Sensor and Control Technologies for Geologic CO_2 Storage Operations – A DOE Carbon Storage Project Review

William Aljoe, Project Manager, Carbon Storage Team

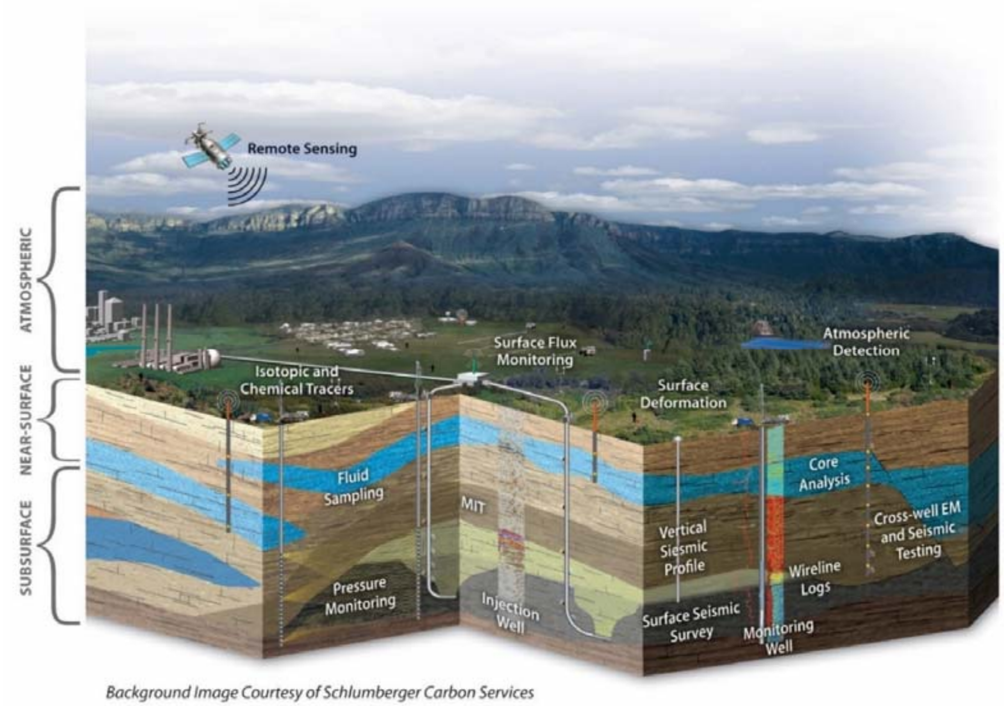
July XX, 2019

NATIONAL ENERGY TECHNOLOGY LABORATORY

Objectives of Sensor Systems in Carbon Storage

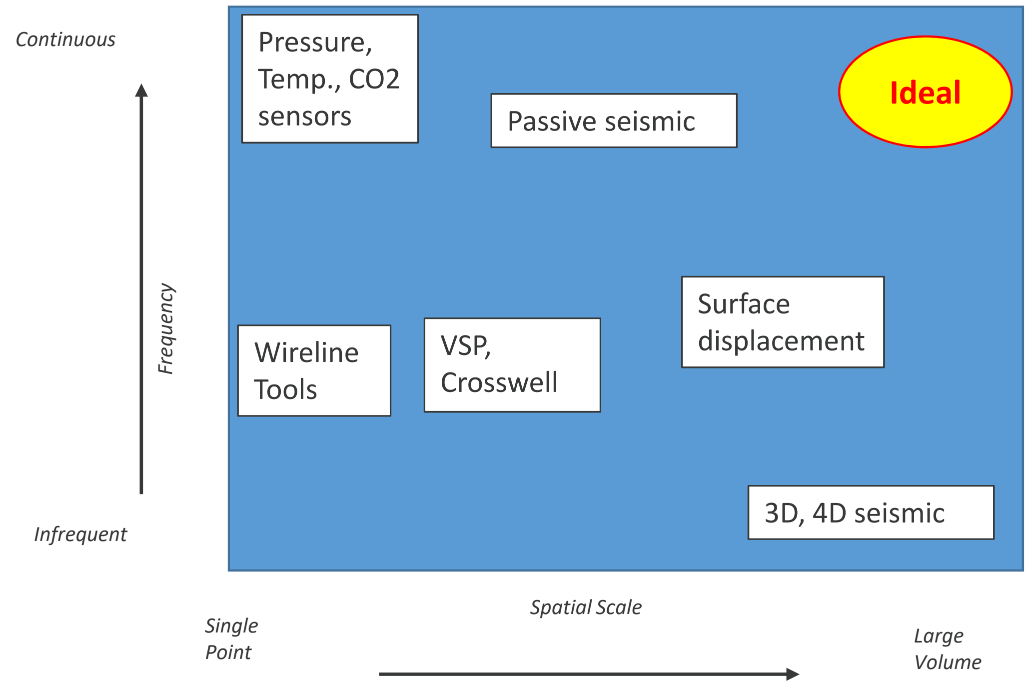
- Plume detection: Track the location of the injected CO_2 plume and pressure front within the storage reservoir
- Leakage potential: Determine whether injection wells, other wells, and surrounding seal formations are damaged or prone to unintended CO_2 release.
- Seismicity potential: Determine whether injection pressures may induce seismic events
- Assurance: Demonstrate that injected CO_2 has not entered overlying groundwater, soil, or the atmosphere
- Compliance: EPA requirements for CO_2 injection wells (UIC Class VI)

Monitoring, Verification, and Accounting (MVA)



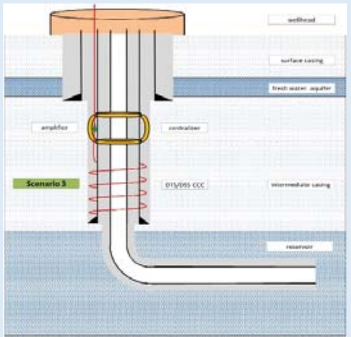
Tools & techniques for detecting CO_2 plume, pressure front, and leakage potential

- Well-established tools & techniques
  - Wellbore deployed sensors & samplers
  - Wireline deployed logging tools
  - Seismic Methods
- Emerging methods
  - Electrical/Magnetic
  - Displacement monitoring
  - Gravity
  - Tracers
- Currently no "ideal" method
  - Goal: Broad coverage + continuous + high resolution + low cost

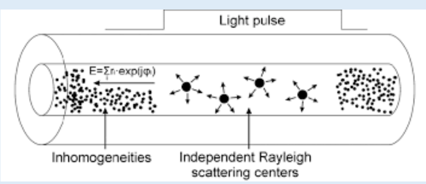


(Adapted from Lawrence Livermore National Laboratory)

Plume Detection: Wellbore-deployed tools & techniques



Helical wound DAS cable for improved sensitivity

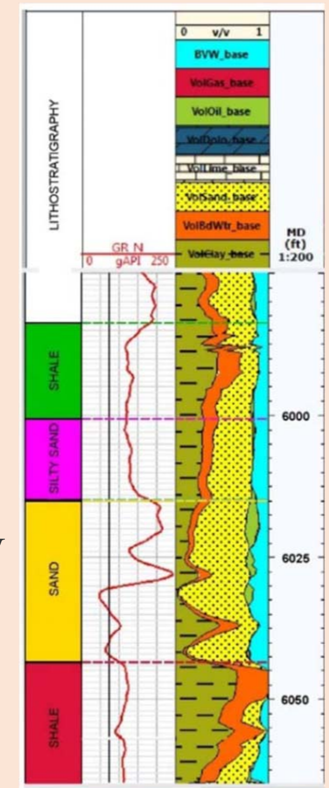


Wellbore-deployed sensors

- Benefits:
  - Commercial technology (P, T, acoustic)
  - Permanent installation
  - Distributed (fiberoptic) sensor locations
  - Can create continuous data stream
- Challenges:
  - Multiple wellbores required
  - Sensor installation & maintenance cost
  - Potential leakage pathways

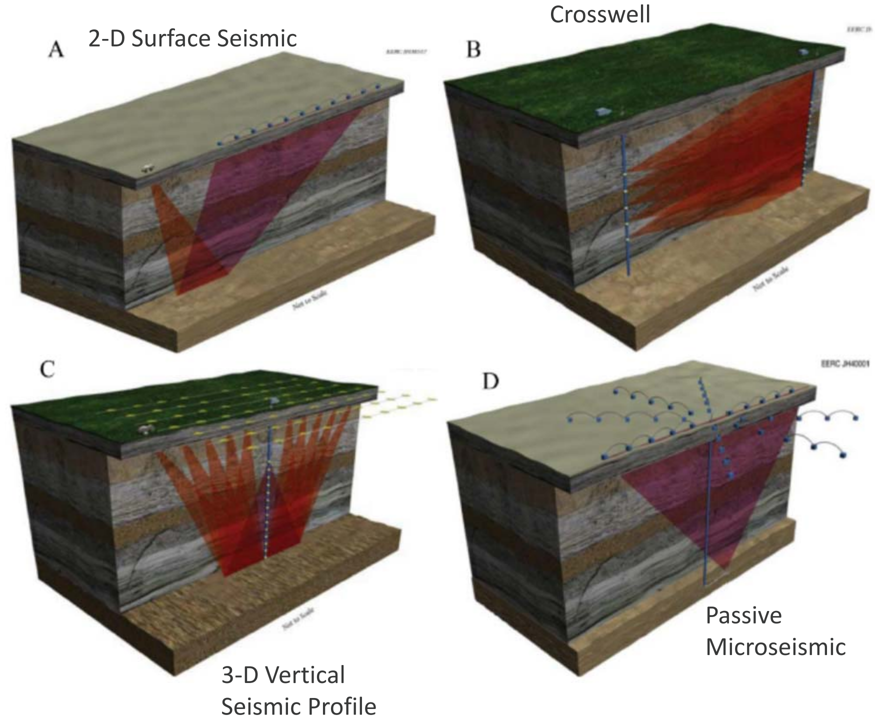
Wireline logs

- Benefits:
  - Commercial technology
  - Can provide reasonable estimate of CO2 saturation
- Challenges:
  - Multiple wellbores required
  - Repeat surveys may be costly
  - Working fluids and wellbore conditions may affect log results



Plume Detection: Seismic methods

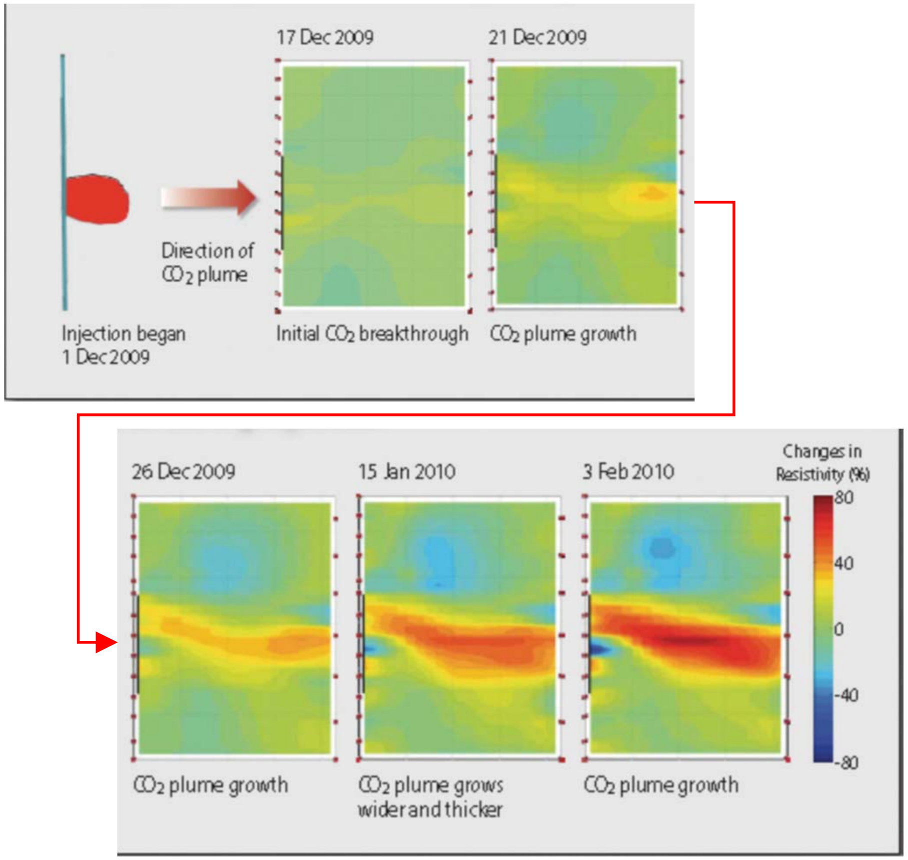
- Tools & Techniques:
  - Surface; crosswell; VSP; passive seismic
- Benefits
  - Can be used for plume detection, leak potential
  - Commercial technology, many providers
  - Can cover large areas
- Challenges:
  - High cost; cannot be done frequently
  - Time delays (data acquisition, processing, interpretation)
  - Difficulties in signal resolution
  - Not sensitive to differences in CO_2 saturation



(Source: Hamling et al., 2011)

Plume Detection: Electrical methods

- Tools & Techniques:
  - Electrical Resistance Tomography (ERT); Electromagnetic tomography (EM);
- Benefits:
  - Allows estimation and mapping of CO_2 saturation in the subsurface
  - Data resolution can be increased by decreasing electrode spacing
- Challenges:
  - Technology and data processing/interpretation not as mature as seismic
  - May require non-conductive well casings
  - Repeat surveys may be costly

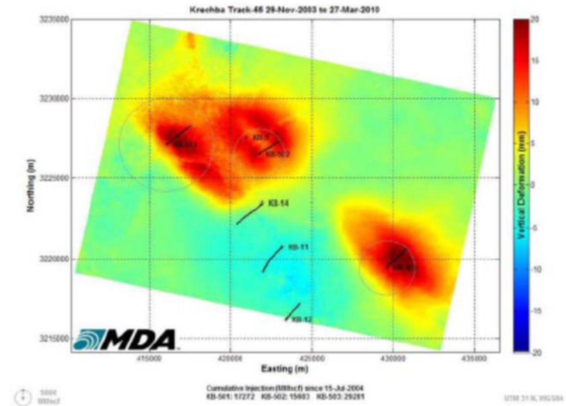


Resistivity Distribution from Crosswell Survey at Cranfield

Plume Detection: Other methods

Surface Displacement (InSAR)

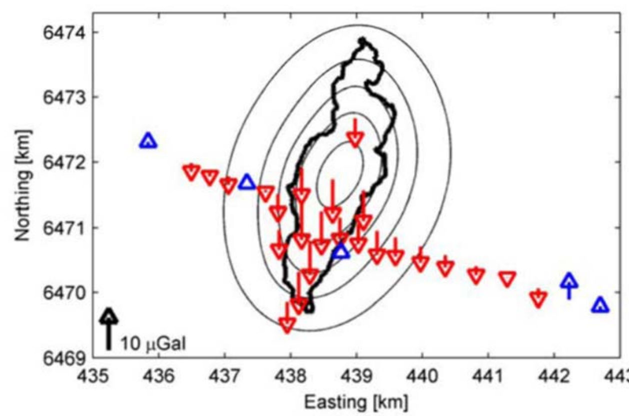
- Benefits:
  - Highly precise measurements (mm) over large area (100 km x 100 km)
- Challenges:
  - Requires surface access and multiple stations
  - Confounding factors: vegetation, complex terrain, human activity
  - Displacement may not indicate risk



Satellite Image of Cumulative Surface Deformation at In Salah) (*Mathieson et al., 2011)*

Gravity

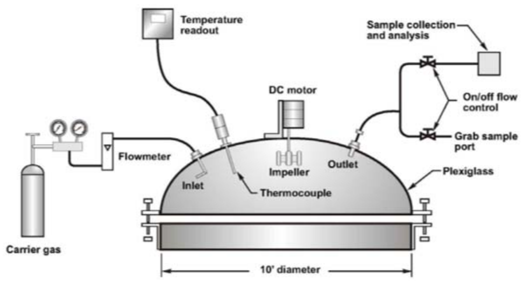
- Benefits:
  - Provides direct assessment of CO_2 mass
- Challenges:
  - Technology data processing/interpretation less mature
  - Confounding factors: tides, instrument drift
  - Limited detection and resolution unless tool located near CO_2 reservoir
  - Multiple surveys (boreholes) required for plume mapping



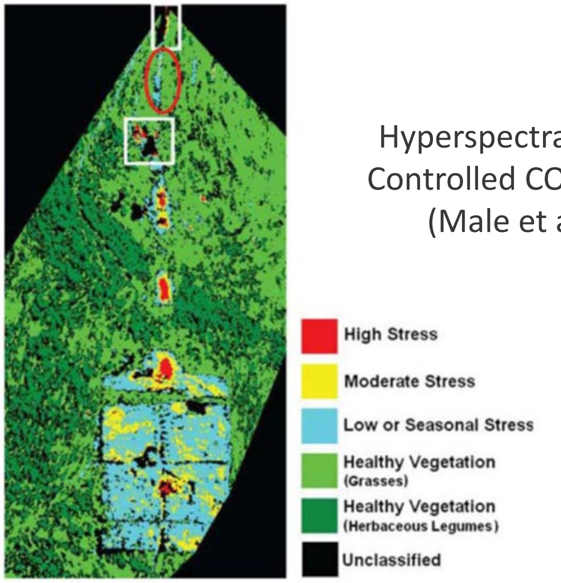
Map of Observed Gravity Changes at Sleipner 2002-2009 *(Alnes et al., 2011)*

Assurance Monitoring (has a leak occurred?)

- Sensor deployment locations:
  - Shallow groundwater (EPA Class VI focus)
  - Soil/vadose zone/vegetation
  - Atmosphere
- Benefits:
  - Commercial sensors and well-accepted sampling techniques are available
  - Continuous data can be obtained
  - Results easily understood by public
- Challenges:
  - Potential for false positives
  - Robust baseline may be difficult to obtain
  - Difficult and expensive to achieve continuous, broad areal coverage
  - May not yield actionable information



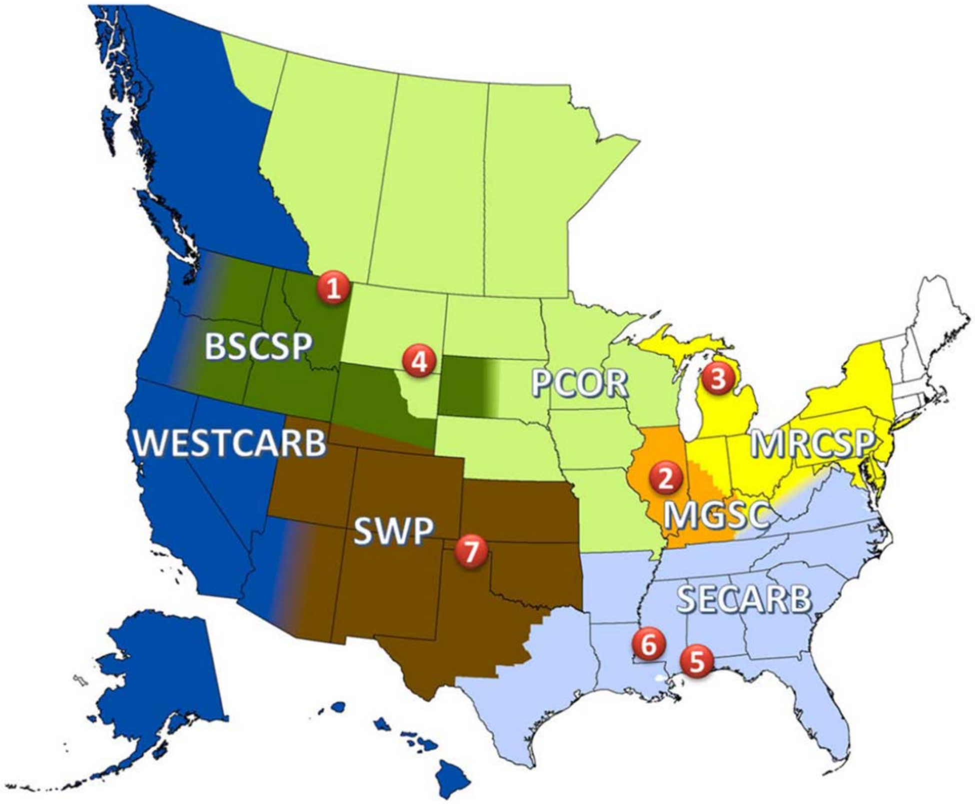
Soil flux chamber (adapted from ASTM, 2006b)



Hyperspectral Imagery at Controlled CO_2 release site (Male et al., 2010)

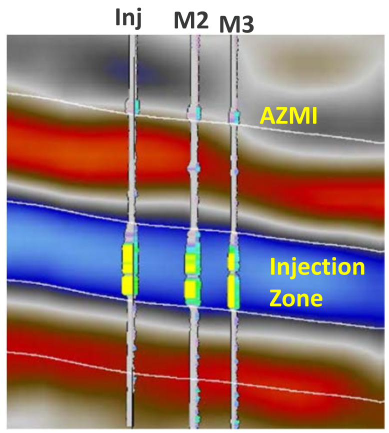
DOE R&D Projects - Technology Validation

- Regional Carbon Sequestration Partnerships (RCSPs)
  - Large-scale field experiments
    - "Learn by Doing"
  - Over 11 million metric tons stored (2009-present)
  - Investigated a wide variety of sensors, systems and techniques for monitoring CO_2 storage operations

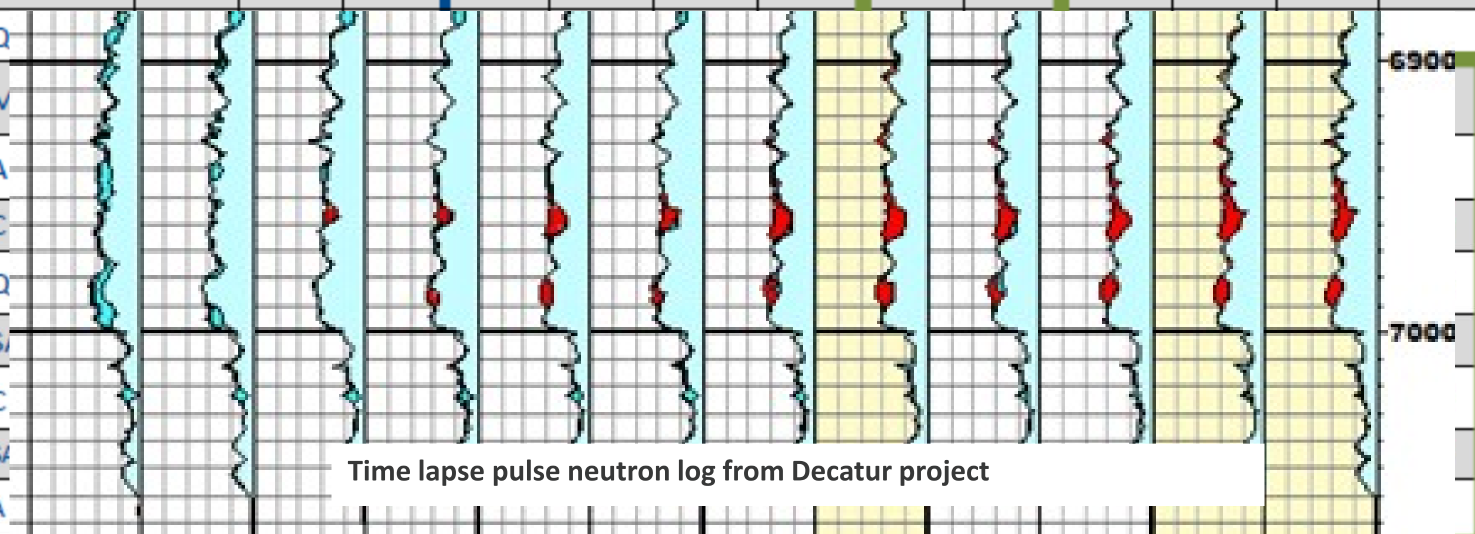


Southeast Regional Carbon Sequestration Partnership (SECARB) - Cranfield Site

- CO_2-EOR site (Denbury Resources)
  - ~12 miles east of Natchez, MS; > 5 years of monitoring; > 5M metric tons stored
  - Technical team led by Bureau of Economic Geology, UT-Austin
- Largest suite of monitoring technologies all focused on one spot
  - In-zone and above-zone temperature, pressure, chemistry
  - Well logs
  - 3D seismic; VSP; crosswell
  - ERT; gravity; shallow GW chemistry; soil gas



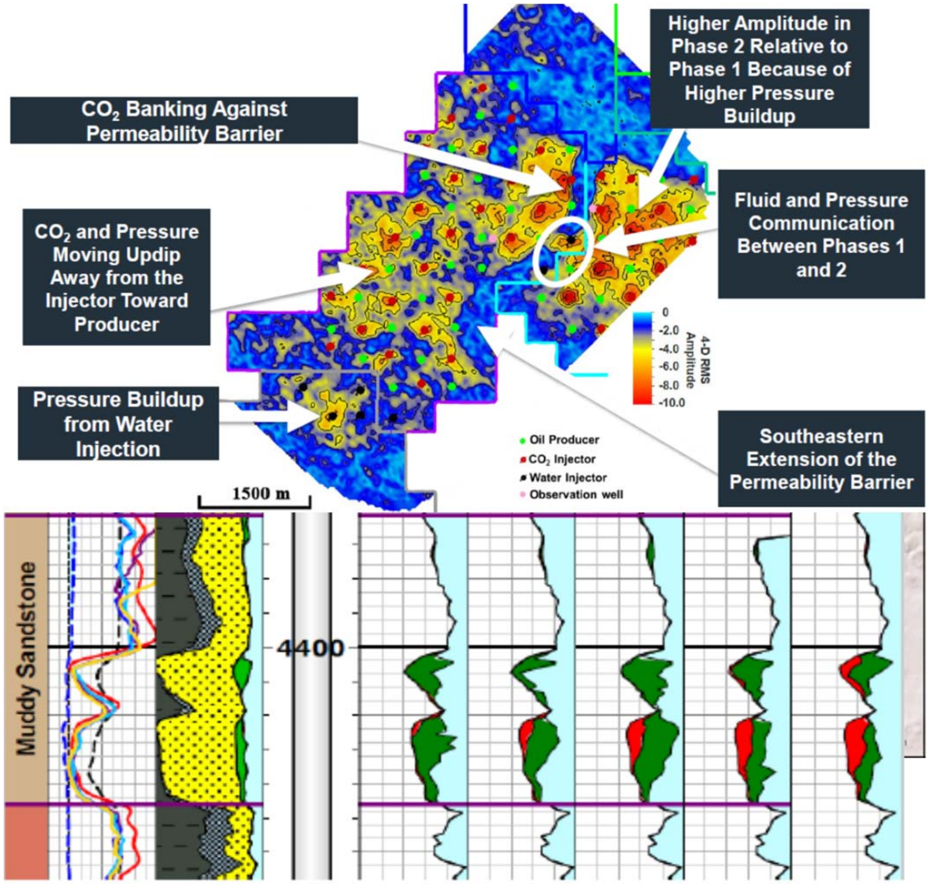
	Monitoring Activity	Freq.	Pre-injection			Injection				Post-Injection					
			2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Surface	Aerial imagery	SA		x	x	x	x	x	x	x	x	x	x	x	x
	Eddy covariance	C					x	x	x						
	Soil flux - network *	W-Q		x	x	x	x	x	x	x					
	Soil flux - multiplexer *	C			x	x	x	x	x	x					
	Tunable diode laser- single path	C					x	x							
	Tunable diode laser- multi path *	C								x					
	InSAR *	BW				x	x								
	Continuous GPS *	C					x	x	x						
Near-Surface	Soil gas sampling	Q													
	Shallow groundwater sampling	M													
	Shallow electrical earth resistivity *	A													
Subsurface	Pressure/temp. - VW1 and CCS1	C													
	Pulsed neutron (CCS1, VW1, GM1)	Q													
	Deep fluid sampling (VW1)	S/													
	Passive seismic monitoring (GM1)	C													
	Seismic/3D VSP imaging	S/													
	Mechanical integrity (CCS1, VW1)	A													



Time lapse pulse neutron log from Decatur project

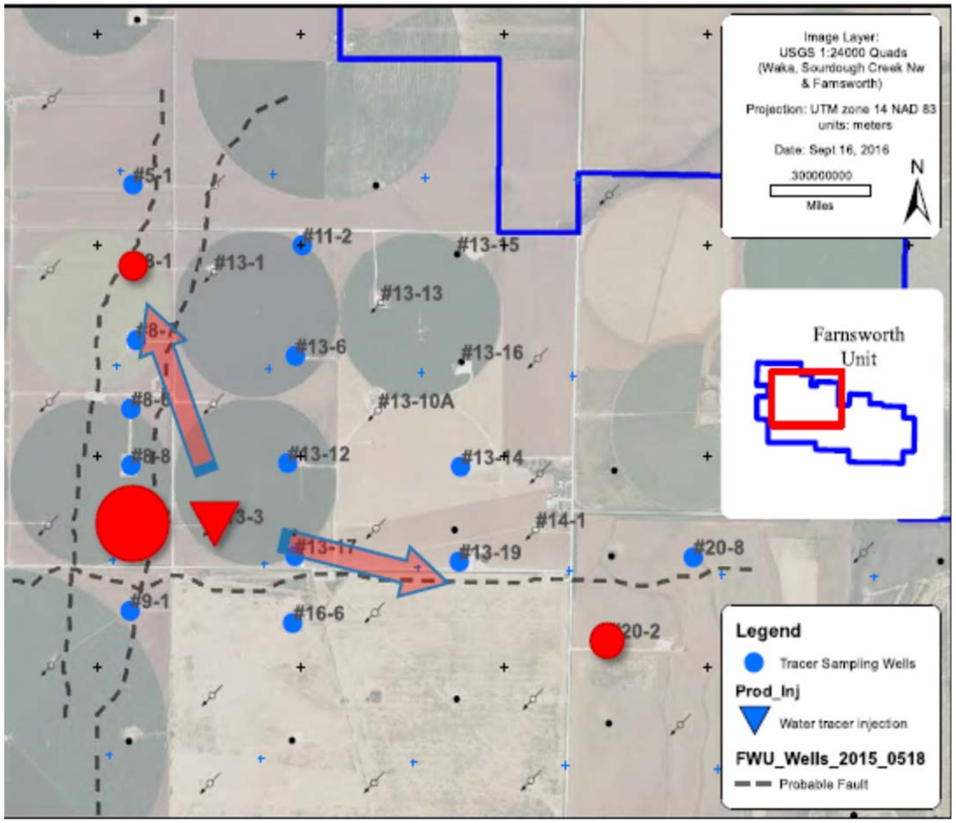
Plains CO_2 Reduction Partnership (PCOR)

- Bell Creek CO_2-EOR site (Denbury Resources)
  - Southeast Montana; ~ 4 million metric tons stored during PCOR monitoring program
  - CO_2 piped in from gas processing plants in Wyoming
- MVA methods:
  - 4D surface seismic & VSPs;
  - Pulsed neutron logs;
  - Reservoir temperature/pressure;
  - Permanent downhole geophone array
  - Shallow and deep groundwater chemistry
  - Soil gas; InSAR



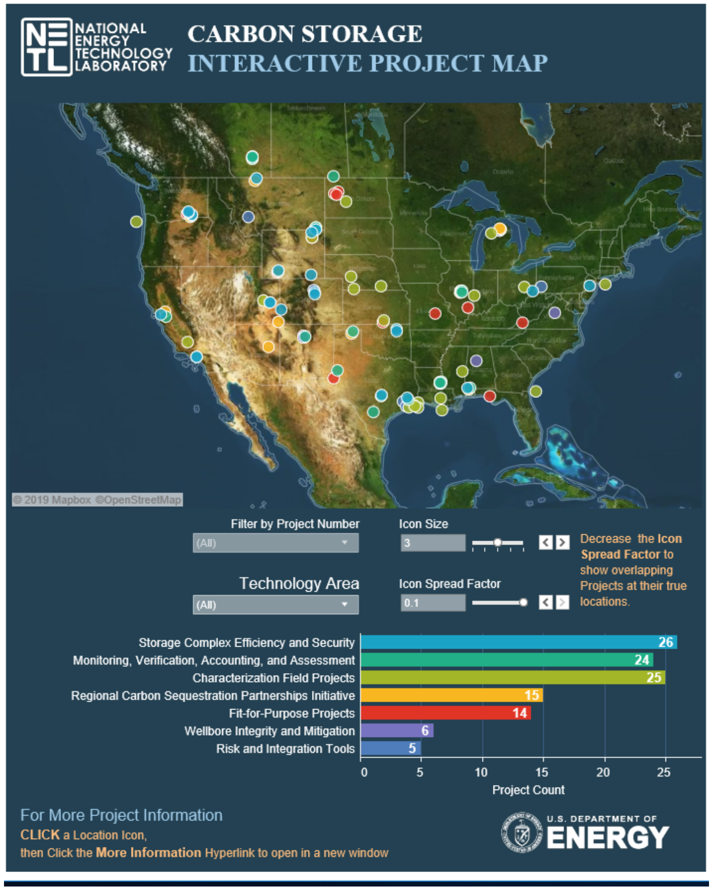
Southwest Regional Partnership on Carbon Sequestration (SWP)

- Tracer studies revealed preferential flow paths within reservoir (probable faults)



DOE R&D Projects: Advanced Sensors

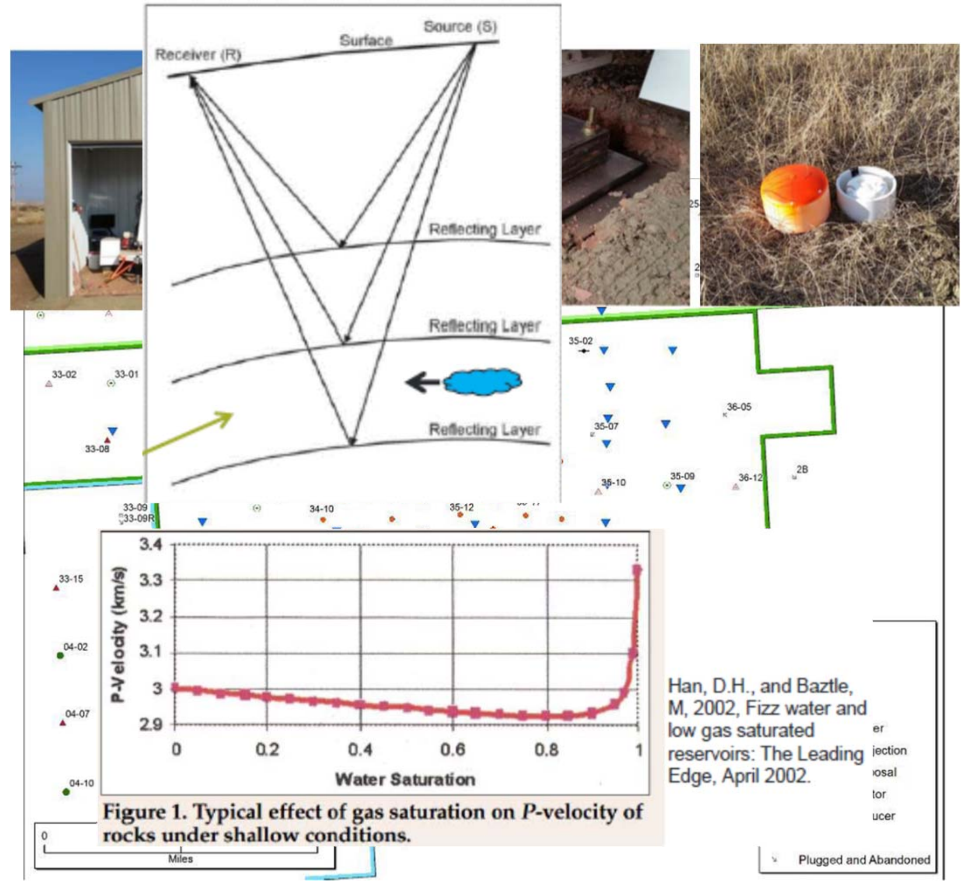
- 6 Funding Opportunity Announcements (FOAs) in past 10 years
  - —"Extramural" research performed by industry and academia
  - — Award Recipient Cost Share ≥ 20%
  - —30 projects on advanced sensors & systems
  - —5 Active projects
- New FOA: DE-FOA0001998:
  - o "Transformational Sensing Systems For Monitoring the Deep Subsurface"
  - o Applications Received: June 21, 2019
  - o Selections expected: Sept. 2019



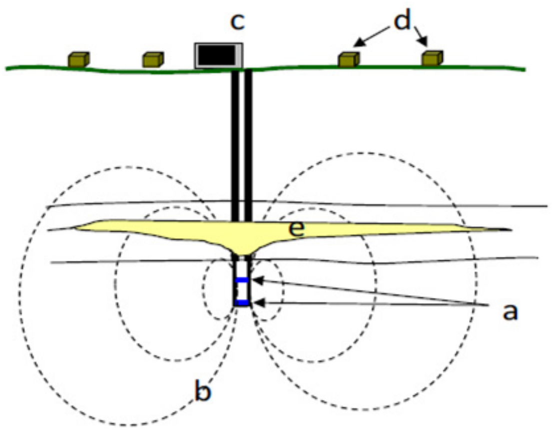
Plume Detection: Automated, Semi-permanent seismic

FE0012665 (EERC)

- Single, stationary seismic source and sparse array of semi-permanent geophones operated remotely via Internet
- “Shots” fired and data collected at frequent intervals (e.g., weekly @ 50 shots/session)
- Plume arrival indicated by change in P-wave
- Tested at PCOR Bell Creek EOR site



Plume Detection: Electrical Methods

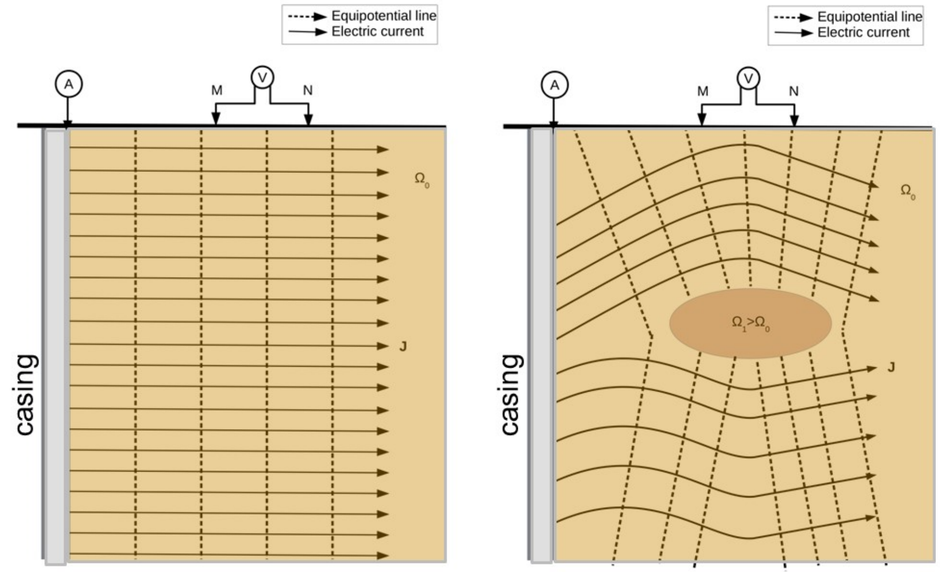


FE0012266 (Multi Phase Technologies, LLC):

- Deep, Controlled-Source Electromagnetic CSEM) System: (a)borehole electrodes; (b) electric field/current flow lines; (c) transmitted/current source (d) mobile surface electric and magnetic field receivers
- Tested at Ketzin, Germany

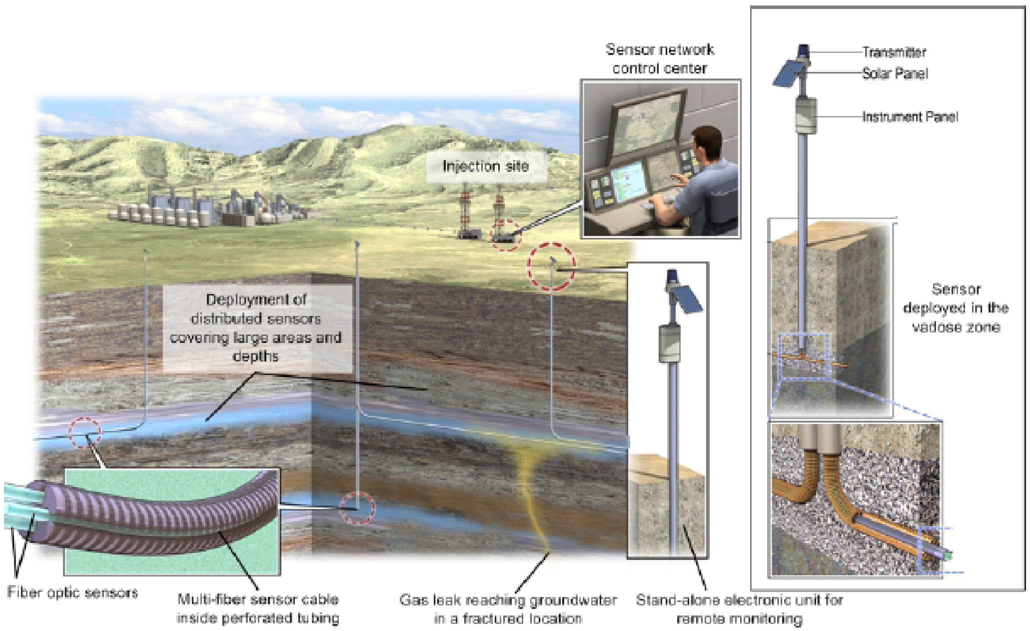
FE0028320 (Colorado School of Mines):

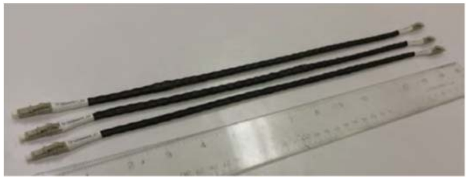
- Charged wellbore casing controlled source electromagnetics (CWC-CSEM)
- Testing at Bell Creek (PCOR) CO_2-EOR site



Assurance Monitoring (Shallow Groundwater): Distributed fiberoptic sensors

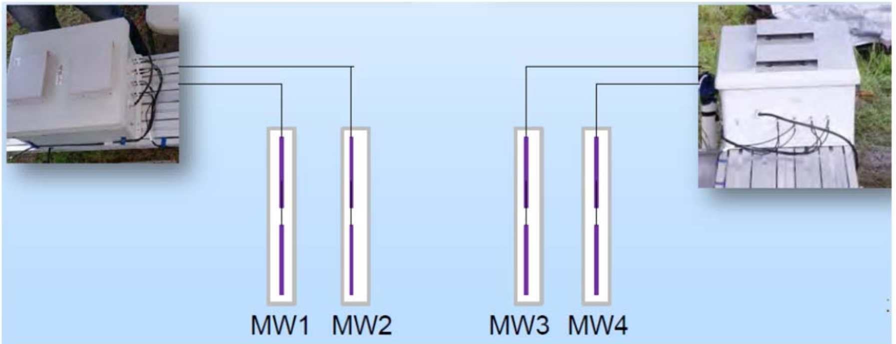
FE0012706 (Intelligent Optical Systems, Inc.): Distributed fiber optics sensors for in-situ, real-time monitoring of geochemical parameters in groundwater





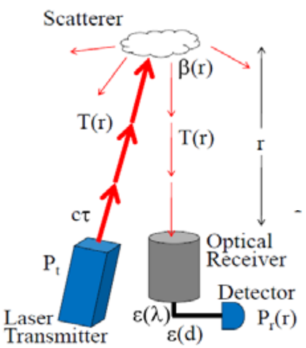
Sensor Unit Fabrication

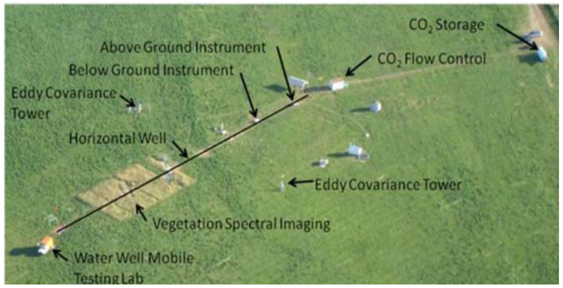
Deployment and Initial Testing



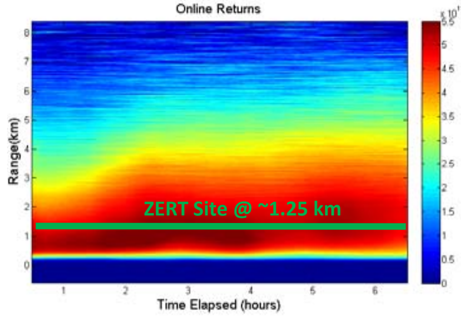
Assurance Monitoring (Atmospheric): Optical Sensors

NATIONAL ENERGY TECHNOLOGY LABORATORY





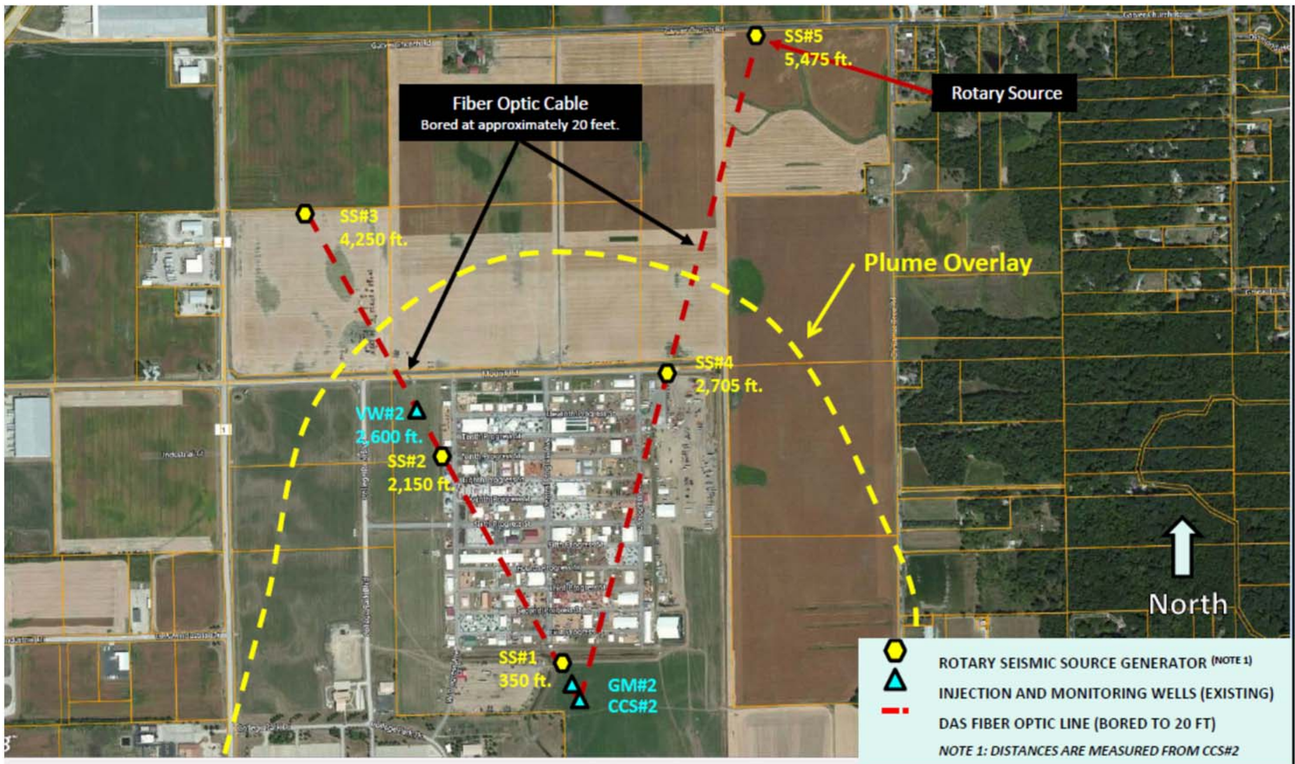
FE00101156 (Montana State University): Deployment of CO2-DIAL at ZERT facility



FE0012574 (Exelis, Inc.): Deployment of GreenLITE system at IBDP

Intelligent Monitoring Systems for Carbon Storage

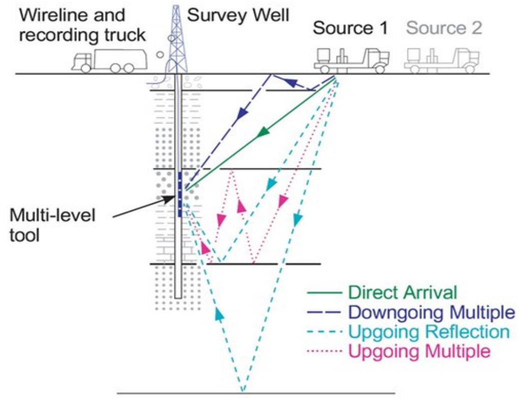
FE0026517 (Archer Daniels Midland): Continuous Active Seismic Source Monitoring (CASSM)

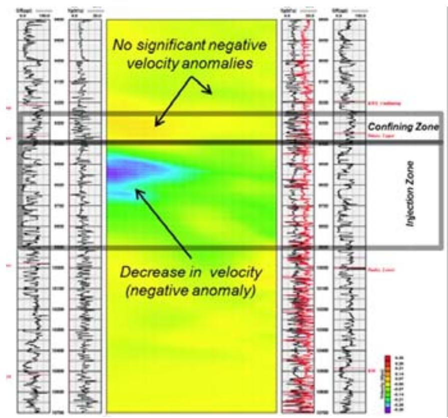


- Tested at ADM Decatur site, ICCS Project
- 5 Permanent, continuous seismic sources
- Fiberoptic DAS ~ 20 ft below ground in horizontal boreholes
- Data processed immediately to update reservoir model and create daily image of reservoir conditions
- Potentially quicker leak detection; less need for external seismic

Summary

- Objectives of Sensor Deployment:
  - Location of CO_2 plume/pressure front
  - Location of potential leakage pathways
  - Potential for induced seismicity
  - Assurance (leak detection)
- Benefits:
  - Commercial technologies sometimes available
  - Ensures reservoir storage containment effectiveness
  - Ensures groundwater and ecosystems remain protected.
- Challenges
  - Time and cost constraints
  - Signal processing and resolution
  - Currently no “gold standard” for verification
    - Multiple methods employed to improve confidence
- New sensors, techniques, and adaptations of existing technology are being developed
- Goal: integrate into Intelligent Monitoring Systems

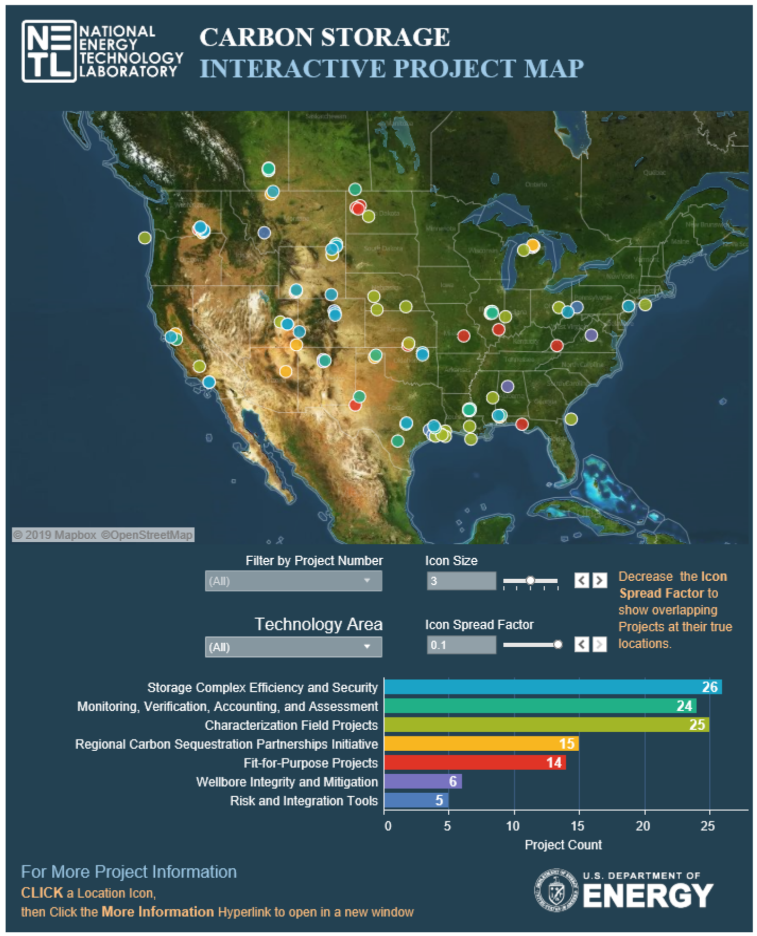




For More Information

NETL Carbon Storage Project Portfolio

https://www.netl.doe.gov/coal/carbon-storage/project-portfolio



Program Contacts

National Energy Technology Laboratory

Traci D. Rodosta

Technology Manager, Carbon Storage
304-285-1345
Traci.Rodosta@netl.doe.gov

DOE Office of Fossil Energy

Darin Damiani

Program Manager, Carbon Storage and Sequestration
202-287-5282
Darin.Damiani@hq.doe.gov