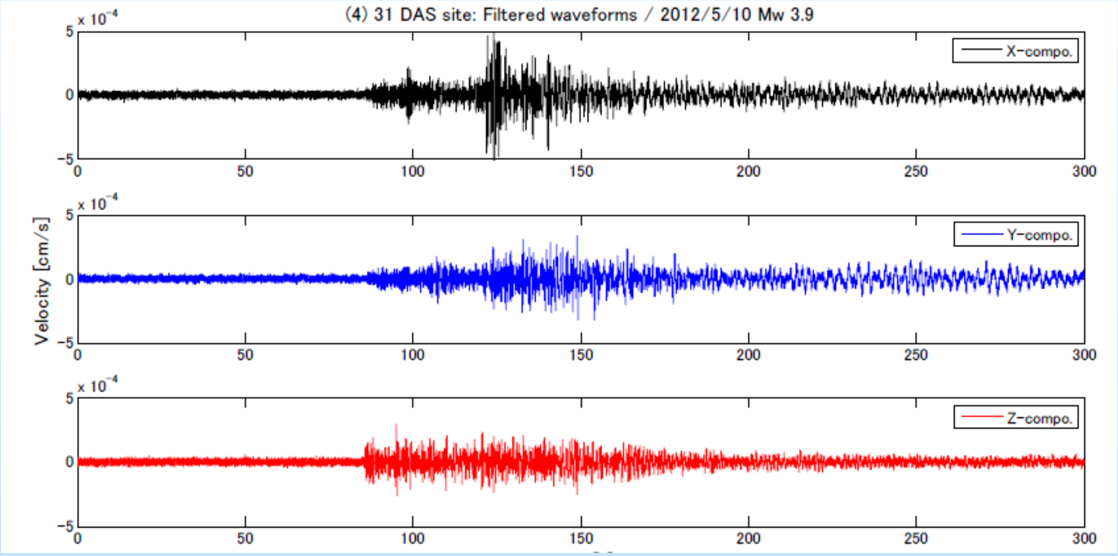
Additional analysis
NETL- EOR accounting
Mei/Dilmore
NETL- Rock-water reaction
BES - LLNL



No detectable seismic

Makiko Takagishi, RITE
Magnitude 0.4 horizontal and .07 vertical





Early Test Motivation

- MIT report “Future of Coal” 2007
  - Set 1 MMT injection goal “proceed .. as soon as possible. Several integrated large-scale demonstrations with appropriate measurement, monitoring and verification are needed. ... establish public confidence for future.”
- In 2007 scale and timing of large-scale capture in region still uncertain
  - SECARB anthropogenic test (2011)
  - >1 MMT Commercial Capture in region (2014, 2017)
- Early Test design to progress in the gap
  - Piggy-back on soon-to-start EOR project
  - Permits, source and infrastructure in place
  - Direct injection – relevant to large scale saline CCS

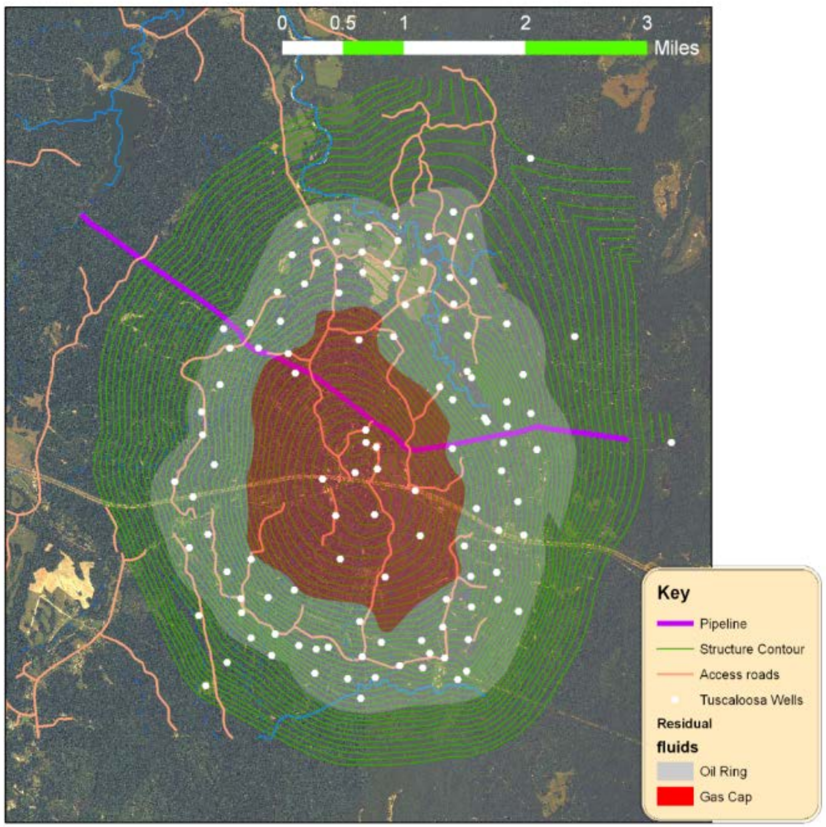
Early Test goals

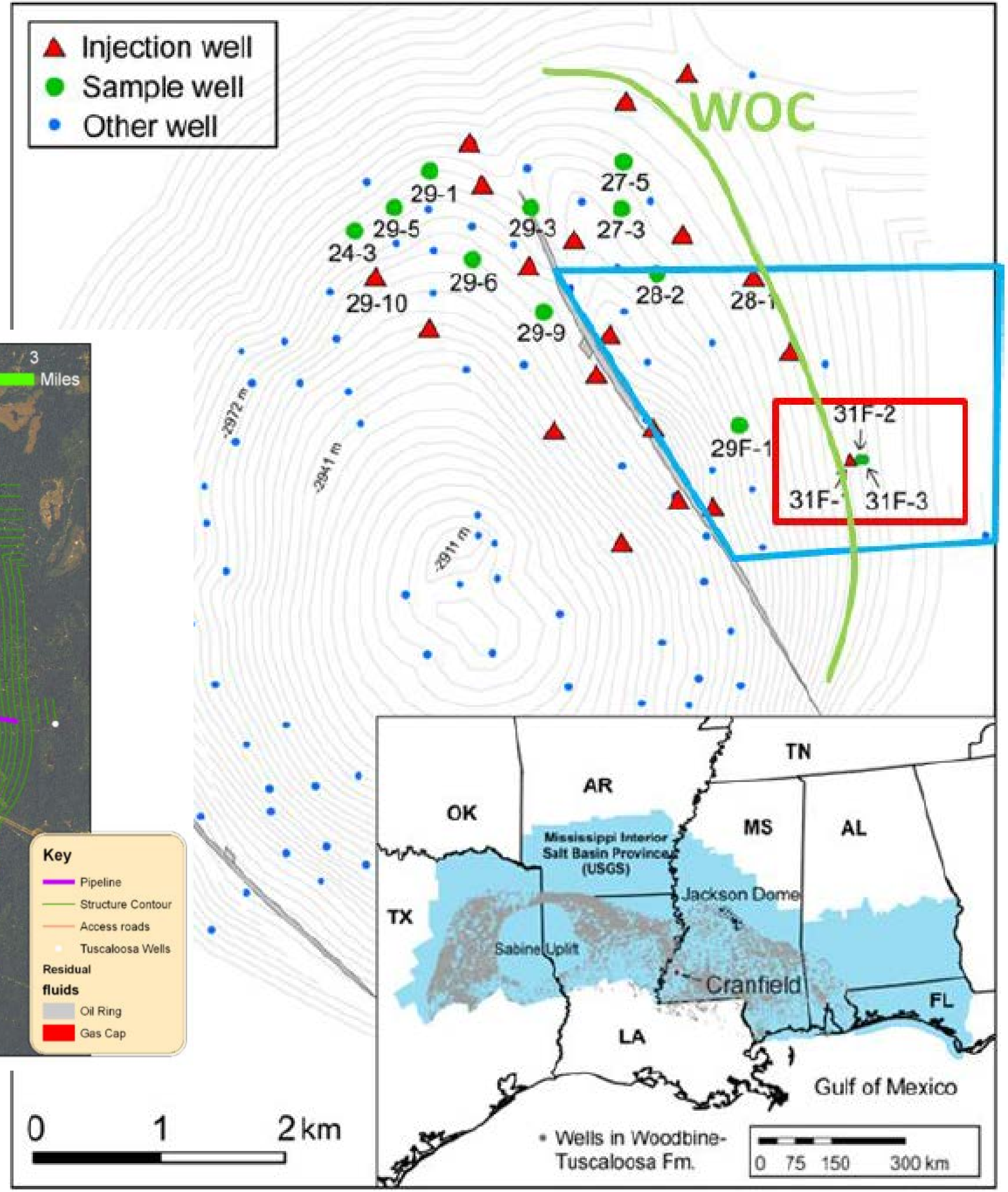
– Large-scale storage demonstration
  - 1 MMT/year over >1.5 years
    - – Periods of high injection rates
    - – Result >5 years with >5 MMT CO_2 stored

– Measurement, monitoring and verification
  - Tool testing and optimization approach
  - Deploy as many tools, analysis methods, and models as possible

– Stacked EOR and saline storage

Location


0 0.5 1 2 3
Miles
Key
Pipeline
Structure Contour
Access roads
Tuscaloosa Wells
Residual
fluids
Oil Ring
Gas Cap


Injection well
Sample well
Other well
WOC
29-1
29-5
24-3
29-10
29-6
29-3
27-5
27-3
28-2
28-1
29-9
29F-1
31F-2
31F-1
31F-3
-2972 m
-2941 m
-2911 m
0 1 2 km
OK
AR
TN
MS
AL
TX
LA
FL
Mississippi Interior Salt Basin Province (USGS)
Jackson Dome
Sabine Uplift
Cranfield
Gulf of Mexico
• Wells in Woodbine-Tuscaloosa Fm.
0 75 150 300 km

Major Contributions

- Early Test Developed monitoring approaches for later commercial projects
  - Process-based soil gas method
  - Effectiveness of groundwater surveillance
  - Pressure and fluid chemistry monitoring in Above-Zone Monitoring Interval (AZMI)
  - ERT for deep CO_2 plume
  - Limitations of 4-D seismic
- Published and propagated techniques for widespread application

Knowledge Transfer to Industry

93 publications

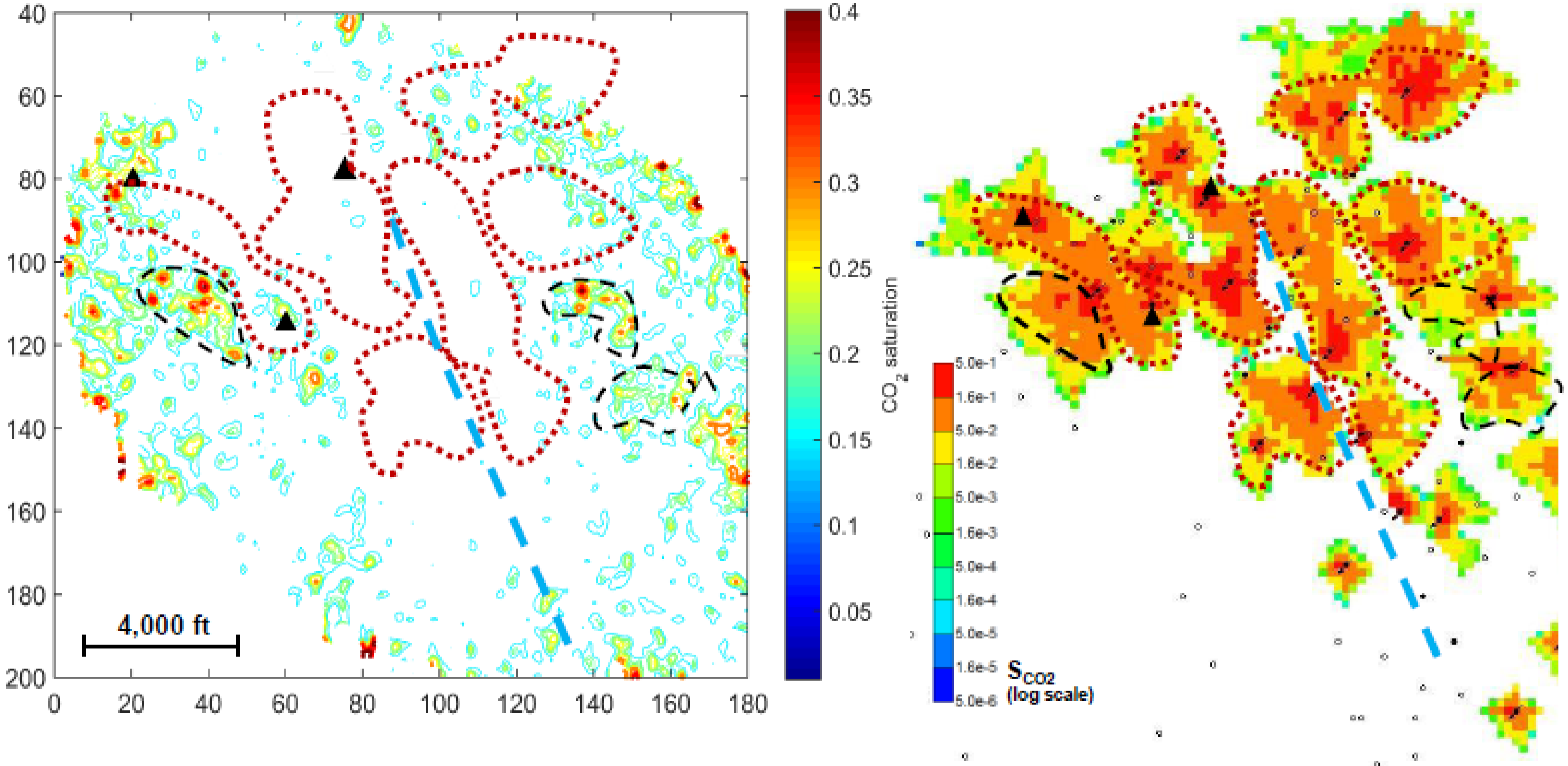
Site visits

Talks, workshops

exchanges

PBS News hour – Miles O'Brien

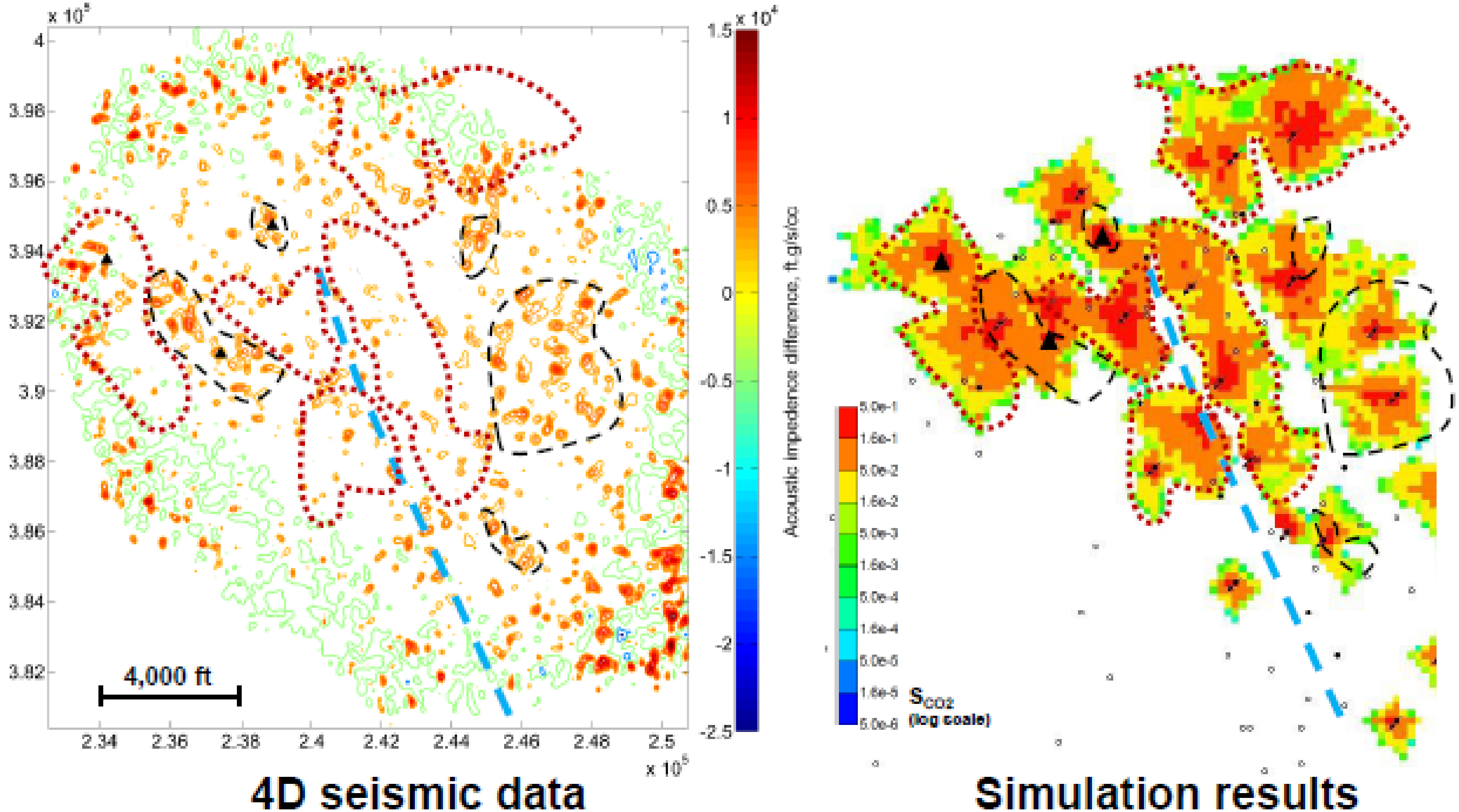
Limitations to 4-D seismic



(b) CO_2 saturation distribution estimate (Carter [18]) compared to fluid flow simulation

Alfi & Hossieni, BEG

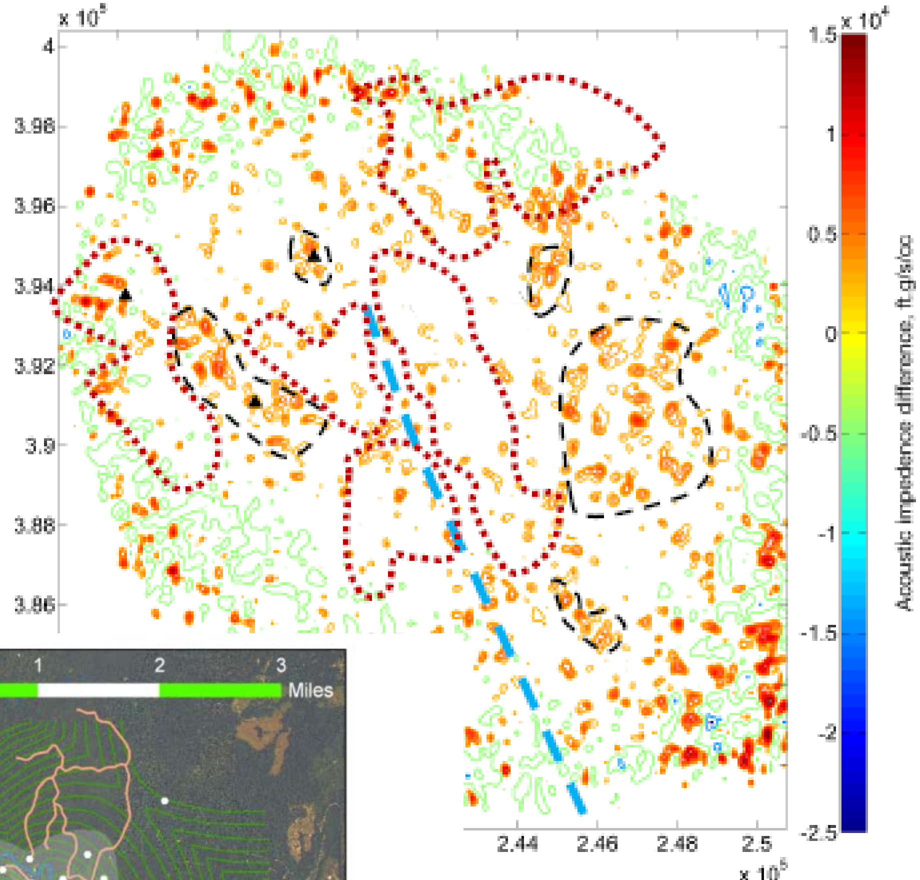
Limitations to 4-D seismic

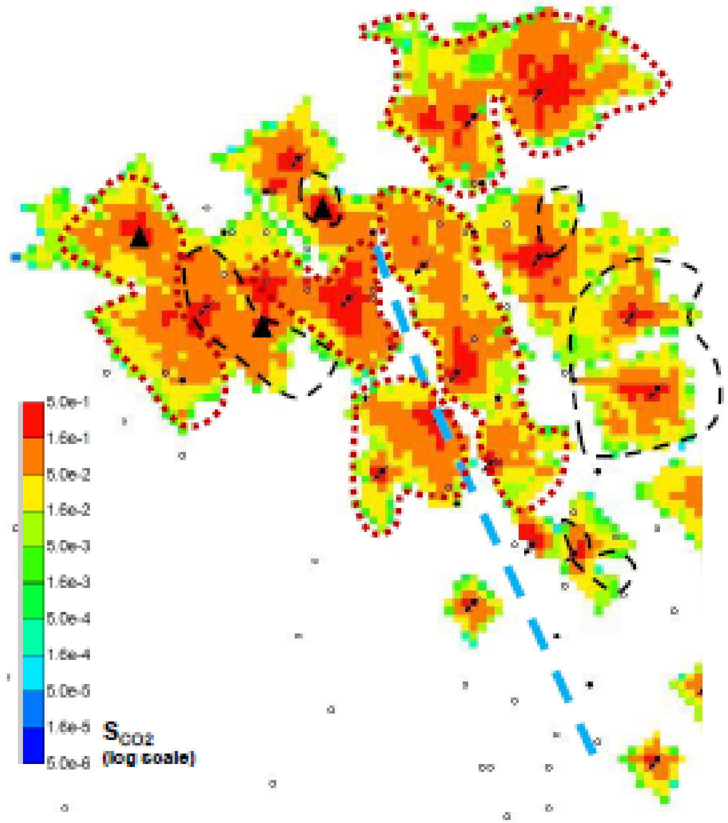


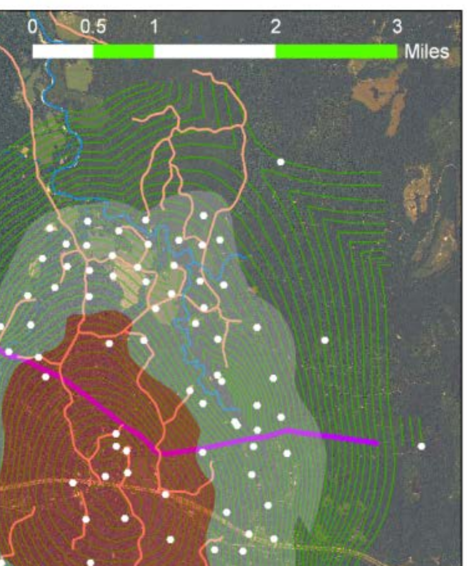
(a) Acoustic impedance difference (Zhang et al. [17]) compared to fluid flow simulation

Alfi & Hossieni, BEG

Limitations to 4-D seismic







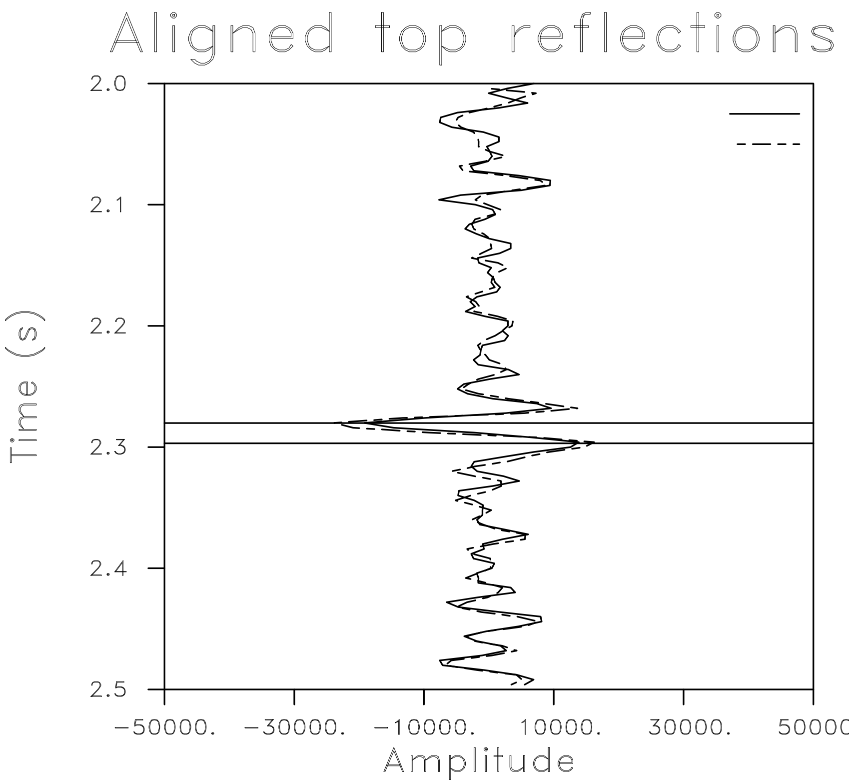
mic data

Simulation results

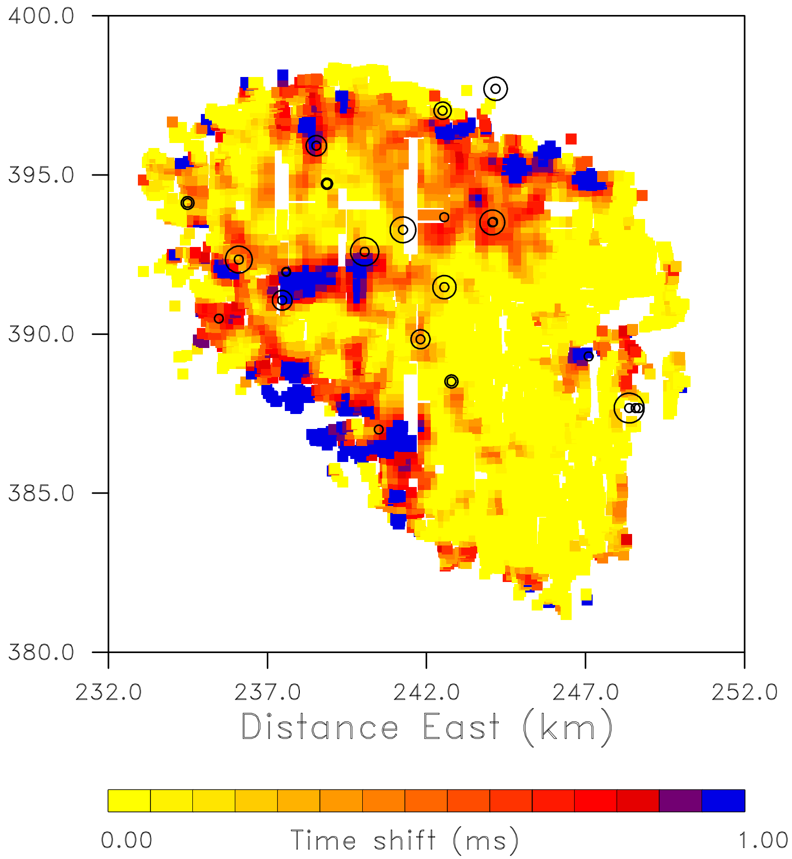
difference (Zhang et al. [17]) compared to fluid flow simulation

Alfi & Hossieni, BEG

Calculate time shifts resulting from CO_2 emplacement for reflections just below the reservoir.

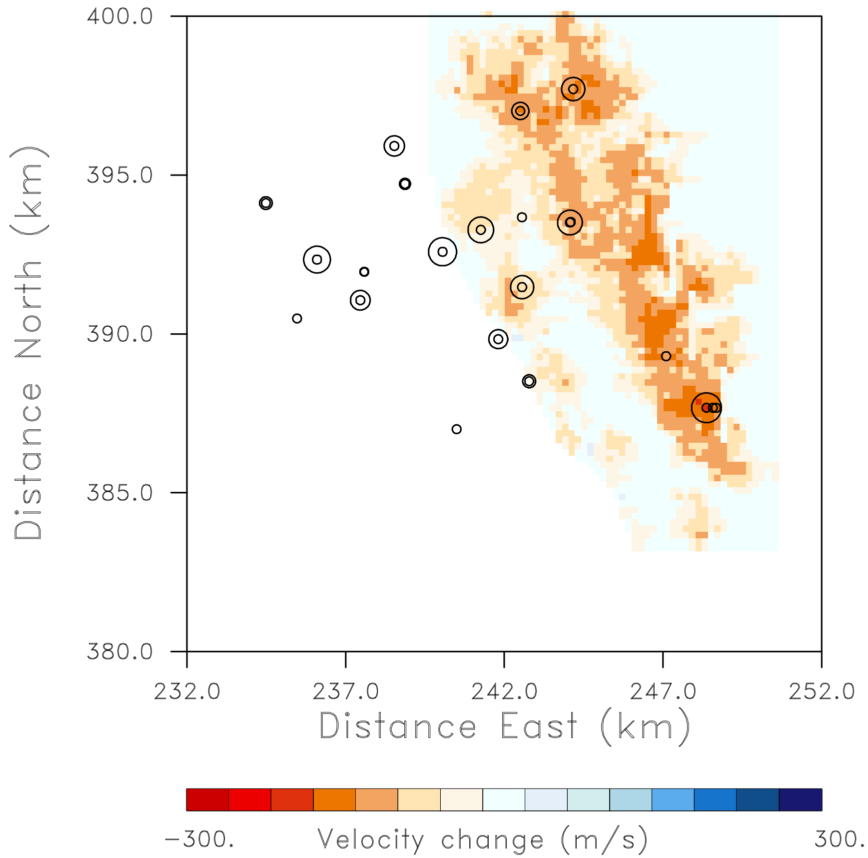


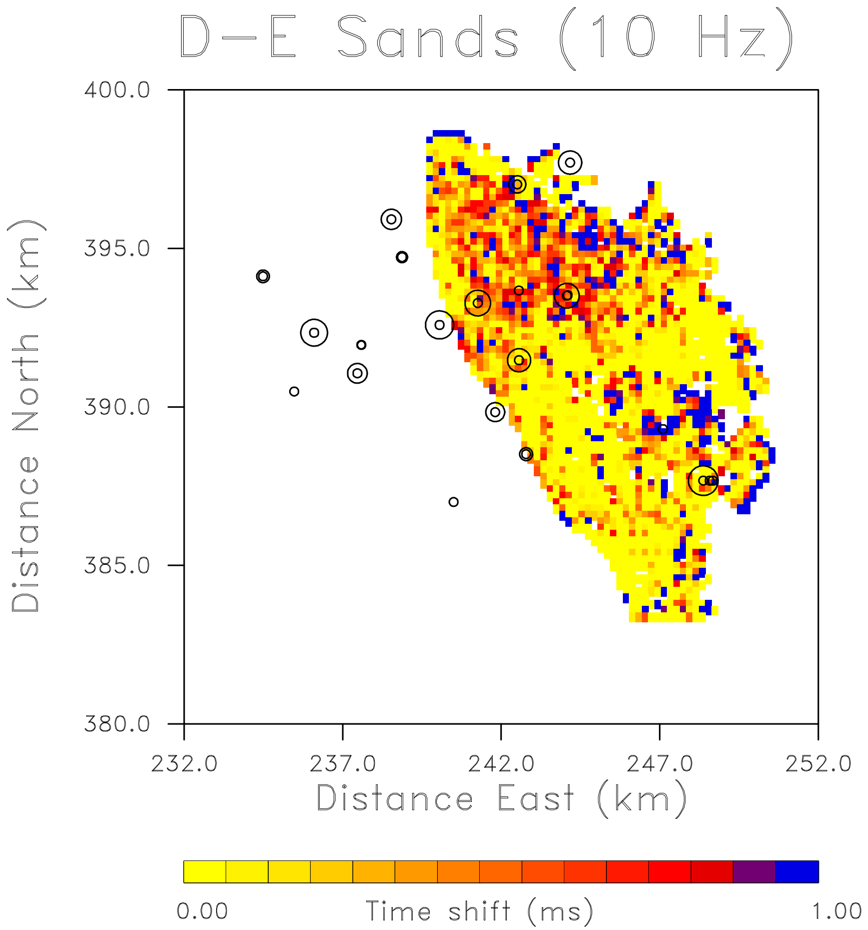
Smoothed Time-Shifts



D. W. Vasco, Tom Daley, Jonathan Ajo-Franklin, LBL

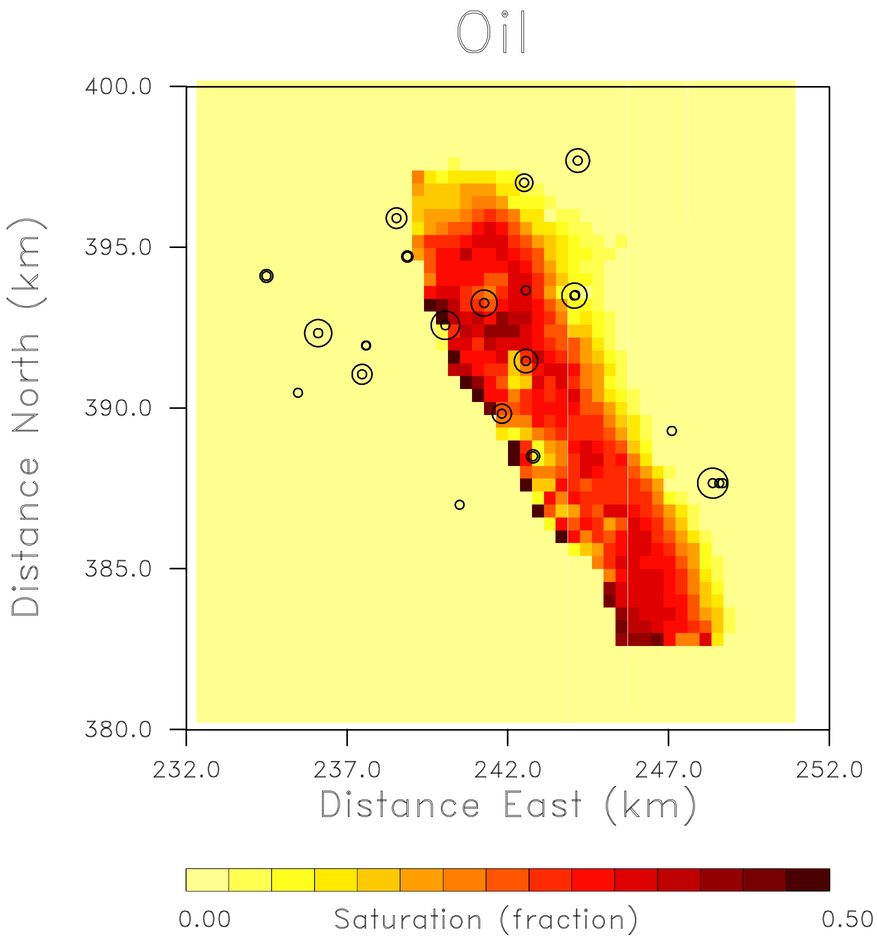
▪Largest seismic time shifts in area with greatest velocity changes

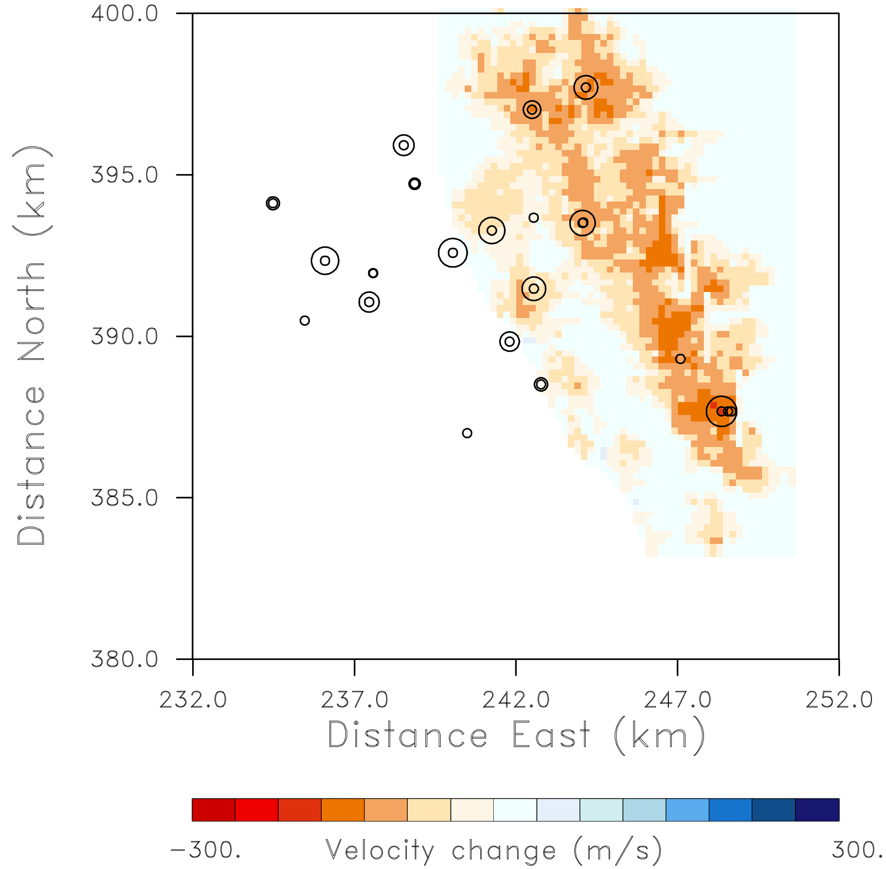




D. W. Vasco, Tom Daley, Jonathan Ajo-Franklin, LBL

▪Biggest velocity changes due to the injection of carbon dioxide are in the water leg

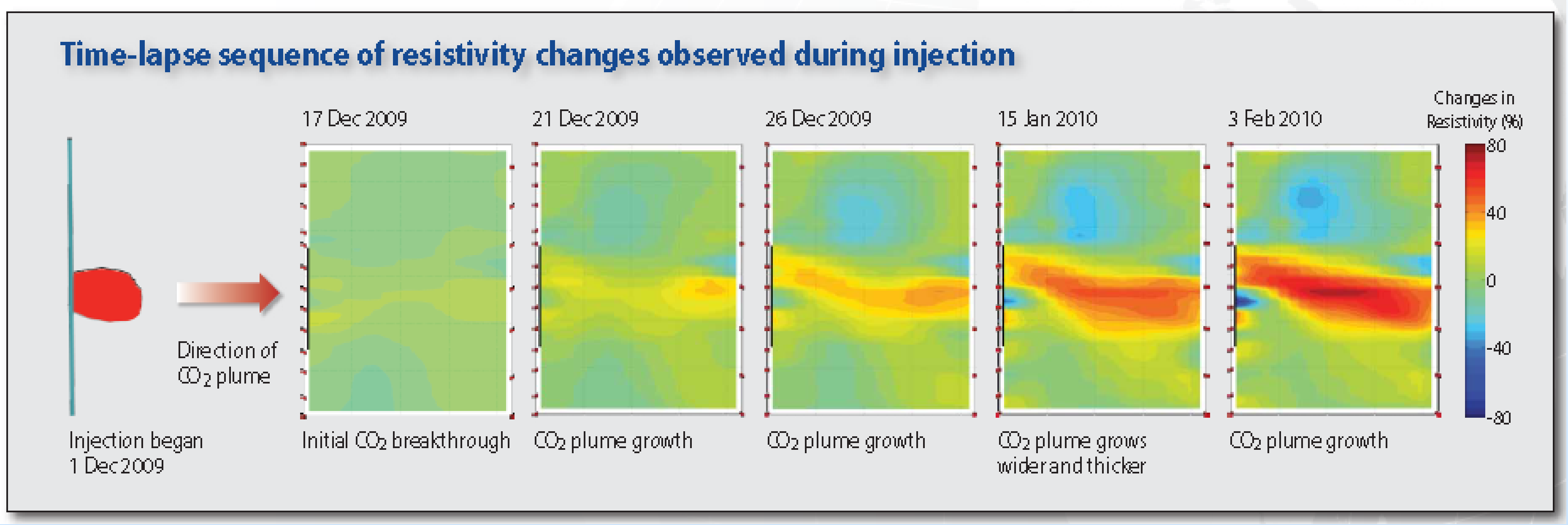




D. W. Vasco, Tom Daley, Jonathan Ajo-Franklin, LBL

LLNL Electrical Resistance Tomography-changes in response with saturation

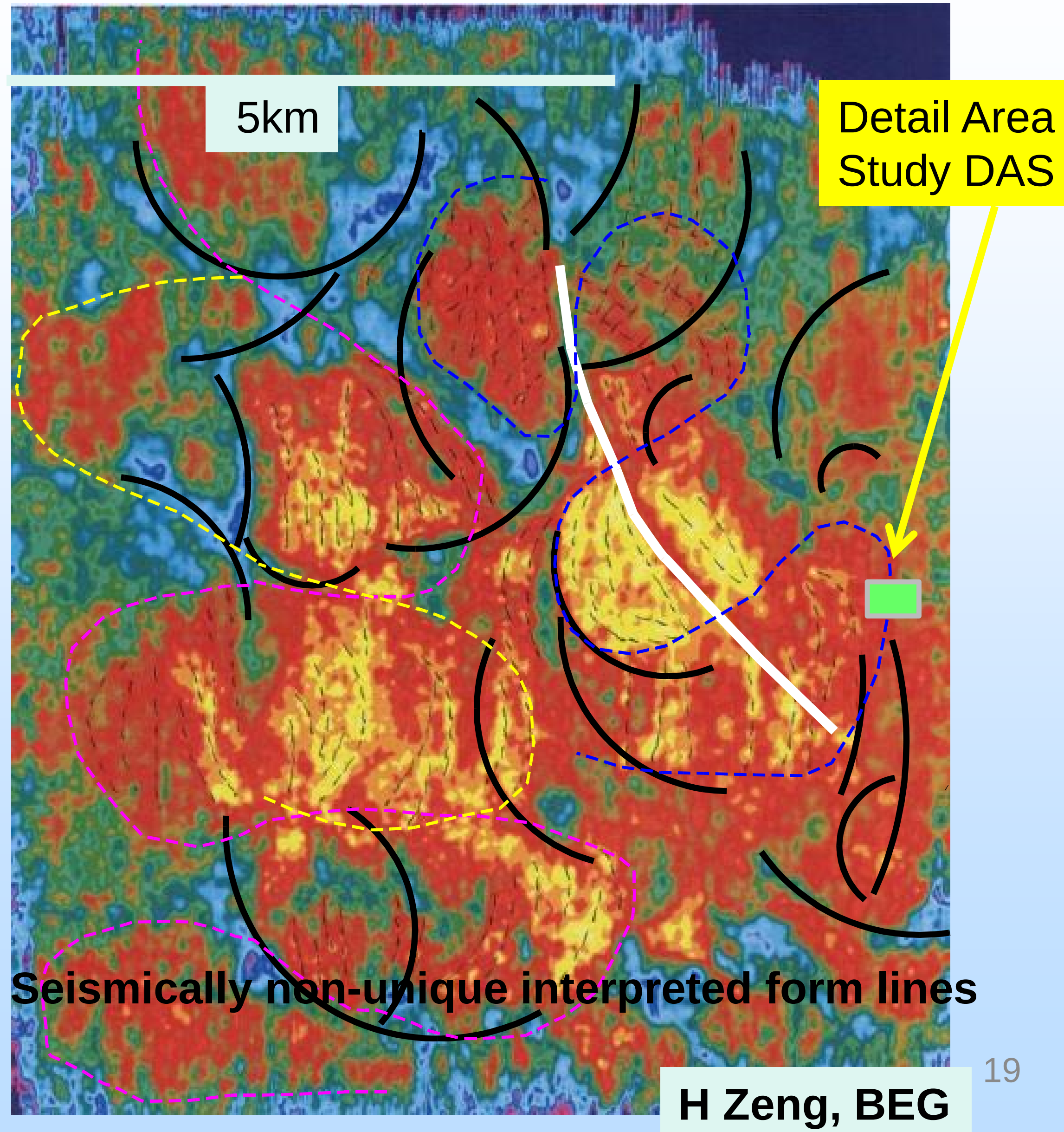
F1 **F2** **F3**



Lawrence Livermore National Laboratory

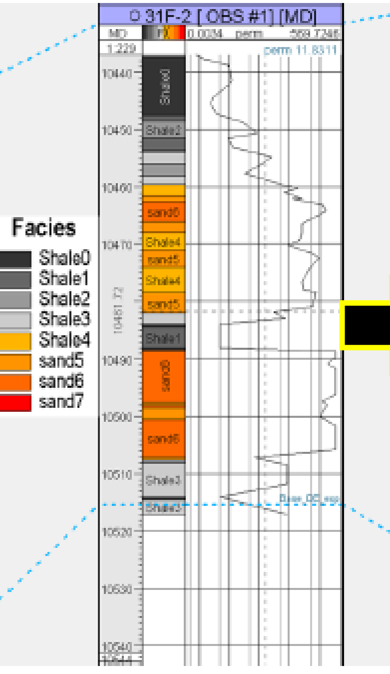
C. Carrigan, X Yang, LLNL
D. LaBrecque Multi-Phase Technologies

Site Characterization Approach

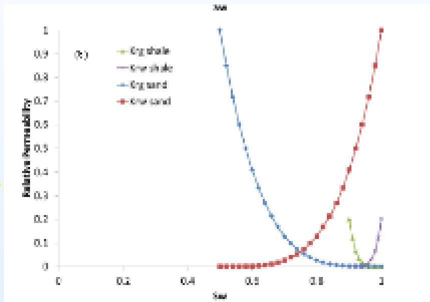


Modeling Approach's

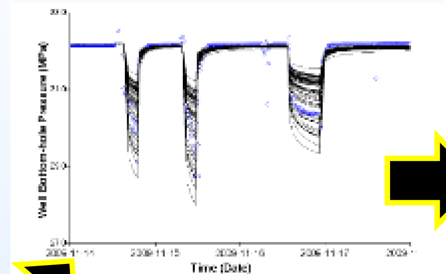
Reservoir characterization



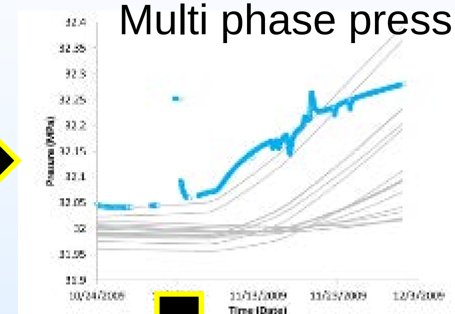
Relative permeablities



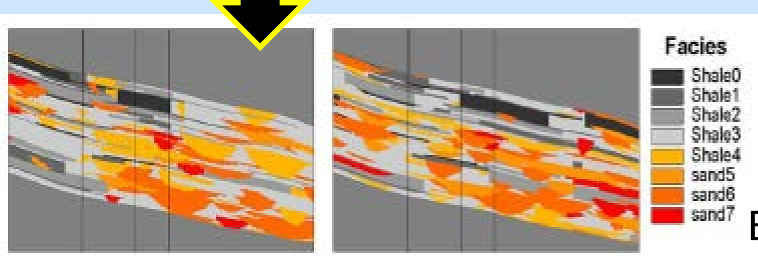
Single phase pressure

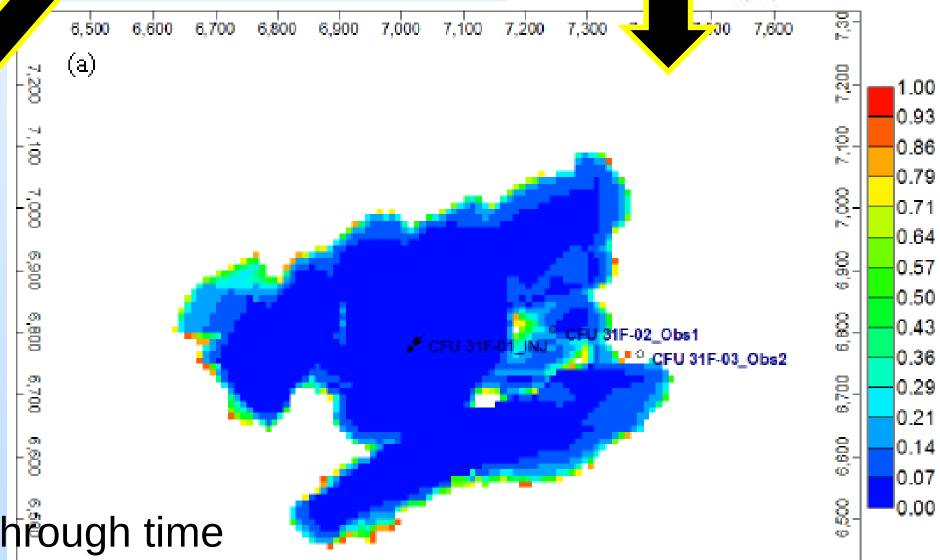


Multi phase pressure



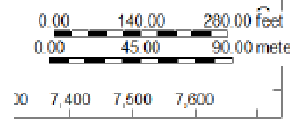
Probabilistic realizations of reservoir architecture





Breakthrough time

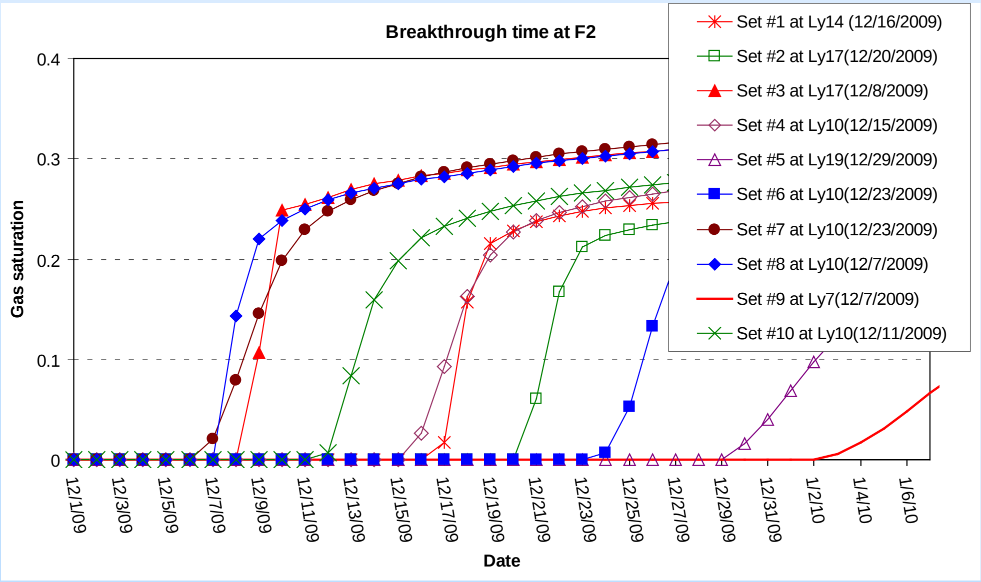
Realization Number	31F-2	31F-2/ Modified	31F-3	31F-3/ Modified
35	12/8/09	12/7/09	12/26/09	12/21/09
18	12/15/09	12/13/09	1/2/10	12/28/10
8	1/3/10	12/28/10	1/24/10	1/15/10
15	12/20/09	12/16/09	1/11/10	1/2/10
ACTUAL		12/12/09		12/16/09



Hosseini and others, 2013
Cranfield

Modeling

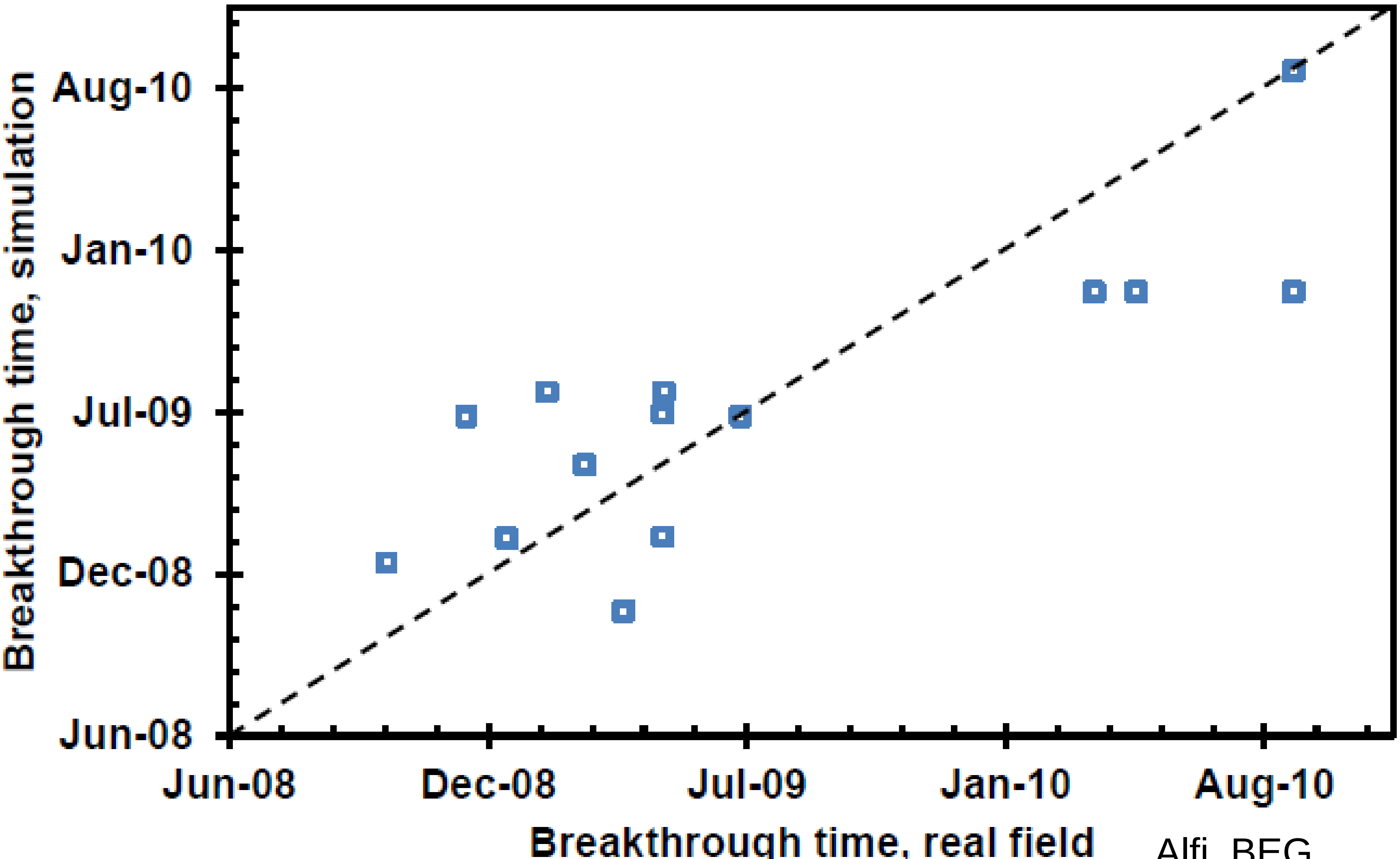
- Multiple models (119)
  - I-PARS
  - SIM-SEQ model approach comparison
- CGM GEM
  - Probabilistic approaches
  - Match 100 realizations to subset of modeled data
  - Forward model scenarios



Pre-injection forward model breakthrough times to design geochemical sampling

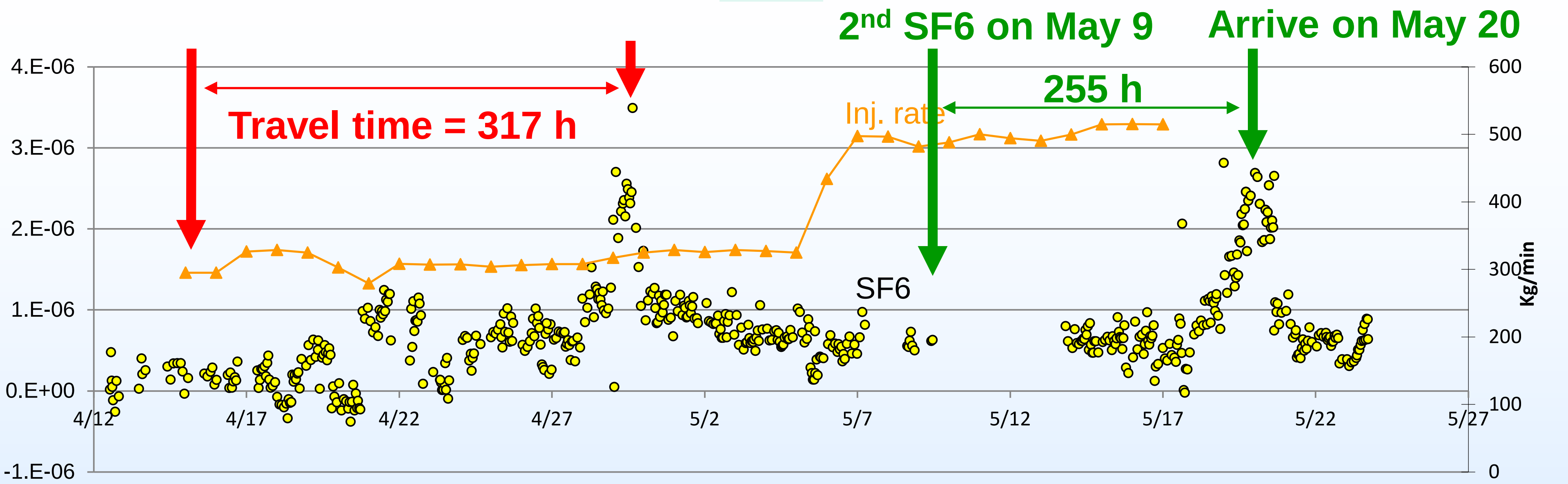
Jong Won Choi BEG

History Match Modeled and measured CO_2 breakthrough

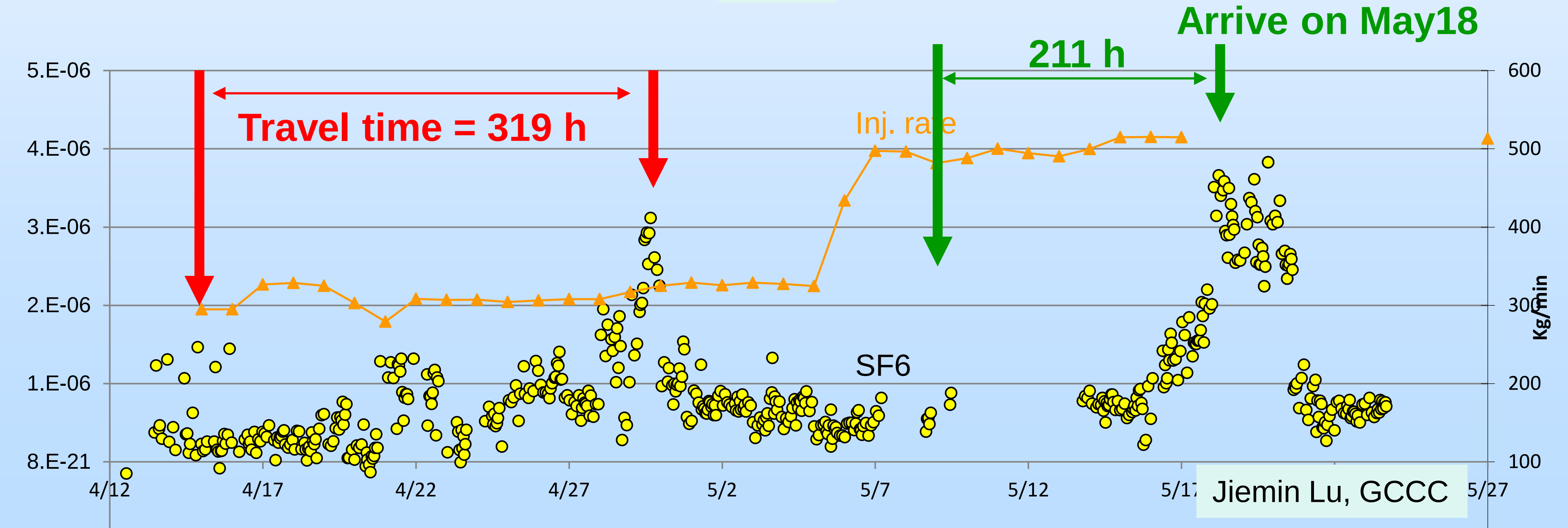


Alfi, BEG

CFU31F-2, 68 m away from injector SF6

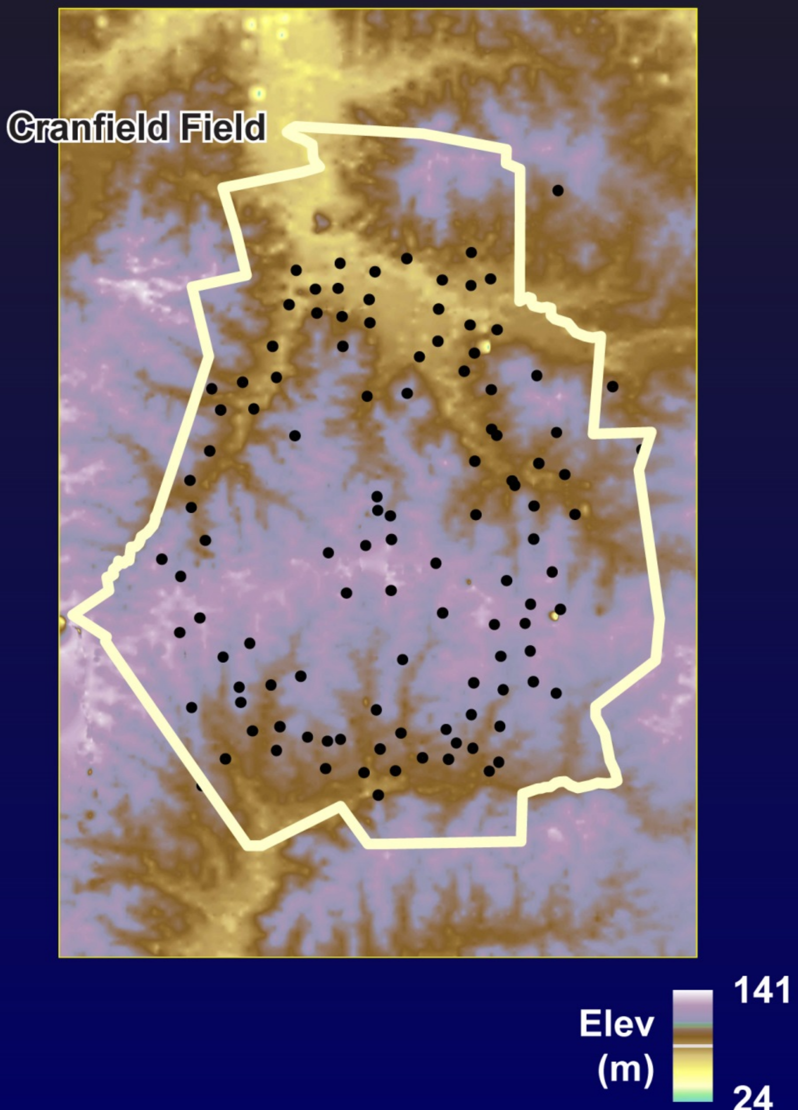


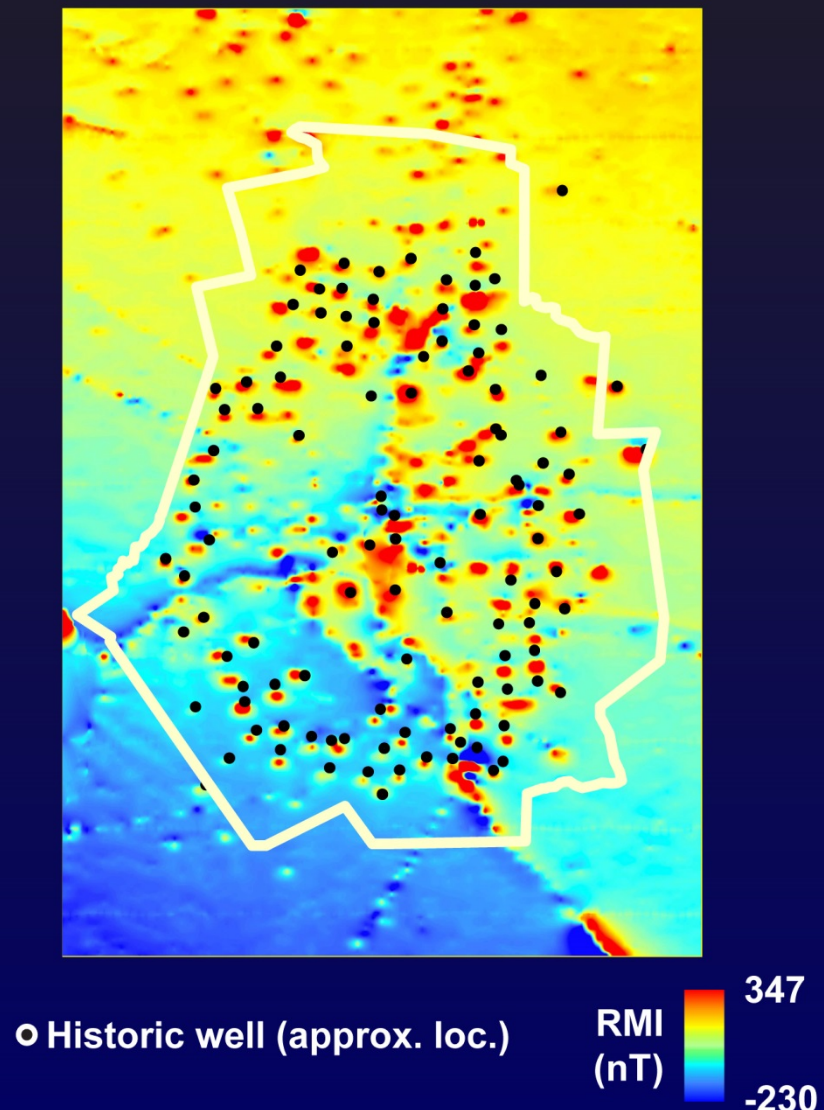
CFU31F-3, 112 m away from injector SF6



Jiemin Lu, GCCC

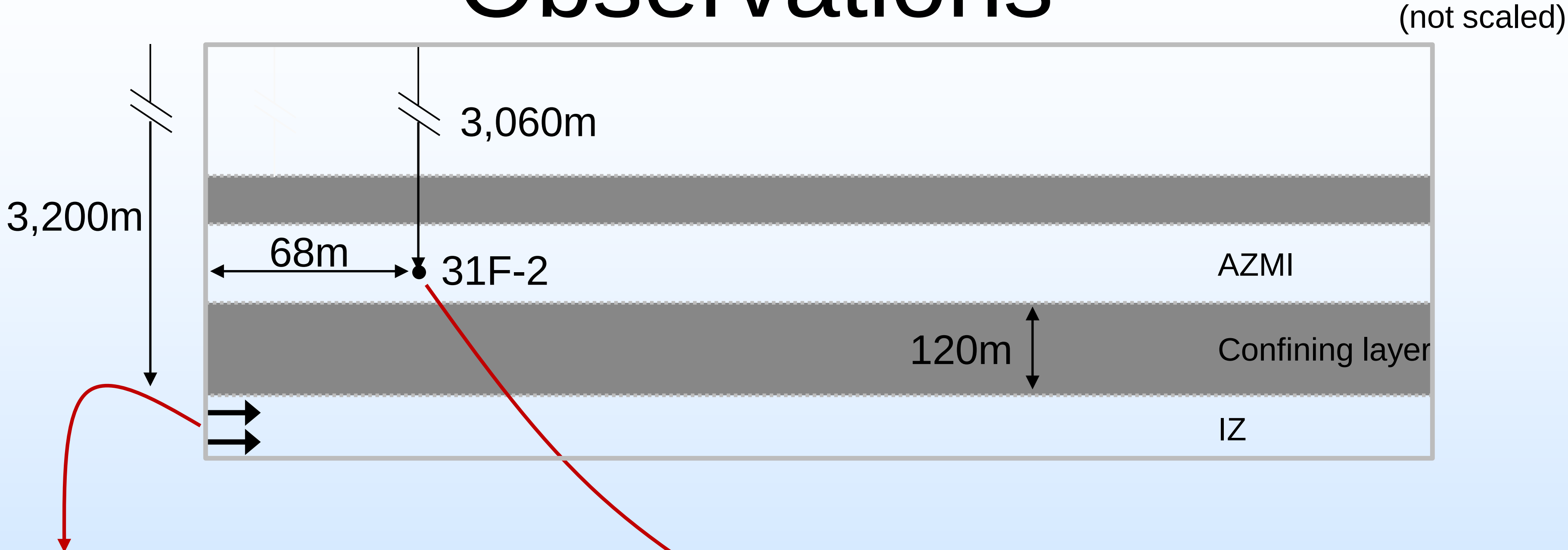
Cranfield Airborne Geophysical Survey

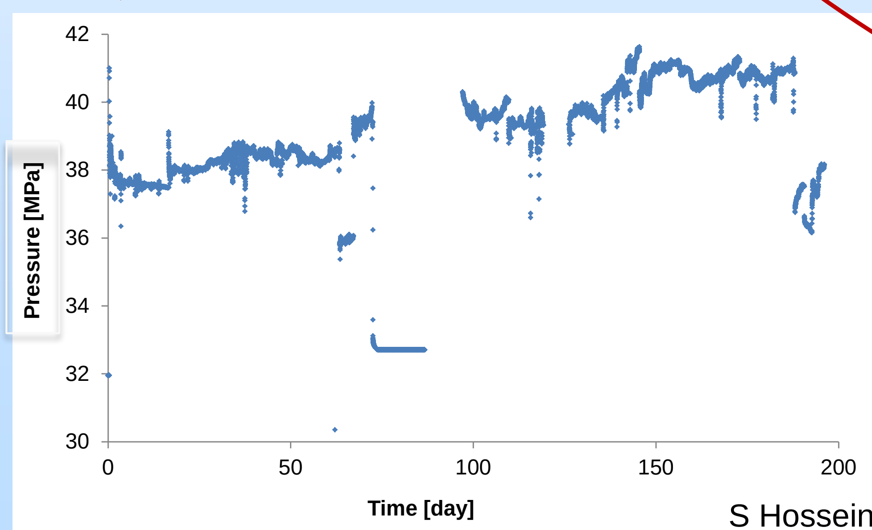


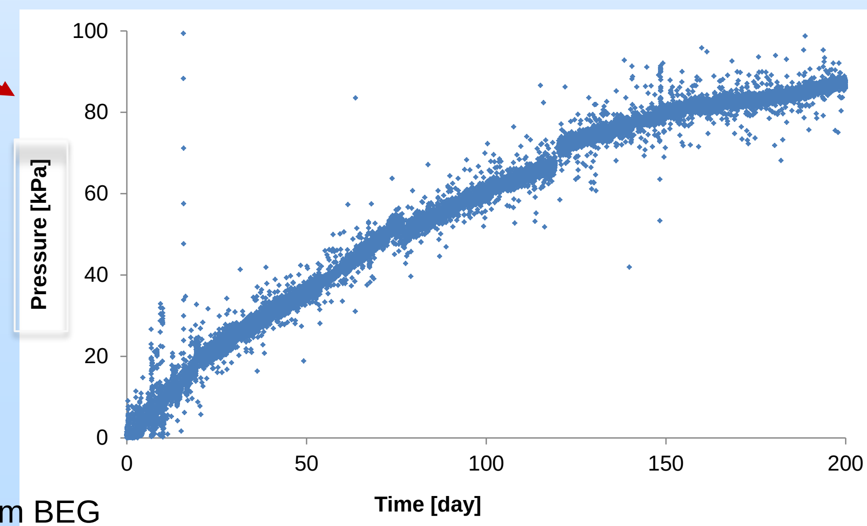


Jeff Paine BEG

Above-Zone Pressure Observations







S Hosseini, S. Kim BEG

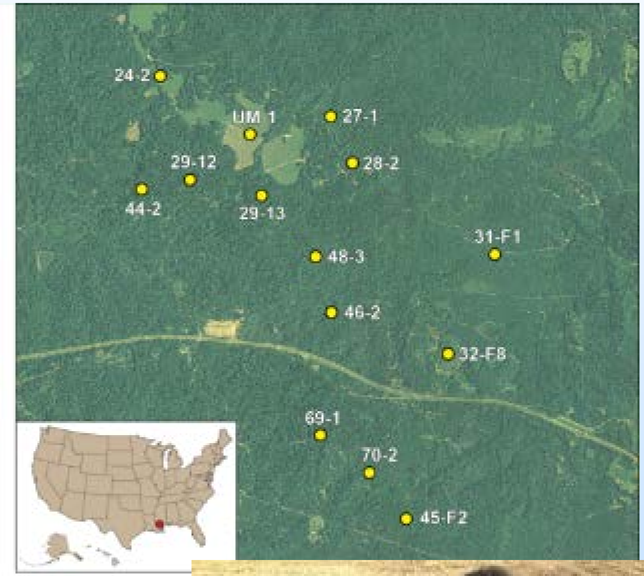
Groundwater at the Cranfield Site: Sampling

- More than 12 field campaigns since 2008
- ~ 130 groundwater samples collected for chemical analysis of

  Cations: Ag, Al, As, Ba, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Pb, Se, Zn
  Anions: F^-, Cl^-, SO_4^{2-}, Br^-, NO_3^-, PO_4^{3-}
  TOC, TIC, pH, Alkalinity, VOC, δC13

  On-site: pH, temperature, alkalinity, water level

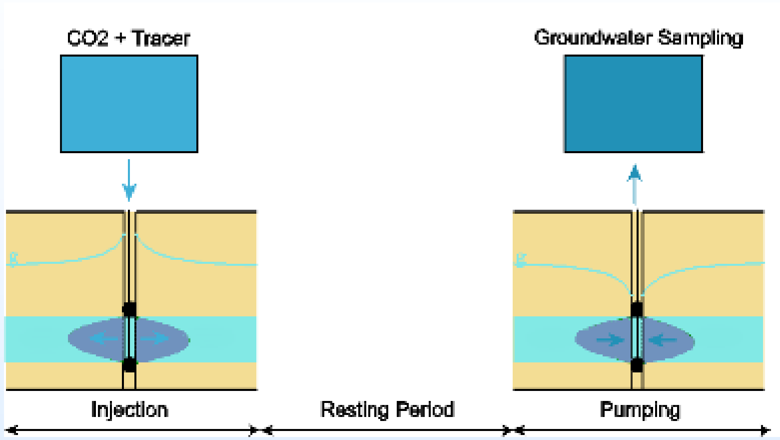
- ~10 samples for noble gases
- ~20 groundwater samples for dissolved CH_4
- 15 Water wells



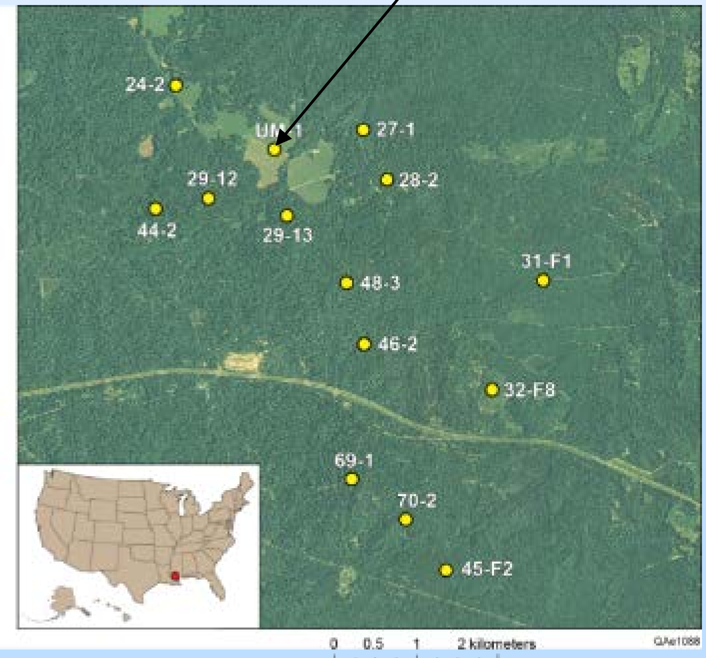
C. Yang, BEG

Groundwater at the Cranfield Site Single-Well Push-Pull Test

- Maximum concentrations of trace metals observed, such as and Pb, are much less than the EPA contamination levels;
- Single well push-pull test appears to be a convenient field controlled-release test for assessing potential impacts of CO_2 leakage on drinking groundwater resources;



Testing well



Results were summarized in the following paper

International Journal of Greenhouse Gas Control 18 (2013) 375–387

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

ELSEVIER

Single-well push–pull test for assessing potential impacts of CO_2 leakage on groundwater quality in a shallow Gulf Coast aquifer in Cranfield, Mississippi

Changbing Yang[a,*], Patrick J. Mickler[a], Robert Reedy[a], Bridget R. Scanlon[a], Katherine D. Romanak[a], Jean-Philippe Nicot[a], Susan D. Hovorka[a], Ramon H. Trevino[a], Toti Larson[b]

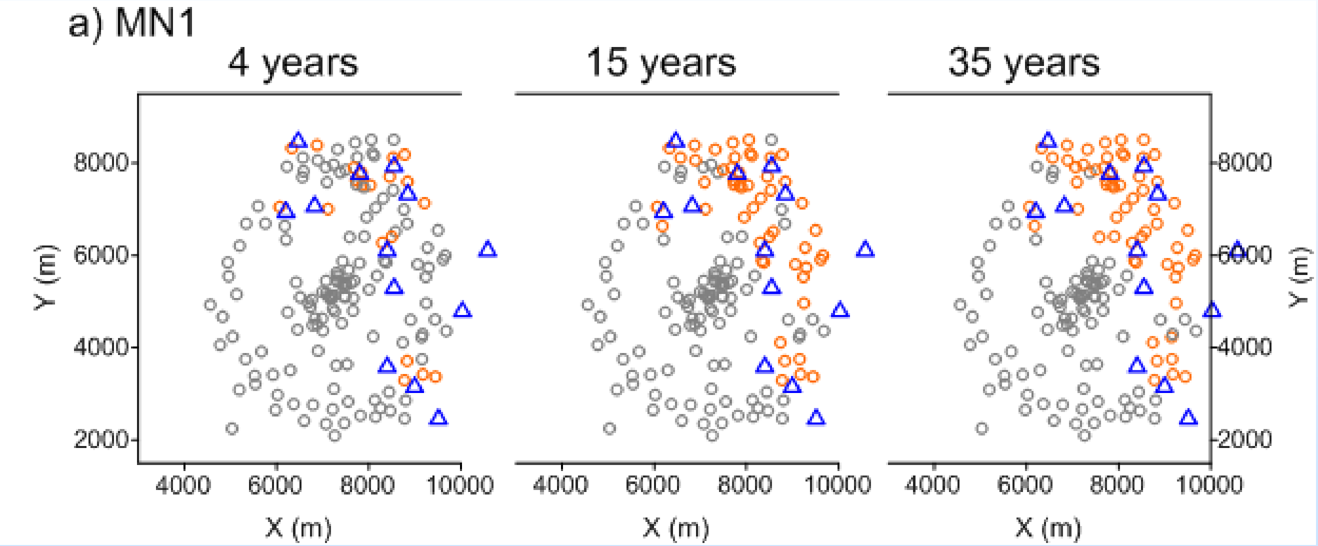
[a] Bureau of Economic Geology, The University of Texas at Austin, 10100 Burnet Road, Bldg 130, Austin, TX 78758, United States
[b] Department of Geological Sciences, The University of Texas at Austin, 2275 Speedway Stop C9000, Austin, TX 78712-1722, United States

C. Yang, BEG

Groundwater Monitoring Network Efficiency

$$ME = \frac{W^d}{W^T}$$

- 20/151=0.13 by 4 years
- 50/151=0.33 by 15 years
- 58/151=0.38 by 35 years



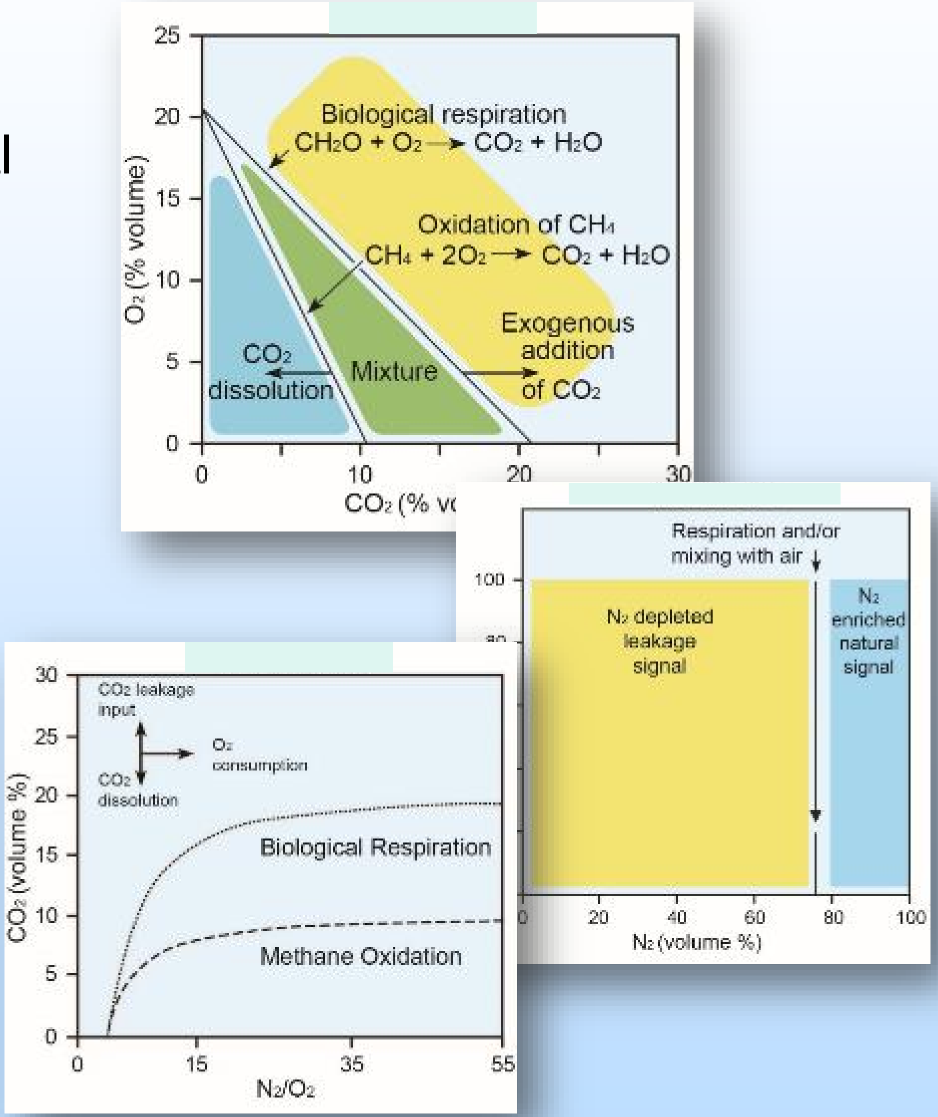
CO_2 leakage from a P&A well is detected by a monitoring net work if change in DIC, dissolved CO_2, or pH in any one of wells of the monitoring network is higher than one standard deviation of the groundwater chemistry data collected in the shallow aquifer over the last 6 years.

Changbing Yang

Process-Based Soil Gas Monitoring

- No need for years of background measurements.
- Promptly identifies leakage signal over background noise.
- Uses simple gas ratios

  (CO_2, CH_4, N_2, O_2)
- Can discern many CO_2 sources and sinks
  - Biologic respiration
  - CO_2 dissolution
  - Oxidation of CH_4 into CO_2 (Important at CCUS sites)
  - Influx air into sediments
  - CO_2 leakage



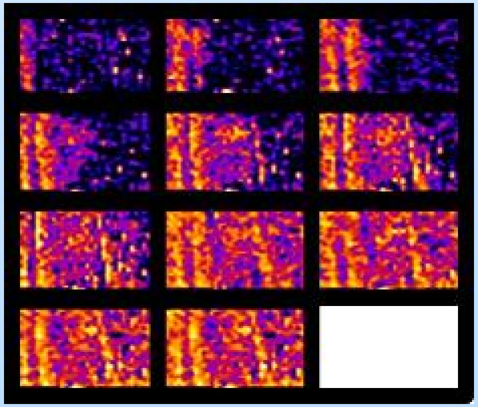
Katherine Romanak BEG

Major Technical Accomplishments

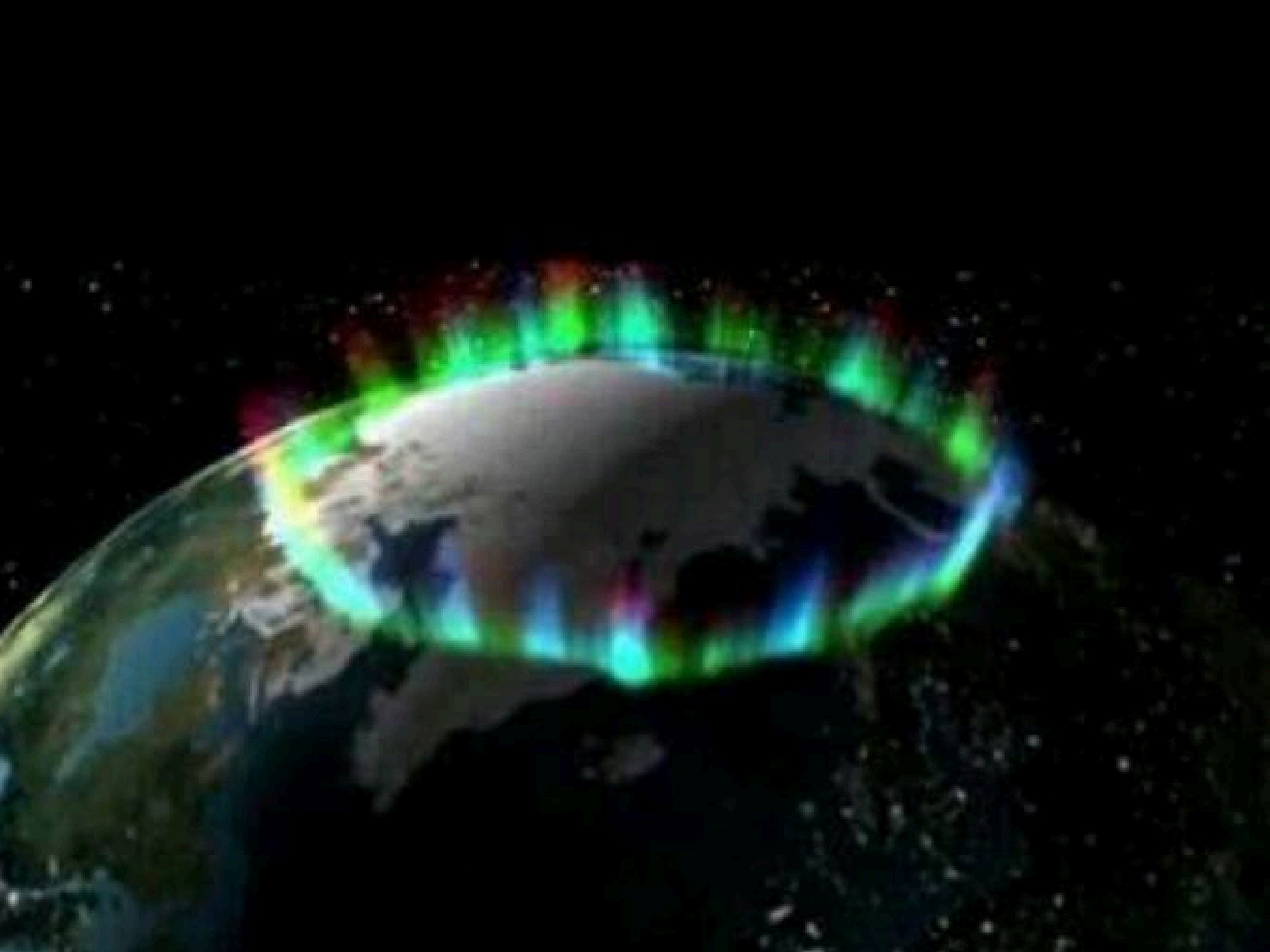
- Multiphysics CO_2 plume detection
  - Surface 4-D; Azimuthal VSP, cross well, ERT, Pulsed neutron, fiber-optic thermal, sonic logs, PNC logs
  - Limits evaluated (depth, gas)
- In-zone and Above-zone pressure method validation
  - Casing deployed BHP with real-time readout
- Minimal geochemical change in-zone, geomechanical softening
- Non-detect of microseismicity by RITE at >1000 psi pressure increase
- Reservoir response to heterogeneity – non-linear breakthrough
- Groundwater sensitivity assessment
  - Value of DIC, sensitivity to carbonate in rock matrix
  - Value for incident or allegation
- Process-based soil gas
  - Reduced sensitivity to environmental fluctuation, not dependent on baseline. Value of attribution

Rate of Progress

- All elements have been completed on plan
  - (three years injection + three “post closure”)
- Under budget
  - Major saving was not needing to purchase CO_2 to meet the project goal; commercial injection was high during early project stages
- Emphasis on publication and technical outreach
  - 93 technical papers published 2009-2017
- Leveraged by data-sharing



Coreflood micro CT J Ajo-Franklin LBNL



Lessons Learned (where is improvement needed?)

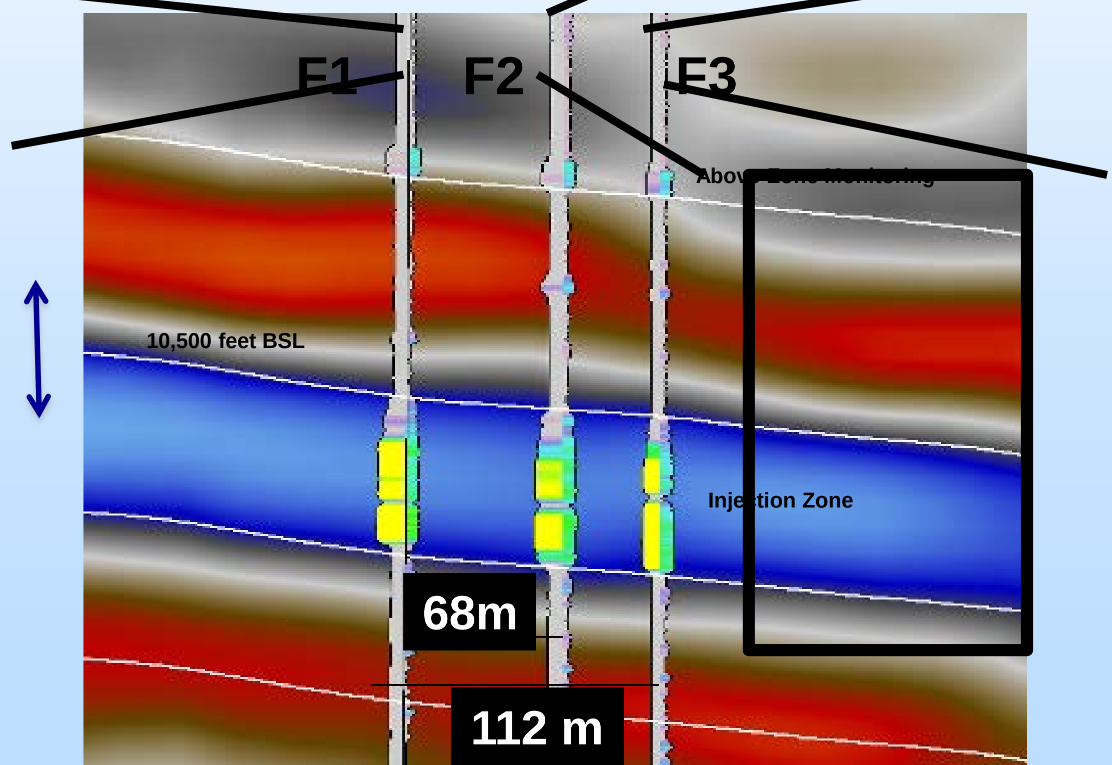
- Simplified AZMI completions
- Improved high temperature and pressure equipment
- Simplified ERT deep installation
- Remote tools for water and soil gas surveillance
- Maturation of monitoring design planning
  - Interaction with international community

Detailed Area Study (DAS)

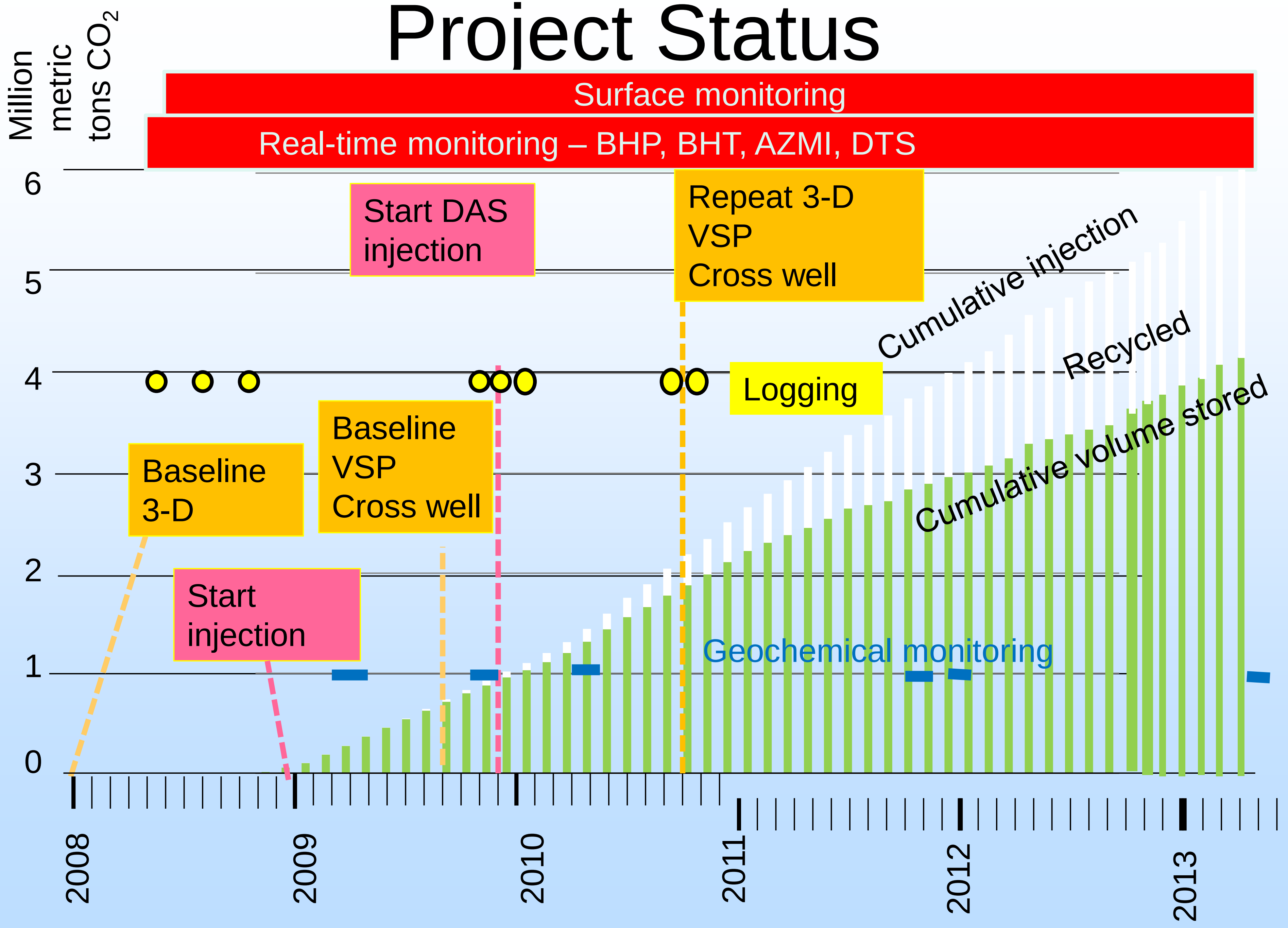
Closely spaced well array to examine flow in complex reservoir

Tuscaloosa D-E reservoir

Petrel model Tip Meckel
Time-lapse cross well Schlumberger



Project Status



SECARB Anthropogenic Test Update

Carbon Storage and Oil and Natural Gas Technologies Review Meeting

Rob Trautz, **Electric Power Research Institute**
David Riestenberg, **Advanced Resources International, Inc.**

August 1-3, 2017
Pittsburgh, PA

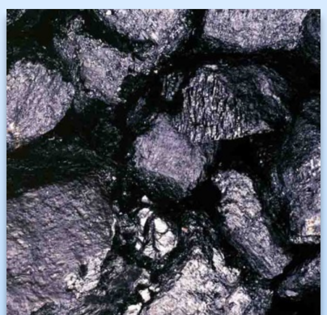
Acknowledgement

This presentation is based upon work supported by the Department of Energy National Energy Technology Laboratory under **DE-FC26-05NT42590** and was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Presentation Outline

1. Project Introduction
2. Project Status
3. VSP Results
4. Simulation Update
5. Supporting Information





SECARB Anthropogenic Test Introduction

Project Goals and Objectives

Baseline 1 year	Injection 2 years	Post 3 years
APR 2011 to AUG 2012	SEP 2012 to SEP 2014	SEP 2014 to SEP 2017

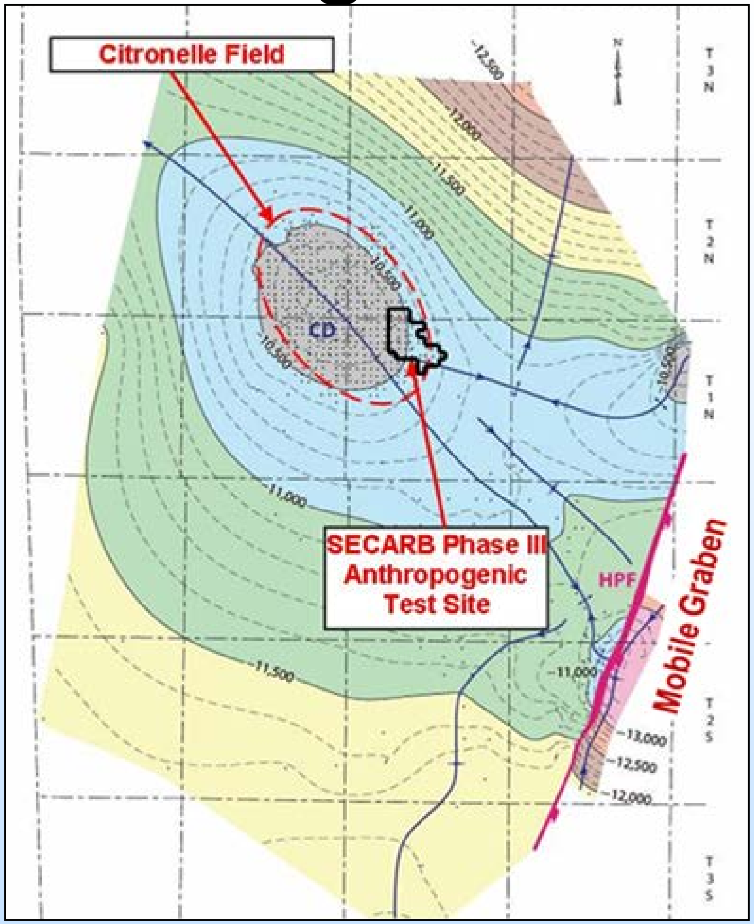
1. Test the CO_2 flow, trapping and storage mechanisms of the Paluxy;
2. Demonstrate how a saline reservoir's architecture can be used to maximize CO_2 storage and minimize the areal extent of the CO_2 plume;
3. Test the adaptation of commercially available oil field tools and techniques for monitoring CO_2 storage;
4. Test experimental CO_2 monitoring activities, where such technologies hold promise for future commercialization;
5. Begin to understand the coordination required to successfully integrate all four components (capture, transport, injection and monitoring) of the project; and
6. Document the permitting process for all aspects of a CCS project;
7. Facilitate and enable CCS commercialization.

Project Accomplishment: Demonstration to Full-Scale Commercialization

SECARB Demo Goes Commercial!

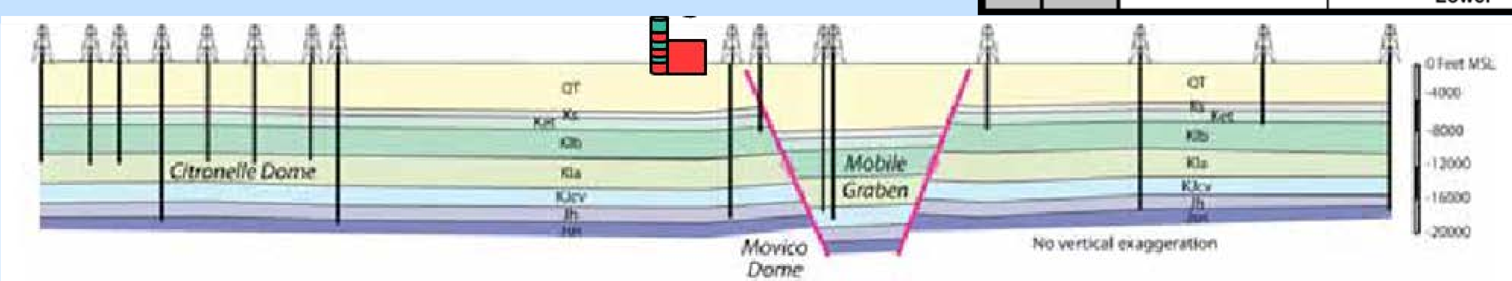
- NRG Energy (Houston, TX)
- Interest in Plant Barry Demonstration
- Plant scale-up to 240 MW
- Post-combustion slip-stream
- Captures 5,200 tons CO_2/day or 90% of CO_2
- Pipeline to Hill Corps West Ranch Oil Field (70 miles)
- EOR 300 bbls/day to 15,000 bbls/day!
- 60 million bbls Recoverable Oil

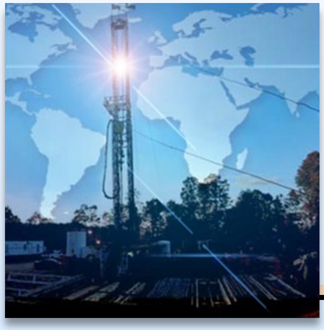
Storage Site: The Citronelle Oilfield



Structure map and cross section by GSA

System	Series	Stratigraphic Unit	Major Sub Units	Potential Reservoirs and Confining Zones
Tertiary	Plio-Pliocene		Citronelle Formation	Freshwater Aquifer
	Miocene	Undifferentiated		Freshwater Aquifer
	Oligocene		Chickasawhay Fm.	Base of USDW
		Vicksburg Group	Bucatunna Clay	Local Confining Unit
	Eocene	Jackson Group		Minor Saline Reservoir
		Claiborne Group	Talahatta Fm.	Saline Reservoir
		Wilcox Group	Hatchetigbee Sand	Saline Reservoir
	Paleocene		Bashi Marl	
			Salt Mountain LS	
		Midway Group	Porters Creek Clay	Confining Unit
Cretaceous	Upper	Selma Group		Confining Unit
		Eutaw Formation		Minor Saline Reservoir
		Tuscaloosa Group	Upper Tusc.	Minor Saline Reservoir
			Mid. Tusc. Marine Shale	Confining Unit
			Lower Tusc. Pilot Sand Massive sand	Saline Reservoir
	Lower	Washita-Fredericksburg	Dantzler sand	Saline Reservoir
			Basal Shale	Primary Confining Unit
		Paluxy Formation	'Upper' 'Middle' 'Lower'	Injection Zone
		Mooringsport Formation		Confining Unit
		Ferry Lake Anhydrite		Confining Unit
		Donovan Sand	Rodessa Fm.	Oil Reservoir
			Upper' 'Middle'	Minor Saline Reservoir
			'Lower'	Oil Reservoir





Project Status

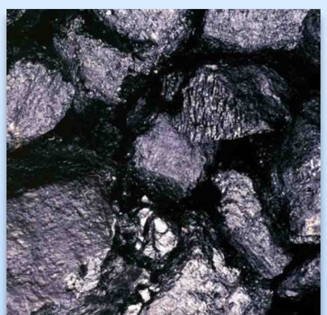
Storage Project Status

- Injected 114,104 metric tonnes from Aug. 22, 2012 – Sept. 1, 2014
- Three-year Post-Injection Site Care (PISC) Period
- PISC Activities
  - Soil CO_2 flux measurements
  - Shallow and deep groundwater sampling
  - Reservoir Temperature/Pressure monitoring
  - Pulse-neutron logging
  - Final VSP survey (Jan. 2017)
  - Reservoir simulation updates

Storage Project Status - continued

- Submitted the UIC permit closure request to the State regulator for review on May 19, 2017
  - Basis for closure includes multiple lines of evidence (e.g., seismic surveys, well logs, tracer sampling, groundwater sampling…) and long-term model predictions
  - Regulatory feedback pending
- Closure Activities
  - Temporary or permanent abandonment of project wells and transfer of test site to oilfield operator
  - Oil and Gas Board of Alabama accepted jurisdiction over the D 9-9#2 well





VSP Results

Vertical Seismic Profile (VSP)

- A key component of the MVA was to capture a vertical seismic profile prior to, and following injection of CO_2
- The chief objective of the VSP was intended to delineate the plume's location in the subsurface
- This technique could also be applied to capture migration of the plume over time.

VSP Acquisitions

- Geophones were run into the injection well to capture the seismic response generated at 9 offset well locations concentrically located around the receiver.

- A baseline survey took place in 2012
- Post injection VSP was conducted in January 2017.

Procedural Differences Between Analyses

2012	2017
• 80 level array	• 10 level array
• 25ft receiver spacing	• 50ft spacing (staggered 500ft to achieve 2000ft aperture)
• 24000lbs Vibroseis source	• 64000lbs Vibroseis source
• Water filled well	• Mud filled well
• Array deployed with tubing conveyed system	• Well lubricator needed for deployment and well control
• Analog Geophones	• Digital Geophones

Key Variations in Analysis Protocol

- Poor tool availability and well constraints necessitated a shorter two-sensor array for the post-injection monitoring survey
- The two level tool was moved up and down the well over the same 2000 foot interval
  - This resulted in a sparse dataset with samples every 500 ft
- The seismic source was different in both analyses (24,000 lbs vs. 64,000 lbs).

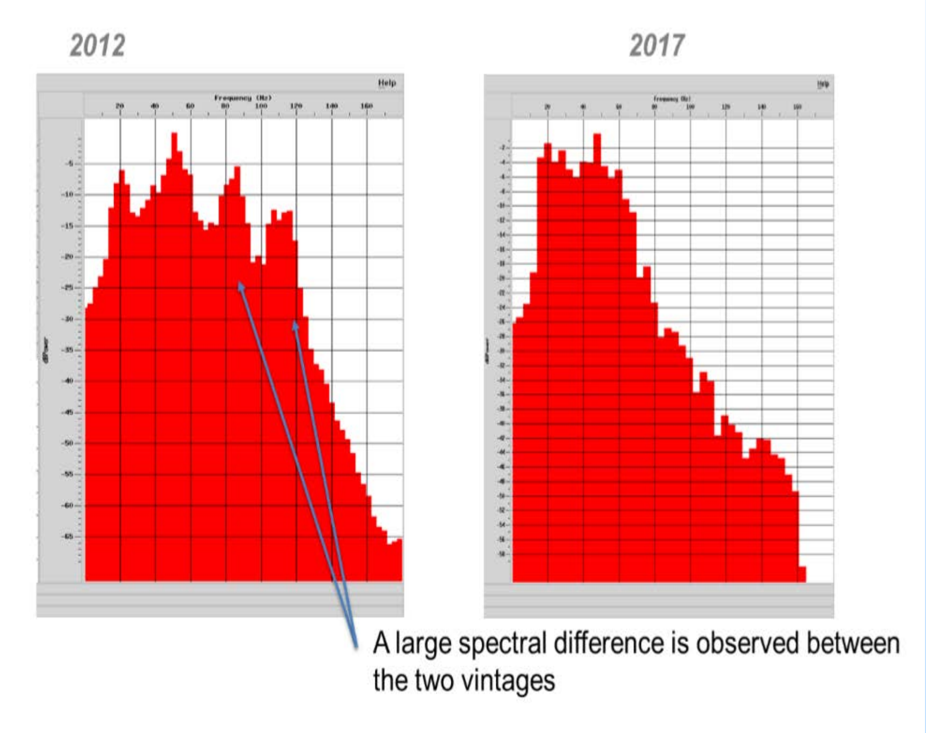
Spectral Analysis

- Spectral analysis for a selected source from the 2012 80-level data (left) and from the 2017 10-level data (right).

- The same source-frequency sweep was used for each.

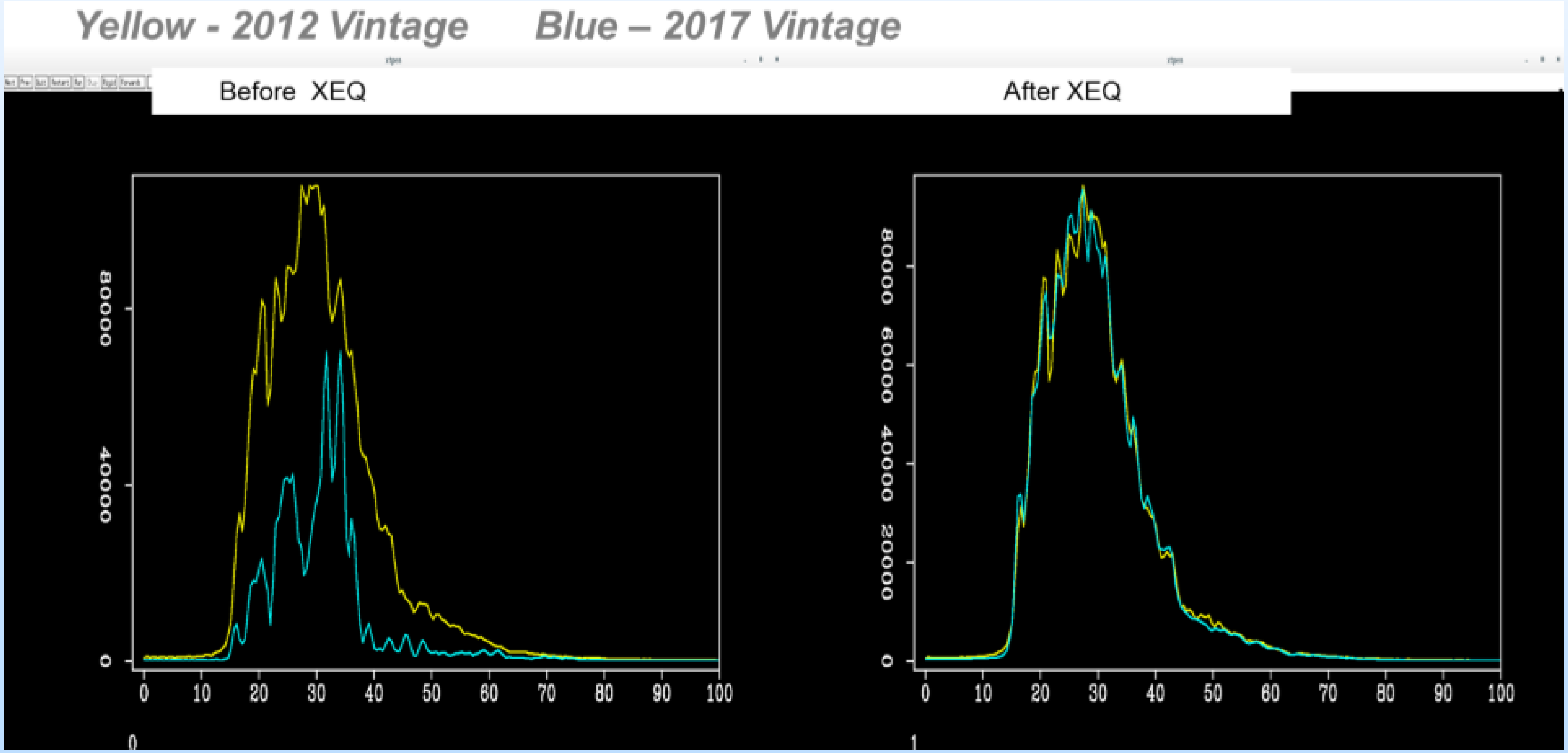
- The spectra of 2012 has higher resonant modes due to the smaller Vibroseis.

- The 2012 vintage also includes resonant modes due to tube wave energy.

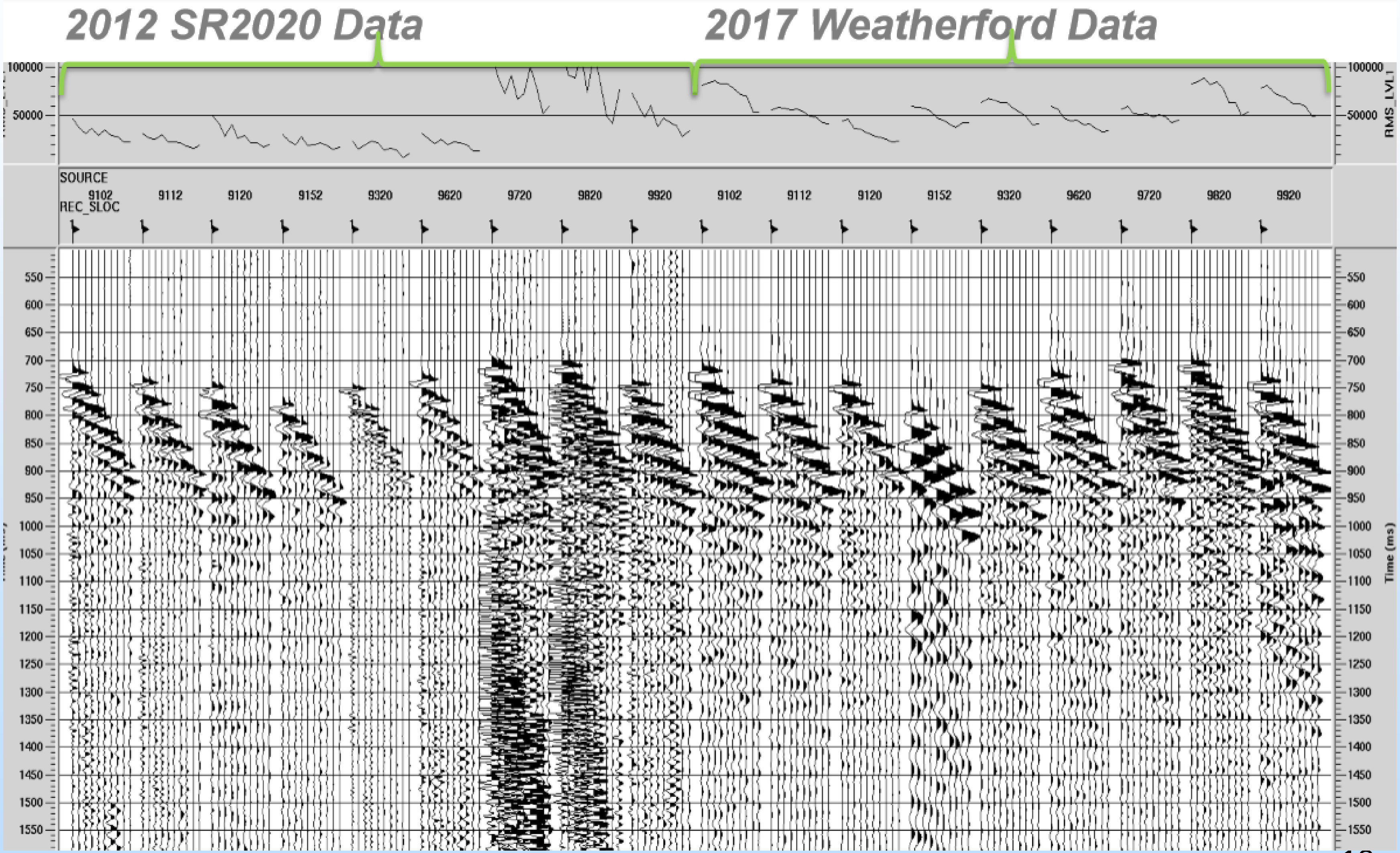


Comparison of Spectral Analysis Before and After Cross Equalization Processing

Spectra of data before (left) and after (right) cross-equalization (XEQ) processing.
The XEQ processing steps have reduced the spectral variation between the two data vintages.

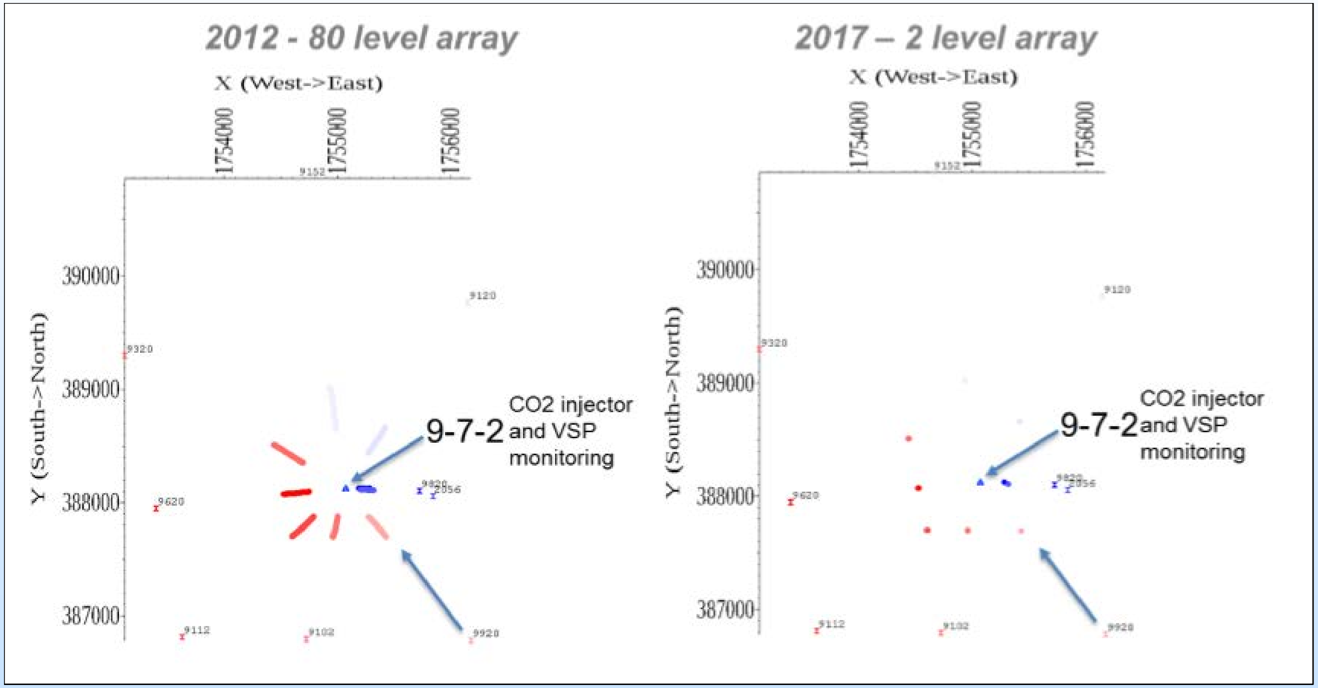


Amplitude Scalar Global Match



Comparison of Subsurface Array Coverage

- Subsurface illumination coverage of the target zone



2012 – 80 level array

2017 – 2 level array

- For the array to see any CO_2 anomaly, the plume must intersect with the coverage pattern.

Data Assessment

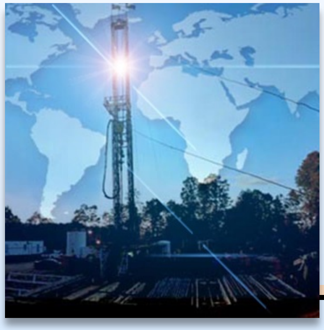
- Various seismic processing techniques were conducted to equalizing the sources from the baseline and monitor surveys
  - This would delineate any difference in the seismic response associated with the CO_2 injection.
- Time-lapse processing was conducted to remove any differences generated by changes in the sensors, the source weight and ground conditions.

HOWEVER:

- Seismic processing yielded large residuals that make it difficult to assess the propagation of the CO_2 at this particular location.
- The input data from the post-injection survey suggests acquisition conditions were much too different to begin with.

VSP Conclusions

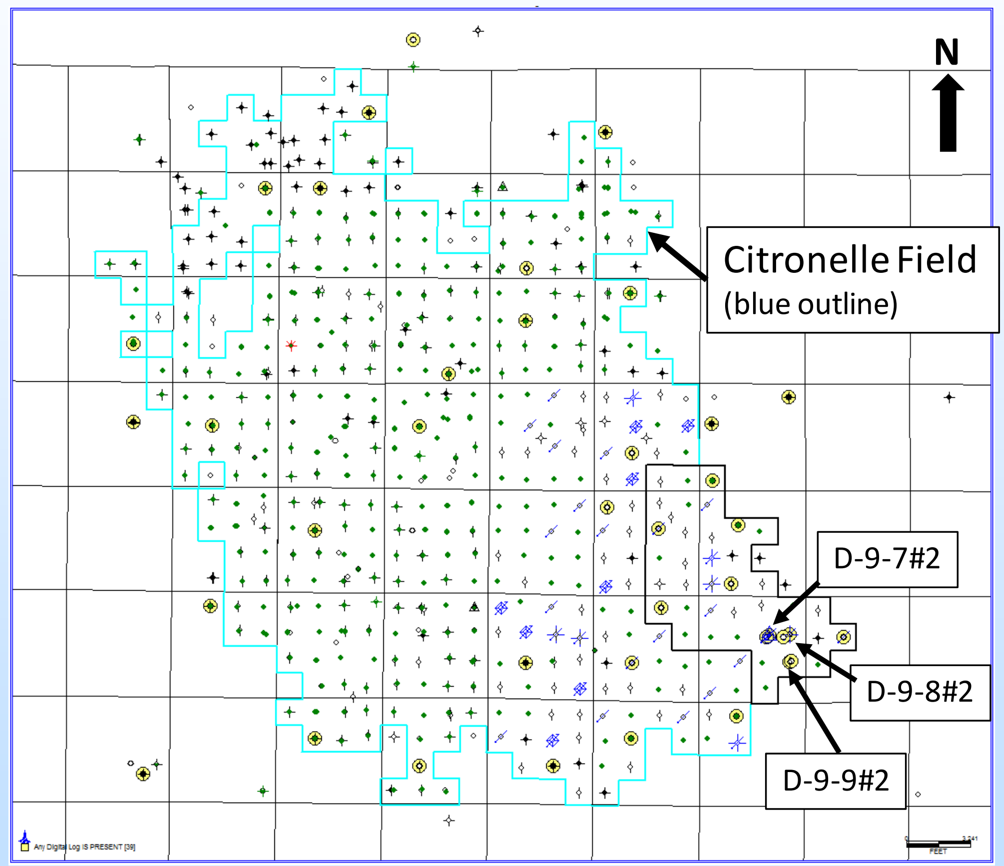
- Two vintages of VSP data were acquired in well D9-7#2 of the Citronelle CO2 storage facility in 2012 and 2017.
- Each vintage was acquired with a different seismic sensor, a different seismic source, and in different well conditions on top of environmental and surficial seasonal changes.
  - These changes make comparing the different data vintages difficult even after carefully processing the seismic data
- In terms of future work for monitoring the subsurface using these type of technologies it is important to consider using <u>repeatable tools.</u>
- It is possible that using another monitoring well, where a larger seismic array can be deployed may be beneficial to create a denser dataset.
- Having more densely-sampled datasets, by using either more sensors or more sources, could help detect very weak CO2-related signals that may be buried within high levels of noise.



Simulation Update

Updating the Porosity and Permeability Maps

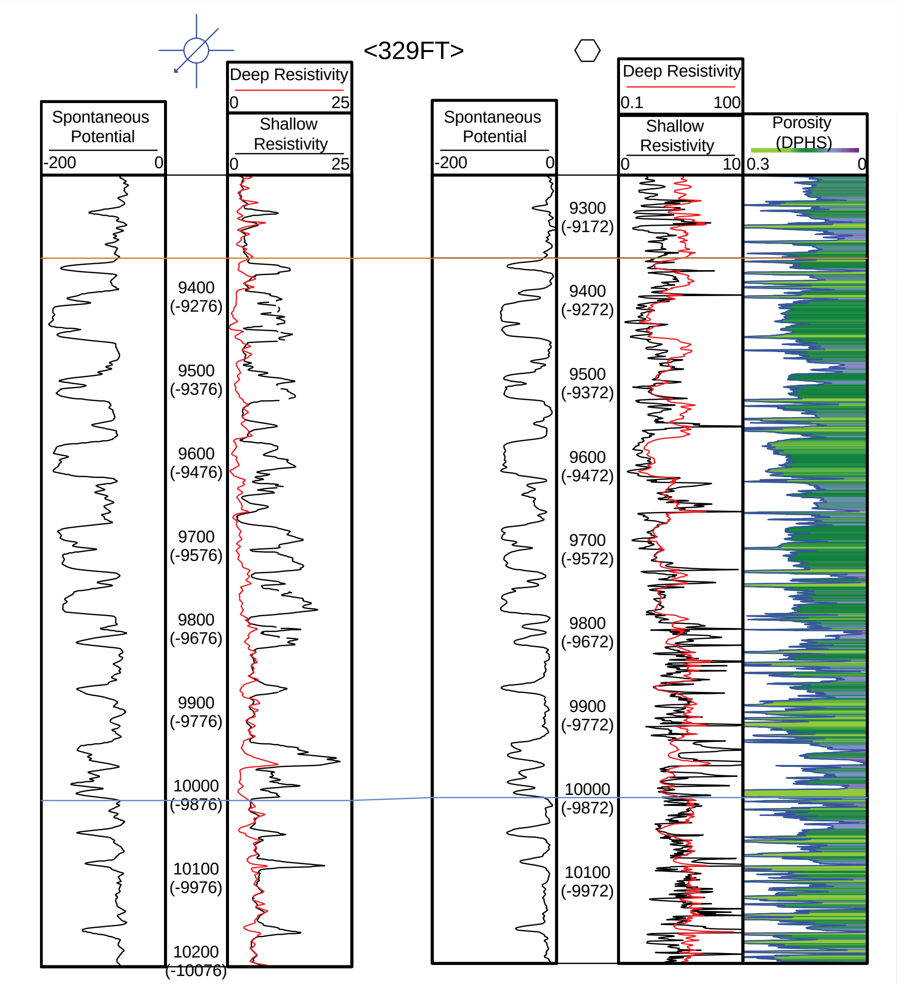
- The previous model had constant porosity and permeability per layer.
- The synthetic porosity logs, generated for the Commercial Scale Project, were used to create porosity maps.
- Porosity-Permeability transforms were developed from the Citronelle Whole Core dataset.
- The transforms were then used to generate permeability maps for the existing layers in the numerical model (55 total).



Synthetic Logs (yellow highlight)

Some Background - Synthetic Logs Generated Using a Neural Network

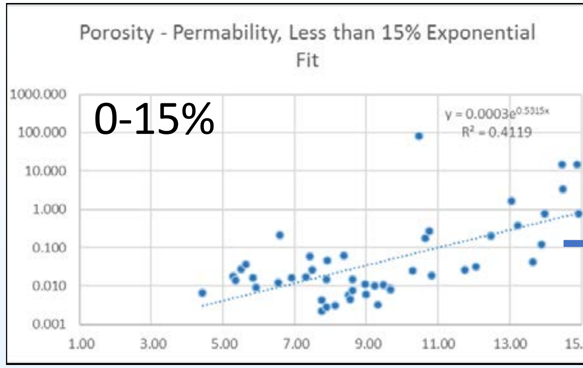
- 400+ total wells in Citronelle field on 40-ac spacing.
- Most of the legacy/vintage wells have resistivity logs only and no porosity logs.
- Digitized the SP & resistivity curves for 36 well logs.
- 3 new wells with modern porosity logs were drilled on well pads with existing abandoned wells.
- Using the paired wells (new + vintage) a neural network approach was used to predict porosity.

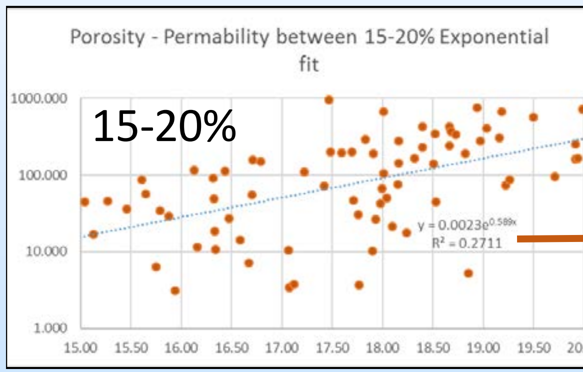


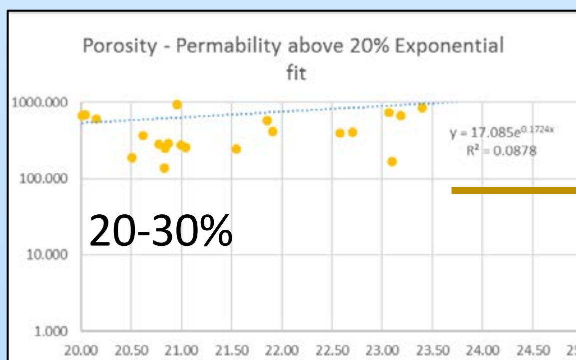
Porosity-Permeability Transforms Results

- Using the whole core dataset from the **D-9-7#2**, **D-9-8#2** and **D-9-9#2** wells Porosity and Permeability Transforms were developed for 3 porosity ranges

- The transforms were then applied to the porosity maps (for the appropriate ranges) to create the permeability maps.

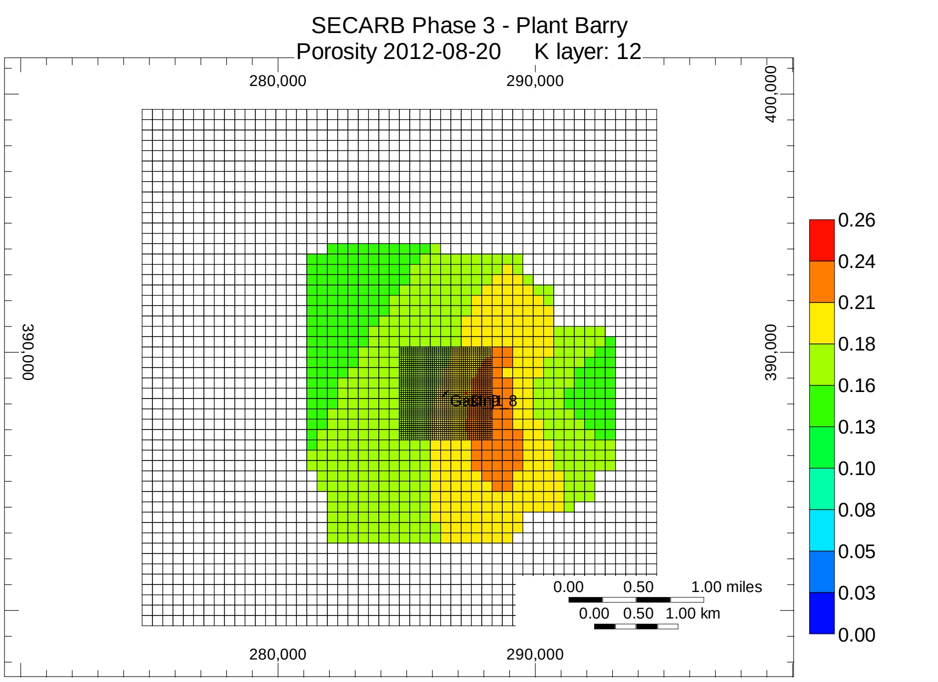




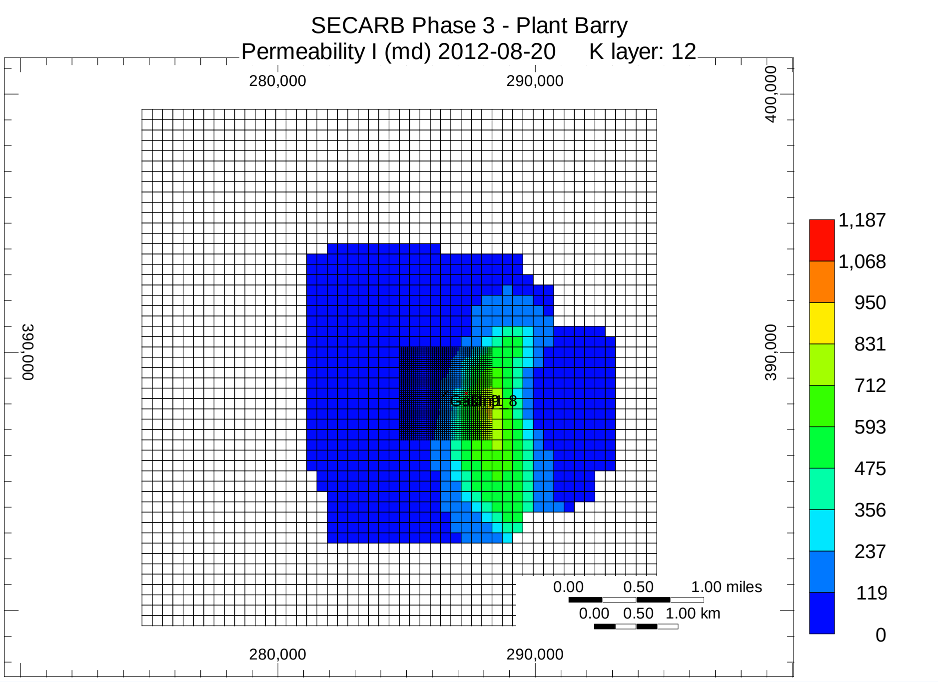


Porosity value	***Porosity Range***		
	>20% exponential	**15-20% exponential**	**>15% exponential**
5	40	0.04	0.004
6	48	0.08	0.007
7	57	0.14	0.012
8	68	0.26	0.021
9	81	0.46	0.036
10	96	0.83	0.061
11	114	1.50	0.10
12	135	2.70	0.18
13	161	5	0.30
14	191	9	0.51
15	227	16	0.87
16	270	28	1.48
17	320	51	2.52
18	380	92	4
19	452	167	7
20	537	300	12
21	638	541	21
22	758	976	36
23	901	1,758	61
24	1070	3,169	104
25	1272	5,711	177
26	1511	10,292	301
27	1795	18,549	512

Porosity and Permeability Map Examples 9460 Sand

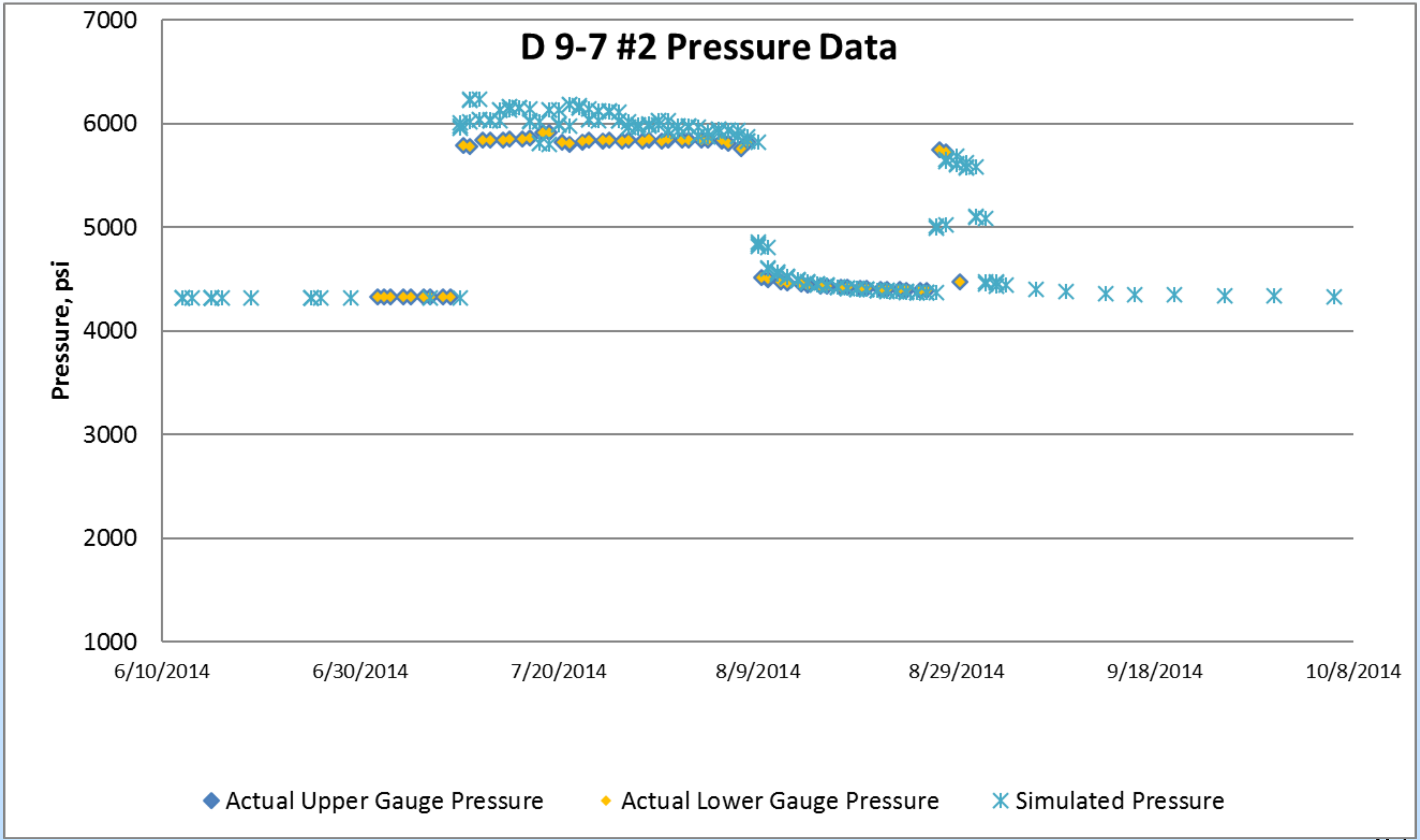


Porosity

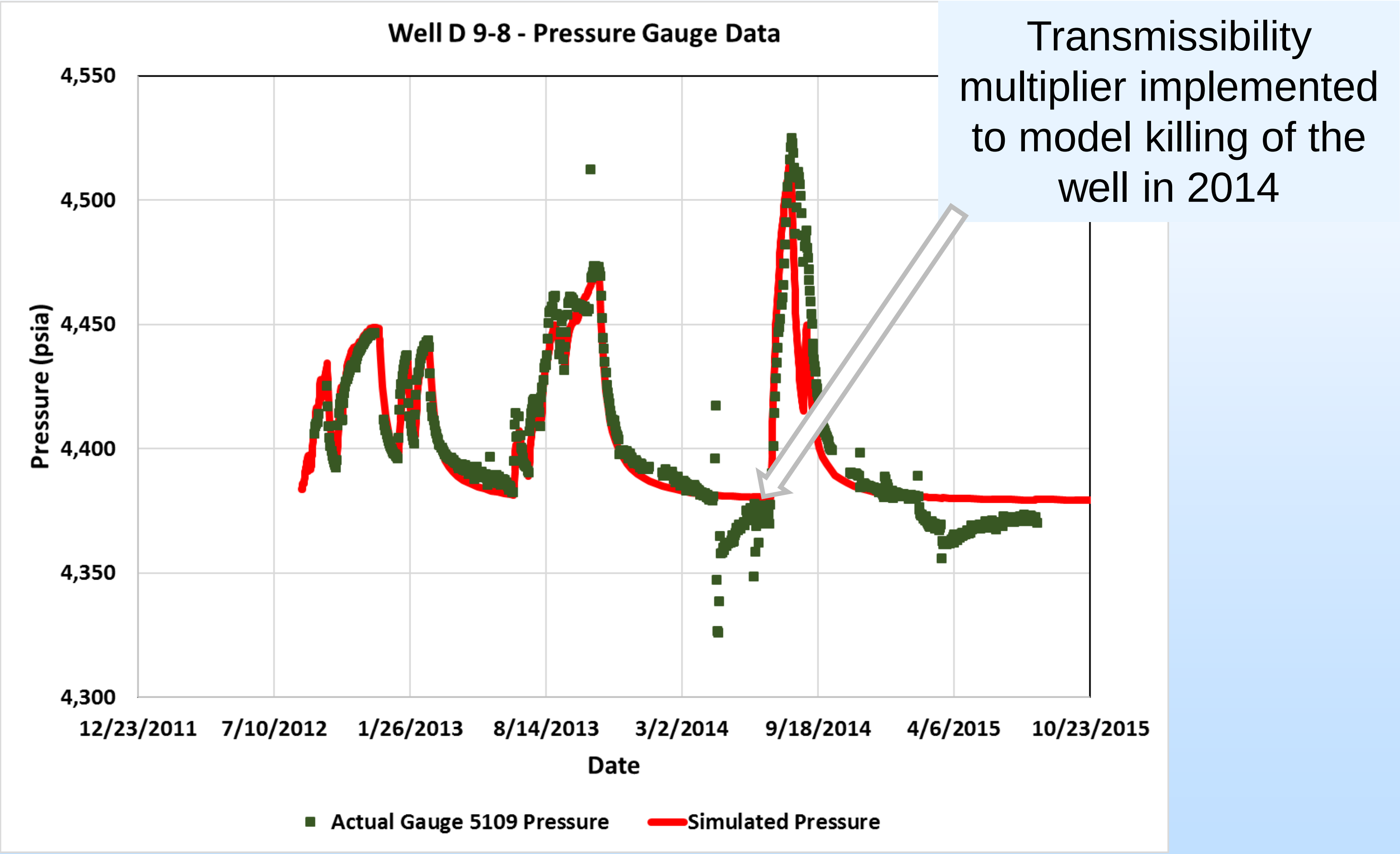


Horizontal Permeability

Injector Well D 9-7#2 Bottomhole Pressure Match

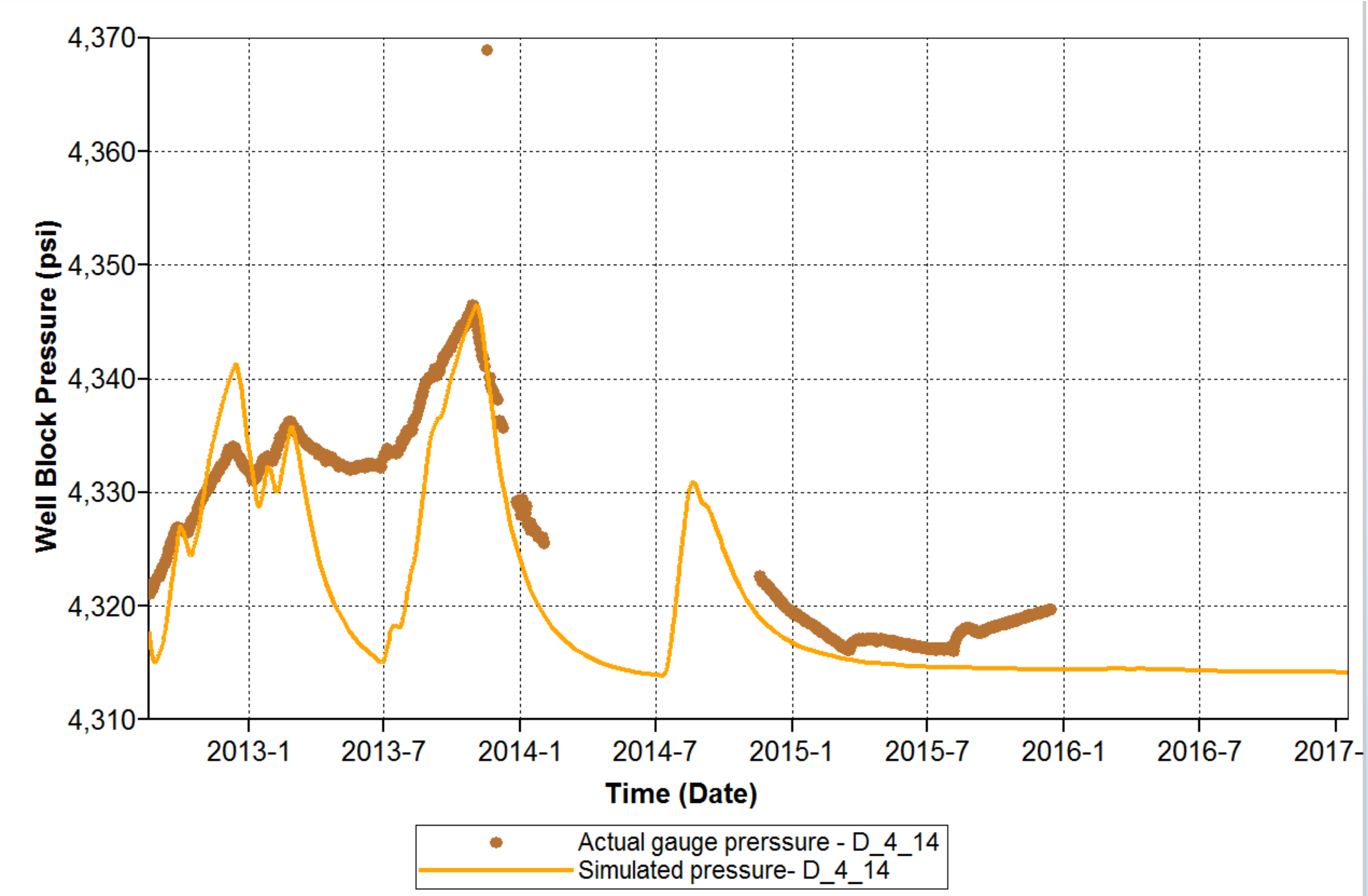


In-Zone Monitoring Well D 9-8#2 Pressure Response Match



Well D 9-8#2 is located 870 feet east of the injector.

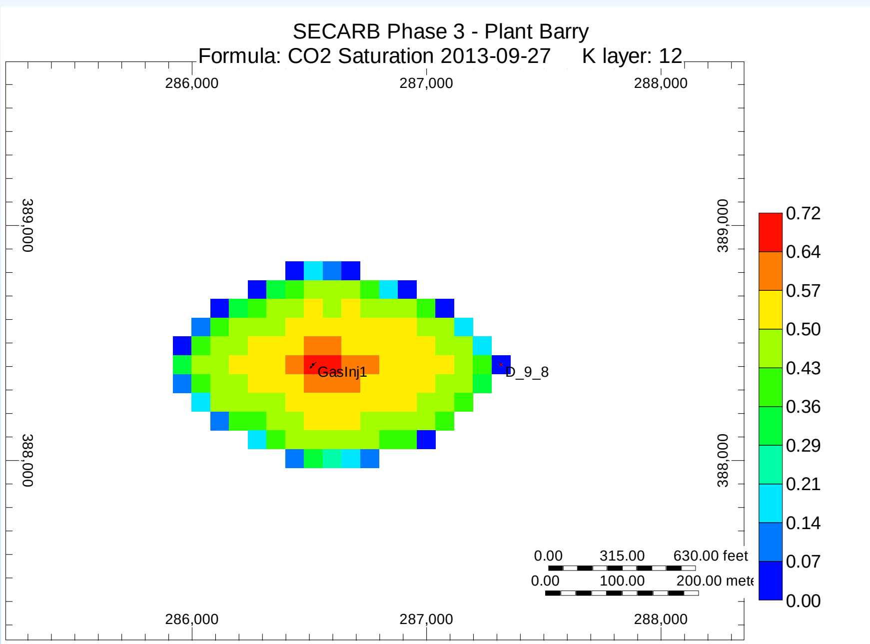
In-Zone Monitoring Well D 4-14 Pressure Response Match



Well D 4-14 is located 3,500 feet northwest of the injector.

Matching CO_2 Breakthrough

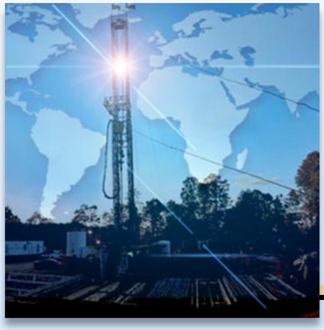
The model predicts breakthrough in the 9460 sand a little early (end of September 2013) as compared to PNC logs results (after April 2014).



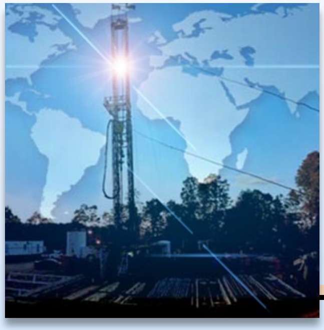
CO2 Plume Top View

CO_2 Plume 3D View

Z/X Aspect Ratio = 7

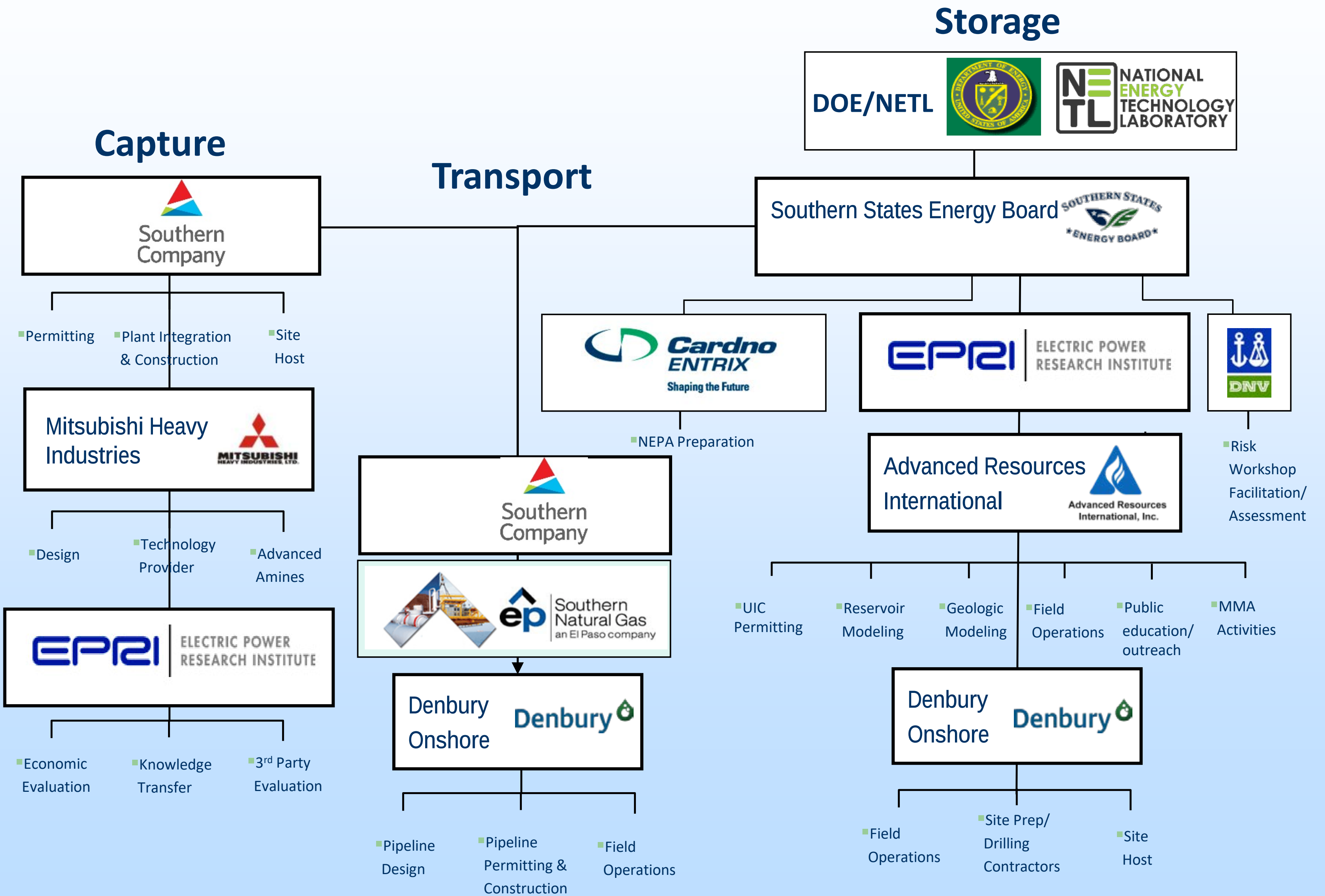




Questions?



Supporting Information

Organizational Chart



Southeast Regional Carbon Sequestration Partnership—Early Test at Cranfield

Award Number: DE-FC26-05NT42590

Susan Hovorka
Gulf Coast Carbon Center,
Bureau of Economic Geology
Jackson School of Geosciences
The University of Texas at Austin

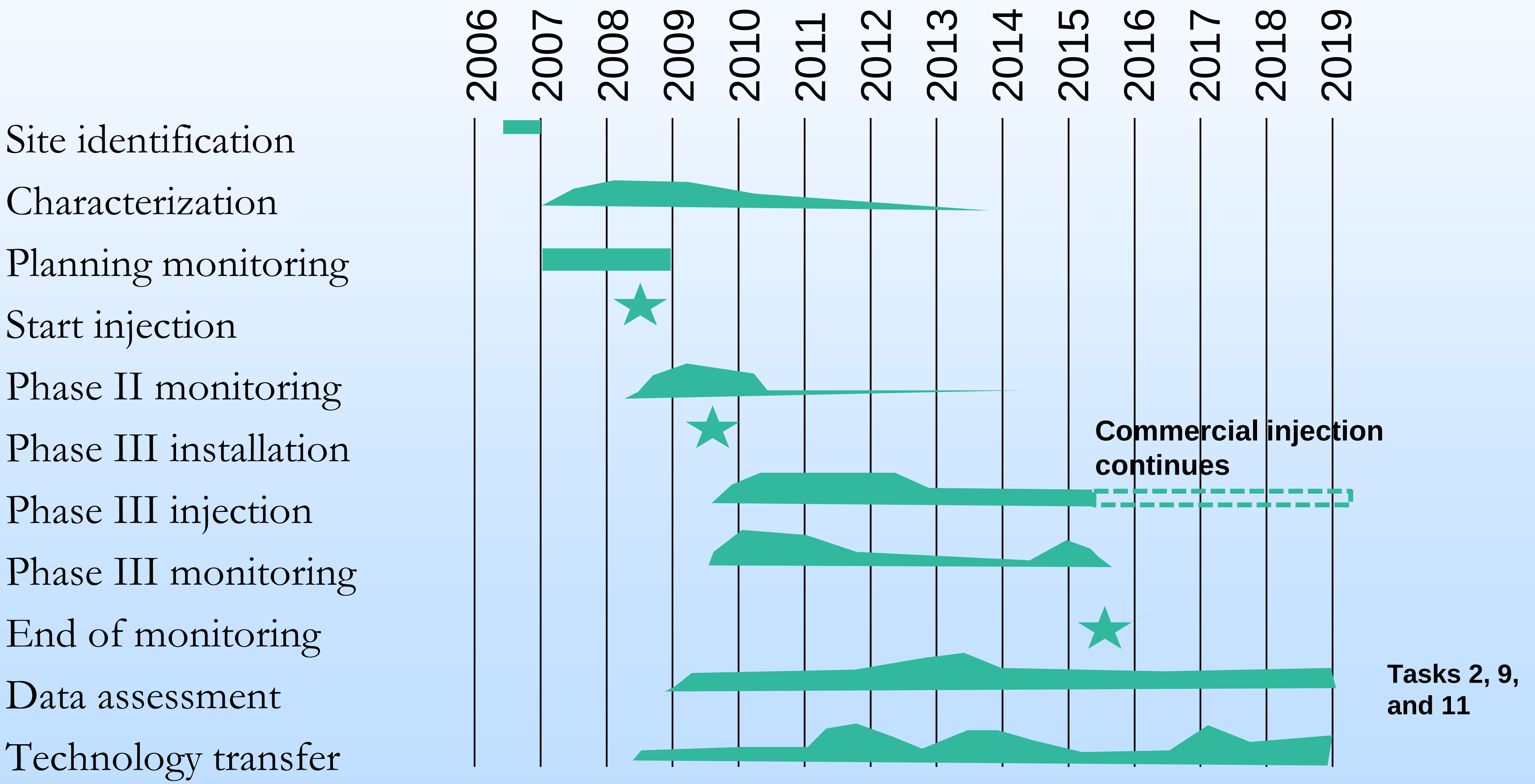
U.S. Department of Energy
National Energy Technology Laboratory
Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting
August 13-16, 2018

Presentation Outline

- Timeline of SECARB Early Test
- Team structure
- Early test goals
- Technical status- Advancing the state of the art
- Current activities
- Lessons learned – review publications

Outreach with China-Australia Group in Xinjian province

Timeline of SECARB Early Test



Team Structure

SECARB
Southeast Regional Carbon Sequestration Partnership

Southern States Energy Board

SECARB Anthropogenic Test At Plant Barry/Citronelle

Bureau of Economic Geology
Gulf Coast Carbon Center
Gulf Coast Carbon Center
Bureau of Economic Geology
Jackson School of Geosciences
The University of Texas at Austin

Denbury Resources
Field owner and injection system design, management, 4-D survey, HS&E

Vendors
e.g. well drilling, landmen

Sandia Technologies
Monitoring Systems Design, Installation, HS&E

50 Vendors
e.g. Schlumberger

Core Lab
UT DoG
Anchor QEA

MSU & UMiss
Hydro & hydrochem

Curtin University
3-D Seismic processing

Federal collaborators
Via FWP

LBNL
Well-based geophysics, U-tube and lab design and fabrication

LLNL
ERT

USGS
Geochemistry

Separately funded

NRAP
VSP deployment & analysis

NETL
Rock-water interaction

Model comparisons
LBNL SIM SEQ study

IPARS Modeling
CFSES M. Wheeler

4-D Seismic analysis
K. Spikes UT DoGS

Rock Mechanics
CFSES Sandia NL

Microseismic deployment
RITE, Japan

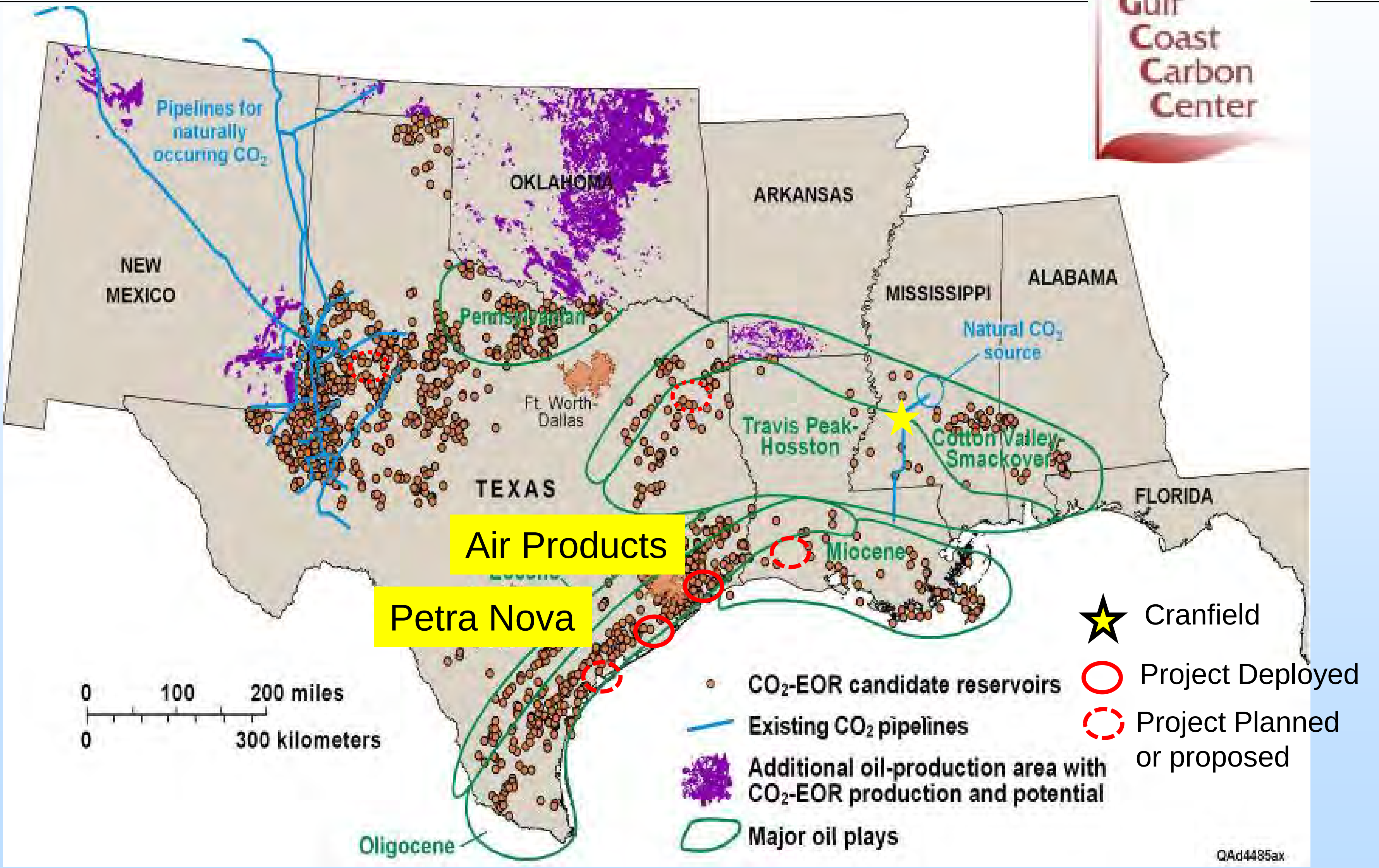
Groundwater controlled release
AWWA

Early Test Goals

- Large-scale storage demonstration
  - 1 MMT/year over >1.5 years
    - Periods of high injection rates
    - Result >5 years monitoring with >5 MMT CO_2 stored
- Measurement, monitoring and verification
  - Tool testing and optimization approach
  - Deploy as many tools, analysis methods, and models as possible
- Stacked EOR and saline storage
- Commercial technology transfer
  - Uploaded data to EDX

Current major effort

Commercialization of learnings at SECARB Early Test Accomplishments to Date



Commercialization of Monitoring

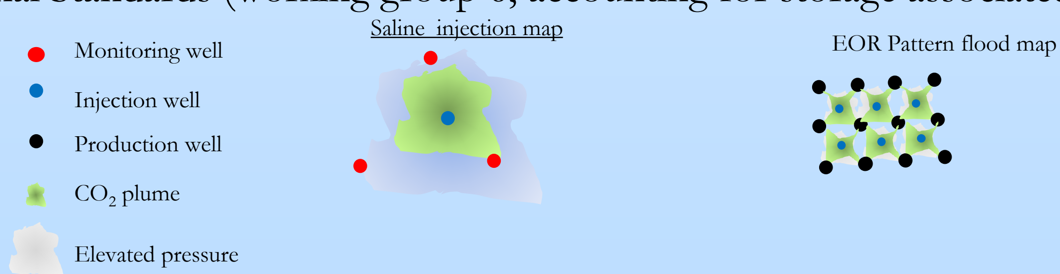
	Mass balance	soil gas	groundwater chem	AZMI chem	AZMI pressure	3D seismic	VSP	ERT	EM	gravity	u-tube	IZ chem	tracers
Frio	x	x	x	x			x		x		x	x	x
SECARB Early test at Cranfield	x	x	x	x	x	x	x	x		x	x	x	x
Industrial capture Air Products - Hastings	x	x	x		x	x	x						
Clean Coal Power initiative Petra Nova/ West Ranch	x	x	x	x	x								

Major Contributions

- Early Test Developed monitoring approaches for later commercial projects
  - Process-based soil gas method
  - Effectiveness of groundwater surveillance
  - Pressure and fluid chemistry monitoring in Above-Zone Monitoring Interval (AZMI)
  - ERT for deep CO_2 plume
  - Limitations of 4-D seismic
- Published and propagated techniques for widespread application
- Advanced to commercialization

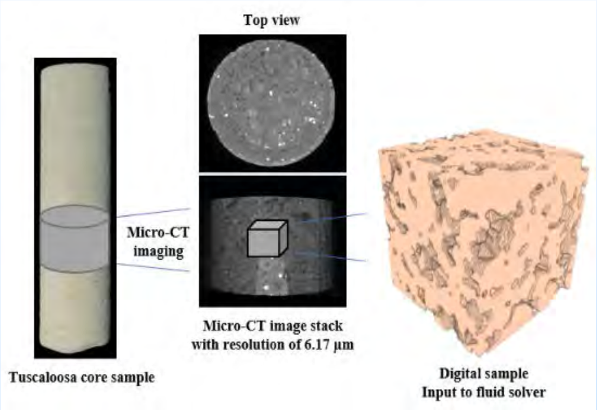
Technical Status - Advancing the state-of-the-art

- Injection scale-up – pushing the limit of injection
  - Assessing what is rate-limiting issue – overpressure or overfill?
- CCUS monitoring and accounting
  - Unique issues in a proven trap with production history – but complex fluids and many wells
- Maximize monitoring testing to minimize commercial monitoring
  - SECARB early test – extensive monitoring – many experiments
  - Commercial monitoring – focus on key issues –ALPMI method
  - Advising California Air Resources Board on their new Carbon Capture and Sequestration Protocol under the Low Carbon Fuel Standard
  - Advising International Standards (working group 6, accounting for storage associated with EOR.

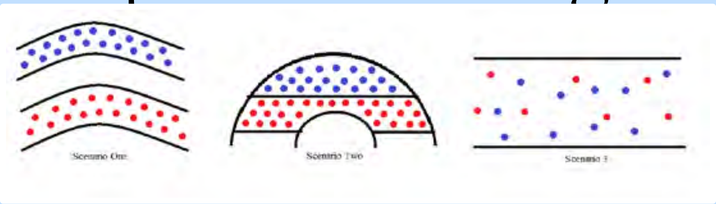


Active and continuing elements

- Pore scale modeling to extend laboratory multiphase parameter measurement – key model input
- Fault stress change from injection
- Post injection fate of CO_2
- RST logs – changes in porosity
- Management of methane impacts on miscibility
- Regional and global impact of findings



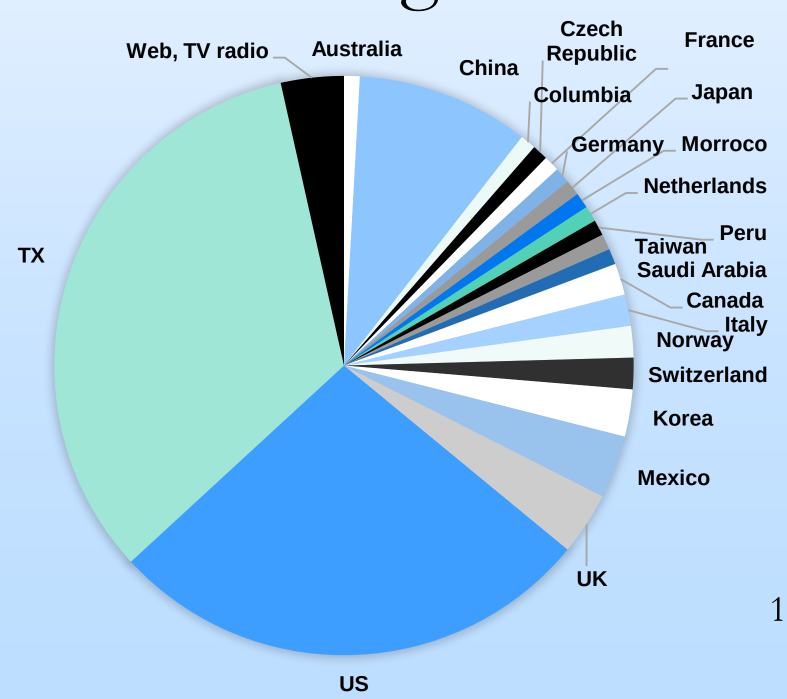
Micro CT-Imaging Espinoza, CFSES



Methane and oil distributions Prentise

(Selected) Lessons Learned

– Value and methods for down-selection of monitoring tools
– Benefits of pressure monitoring
– Limitation of groundwater and soil gas monitoring



Distribution of GCCC presentation 2014-18

Value and methods for down-selection of monitoring tools

- Optimized tool selection (Assessment of low probability material impact: ALPMI)

Risk assessment method as usual

- Avoid subjective terms like safe and effective.
- E.g. : Specify mass of leakage at identified horizon or magnitude of seismicity.
- Specify certainty with which assurance is needed

Quantify risks to define material impact

Specify magnitude, duration, location, rate of material impact

Model material impact scenarios

Explicitly model unacceptable outcomes showing leakage cases.

ALPMI uses models differently than the typical history matching the expected performance

Identify signals in the earth system that indicate or preferably precede material impact

Method down selects only signals that indicate material impact may occur or may be occurring

Select monitoring tools that can detect these signals at required sensitivity

Approaches like those normally used for seismic survey design should be deployed for all modeling tools

Forward modeling tool response is essential to developing the expected negative finding: “No material impact was detected by a system that could detect this impact.”

Deploy tools; collect and analyze data

This activity as traditionally conducted. Include all the expected components, such as attribution, updating as needed, feedback , etc.

Report if material impact did/did not occur

Via this ALPMI process can a finding that the material impact did not occur be robustly documented

Value and methods for down-selection of monitoring tools

You can't have everything! Example limitations:

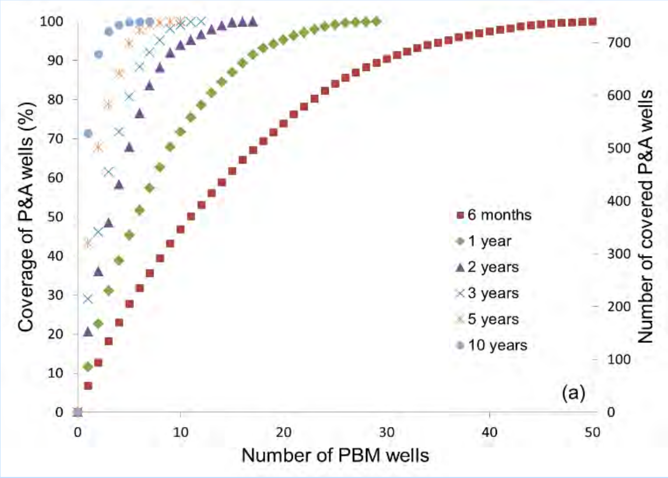
- Tool interference

  e.g. "jewelry" on casing interferes with log response

  Perforated well – geochemical and geophysical tool deployment interference

- Tool limitations – cost, cost of analysis

  Paper on cost/value in preparation



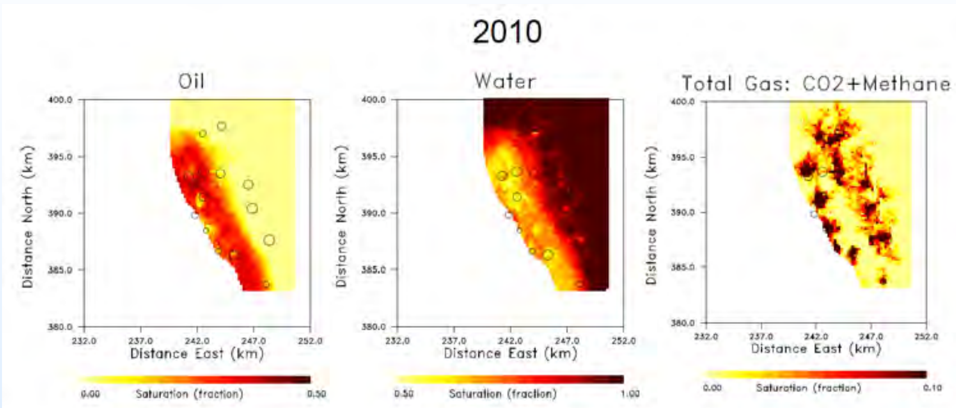
Sensitivity of time until detection of leakage on number of wells installed, Bolhassani (*in prep.)*

New assessment forward modeling seismic response

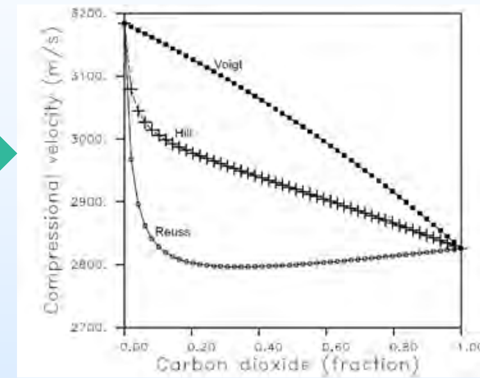
- Calibrated compositional fluid flow model of northeast quadrant of field (BEG team)
- Another look at seismic processing by Don Vasco, LBNL
- Seismic modeling of expected response
- Identify signal reduction related to hydrocarbons

Seismic forward modeling study outcomes

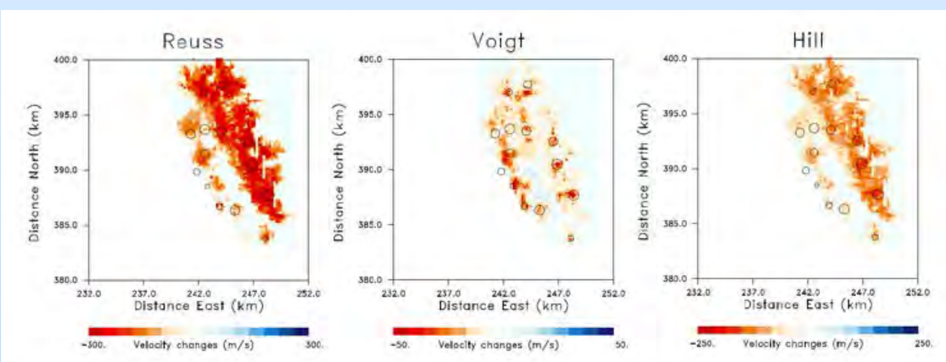
Fluid flow model outcomes



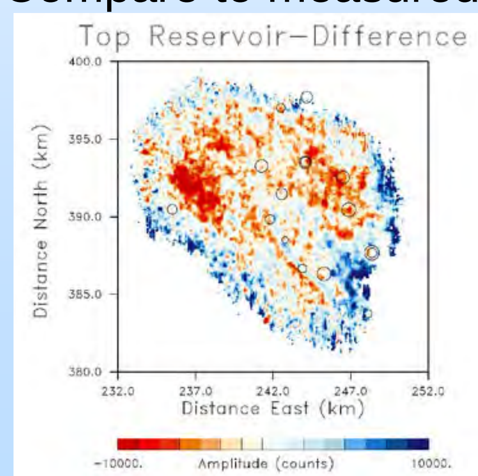
Rock physics models



Forward model seismic response to fluid substitutions



Compare to measured response

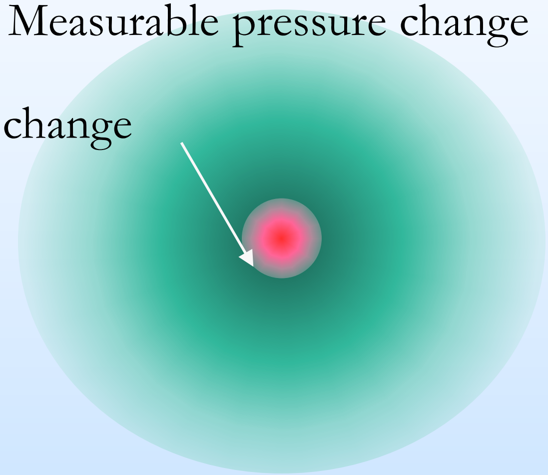


Vasco et al

Benefits of pressure monitoring

– Pressure is a key parameter in risk reduction

– Diffusive parameter



– Robust history matching-

- Model validation
- Plume conformance to model

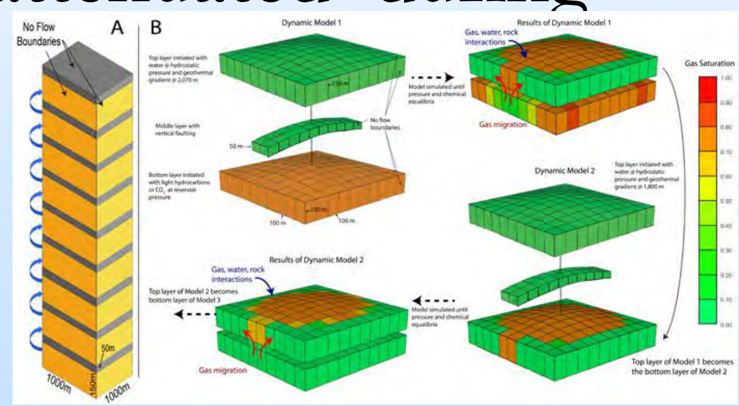
– Above-zone diagnostic

– Not especially sensitive in post-injection context

Limitation of groundwater and soil gas monitoring

– Extensive published work by Katherine Romanak, Changbing Yang, Sean Porse, Jacob Anderson

– Leakage signal changed and attenuated during lateral and vertical transport



Anderson et al, 2018

– Issue of noise and trend in near-surface signal

– CO_2 is non-unique signal

Synergies

Field data collection

Microseismic – RITE
CO_2 Geothermal – LBNL
PIDAS – Sun
CCP-BP gravity
Microbes – U KY
NRAP 3-D VSP
Borehole seismic – Ground metrics
Nobles gasses U. Edinburgh
Fluid Chem – Ohio State
Well integrity – Schlumberger/Battelle

Additional analyses

NETL- EOR accounting Mei/Dilmore
NETL- Rock-water reaction BES – LLNL

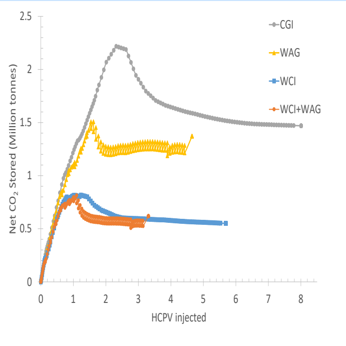
Modeling efforts

SIMSEQ –LBNL
15 teams
CFSES – UT/ SNL
IPARS --Wheeler
NRAP
NCNO
LBNL
CCP3
UT- LBNL Zhang
LLNL
LBNL – Don Vasco study

119 history match efforts

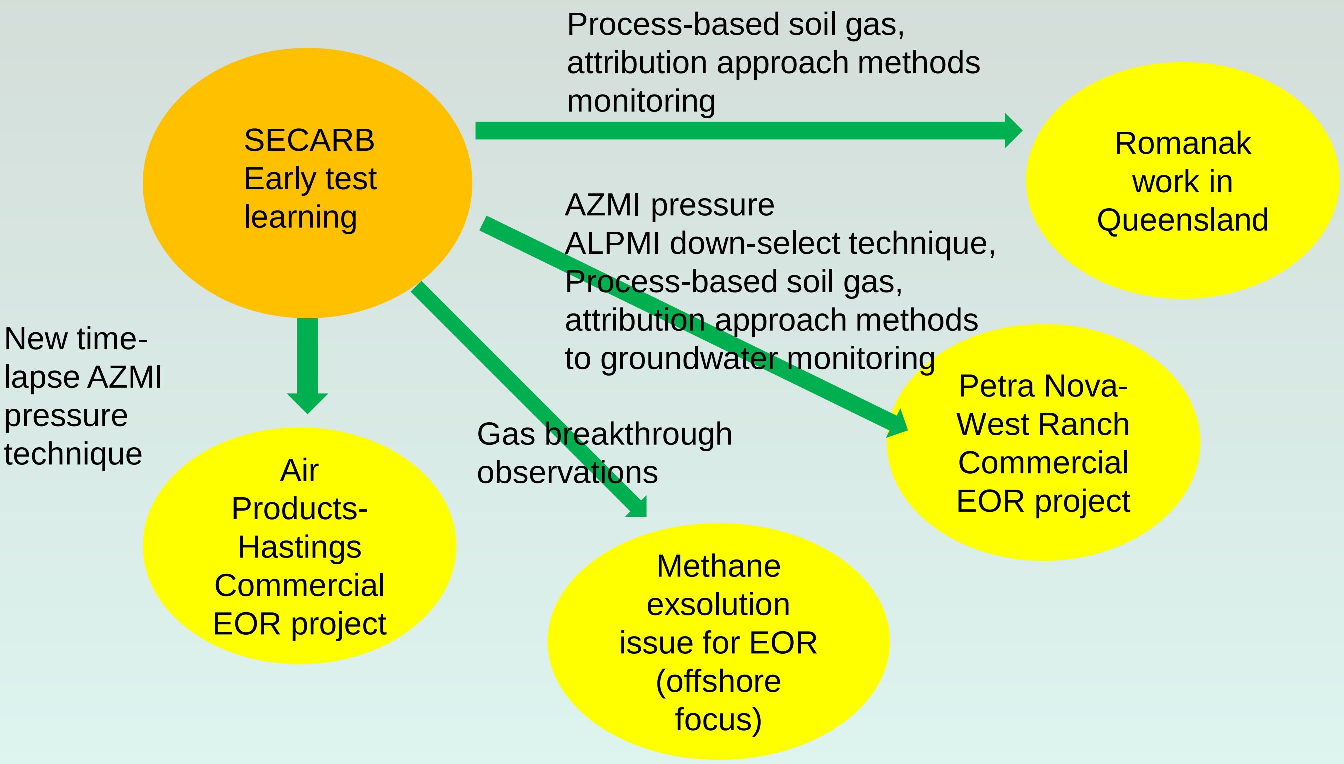
Support other studies

NCNO



Nunez- Cranfield data supporting NCNO study

Technology transfer from SECARB early test to other projects



Recent submissions and publications (108 total)

- Uploads to EDX (data) https://edx.netl.doe.gov
- Texas Scholar Works https://repositories.lib.utexas.edu
- Hovorka, S. D., Case study – testing geophysical methods for assessing CO_2 migration at the SECARB early test, Cranfield Mississippi "Geophysical Monitoring for Geologic Carbon Storage and Utilization" to be published by Wiley for the American Geophysical Union.
- D. W. Vasco, Masoud Alfi, Seyyed A. Hosseini, Rui Zhang, Thomas Daley, Jonathan B. Ajo-Franklin, and Susan D. Hovorka "The seismic response to injected carbon dioxide: Comparing observations to estimates based upon fluid flow modeling"
- Hosseini, S. A., Masoud Alfi, Donald Vasco, Susan Hovorka, Timothy Meckel, Validating compositional fluid flow simulations using 4D seismic interpretation and vice versa in the SECARB Early Test—A critical review
- Anderson, Jacob; Romanak, Katherine; Alfi, Masoud; Hovorka, Susan, Light Hydrocarbon and Noble Gas Migration as an Analog for Potential CO_2 leakage: Numerical Simulations and Field Data from Three Hydrocarbon Systems
- Fietz and Hovorka, Capturing the magic of carbon dioxide
- Hovorka, S.D. and Lu, J., Field observation of geochemical response to CO_2 injection at the reservoir scale, in Newel and Ilgen, Science of Carbon Storage in Deep Saline Formations , Elsevier

Appendix

Benefit to the Program

Development of large-scale (>1 million tons of CO_2) Carbon Capture and Storage (CCS) projects, which will demonstrate that large volumes of CO_2 can be injected safely, permanently, and economically into geologic formations representative of large storage capacity.

Project Overview

Goals and Objectives

The Southeast Regional Carbon Sequestration Partnership's (SECARB) Phase III work focuses on the large scale demonstration of safe, long-term injection and storage of CO_2 in a saline reservoir that holds significant promise for future development within the SECARB region. The project will promote the building of experience necessary for the validation and deployment of carbon sequestration technologies in the region. Phase III will continue refining Phase II sequestration activities, sequestration demonstrations and will begin to validate sequestration technologies related to regulatory, permitting and outreach. The multi-partner collaborations that developed during Phase I and Phase II will continue in Phase III with additional support from resources necessary to implement strong and timely field projects.

SECARB Anthropogenic Test Update

Project Number DE-FC26-05NT42590

Rob Trautz, Electric Power Research Institute

Anne Oudinot, Advanced Resources International

David Riestenberg, Advanced Resources International

U.S. Department of Energy

National Energy Technology Laboratory

Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

August 13-16, 2018

Acknowledgement

This presentation is based upon work supported by the Department of Energy National Energy Technology Laboratory under **DE-FC26-05NT42590** and was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

SECARB
Southeast Regional Carbon Sequestration Partnership

SOUTHERN COMPANY
Energy to Serve Your World℠

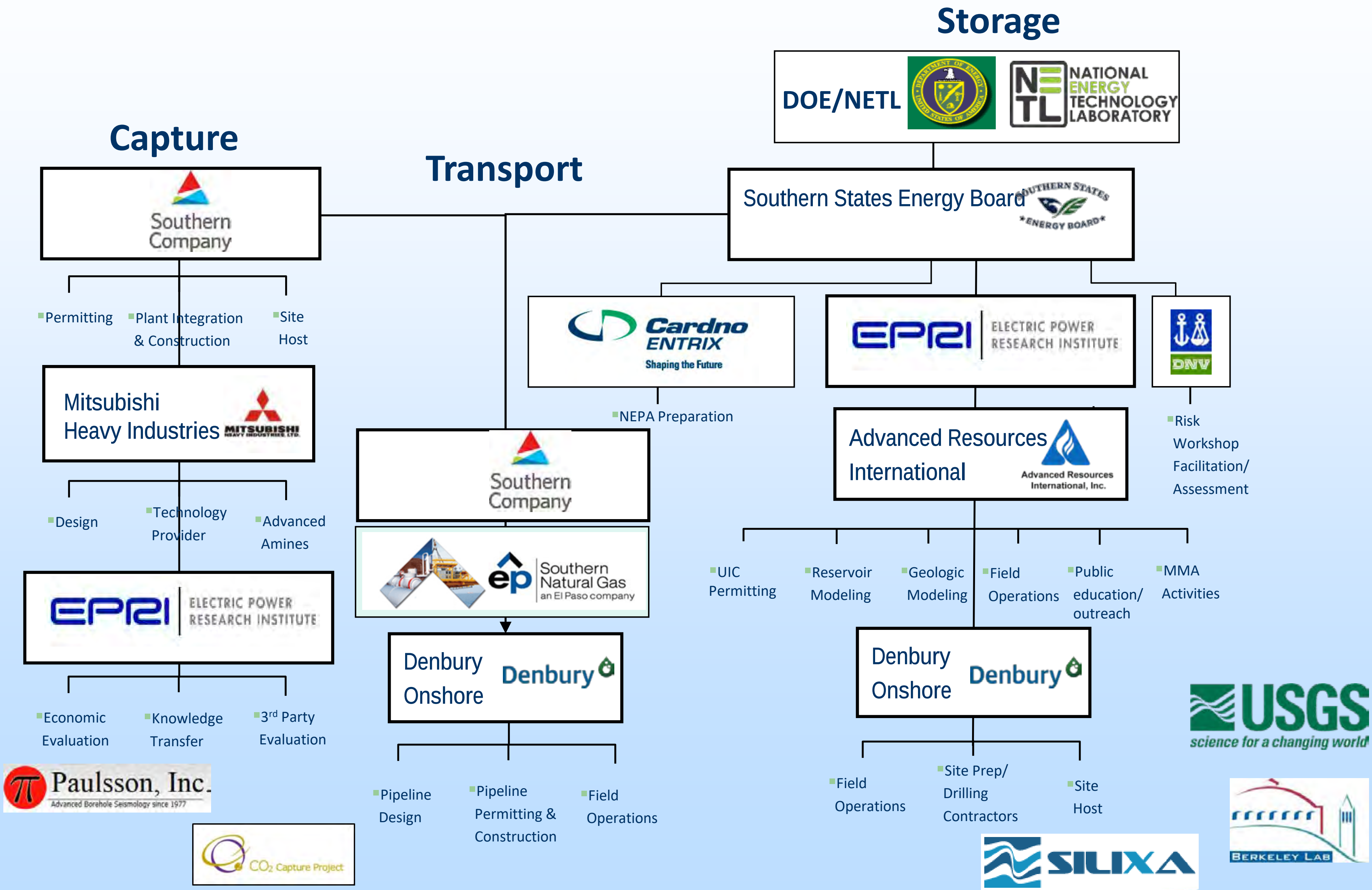
SOUTHERN STATES ENERGY BOARD

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Denbury

Advanced Resources International, Inc.

Organizational Chart



Presentation Outline

1. Project Introduction
2. Permit is closed!
3. Next (Last) Steps
4. Research and Operational Highlights (and lowlights…)



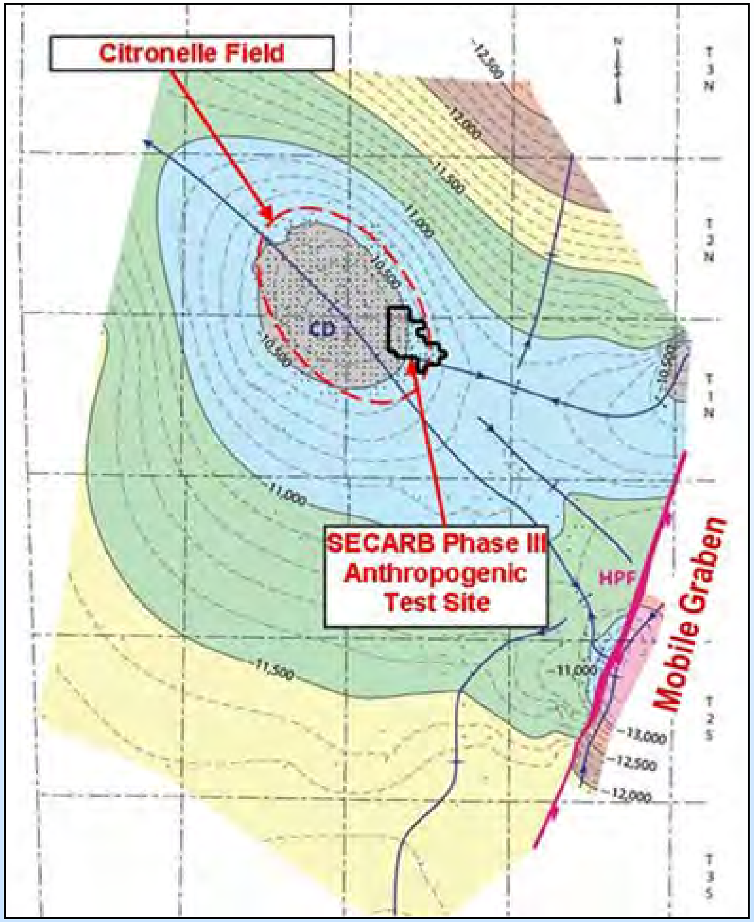
SECARB Anthropogenic Test Introduction

Project Goals and Objectives

Baseline 1 year	Injection 2 years	Post 3 years
APR 2011 to AUG 2012	SEP 2012 to SEP 2014	SEP 2014 to SEP 2017

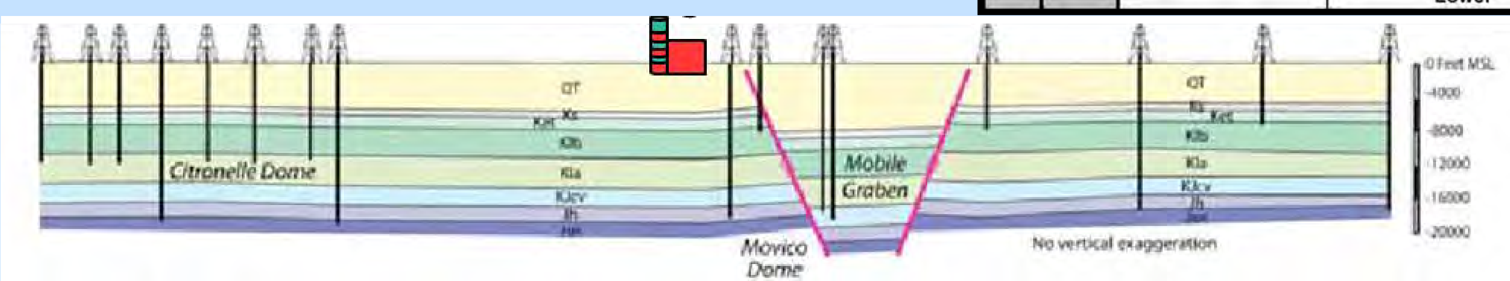
1. Support the United States' largest (*at the time*) prototype CO_2 capture and transportation demonstration, with injection, monitoring and storage activities;
2. Test the CO_2 flow, trapping and storage mechanisms of the Paluxy;
3. Demonstrate how a saline reservoir's architecture can be used to maximize CO_2 storage and minimize the areal extent of the CO_2 plume;
4. Test the adaptation of commercially available oil field tools and techniques for monitoring CO_2 storage;
5. Test experimental CO_2 monitoring activities, where such technologies hold promise for future commercialization;
6. Begin to understand the coordination required to successfully integrate all four components (capture, transport, injection and monitoring) of the project; and
7. Document the permitting process for all aspects of a CCS project.

Storage Site: The Citronelle Oilfield

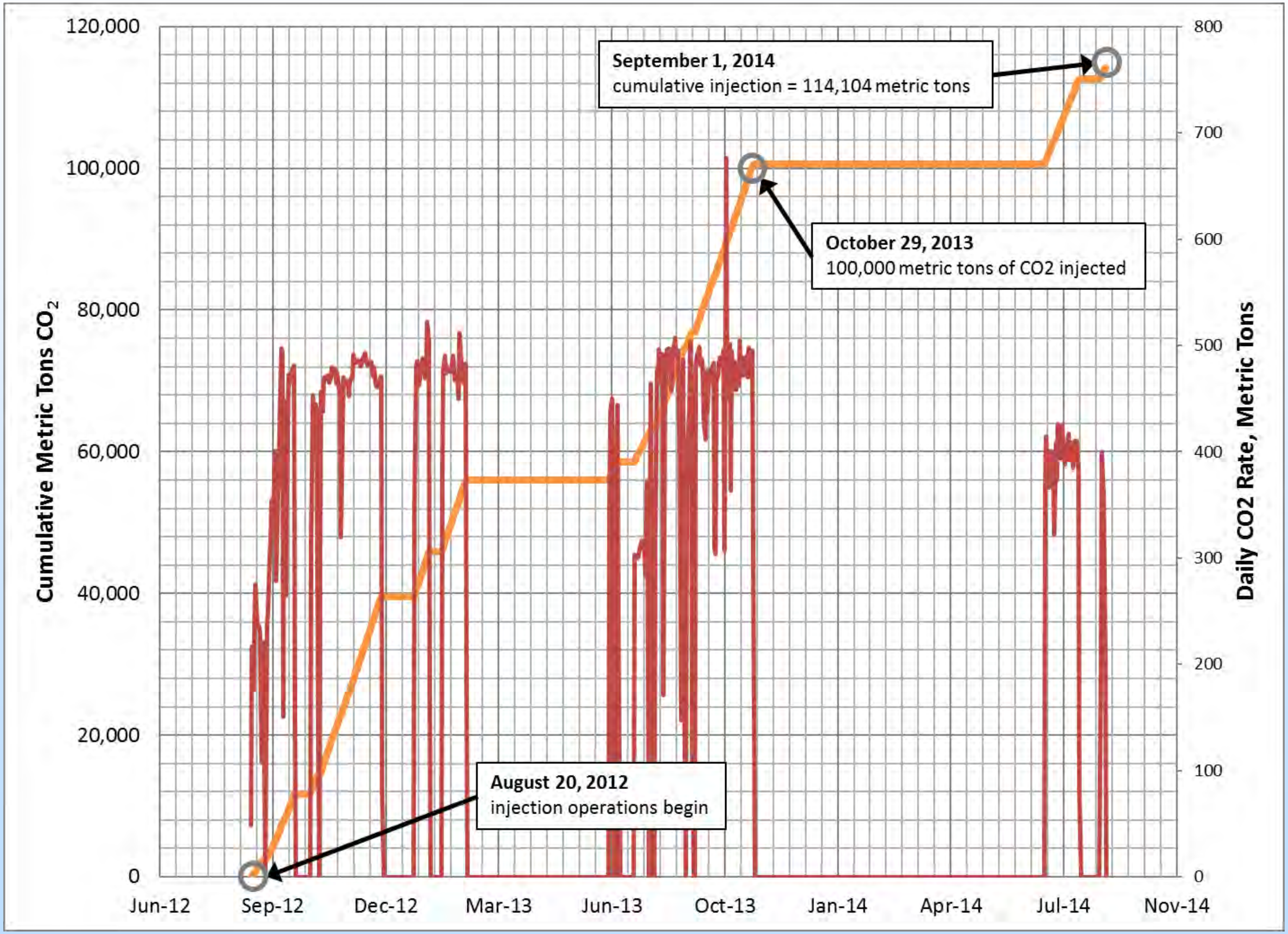


Structure map and cross section by GSA

System	Series	Stratigraphic Unit	Major Sub Units	Potential Reservoirs and Confining Zones
Tertiary	Plio-Pliocene		Citronelle Formation	Freshwater Aquifer
	Miocene	Undifferentiated		Freshwater Aquifer
	Oligocene		Chickasawhay Fm.	Base of USDW
		Vicksburg Group	Bucatunna Clay	Local Confining Unit
	Eocene	Jackson Group		Minor Saline Reservoir
		Claiborne Group	Talahatta Fm.	Saline Reservoir
		Wilcox Group	Hatchetigbee Sand	Saline Reservoir
	Paleocene		Bashi Marl	
			Salt Mountain LS	
		Midway Group	Porters Creek Clay	Confining Unit
Cretaceous	Upper	Selma Group		Confining Unit
		Eutaw Formation		Minor Saline Reservoir
		Tuscaloosa Group	Upper Tusc.	Minor Saline Reservoir
			Md. Tusc. Marine Shale	Confining Unit
			Lower Tusc. Pilot Sand Massive sand	Saline Reservoir
	Lower	Washita-Fredericksburg	Dantzler sand	Saline Reservoir
			Basal Shale	Primary Confining Unit
		Paluxy Formation	'Upper' 'Middle' 'Lower'	Injection Zone
		Mooringsport Formation		Confining Unit
		Ferry Lake Anhydrite		Confining Unit
		Donovan Sand	Rodessa Fm. 'Upper' 'Middle' 'Lower'	Oil Reservoir / Minor Saline Reservoir / Oil Reservoir



CO_2 Injection History





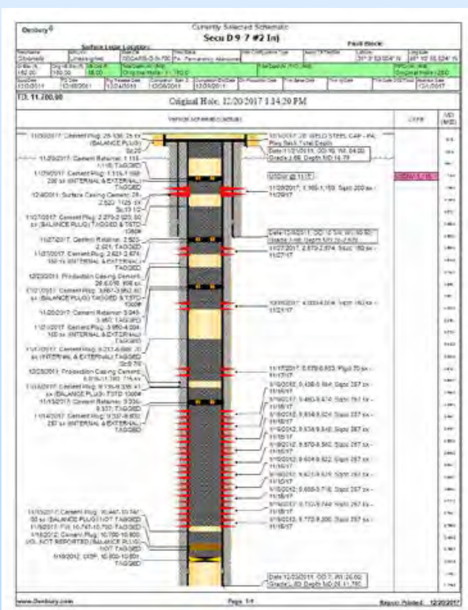
Permit is closed!!

Permit Closure

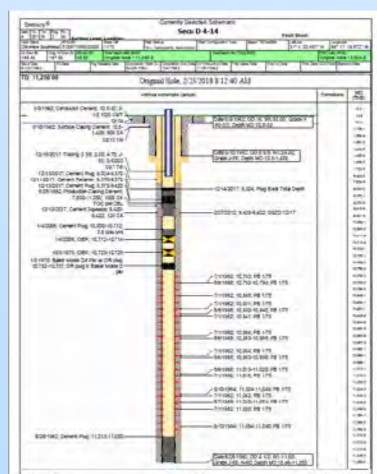
- Permit was officially closed by ADEM on May 11th
- Temporary or permanent abandonment of all project wells is complete
- Post-injection monitoring (groundwater and soil flux) is complete
- Non-endangerment of USDWs and CO_2 confinement in the injection zone have been demonstrated using modeling and monitoring results to obtain closure

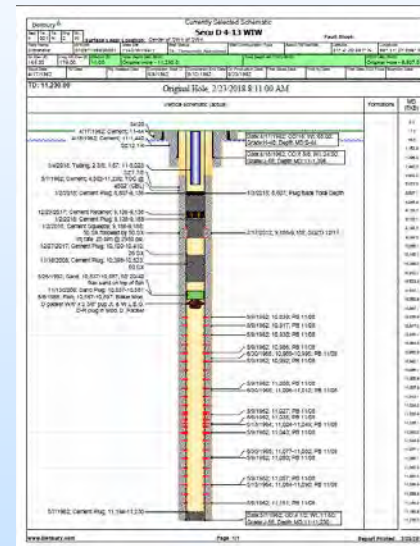
Wells Temporary and Permanent Abandonment

D 9-7#2 on December 10th, 2017



D 4-14 on December 10th, 2017





D 4-13

Demonstrating Non-Endangerment of USDWs and CO_2 Confinement

- The Class V permit required several levels of monitoring
  - Surface monitoring
    - Soil flux, tracers
  - Shallow groundwater monitoring
  - Deep reservoir monitoring
    - PNC logs, fluid sampling, seismic, pressure monitoring
- Experimental MVA activities
- Numerical modeling
  - Developed to determine the project’s Area of Review (AoR) and investigate the advancement of the CO_2 plume

Surface Monitoring: Tracer

- Leakage most likely to occur along wellbores that penetrate the injection zone and/or confining unit
- Periodic injection of a mix of perfluorocarbon tracers (PFTs) into the CO_2 stream
- Surficial monitoring for PFTs occurred at the injection well and an additional 8 offset locations

⇒ **No evidence of tracer release at any of the nine monitoring locations.**

Date	Well ID	
August 2012	D-9-1	ND
	D-9-2	ND
	D-9-3	ND
	D-9-6	ND
	D-9-7-1	ND
	D-9-7 Air Blank	Invalid Data
	D-9-8	Invalid Data
	D-9-9	ND
	D-9-9 Air Blank	Air
	D-9-10	Invalid Data
	D-9-11	ND
	Air Blank 1	ND
	Air Blank 2	Invalid Data
	Air Blank 3	Invalid Data
	~	
June 21-22,2016	D-9-1	ND
	D-9-2	ND
	D-9-3	ND
	D-9-6	ND
	D-9-7	ND
	D 9-8 #2	ND
	D-9-9 +abandoned	ND
	D-9-10	ND
	D-9-11	ND
	D-982_gaugesample_1 (stream from D-9-8#2)	DETECTION
	voa_dec23cylinder_1 (Denbury cylinder from Dec 23)	ND
	System Blank	ND

Shallow Groundwater Monitoring

- Performed on a quarterly basis as required by the UIC permit at 4 locations
- A total of 24 events occurred (3 baseline, 8 during injection and 13 post-injection)
- Multiple lines of evidence are required to determine that injected CO_2 is not influencing the USDWs

Monitoring Well	Decrease in pH	Increase in TIC	Increase in Alkalinity	Increase in Metals Concentrations
D-9-7 MW-2D	Yes	No	No	No
D-9-7 MW-2S	No	No	No	No
D-9-9 MW-1	No	No	No	Fe
Water Supply Well	No	No	No	No

Purple Shading = A potential line of evidence for carbon dioxide influence is present
Blue Shading = A potential line of evidence for carbon dioxide influence is not present
TIC = total inorganic carbon

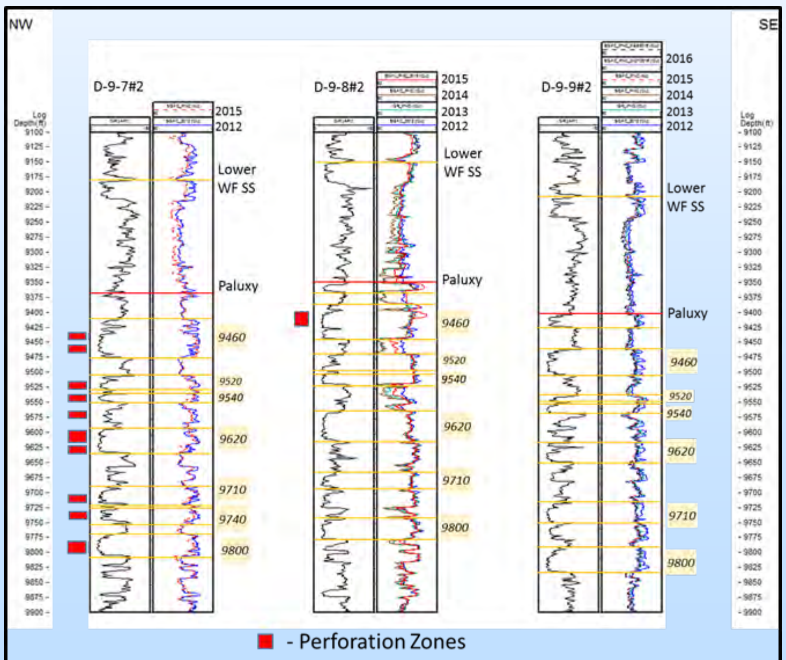
- **⇒ Multiple lines of evidence do not indicate CO_2 leakage into USDWs.**

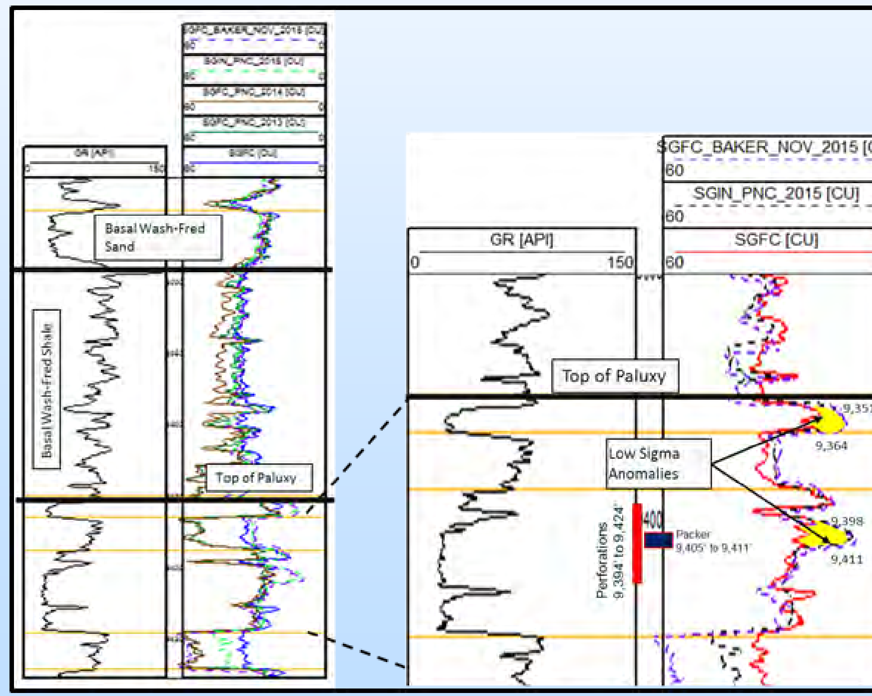
Deep Reservoir Monitoring

- Deep PNC logs
- Deep fluid sampling
  - Unreliable results due to poor sampling procedures
- Seismic Program
  - Cross-well seismic
  - Vertical Seismic Profile
    - Inconclusive
- Pressure monitoring

Pulsed Neutron Capture (PNC) Logs

- Application: measure changes in formation gas saturation behind casing
- CO_2 breakthrough was observed at the D 9-8 #2 well in the August 2015 PNC log and confirmed in a November 2015 repeat
- No evidence of gas saturation was observed within or above the confining zone

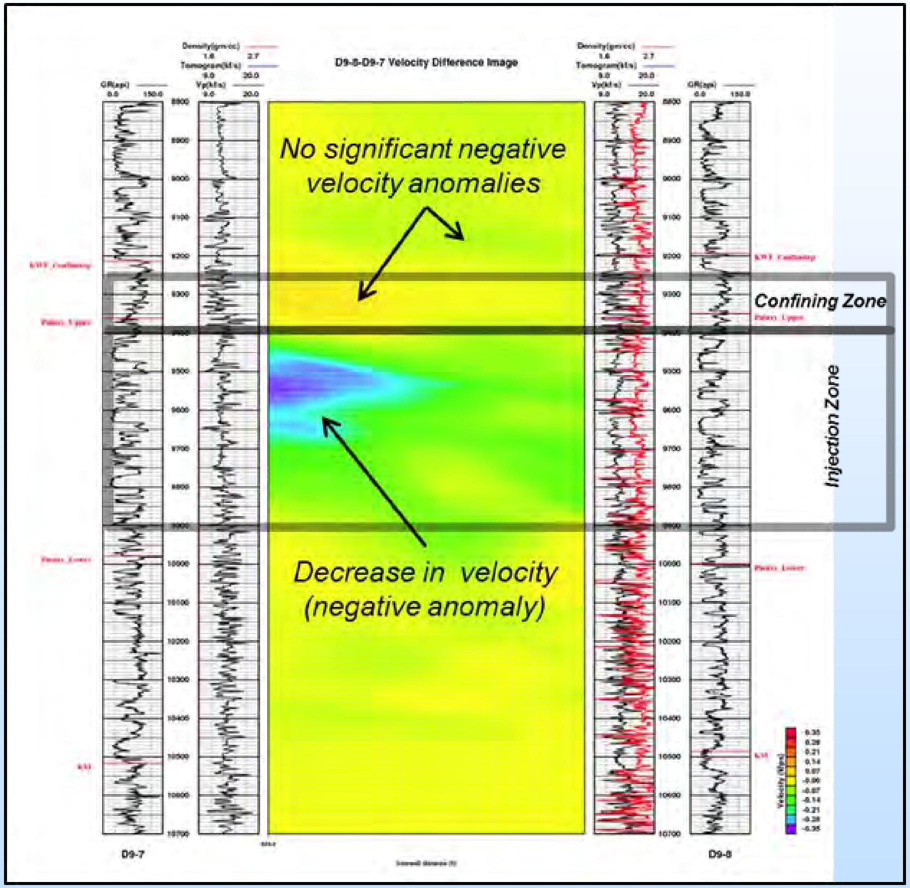




- **⇒ Results of the PNC logs demonstrate confinement in the injection zone.**

Time-lapse Cross-well Seismic

- Replacement of brine with CO_2 will result in an increase in travel time through a geologic unit
- Crosswell seismic was acquired between the D 9-7#2, and the D 9-8 #2
- Baseline in January 2012 and time-lapse survey during injection in June 2014



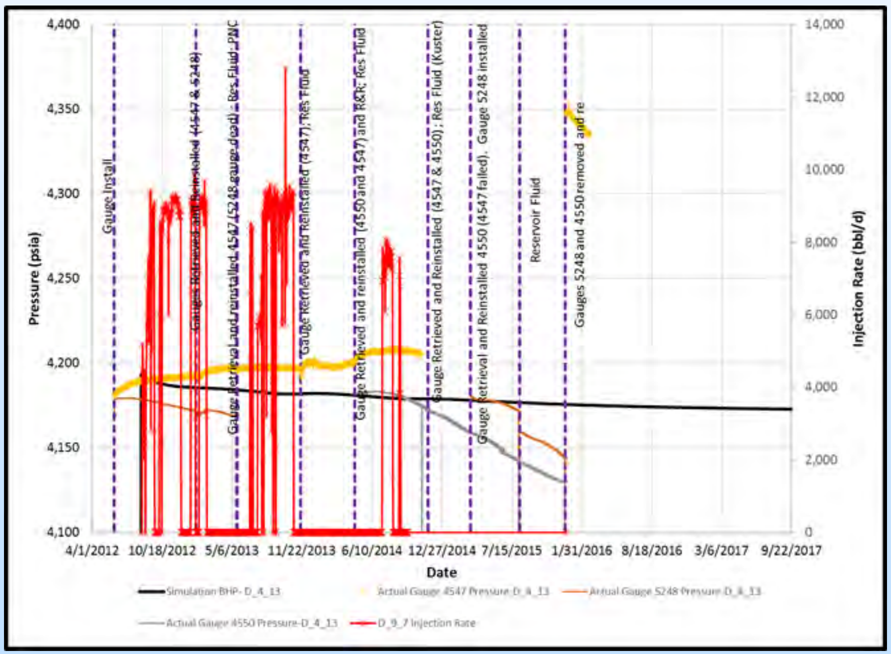
Comparison between 2012 and 2014

⇒ No anomaly in or above the confining unit.

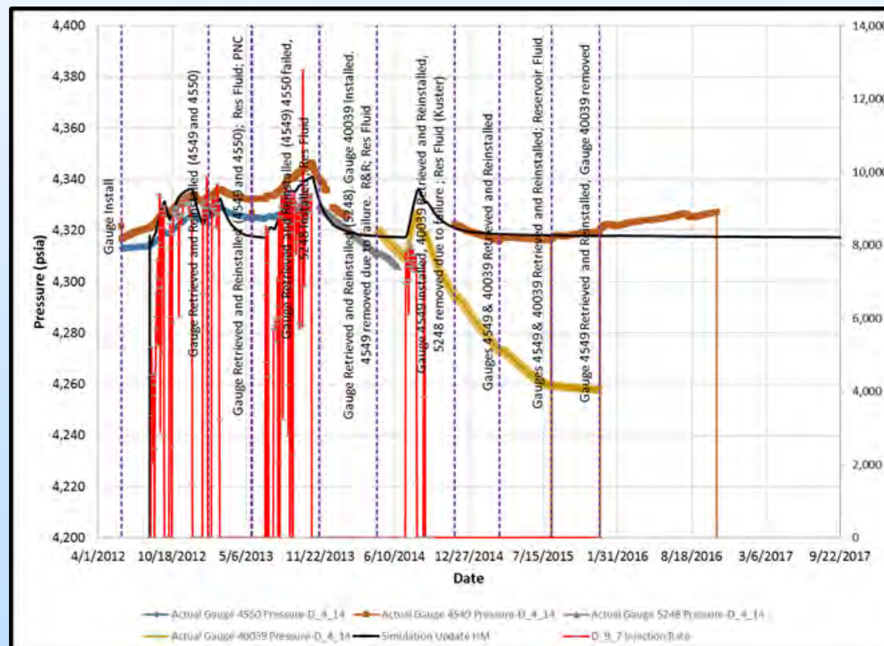
Pressure Monitoring

- Pressure monitored in 4 wells: D9-7#2, D9-8#2, D4-13 and D4-14

D4-13 Above Zone Monitoring



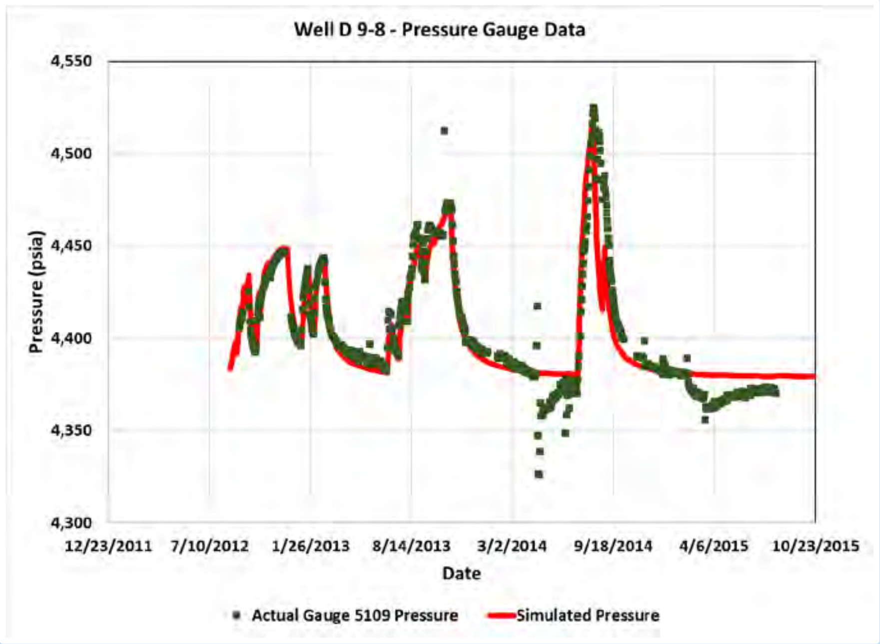
D4-14 In Zone Monitoring

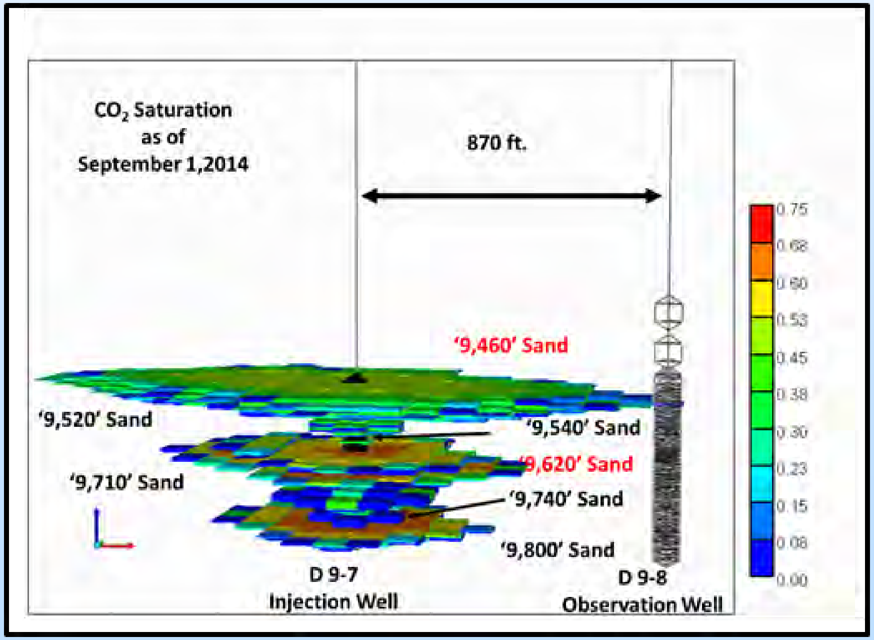


Pressure clearly follows the trend of injection in the D9-7#2

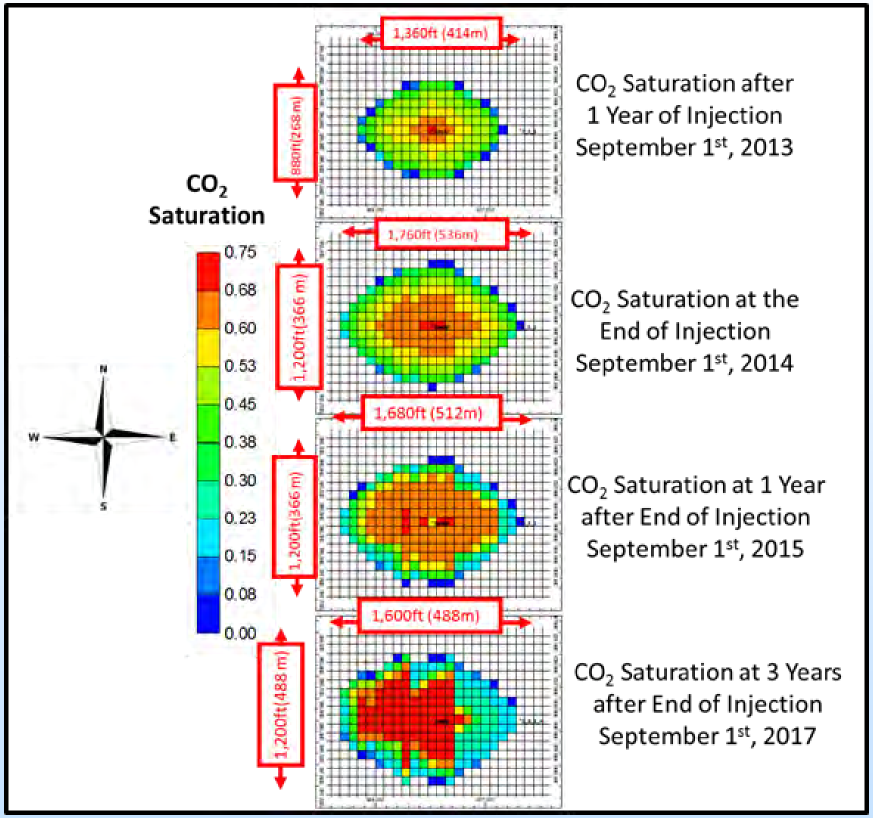
Numerical Modeling

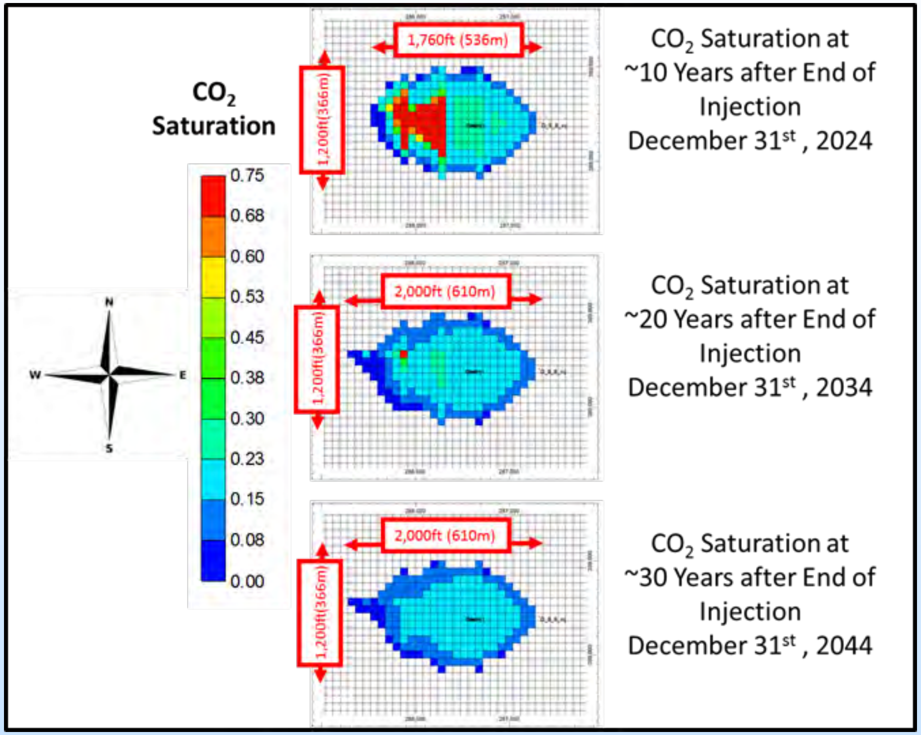
- Monitoring results are matched from the onset of injection through March 2016, which includes the observed CO_2 breakthrough at the D 9-8 #2 monitoring well
- With the addition of permeability anisotropy and a high permeability zone within the '9460' sand, CO_2 breakthrough at the D 9-8#2 is modeled within the timeframe delineated by the PNC logs.





Area of Review

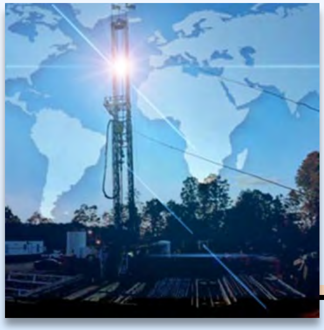




The estimated radius of the CO_2 plume 30 years after cessation of injection is approximately 1000 ft. (305m), which is less than the project's initial AoR of 1,700 ft.

Non-endangerment Summary

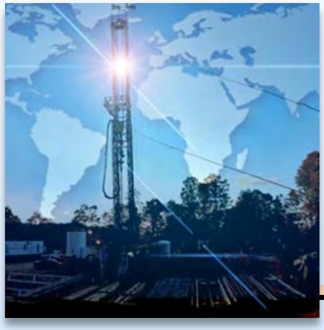
- Sufficient evidence was provided by the suite of surface and shallow monitoring, deep MVA and modeling efforts to indicate successful non-endangerment at the site.
  - No CO_2 release or buildup was detected using groundwater analysis, tracer detection, and soil flux monitoring.
  - PNC logs, cross-well seismic, VSP and pressure monitoring were all parts of deep monitoring activities.
  - No evidence of gas saturation was observed within or above the confining zone based on the results of repeated runs of the pulsed neutron capture (PNC) log during the injection operation.
  - Cross-well seismic results show no negative velocity anomalies in or above the confining unit implying no detectable leakage out of the injection zone, and containment of CO_2.
  - Simulated distribution of CO_2 through the injected geological layers demonstrated confinement within the injected zone
  - Models indicate that the plume does not exceed the original AoR predicted in the baseline model.
  - The maximum movement of CO_2 is less than 1,000 ft. (305 m) in any direction 30 years after the injection ceases


Next (Last) steps

Project's Last Steps

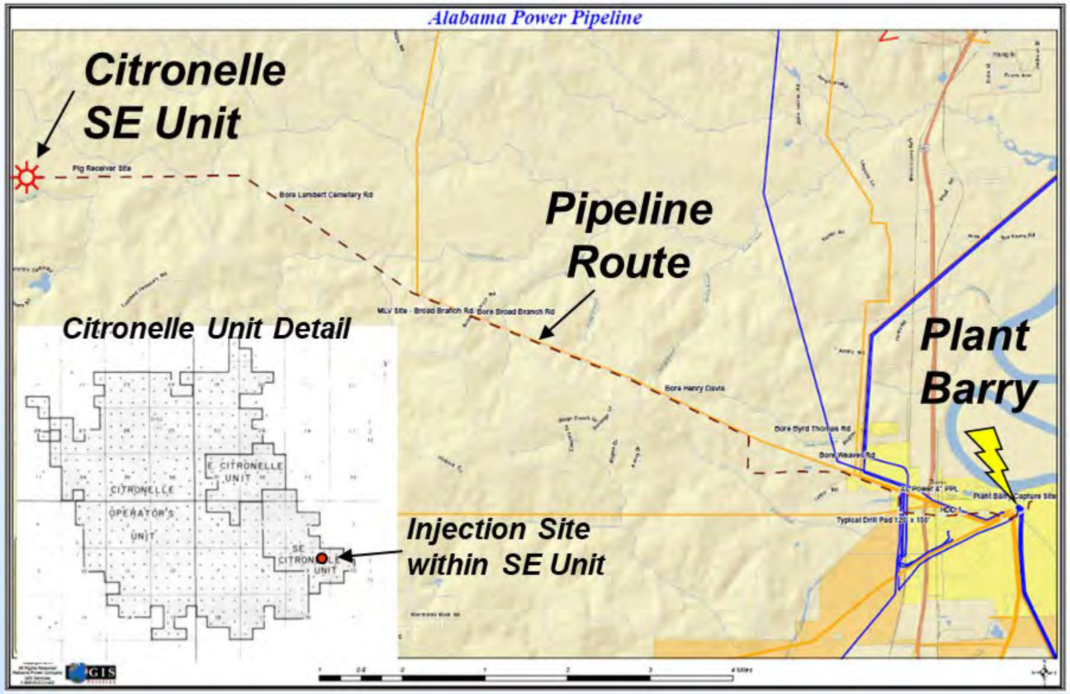
- Plugging and abandonment of groundwater wells is happening right now
- Transfer of test site to oilfield operator
- Peer reviewed geology and simulation papers in progress per DOE requirements
- EDX upload (currently 60% complete).


Operational and Research Highlights
(and a few lowlights…)

CO_2 Transportation via Pipeline

- 12 mi to the Injection Site
- Right-of-Way
  - Utility corridor for 80%; 9 land owners
- Pipe specifications
  - 4-in pipe dia.
  - X70 carbon steel
  - DOT 29 CFR 195 liquid pipeline; buried 3 feet with surface vegetation and maintenance
  - Purity is 97% dry CO_2 at 115ºF, 1,500 psig (< 20 ppm H_2S)



- **CO_2-EOR industry pipeline construction and operational standards worked quite well for CCS transportation**

Cardno ENTRIX Shaping the Future

Denbury

CO_2 Transportation via Pipeline

- Eighteen horizontal directional drills required (Esposito et al., GHGT-11)
  - Avoid Plant Barry surface facilities
  - Railroad and road crossings
  - Wet areas
  - However, most of the HDDs were performed to minimize impacts on gopher tortoise burrows or colonies
  - Directional drilling under tortoise burrows/colonies less expensive than temporary relocation
- **Routing complexity added considerably to pipeline installation costs**

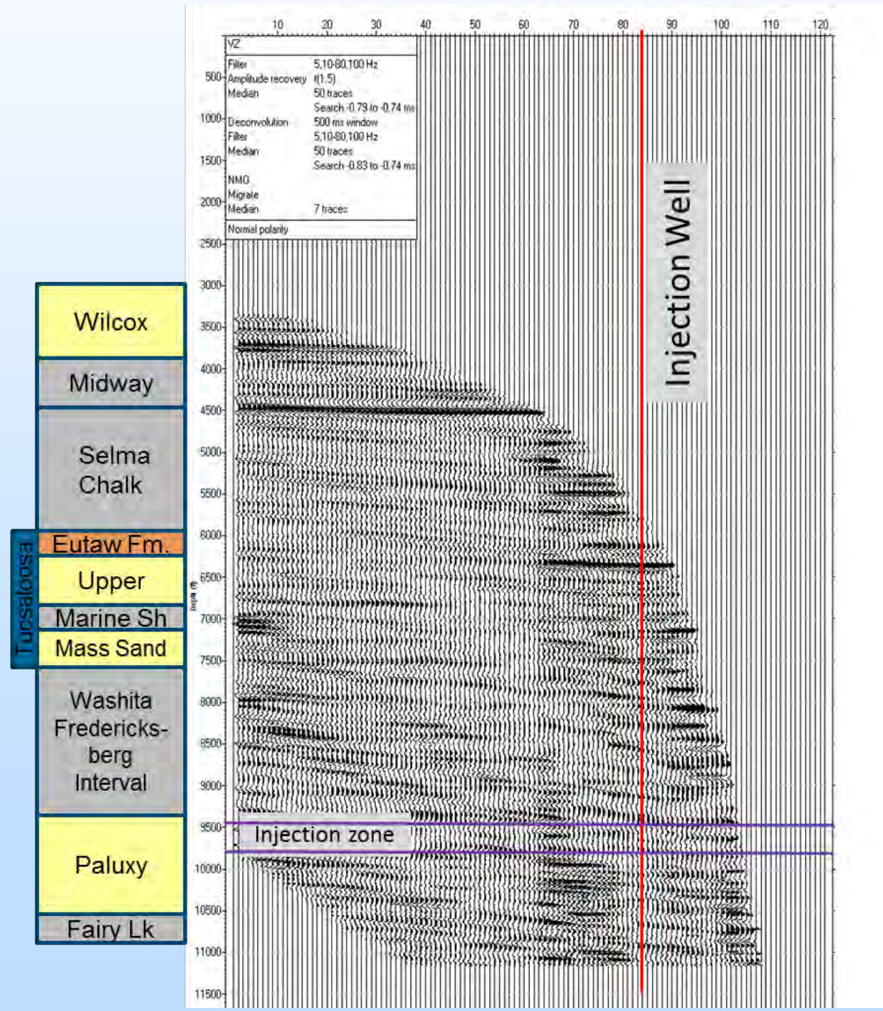
Horizontal Directional Drilling under Alabama Highway U.S. Route 43.

Cardno ENTRIX Shaping the Future

Denbury

Fiber Optic Distributed Acoustic Sensing (DAS)

- Fiber optic cable for distributed temperature and acoustic measurements one sensing technology tested in the Modular Borehole Monitoring (MBM) System
- Migrated image →
  - Observed strong reflectors
  - Good tie to formation logs (e.g., Selma Chalk)
- No “bright” spot observed where CO_2 was injected
- Image has sufficient quality to conduct time-lapse analysis using results from the second (final) survey



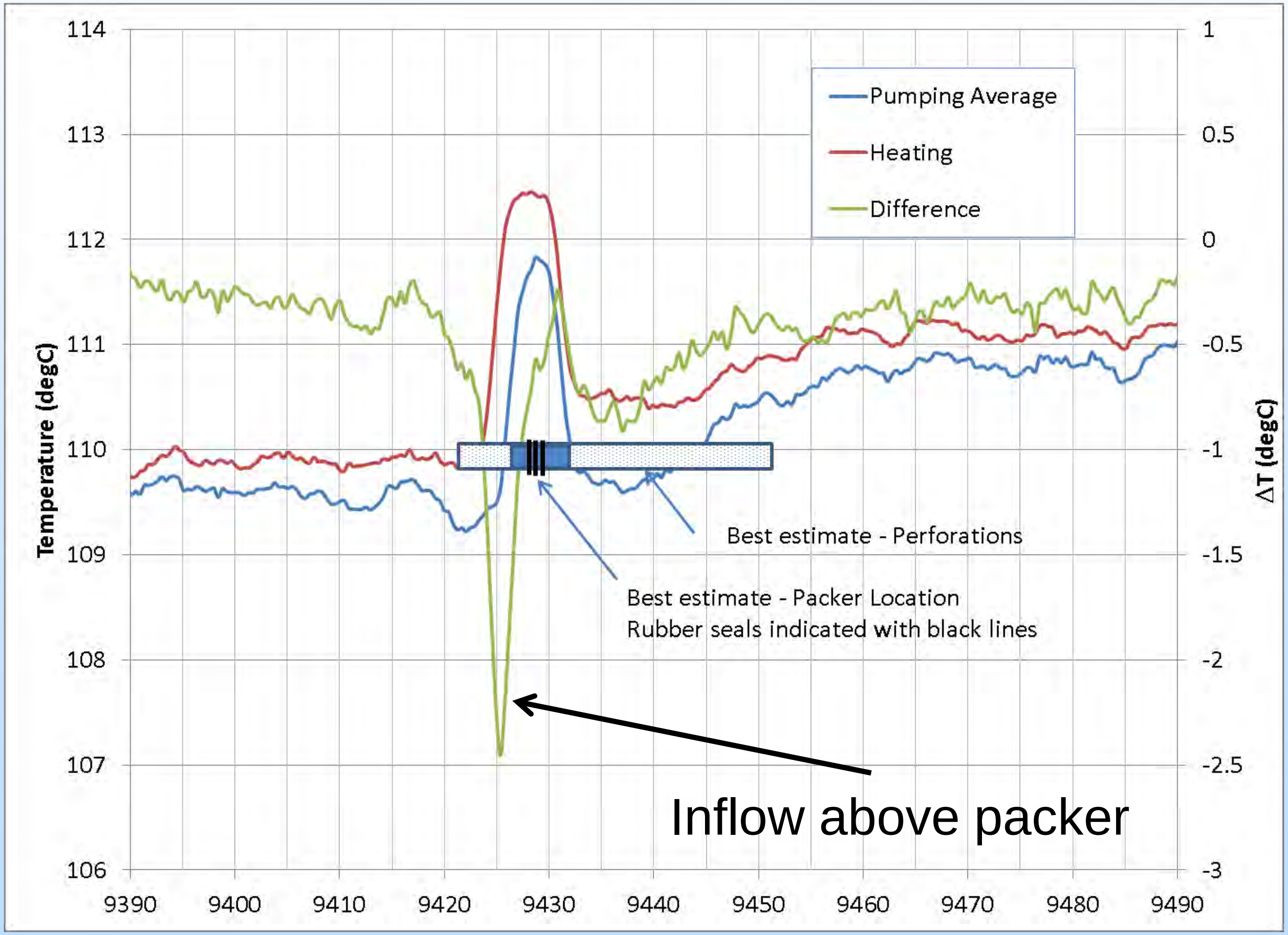
CO2 Capture Project

SILIXA

BERKELEY LAB

Fiber Optic Distributed Temperature Sensing (DTS)

FO-Based Distributed Temperature Sensing (DTS) Allowed Us to Diagnose a Completion Problem with Our Observation Well



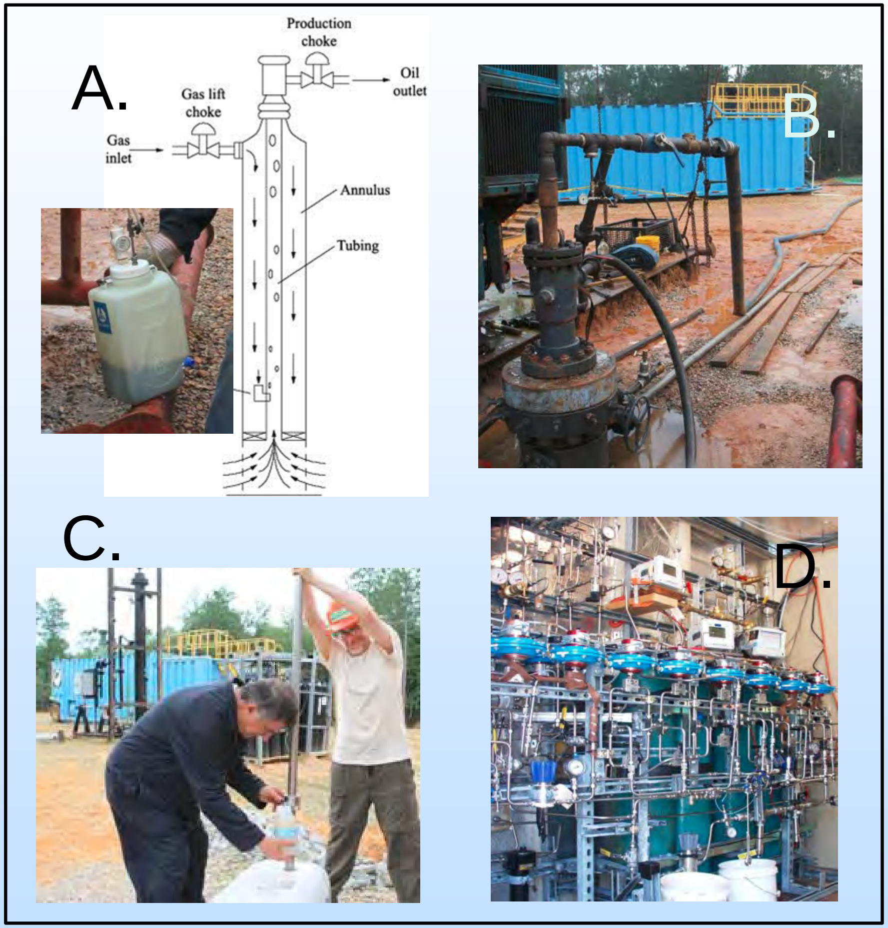
In-zone Comparison of Fluid Sampling Methods (U-tube, Gas lift, Pumping, Kuster Sampler) (Conaway et al., IJCG, 2016)

A. Gas-lift
   - Samples had the highest pH indicating possible loss of dissolved gas
   - Sampling method should be limited to major and unreactive solutes

B. Pumping
   - Relatively high Fe concentrations compared to other methods, showing evidence of contamination or geochemical changes in samples
   - Sampling method should be limited to major and unreactive solutes

C. Kuster sampler:
   - Field measurements of initial pH had the lowest value
   - Geochemical data consistent in repeated sampling

D. U-tube:
   - In general, sample results are comparable to the Kuster method



USGS collecting in-zone groundwater samples using:
A. gas-lift; B. electric submersible pump; C. Kuster sampler; and D. u-tube sampler

USGS science for a changing world

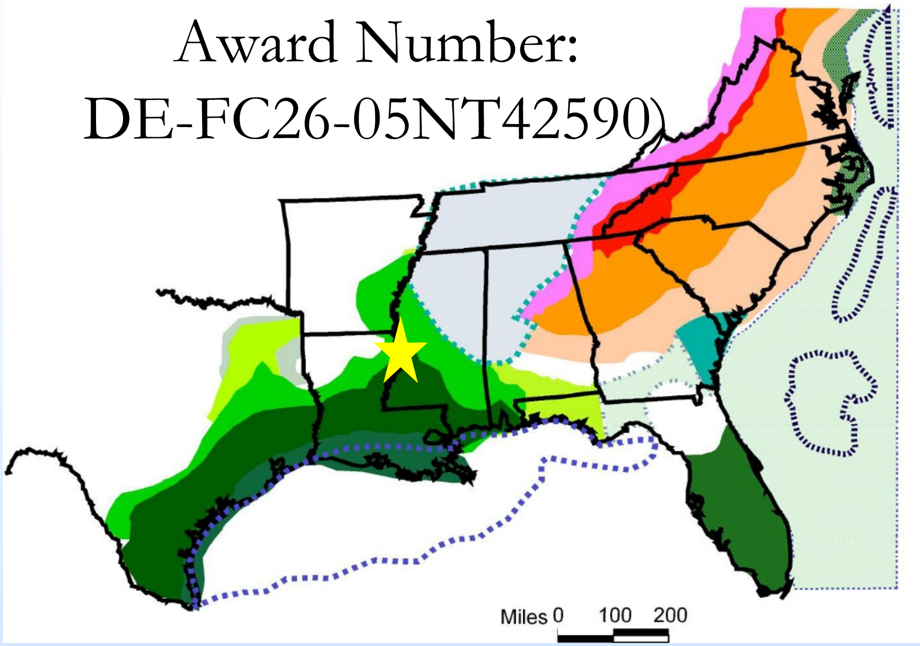
All Good Things Come to an End, but CO_2 Storage is Forever

Installation of Injection Well D9-7 #2

Abandoned Well Pad Prior to Drilling D9-7 #2

Southeast Regional Carbon Sequestration Partnership—Early Test at Cranfield

Award Number:
DE-FC26-05NT42590)



Susan Hovorka, Gulf Coast Carbon Center,

Bureau of Economic Geology Jackson School of Geosciences

T, he University of Texas at Austin

U.S. Department of Energy

National Energy Technology Laboratory

Addressing the Nation's Energy Needs Through Technology Innovation – 2019 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting

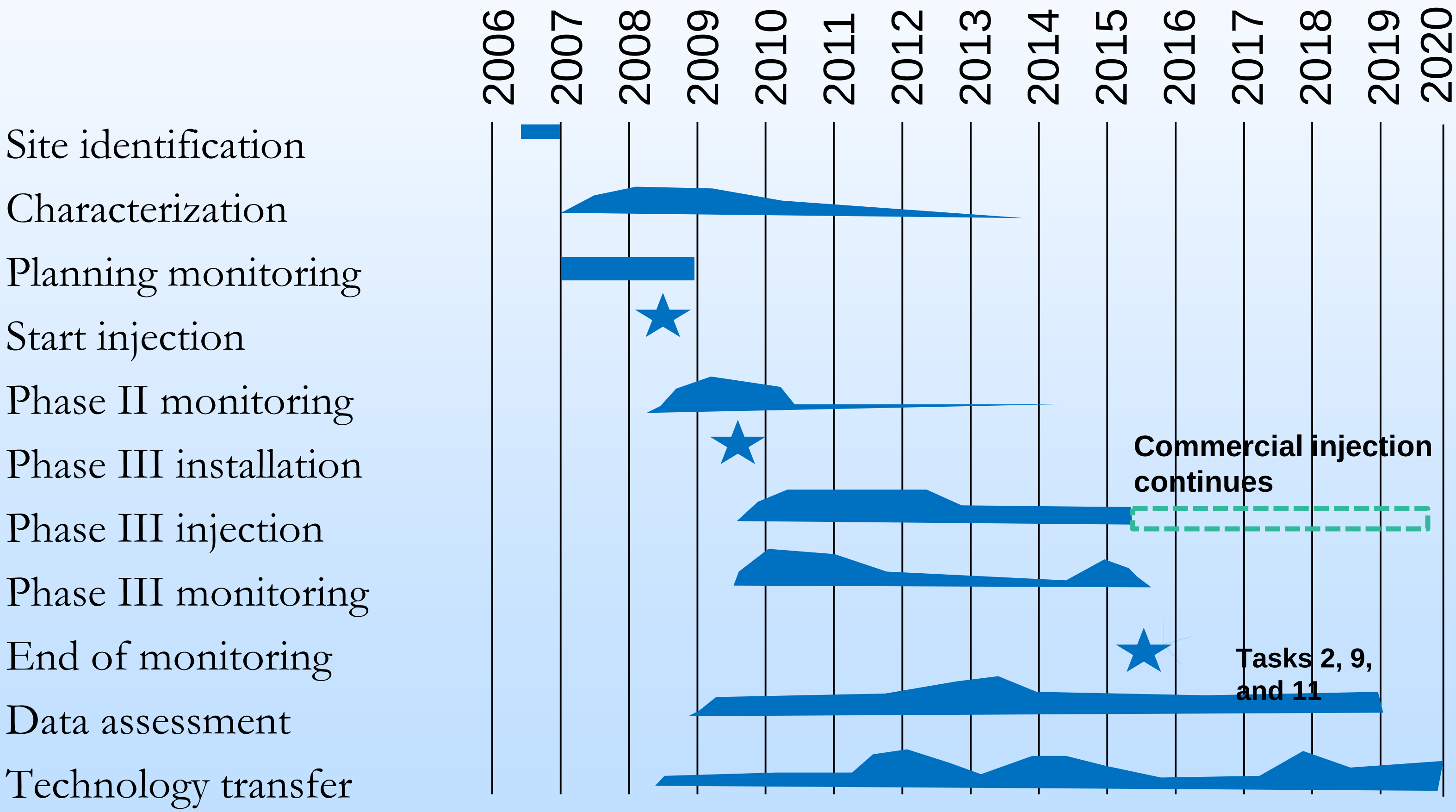
August 26-30, 2019

Presentation Outline

- Timeline of SECARB Early Test
- Team structure
- Early test goals
- Technical status- Commercializing the learnings
- Current activities
- Lessons learned – review publications

Real-time communication array

Timeline of SECARB Early Test



Team Structure

SECARB
Southeast Regional Carbon Sequestration Partnership

Bureau of Economic Geology
Gulf Coast Carbon Center

Gulf Coast Carbon Center
Bureau of Economic Geology
Jackson School of Geosciences
The University of Texas at Austin

Southern States Energy Board

SECARB Anthropogenic Test At Plant Barry/Citronelle

Denbury Resources
Field owner and injection system design, management, 4-D survey, HS&E

Vendors
e.g. well drilling, landmen

Sandia Technologies
Monitoring Systems Design, Installation, HS&E

50 Vendors
e.g. Schlumberger

Core Lab
UT DoG
Anchor QEA

MSU & UMiss
Hydro & hydrochem

Curtin University
3-D Seismic processing

Federal collaborators
Via FWP

LBNL
Well-based geophysics, U-tube and lab design and fabrication

LLNL
ERT

USGS
Geochemistry

Separately funded

NRAP
VSP deployment & analysis

NETL
Rock-water interaction

Model comparisons
LBNL SIM SEQ study

IPARS Modeling
CFSES M. Wheeler

4-D Seismic analysis
K. Spikes UT DoGS

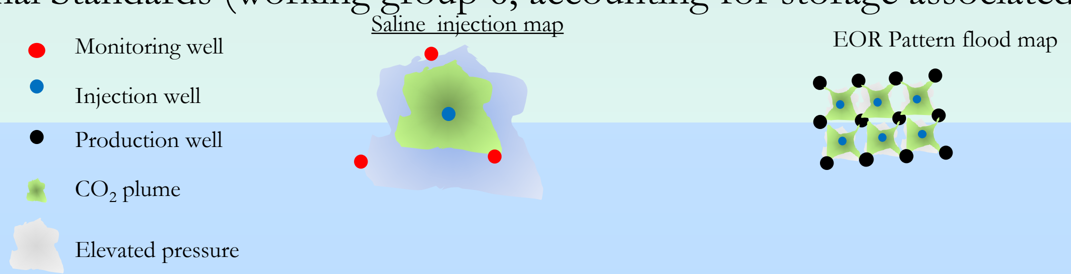
Rock Mechanics
CFSES Sandia NL

Microseismic deployment
RITE, Japan

Groundwater controlled release
AWWA

Technical Status - Moving information to commercial

- Injection scale-up – pushing the limit of injection
  - Assessing what is rate-limiting issue – overpressure or overfill?
- CCUS monitoring and accounting
  - Unique issues in a proven trap with production history – but complex fluids and many wells
- Maximize monitoring testing to minimize commercial monitoring
  - SECARB early test – extensive monitoring – many experiments
  - Commercial monitoring – focus on key issues –ALPMI method
  - Advising California Air Resources Board on their new Carbon Capture and Sequestration Protocol under the Low Carbon Fuel Standard
  - Advising International Standards (working group 6, accounting for storage associated with EOR.



GCCC GULF COAST CARBON CENTER
BUREAU OF ECONOMIC GEOLOGY

Early Test Scope

- Monitoring saline and EOR in a commercial EOR project
- “Early” because project was nearly ready to start at time SECARB entered
- 10,000 ft deep Cretaceous Tuscaloosa Formation

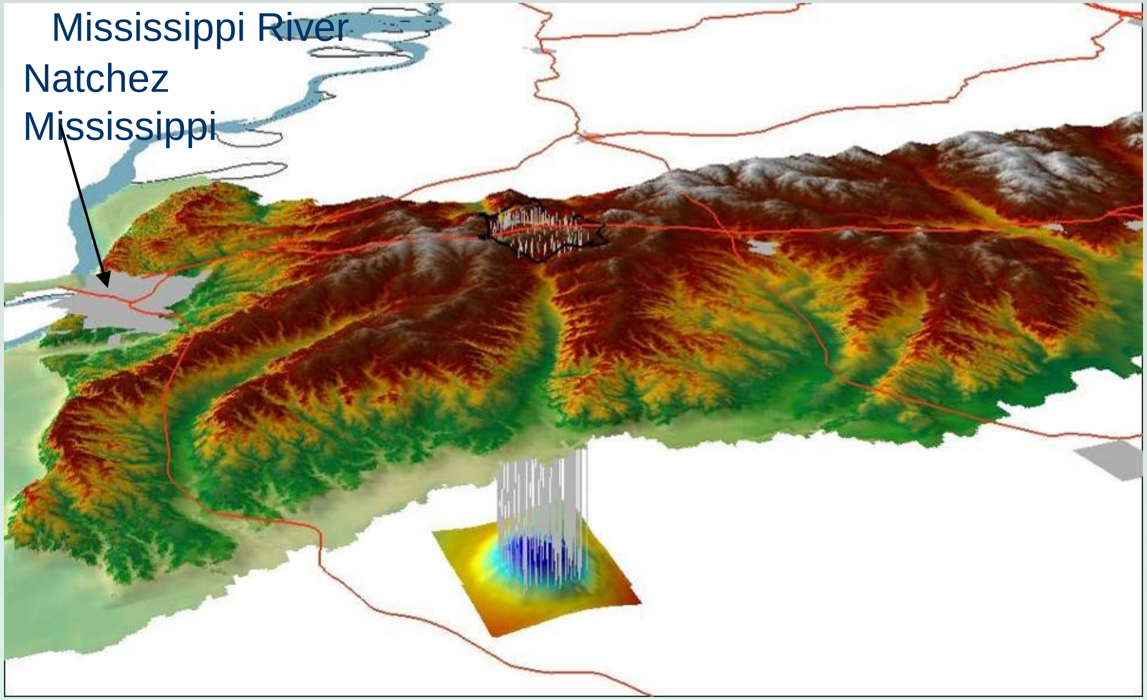
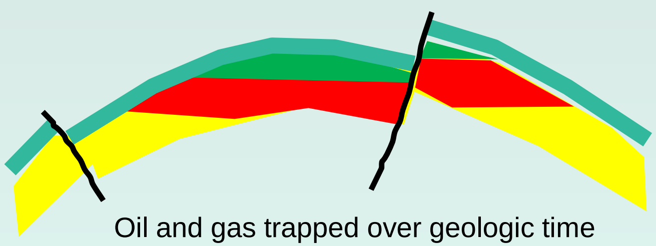


Figure Tip Meckel

Stacked storage EOR and Saline

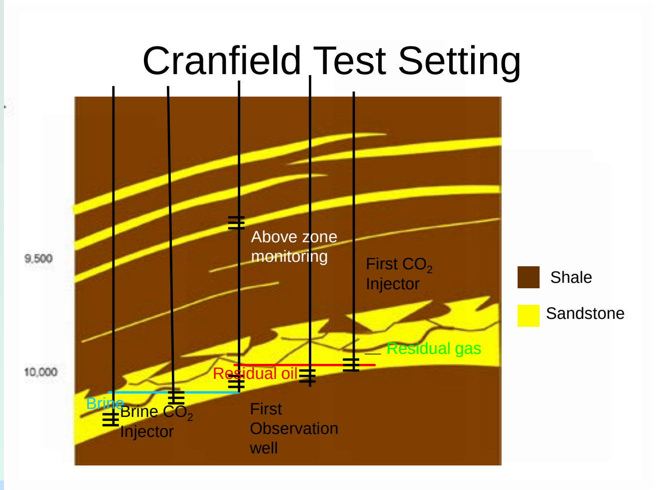
- Characterization based on long production history
- Balanced flood
  - Fluid withdrawal (oil, water, gas CO_2) = Fluid injection (water, CO_2) during most of the operation
  - Area and magnitude of elevated pressure controlled by production
  - Area occupied by CO_2 controlled by production
- Controlled flood
  - Injection and production patterns
- Active surveillance
  - Production, pressure
  - Other techniques as needed
    - Wireline log, seismic, tracers,



Oil and gas trapped over geologic time

Major Contributions

- Early Test Developed monitoring approaches for later commercial projects
  - Process-based soil gas method
  - Effectiveness of groundwater surveillance
  - Pressure and fluid chemistry monitoring in Above-Zone Monitoring Interval (AZMI)
  - ERT for deep CO_2 plume
  - Limitations of 4-D seismic
- Published and propagated techniques for widespread application
- Advanced to commercialization



Early Test Goals

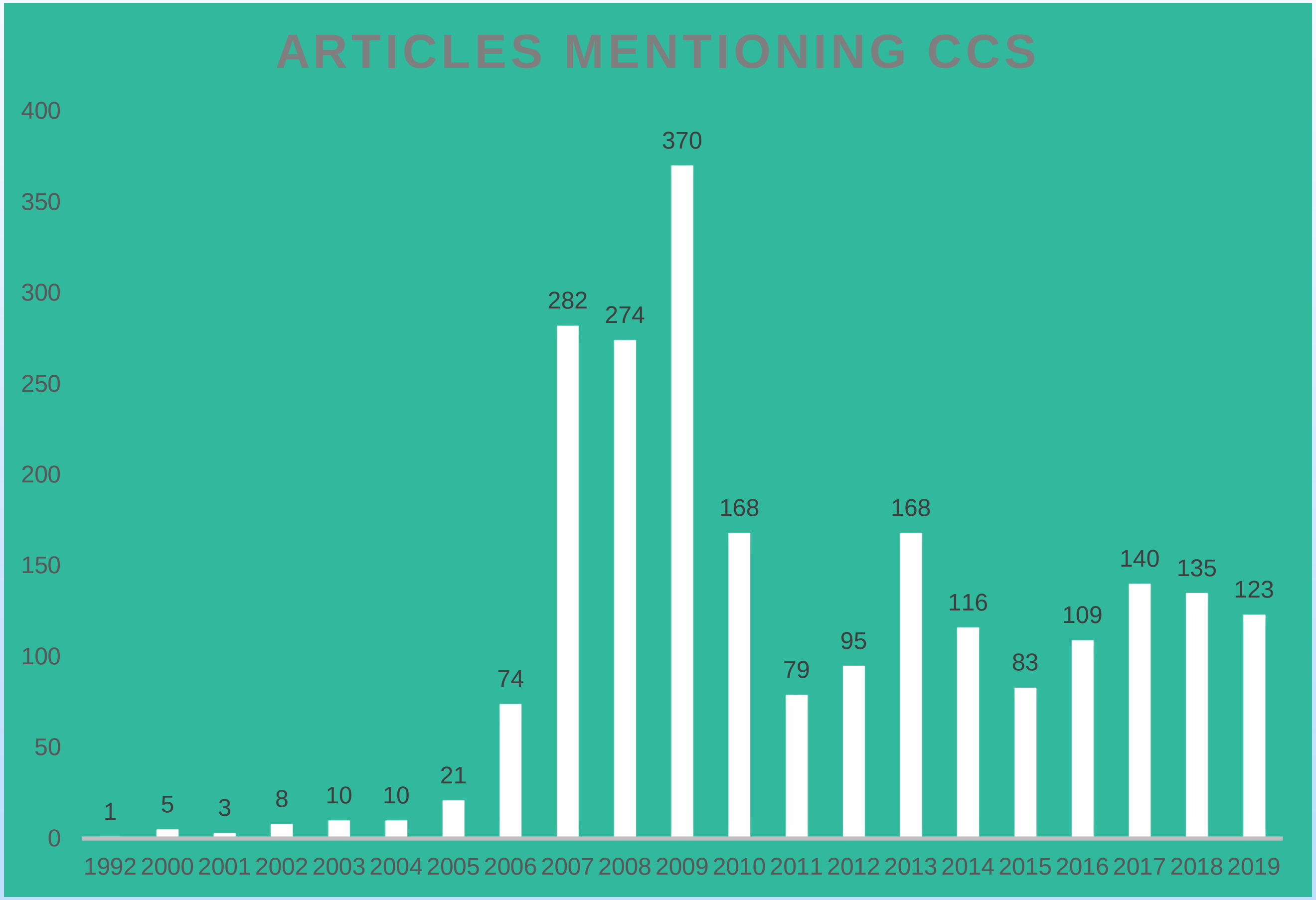
- Large-scale storage demonstration
  - 1 MMT/year over >1.5 years
    - Periods of high injection rates
    - Result >5 years monitoring with >5 MMT CO_2 stored
- Measurement, monitoring and verification
  - Tool testing and optimization approach
  - Deploy as many tools, analysis methods, and models as possible
- Stacked EOR and saline storage
- Commercial technology transfer ⇐ 2019 major effort
- Support Atlas, Maximize impact ⇐ 2020 major effort

GCCC GULF COAST CARBON CENTER
BUREAU OF ECONOMIC GEOLOGY

Media Analysis

Emily Moskal

- What is limiting US press coverage of CCUS?



Statistics from more than 1000 US media outlets

Follow-up detailed interviews

- 1) freelance science journalists,
- 2) highly-engaged female science journalists
- 3) journalists who had covered the topic before.

Major media concerns per interviewees:

" there have been many failed projects"

"the ones that exist are too expensive"

"we don't know if CO_2 will leak to the surface"

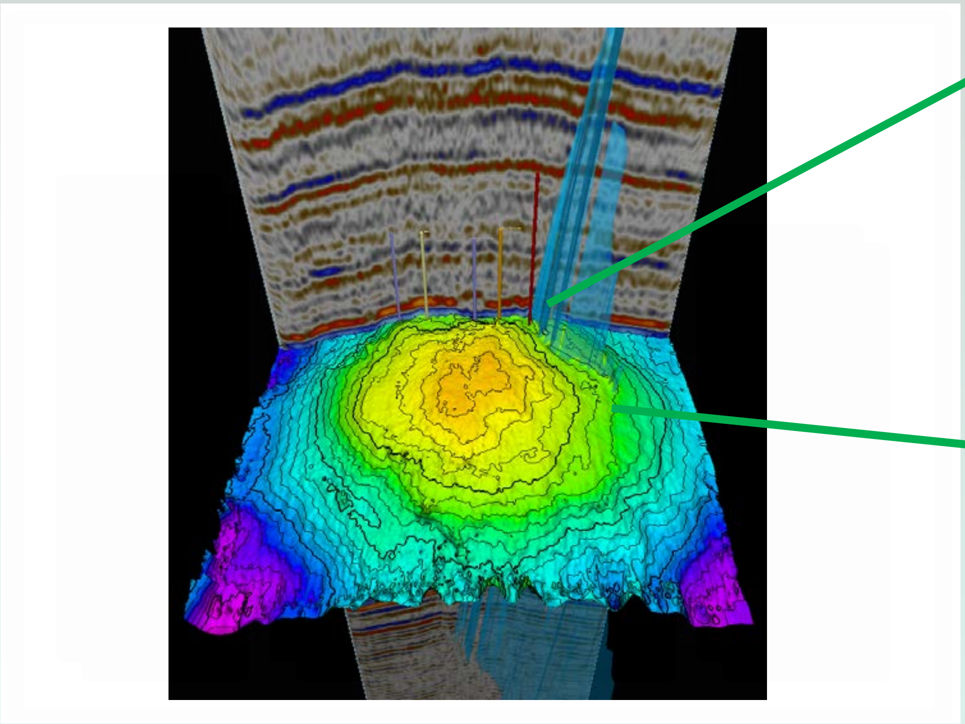
"environmental damage will be similar to those caused by fracking."

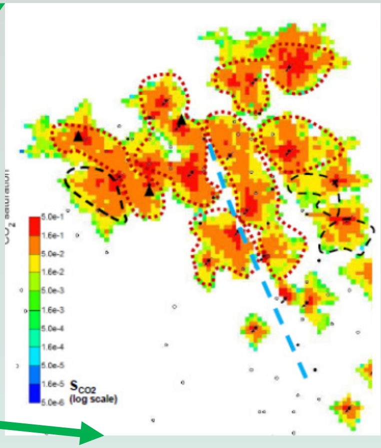
GCCC GULF COAST CARBON CENTER BUREAU OF ECONOMIC GEOLOGY

Outreach - reaching further

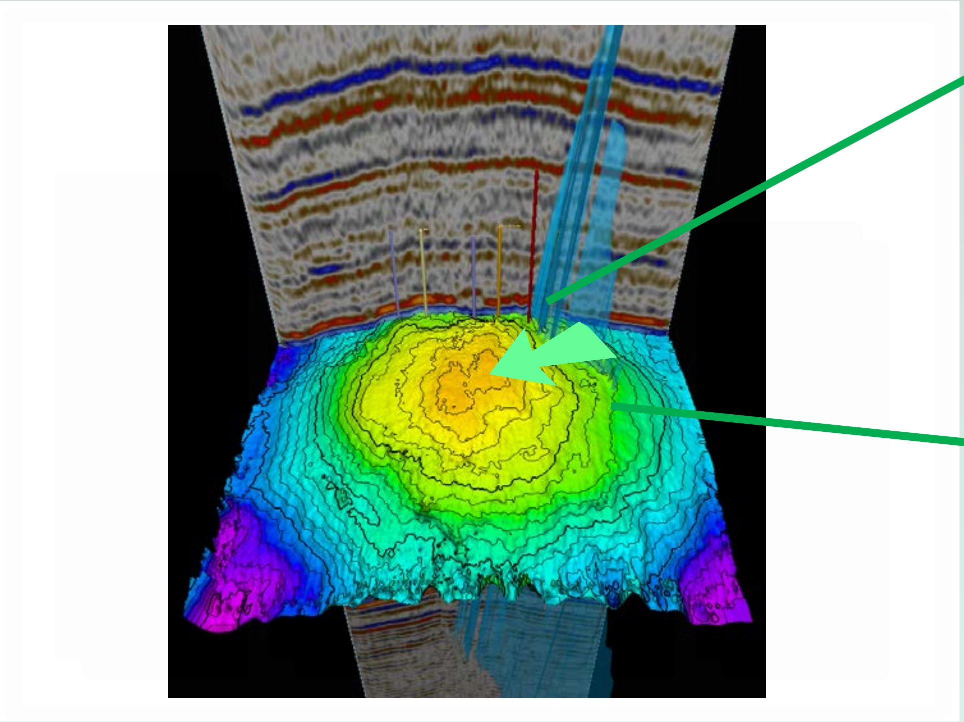
GCCC GULF COAST CARBON CENTER
BUREAU OF ECONOMIC GEOLOGY

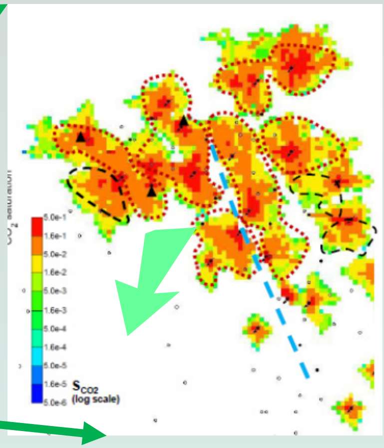
Physics of plume stabilization





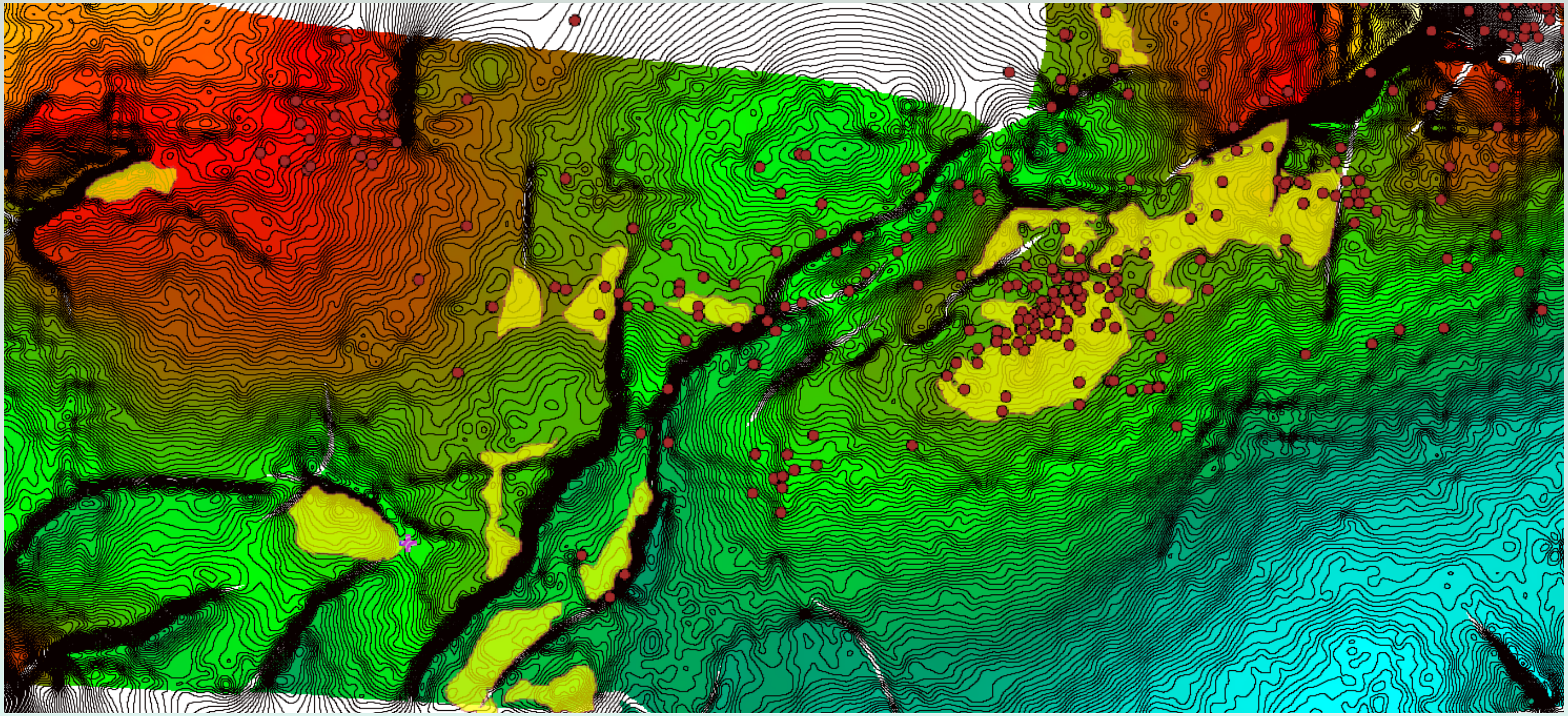
Physics of plume stabilization





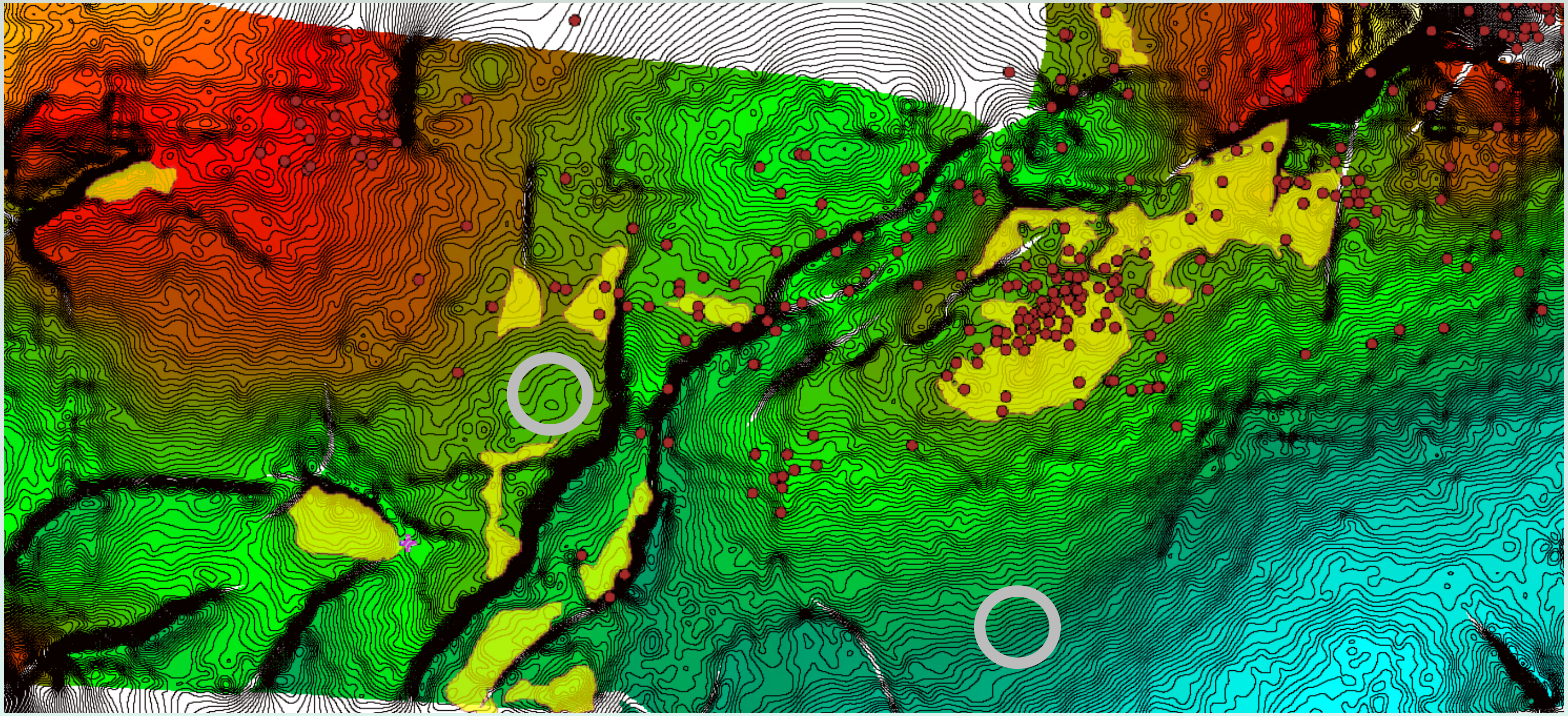
How fast and how far will CO2 migrate on dip before stabilizing?

Upscaling to regional saline aquifers

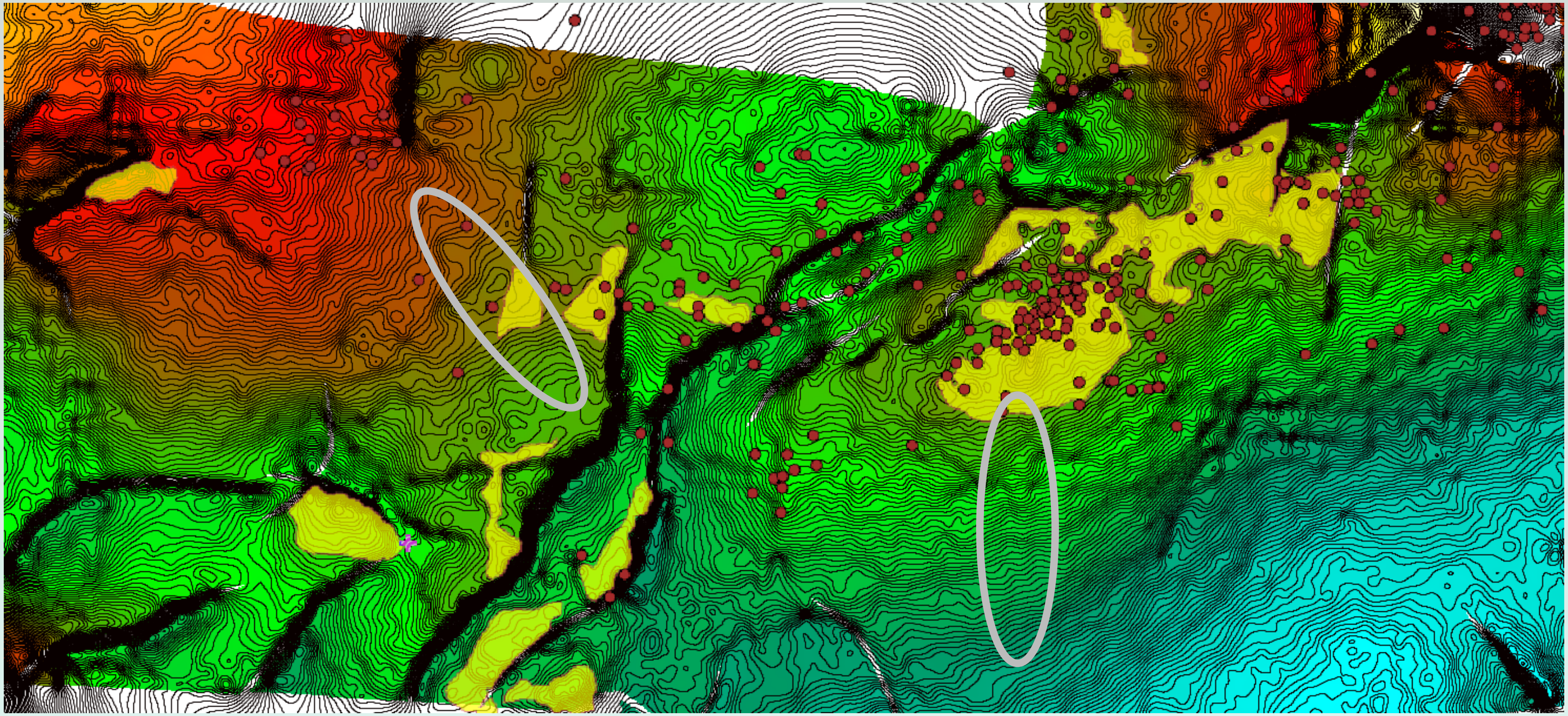


GCCC GULF COAST CARBON CENTER BUREAU OF ECONOMIC GEOLOGY

Upscaling to regional saline aquifers



Upscaling to regional saline aquifers

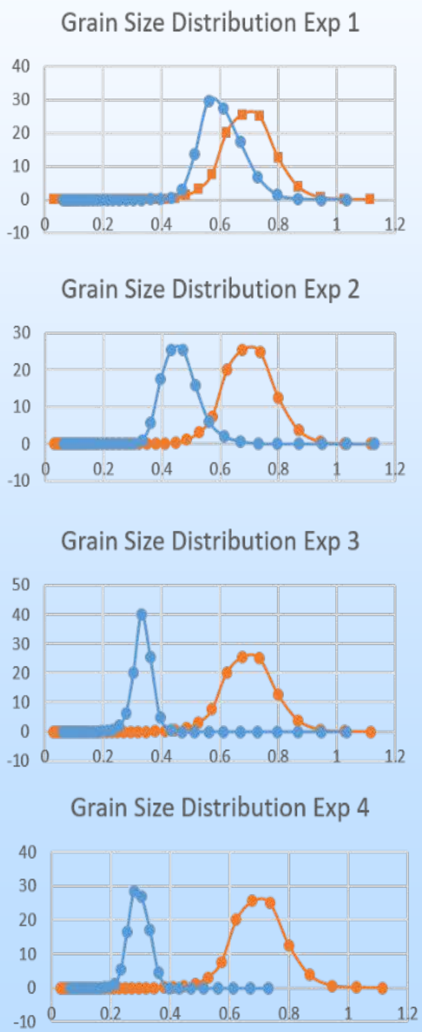


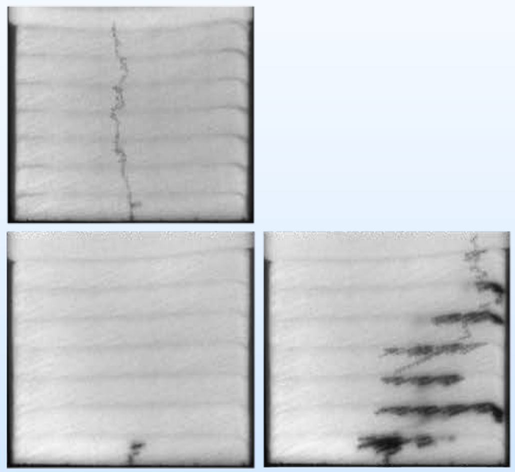
Physics of plume stabilization

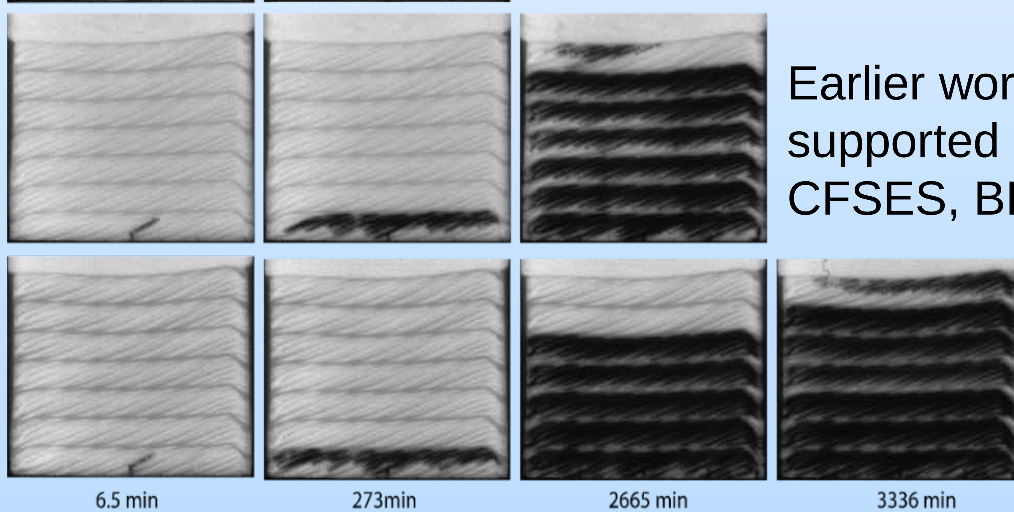
- Dynamics of CO_2 capillary trapping and influence of factors on stability of trapped CO_2: A pore-scale study
- Convection-diffusion-reaction of CO_2-enriched brine in Tuscaloosa sample: A pore-scale study
- Mechanism of CO_2 dissolution trapping: Combined pore-scale and Darcy-scale study
- Influence of small scale geologic heterogeneities on CO_2 plume stabilization and trapping: An experimental study
- Visualization and analysis of CO_2 injection and oil production data in the Cranfield site

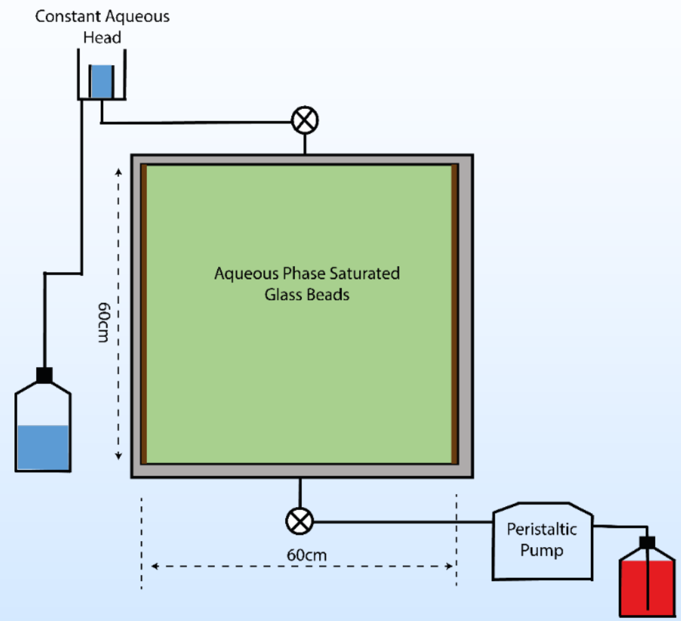
Small scale geologic heterogeneities influence CO_2 plume stabilization and trapping

Prasanna G. Krishnamurthy





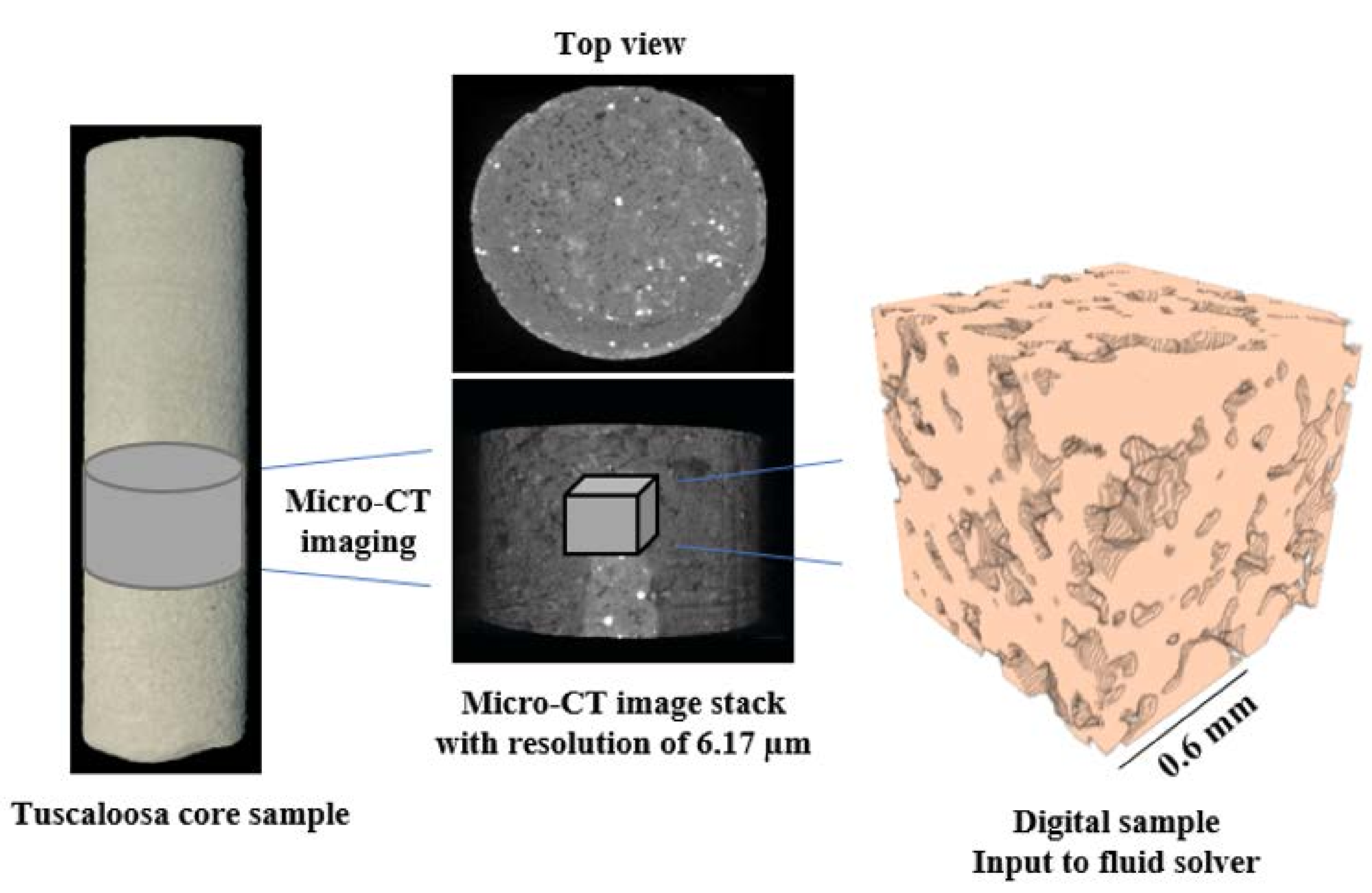




Earlier work supported by CFSES, BES

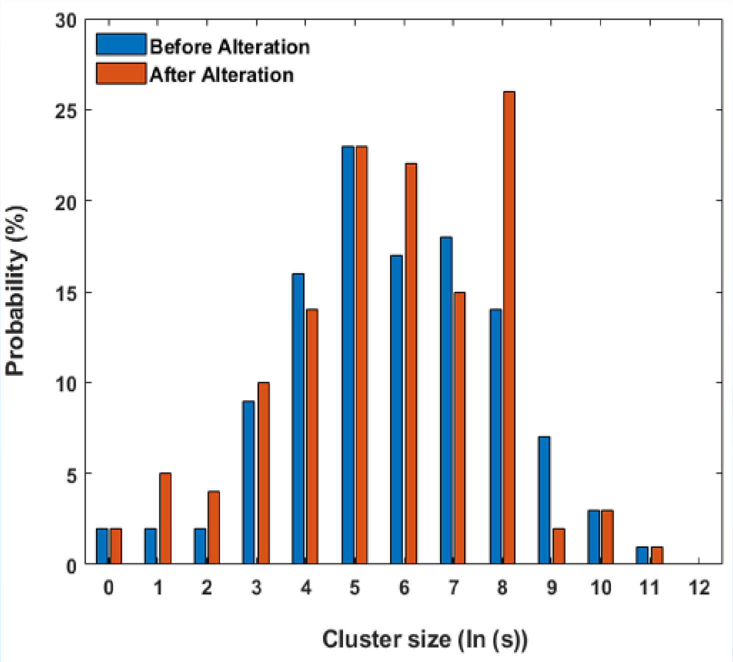
Pore scale flow in Tuscaloosa

Mehrdad Alfi

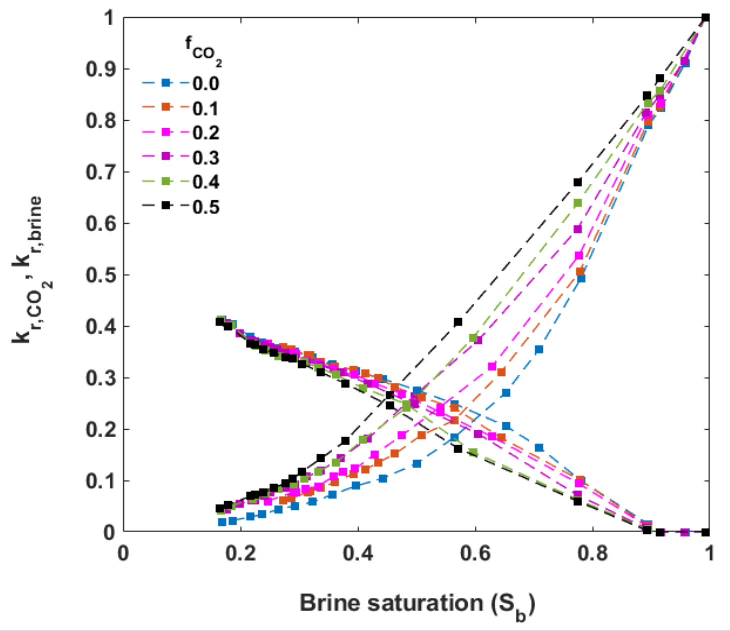


Effect of wettability alteration on CO_2 plume stabilization

Sahar Bakhshian



- Cluster-size distribution of CO_2 ganglia before and after wettability alteration



The relative permeability curves of $scCO_2$ and brine in samples with heterogeneous wettabilities fCO2 =fractional wettability

Value and methods for down-selection of monitoring tools

- Optimized tool selection (Assessment of low probability material impact: ALPMI)

- Avoid subjective terms like safe and effective.
- E.g. : Specify mass of leakage at identified horizon or magnitude of seismicity.
- Specify certainty with which assurance is needed

Risk assessment method as usual

Quantify risks to define material impact — Specify magnitude, duration, location, rate of material impact

Model material impact scenarios — Explicitly model unacceptable outcomes showing leakage cases. ALPMI uses models differently than the typical history matching the expected performance

Identify signals in the earth system that indicate or preferably precede material impact — Method down selects only signals that indicate material impact may occur or may be occurring

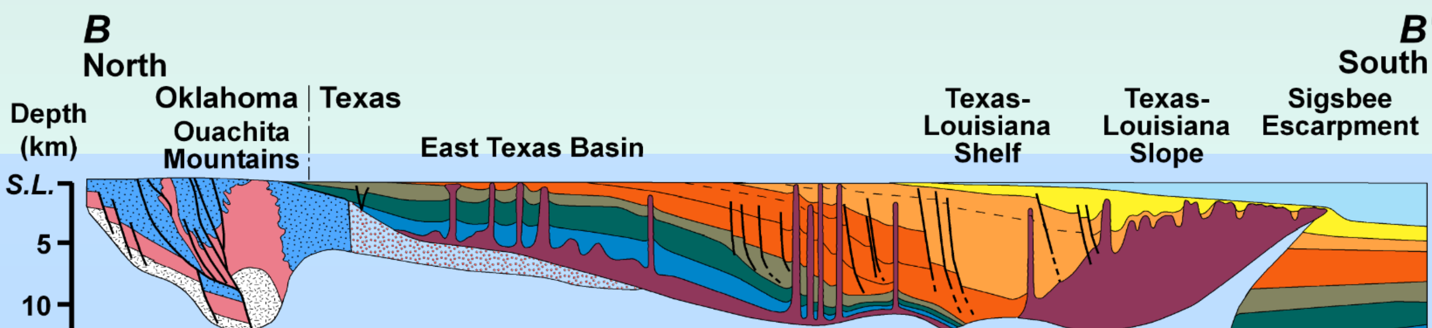
Select monitoring tools that can detect these signals at required sensitivity — Approaches like those normally used for seismic survey design should be deployed for all modeling tools. Forward modeling tool response is essential to developing the expected negative finding: “No material impact was detected by a system that could detect this impact.”

Deploy tools; collect and analyze data — This activity as traditionally conducted. Include all the expected components, such as attribution, updating as needed, feedback , etc.

Report if material impact did/did not occur — Via this ALPMI process can a finding that the material impact did not occur be robustly documented

Lessons Learned

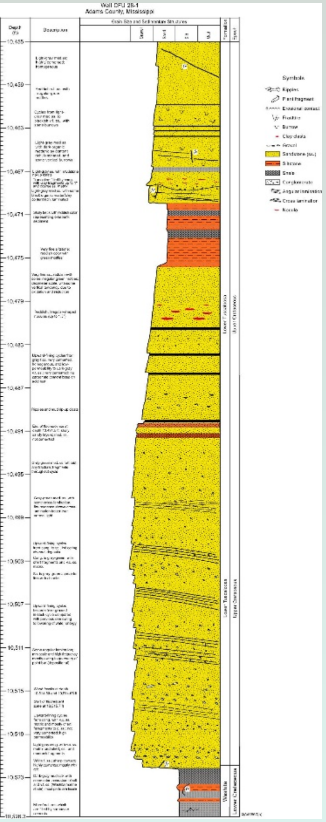
- Need for reproducible method of determining how much monitoring is enough in a commercial setting.
- Need for improved physics-based models that correctly estimate process and rate of stabilization
- Need for improved and renewed dialog with the media
- Increasing confidence in site selection and monitoring
  - ISO standard released
  - California LCFS
  - 45Q tax Credit



GCCC GULF COAST CARBON CENTER

BUREAU OF ECONOMIC GEOLOGY

Synergy Opportunities

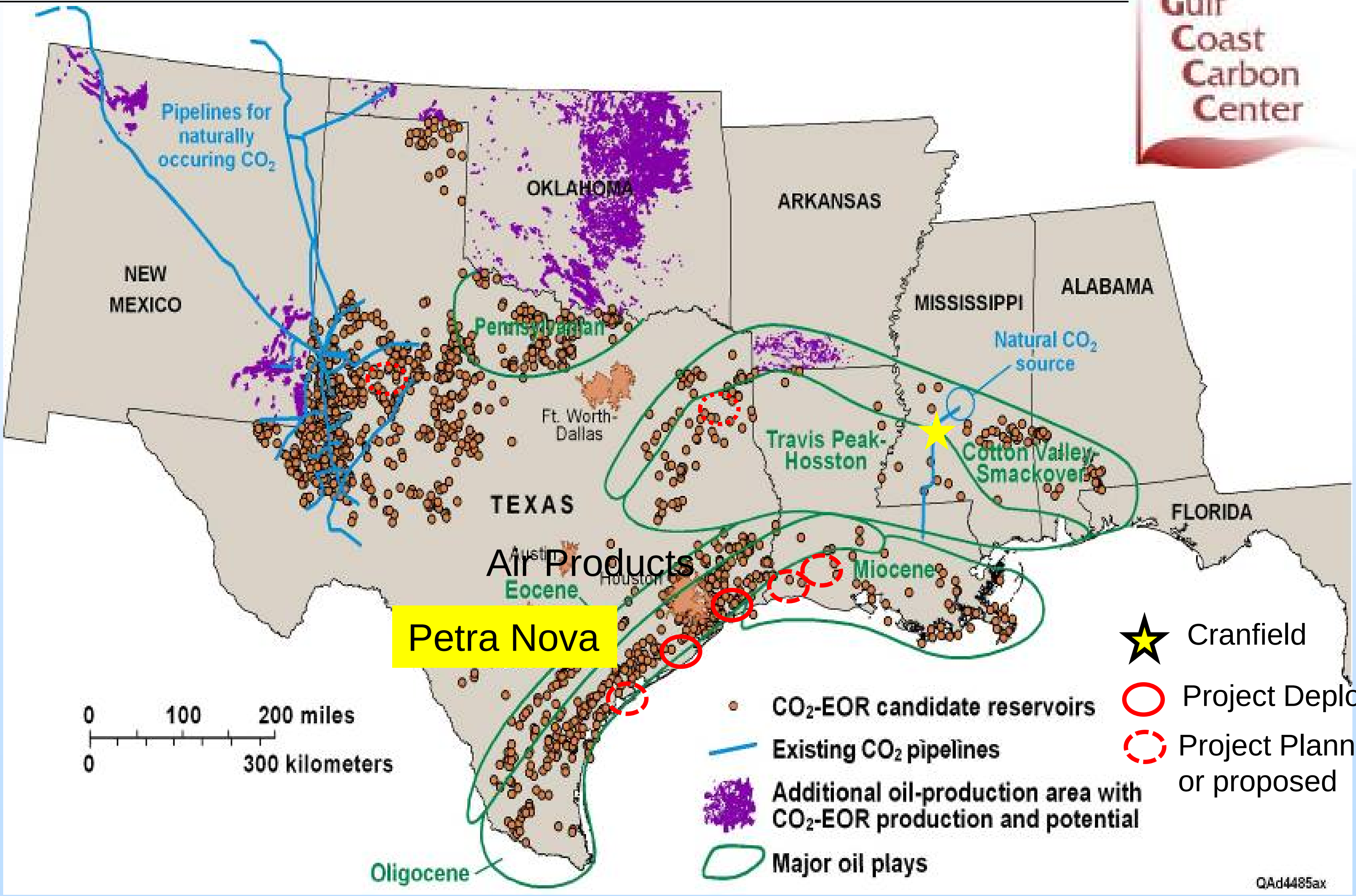


– Support technology transfer to commercial entities
  - Where can I inject?
  - What are first steps?
  - Explain retention and monitoring
– US – International collaboration of high value
  - ISO
  - IEAGHG

Looking for injectivity – core at Cranfield field, MS

Commercialization of learnings at SECARB Early Test Accomplishments to Date

Gulf Coast Carbon Center



Appendix

一 .

Recent submissions and publications (108 total)

- Uploads to EDX (data) https://edx.netl.doe.gov
- Texas Scholar Works https://repositories.lib.utexas.edu
- Hovorka, S. D., Case study – testing geophysical methods for assessing CO_2 migration at the SECARB early test, Cranfield Mississippi "Geophysical Monitoring for Geologic Carbon Storage and Utilization" to be published by Wiley for the American Geophysical Union.
- D. W. Vasco, Masoud Alfi, Seyyed A. Hosseini, Rui Zhang, Thomas Daley, Jonathan B. Ajo-Franklin, and Susan D. Hovorka "The seismic response to injected carbon dioxide: Comparing observations to estimates based upon fluid flow modeling"
- Hosseini, S. A., Masoud Alfi, Donald Vasco, Susan Hovorka, Timothy Meckel, Validating compositional fluid flow simulations using 4D seismic interpretation and vice versa in the SECARB Early Test—A critical review
- Anderson, Jacob; Romanak, Katherine; Alfi, Masoud; Hovorka, Susan, Light Hydrocarbon and Noble Gas Migration as an Analog for Potential CO_2 leakage: Numerical Simulations and Field Data from Three Hydrocarbon Systems
- Fietz and Hovorka, Capturing the magic of carbon dioxide
- Hovorka, S.D. and Lu, J., Field observation of geochemical response to CO_2 injection at the reservoir scale, in Newel and Ilgen, Science of Carbon Storage in Deep Saline Formations , Elsevier

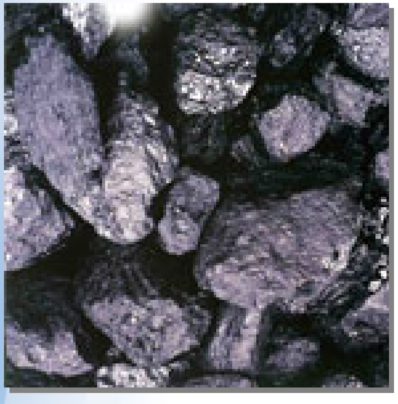
Benefit to the Program

Development of large-scale (>1 million tons of CO_2) Carbon Capture and Storage (CCS) projects, which will demonstrate that large volumes of CO_2 can be injected safely, permanently, and economically into geologic formations representative of large storage capacity.

Project Overview

Goals and Objectives

The Southeast Regional Carbon Sequestration Partnership's (SECARB) Phase III work focuses on the large scale demonstration of safe, long-term injection and storage of CO_2 in a saline reservoir that holds significant promise for future development within the SECARB region. The project will promote the building of experience necessary for the validation and deployment of carbon sequestration technologies in the region. Phase III will continue refining Phase II sequestration activities, sequestration demonstrations and will begin to validate sequestration technologies related to regulatory, permitting and outreach. The multi-partner collaborations that developed during Phase I and Phase II will continue in Phase III with additional support from resources necessary to implement strong and timely field projects.

SECARB (Citronelle) Phase III

Prepared For:

2019 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting

Prepared By:

George Koperna
ADVANCED RESOURCES INTERNATIONAL, INC.

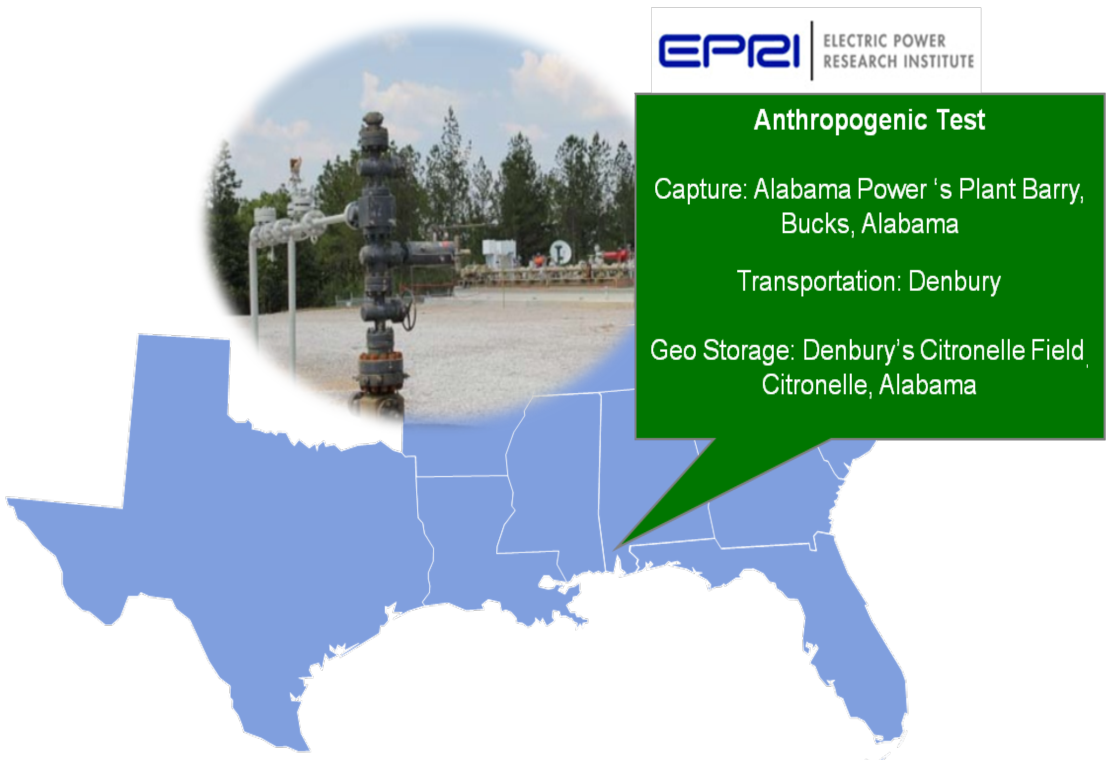
August 27, 2019

Acknowledgement

This presentation is based upon work supported by the Department of Energy National Energy Technology Laboratory under **DE-FC26-05NT42590** and was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Citronelle Phase III Project

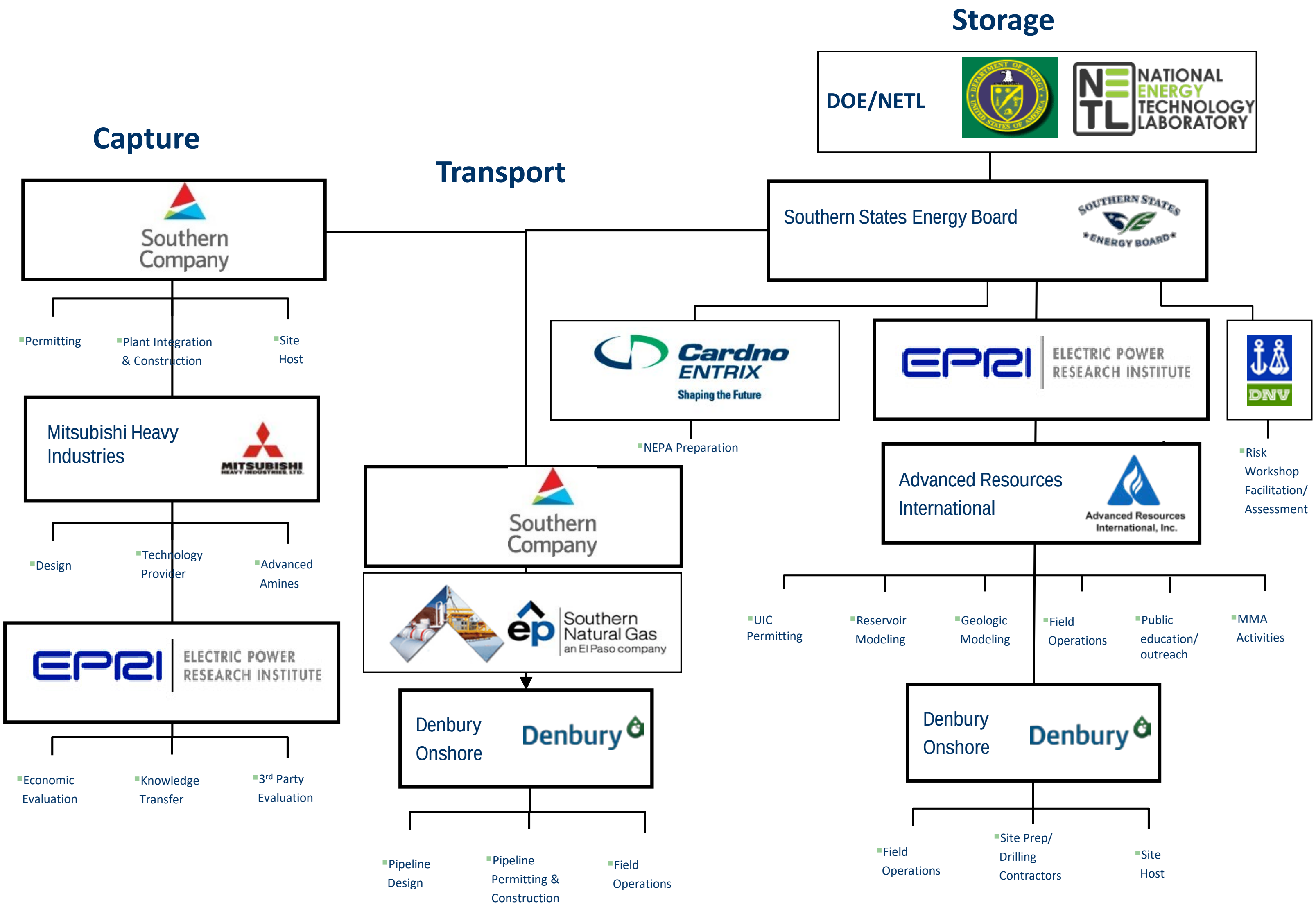
Baseline	Injection	Post
1 year	2 years	3 years
APR 2011 to AUG 2012	SEPT 2012 to SEPT 2014	OCT 2014 to SEPT 2017



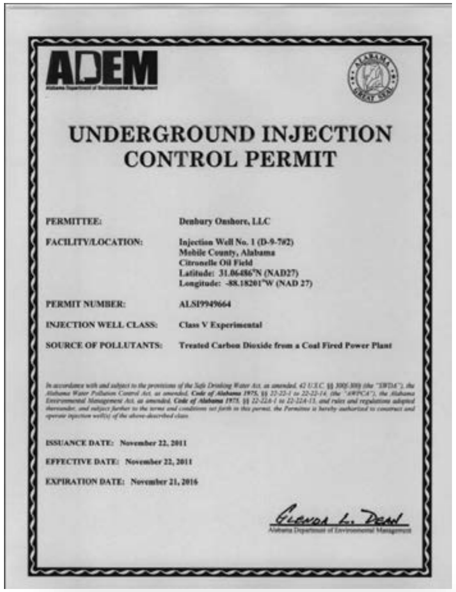
Project Objectives

1. Understand the coordination required to successfully integrate all four components (capture, transport, injection and monitoring) of the project;
2. Document the permitting process for all aspects of a CCS project;
3. Test the CO_2 flow, trapping and storage mechanisms of the Paluxy Formation, a regionally extensive Gulf Coast saline formation;
4. Demonstrate how a saline reservoir's architecture can be used to maximize CO_2 storage and minimize the areal extent of the CO_2 plume;
5. Test the adaptation of commercially available oil field tools and techniques for monitoring CO_2 storage (e.g., VSP, cross-well seismic, cased-hole neutron logs, tracers, pressure, etc.);
6. Test experimental CO_2 monitoring activities, where such technologies hold promise for future commercialization; and
7. Support the United States' largest commercial prototype CO_2 capture and transportation demonstration with injection, monitoring and storage activities.

1. Project Coordination



2. CCS Permitting Process



ADEM

UNDERGROUND INJECTION CONTROL PERMIT

PERMITTEE: Denbury Onshore, LLC

FACILITY/LOCATION: Injection Well No. 1 (D-9-7#2)
Mobile County, Alabama
Citronelle Oil Field
Latitude: 31.06486°N (NAD27)
Longitude: -88.18201°W (NAD 27)

PERMIT NUMBER: ALSI9949664

INJECTION WELL CLASS: Class V Experimental

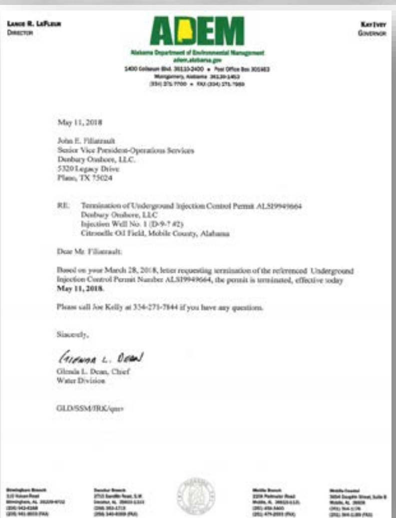
SOURCE OF POLLUTANTS: Treated Carbon Dioxide from a Coal Fired Power Plant

ISSUANCE DATE: November 22, 2011

EFFECTIVE DATE: November 22, 2011

EXPIRATION DATE: November 21, 2016

Glenda L. Dean
Alabama Department of Environmental Management



Lance R. LeFleur
Director

ADEM
Alabama Department of Environmental Management

Kay Ivey
Governor

May 11, 2018

John E. Filiatrault
Senior Vice President-Operations Services
Denbury Onshore, LLC.
5320 Legacy Drive
Plano, TX 75024

RE: Termination of Underground Injection Control Permit ALSI9949664
Denbury Onshore, LLC
Injection Well No. 1 (D-9-7 #2)
Citronelle Oil Field, Mobile County, Alabama

Dear Mr. Filiatrault:

Based on your March 28, 2018, letter requesting termination of the referenced Underground Injection Control Permit Number ALSI9949664, the permit is terminated, effective today **May 11, 2018**.

Please call Joe Kelly at 334-271-7844 if you have any questions.

Sincerely,

Glenda L. Dean
Glenda L. Dean, Chief
Water Division

GLD/SSM/JRK/qmr

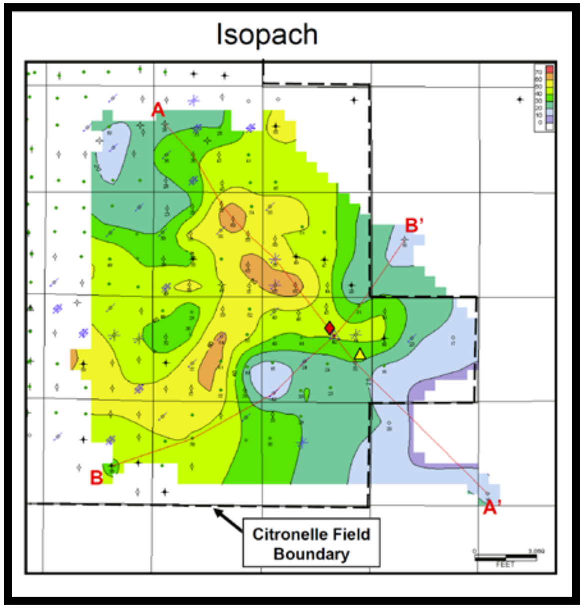
Select References

A. Oudinot et al. GHGT-14 **(2018)**
- Details UIC Class V permit application process, requirements and permit closure

D. Riestenberg et al. CMTC **(2015)**
- Details UIC Class V permit details including: injection well permit and CO_2 sequestration well standards

R. Esposito et al. Energy Procedia 4 **(2011)**
- Details capture facility permitting, transportation permitting and storage permitting

3. Test the CO_2 Flow, Trapping and Storage Mechanisms of the Paluxy



Baseline Reservoir Characterization:

- Analysis of over 80 existing oilfield well logs for porosity, thickness and depositional
- Sand mapping to determine "open" or "closed" sand units.

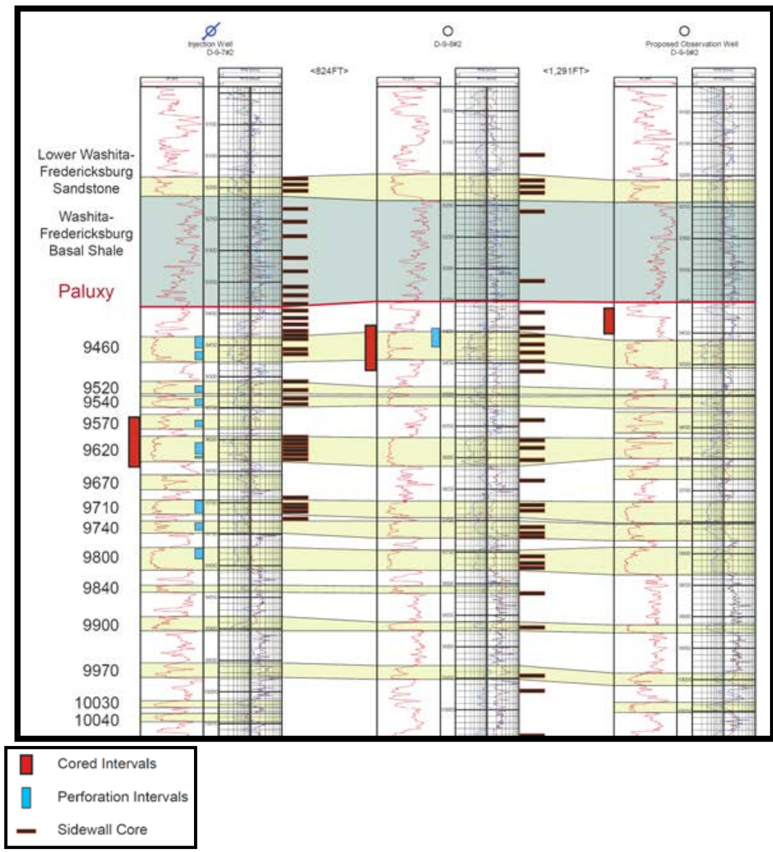
System	Series	Stratigraphic Unit	Major Sub Units	Potential Reservoirs and Confining Zones
Tertiary	Plio-Pliocene		Citronelle Formation	Freshwater Aquifer
	Miocene	Undifferentiated		Freshwater Aquifer
	Oligocene		Chickasawhay Fm.	Base of USDW
		Vicksburg Group	Bucatunna Clay	Local Confining Unit
	Eocene	Jackson Group		Minor Saline Reservoir
		Claiborne Group	Talahatta Fm.	Saline Reservoir
	Paleocene	Wilcox Group	Hatchetigbee Sand Bashi Marl Salt Mountain LS	Saline Reservoir
		Midway Group	Porters Creek Clay	Confining Unit
Cretaceous	Upper	Selma Group		Confining Unit
		Eutaw Formation		Minor Saline Reservoir
		Tuscaloosa Group	Upper Tusc.	Minor Saline Reservoir
			Mid. Tusc. Marine Shale	Confining Unit
			Lower Tusc. Pilot Sand Massive sand	Saline Reservoir
	Lower	Washita-Fredericksburg	Dantzler sand	Saline Reservoir
			Basal Shale	Primary Confining Unit
		Paluxy Formation	'Upper' 'Middle' 'Lower'	Injection Zone
		Mooringsport Formation		Confining Unit
		Ferry Lake Anhydrite		Confining Unit
		Donovan Sand	Rodessa Fm. Upper'	Oil Reservoir
			'Middle'	Minor Saline Reservoir
			'Lower'	Oil Reservoir

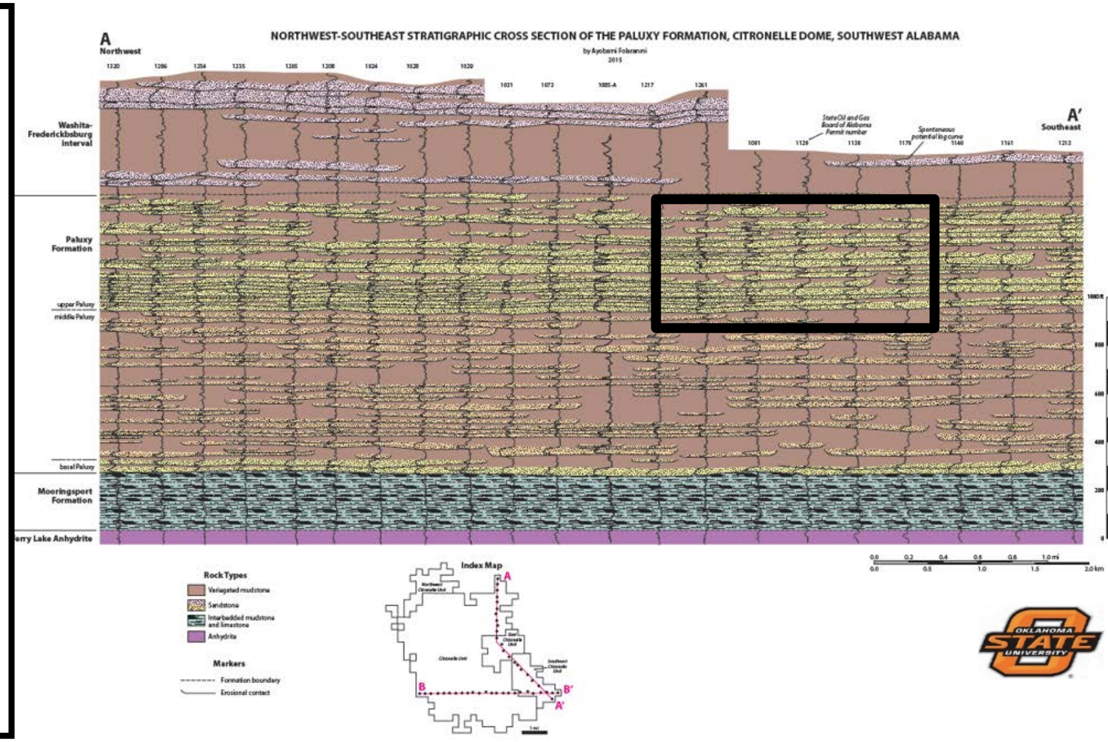
Collected new geologic data on the Paluxy reservoir and confining unit with the drilling of the project's three new wells:

- 210 feet of whole core and 70 percussion sidewall cores
- Full set of open hole logs on all three wells (quad combo, MRI, spectral gamma, mineralogical evaluation, waveform sonic, cement quality, pulsed neutron capture)
- Baseline vertical seismic profiles and crosswell seismic collected in Feb 2012

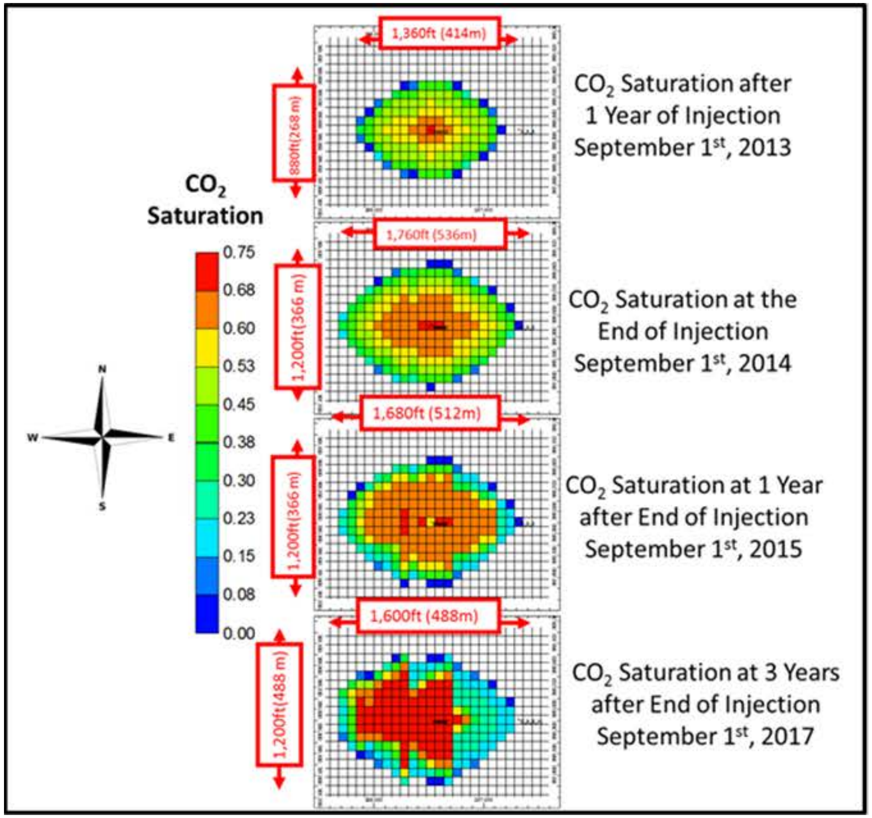
Geologic Characterization Results

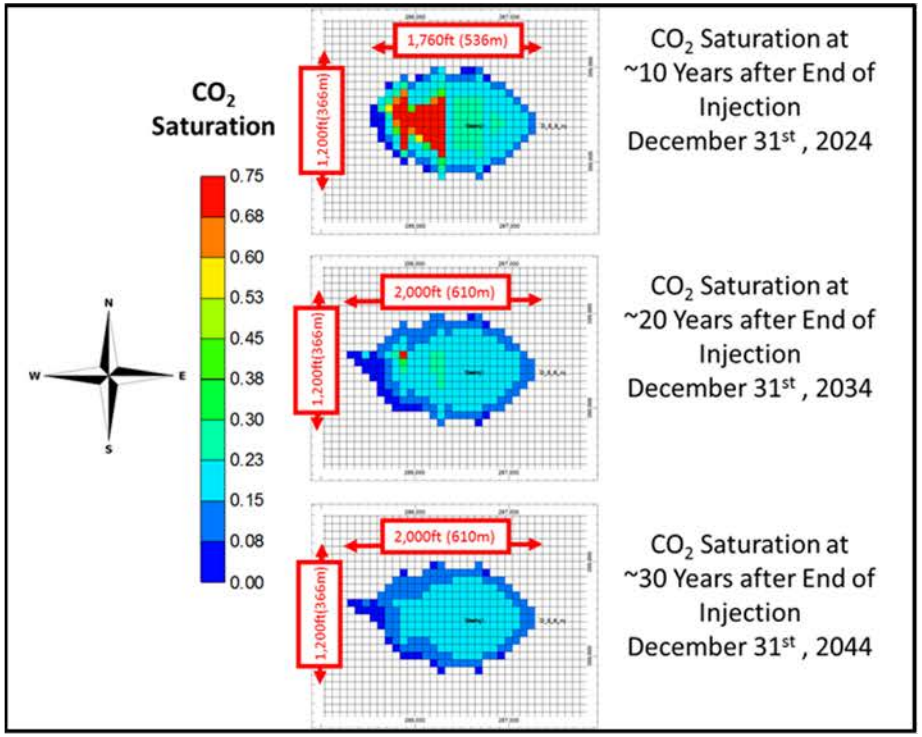
- Sandstone and mudstone units are continuous at this scale
- CO_2 dispersion vertically
- Multiple stacked plumes





Storage Mechanisms of Paluxy Form.

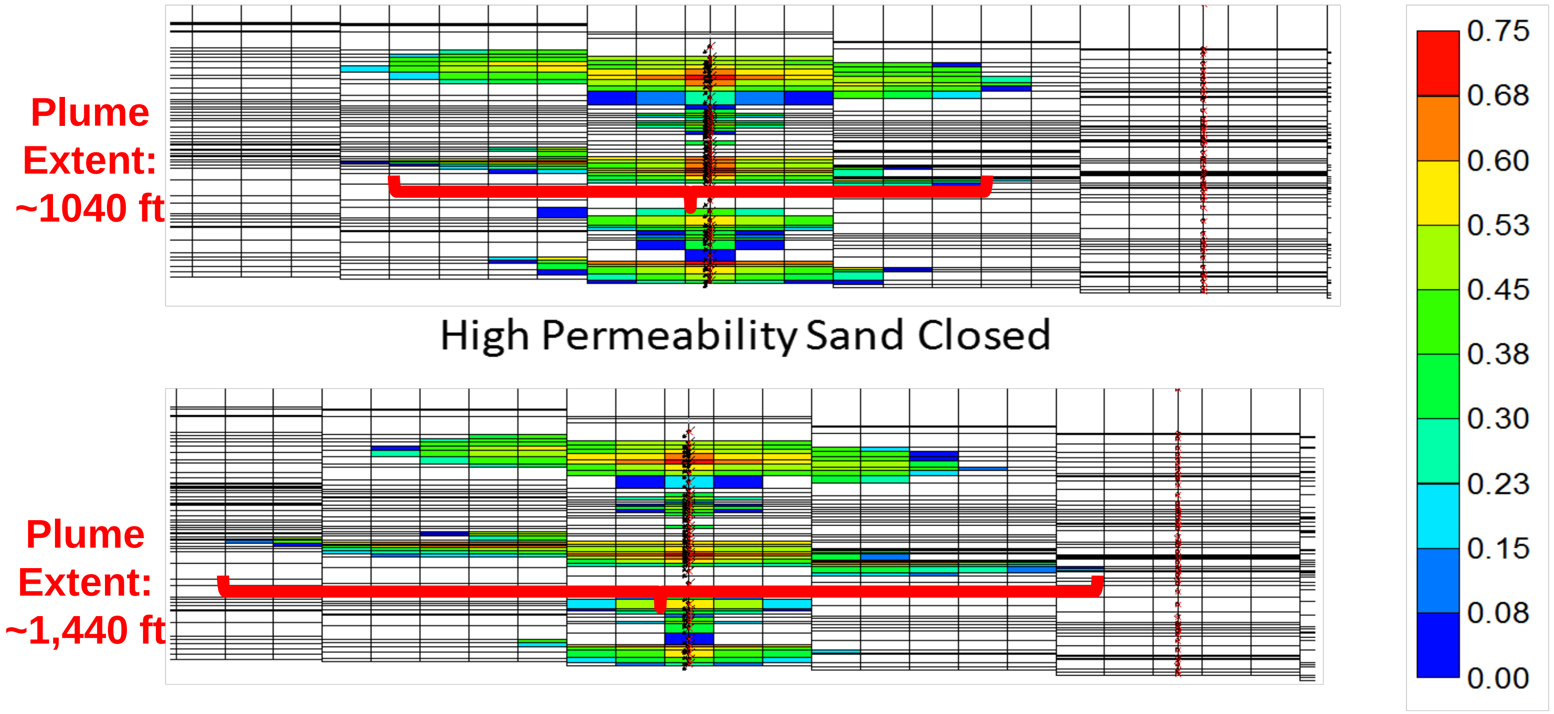




The estimated radius of the CO_2 plume 30 years after cessation of injection is approximately 1000 ft. (305m), which is less than the project's initial AoR of 1,700 ft.

4. Utilizing Reservoir Architecture

- Limiting the extent of the CO_2 plume by not completing high permeability sand layers
- By shutting in the high permeability sand layer, the plume radius was decreased by ~200 ft

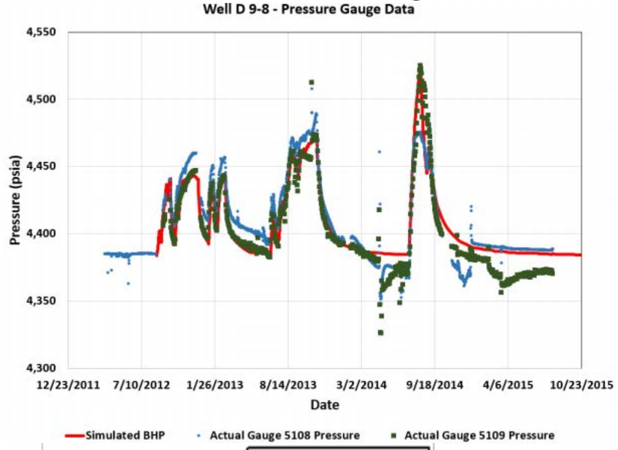


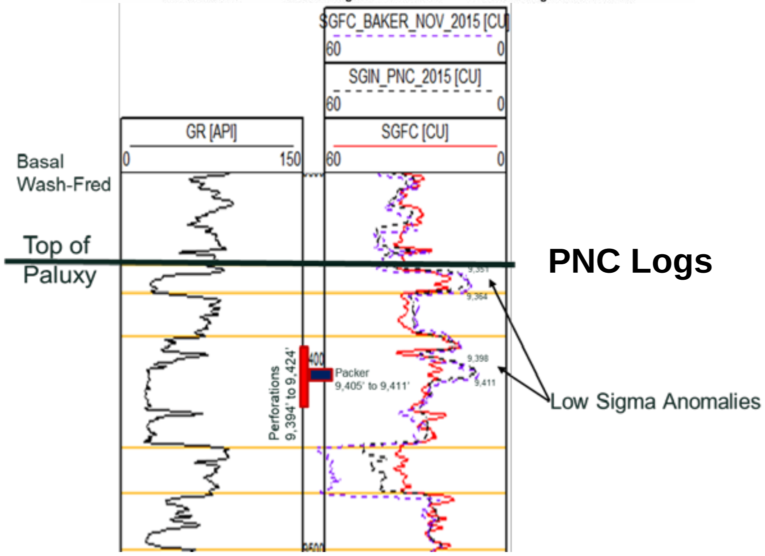
High Permeability Sand Closed

High Permeability Sand Opened

5. Commercial Monitoring Protocols

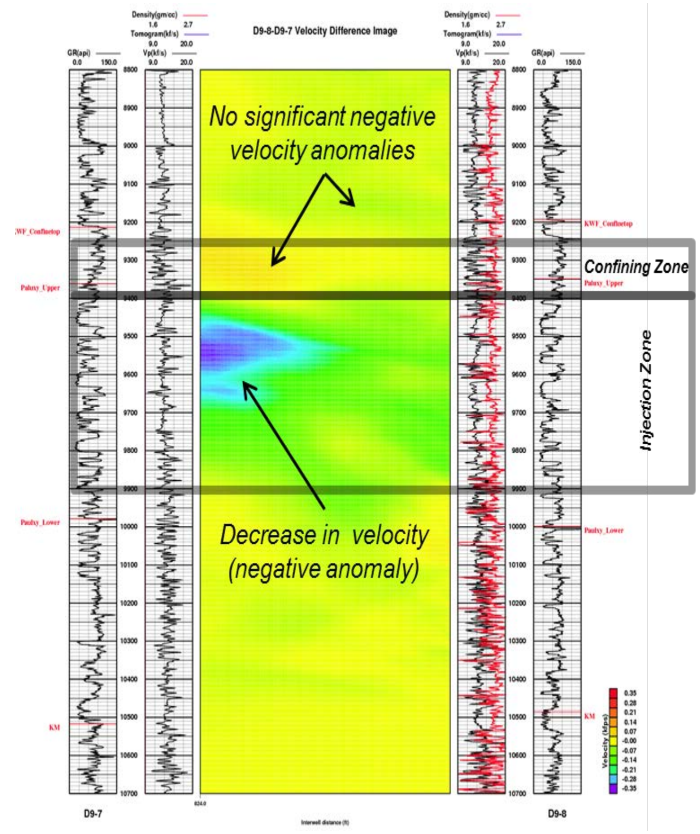
Pressure Gauges





PNC Logs

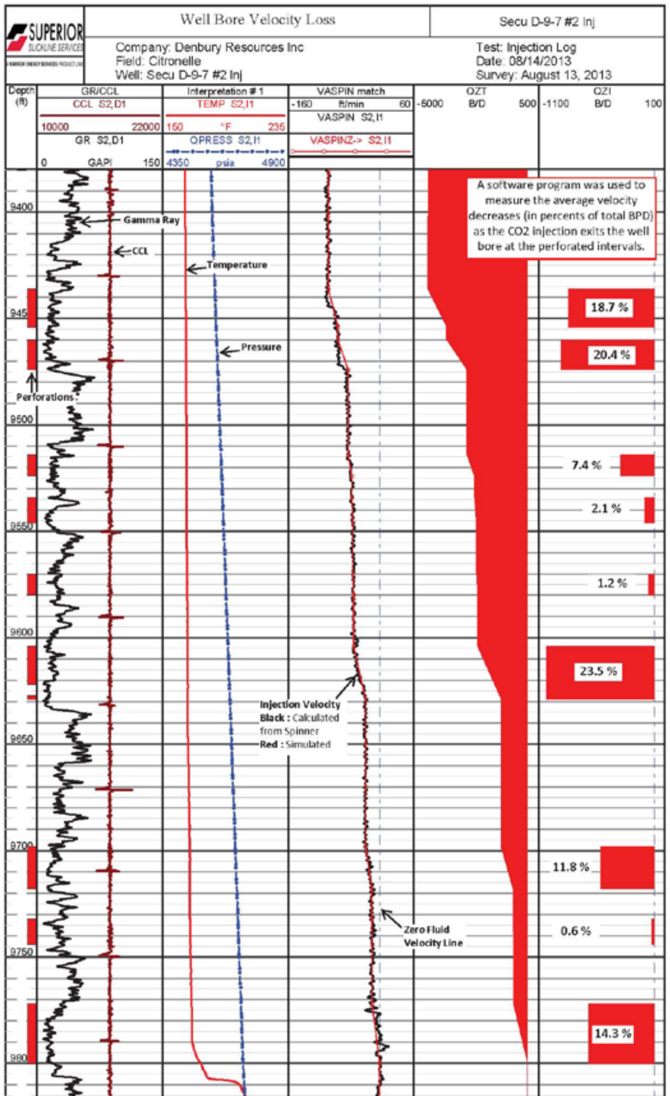
⇒ Results of the PNC logs demonstrate confinement in the injection zone.



Crosswell Seismic

- Replacement of brine with CO_2 caused a decrease in velocity through the storage geologic unit
- Time-lapse survey during injection in June 2014

Spinner Surveys

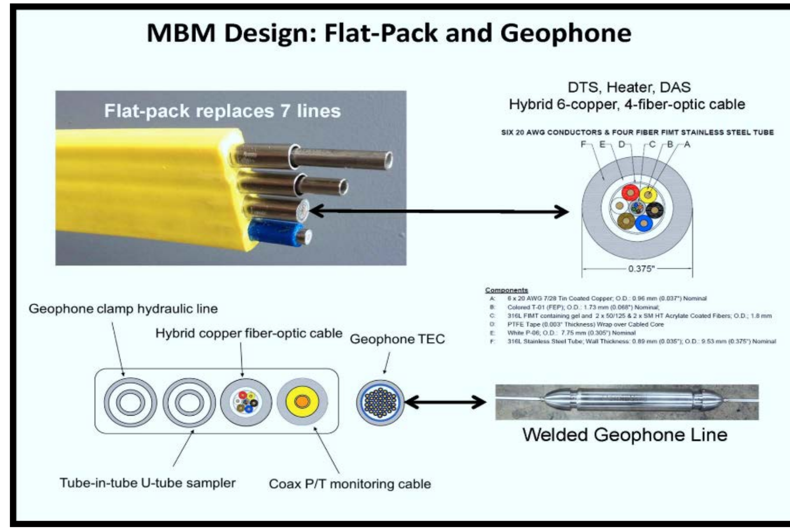


Sand	Sand Unit Properties (ft)			Nov 2012	Aug 2013	Oct 2013
Unit	Bottom	Top	Thickness	Flow %	Flow %	Flow %
J	9,454	9,436	18	14.8	18.7	16.7
I	9,474	9,460	14	8.2	20.4	19.6
H	9,524	9,514	10	2.8	7.4	7.7
G	9,546	9,534	12	2.7	2.1	0.9
F	9,580	9,570	10	0.0	1.2	1.2
E	9,622	9,604	18	26.8	23.5	30.8
D	9,629	9,627	2	0.0	0.0	0.0
C	9,718	9,698	20	16.5	11.8	10.3
B	9,744	9,732	12	4.9	0.6	0.4
A	9,800	9,772	28	23.3	14.3	12.4

Caged Fullbore Flowmeter (6 arm CFBM)

6. Experimental Monitoring: MBM

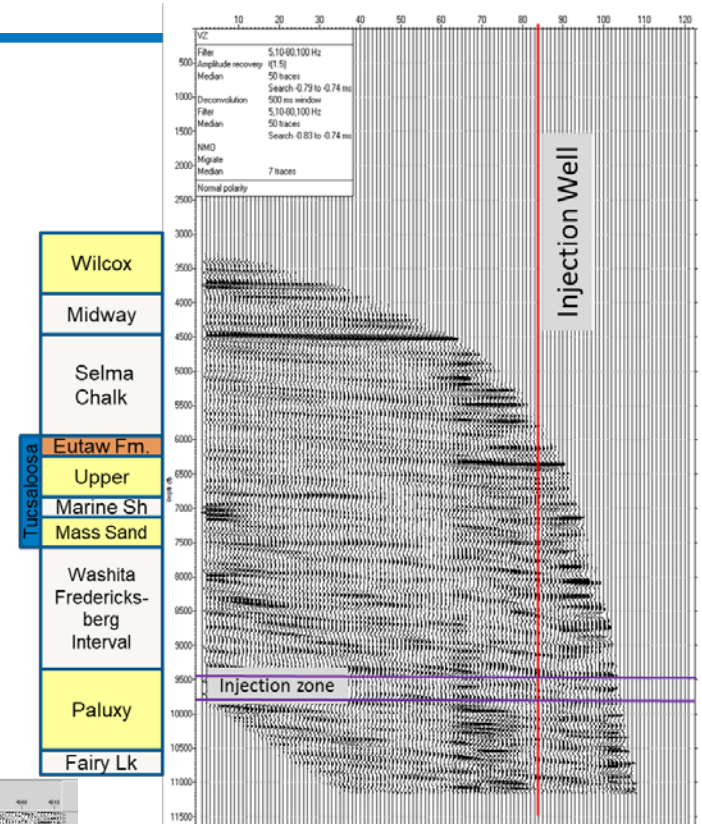
- 18 Level, tubing deployed, clamping geophone array (6,000-6,850 ft)
- Two in-zone quartz pressure/temperature gauges for reservoir diagnostics
- U-tube for high frequency, in-zone fluid sampling (tube-in-tube design)
- **Fiber optic cables** for distributed temperature (DTS) and acoustic measurements (DAS)
  - Heat-pulse monitoring for CO_2 leak detection
  - **Acoustic array for seismic (equivalent to 3m spacing)**
- 2 7/8” production tubing open for logging



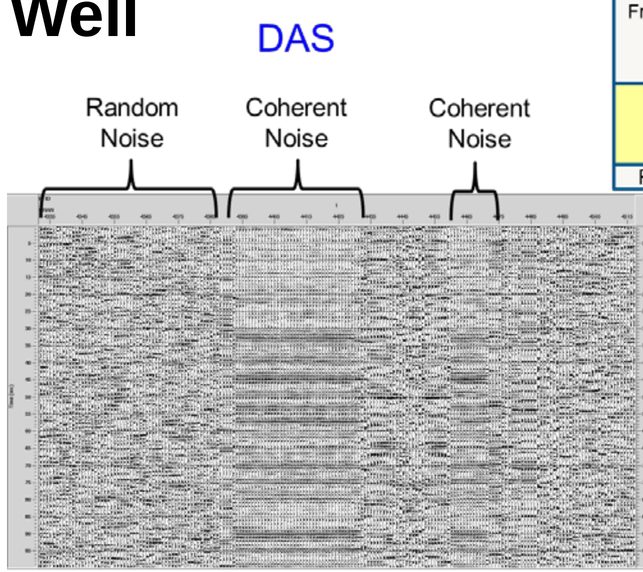
Experimental Monitoring: DAS

2014 DAS-VSP Survey Results

- Migrated image →
  - Observed strong reflectors
  - Good tie to formation logs (e.g., Selma Chalk)
- No “bright” spot observed where CO_2 was injected



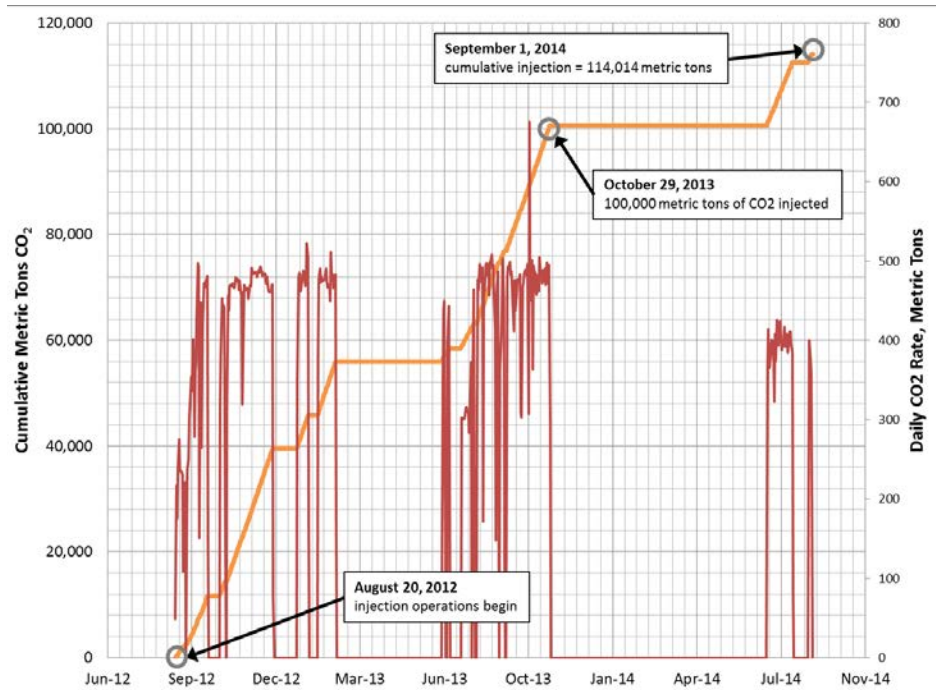
2014 DAS-Cross Well Survey Results



DAS Data at 9,340 ft – Only See Random Noise, Except Some Coherent Noise Not related to sweep

7. Support the United States' Largest Commercial Prototype CO_2 Capture and Transportation Demonstration

1. Injected, stored, and monitored 114 kt for the largest (at the time) integrated commercial prototype CCTS project at a coal-fired power plant.
2. First time CO_2 transfer of custody occurred between an anthropogenic source and a transport/storage operator.
3. First with Class VI elements in their CO_2 injection permit.
4. Demonstrated non-endangerment (Class VI protocols) and closed permit (first).



Contact

Office Locations

Washington, DC
4501 Fairfax Drive, Suite 910
Arlington, VA 22203
Phone: (703) 528-8420
Fax: (703) 528-0439

Knoxville, TN
1210 Kenesaw Ave, Suite 1210A
Knoxville, TN 37919
Phone: (865) 240-3944

Advanced Resources International, Inc.