Distributed Fiber Optic Arrays: Integrated Temperature and Seismic Sensing for Detection of CO_2 Flow, Leakage and Subsurface Distribution
DE-FE0012700

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SECARB Southeast Regional Carbon Sequestration Partnership · Southern States Energy Board · Advanced Resources International, Inc. · Southern Company Energy to Serve Your World · Denbury · CO_2 Capture Project

Presentation Outline

- Project benefits and goals
- Principles of operation
  - Distributed acoustic sensing (DAS)
  - Heat-pulse monitoring coupled with distributed temperature sensing (DTS)
- Task 2 - SECARB Citronelle Alabama
  - Cross well seismic survey (June 2014)
  - Vertical seismic profile survey (June 2014)
- Task 3 - Livingston Field Louisiana
  - Heat-pulse monitoring to determine flow allocation in a horizontal CO_2 injector
  - Site host cancelled their project!!!

Benefit to the Program

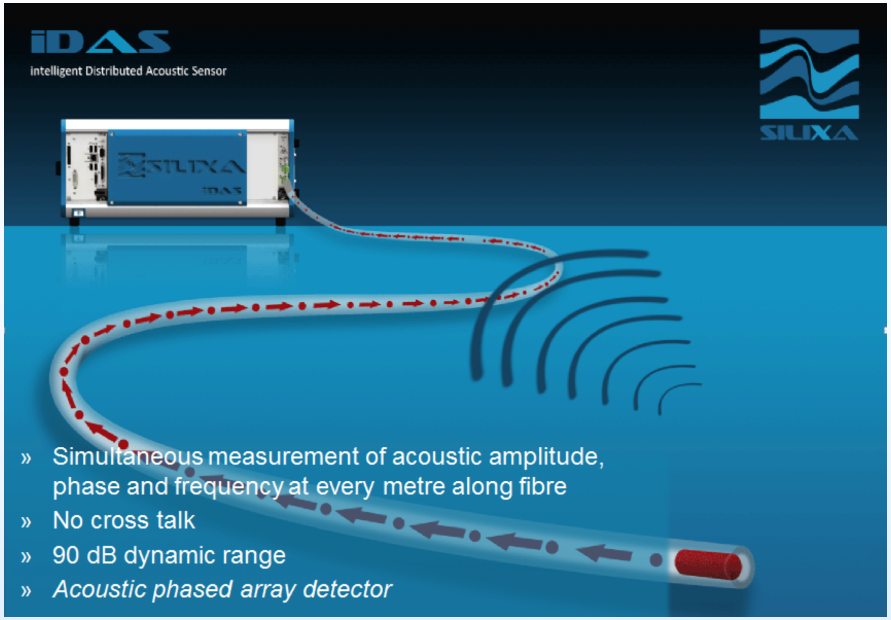
- Program goals
  - Develop and validate technologies to ensure 99 percent storage permanence.
- Benefit Statement
  - The project uses Distributed Acoustic Sensor (DAS) arrays to detect and image the CO_2 plume using seismic methods
  - Heat-pulse monitoring using Distributed Temperature Sensing (DTS) to detect vertical CO_2 leakage along the wellbore and flow outside of the casing
  - If successful, this project will contribute to the Carbon Storage Program goal to develop and validate technologies to measure and account for 99 percent of injected CO_2 in the injection zones.

Project Overview: Goals and Objectives

- **Overall objective**: Develop cost effective monitoring tools that can be used to demonstrate safe, permanent storage of carbon dioxide (CO_2) in deep geologic formations.
- **Specific objectives include**:
  - Make hi-res spatial measurements of the CO_2 plume using permanent distributed acoustic seismic receiver arrays that utilize FO at a lower cost and with greater repeatability;
  - Monitor for CO_2 leakage out of the storage reservoir along wellbores and through the caprock for regulatory compliance;
  - Make hi-res measurements of the vertical distribution of CO_2 in the storage reservoir, allowing site operators to better manage their CO_2 floods and assess leakage risks;
  - Make hi-res spatial measurements of injection rates and CO_2 distributions in injection wells to manage and optimize EOR floods
  - Develop best available practices for deploying FO sensors in deep wells
  - Evaluate long-term robustness of FO sensor arrays in situ

Principle of Operation: Distributed Acoustic Sensing (DAS) for CO_2 Plume Imaging

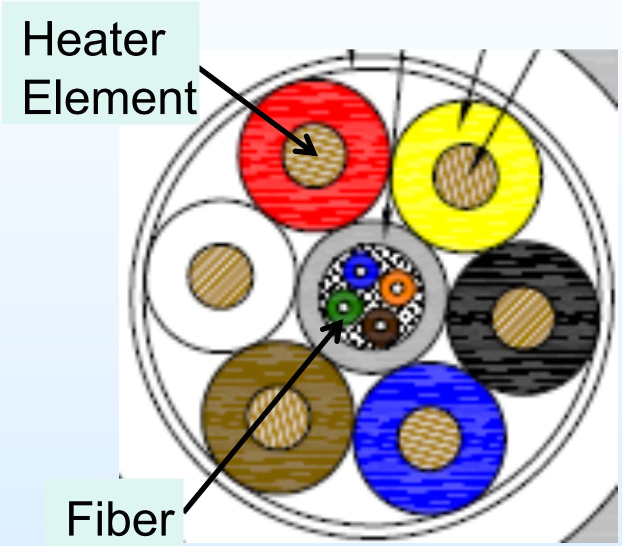
- Light emitted into a fiber is reflected throughout the fiber's length by Rayleigh scattering
- DAS system measures the modulation of the backscattered light
- An acoustic field around the fiber exerts tiny pressure/ strain changes on the fiber, resulting in changes to the backscattered light
- The DAS measures these changes by generating a repeated light pulse every 100 μs and continuously processing the returned optical signal, thus interrogating each meter of fiber up to 10 km in length at a 10 kHz sample rate
- Unlike other methods, the system records the full acoustic signal, including amplitude and phase



A 10 km single mode fiber becomes a high density acoustic array with 10,000 linear sensors with 1 meter spatial resolution

Principle of Operation: Distributed Temperature Sensing (DTS) and Heat Pulse Monitoring for Leak Detection/Flow Allocation

- Measurement of Raman backscattering combined with Optical Time-Domain Reflectometry (OTDR) are used to determine distributed temperatures along the fiber length
  - DTS used for past 20 years
  - 5 km fiber: spatial resolution 25 cm, temperature resolution 0.01°C measurement time 1 s
- Copper heater elements integrated with DTS fiber in the same cable provide pulse of heat
- Fluid substitution in well or rock pores changes thermal properties in/near wellbore
- Detected by time-lapse measurement of temperature build up/fall off during/after heating
- Or can be used like a hot-wire anemometer in a CO_2 injector to measure flow



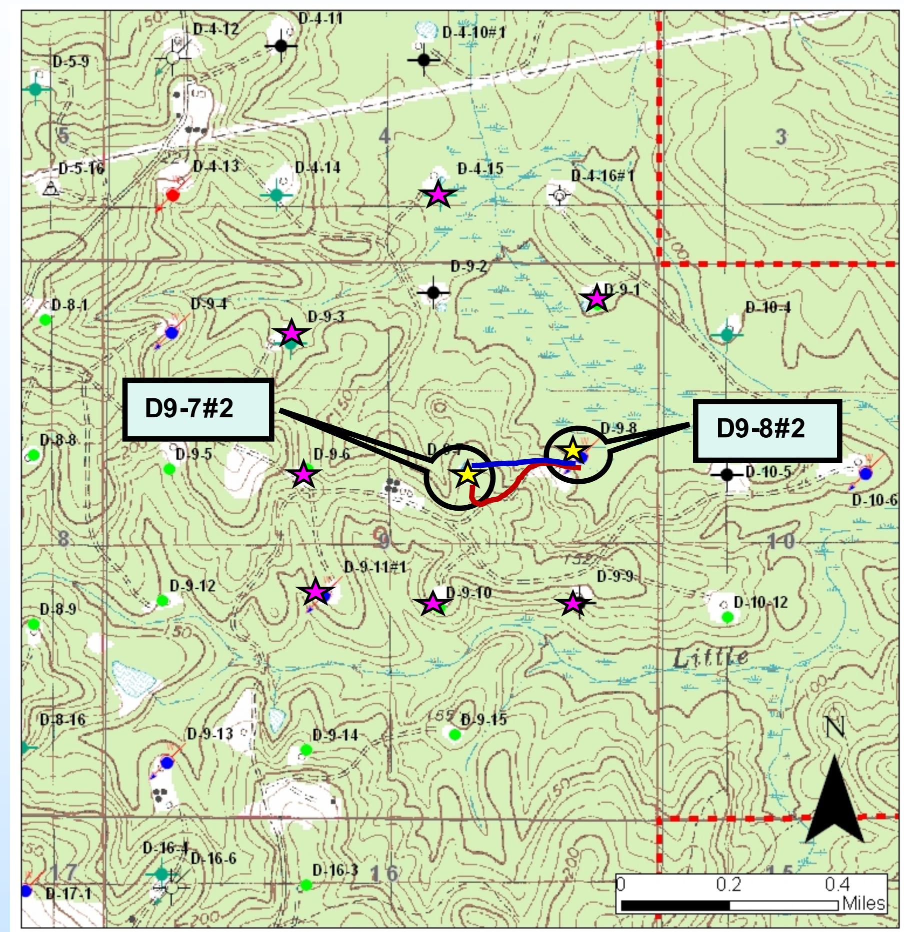
Multiple heater elements and fibers are integrated into a 3/8” OD stainless steel control line

Application at SECARB Anthropogenic Test Site, Citronelle Alabama

- First integrated CO_2 capture, transportation and storage project on a coal-fired power station using advanced amines in the U.S.
- Southern Co. and MHI have captured over 210,000 metric tons of CO_2 to date
- Denbury Resources has transported, injected and stored over 114,104 metric tons in the Paluxy Formation
- Project stopped injecting and entered the Post Injection Site Care period September 1, 2014

Citronelle Offers a Unique Opportunity to Compare Seismic Methods to Monitor CO_2 Plume Location

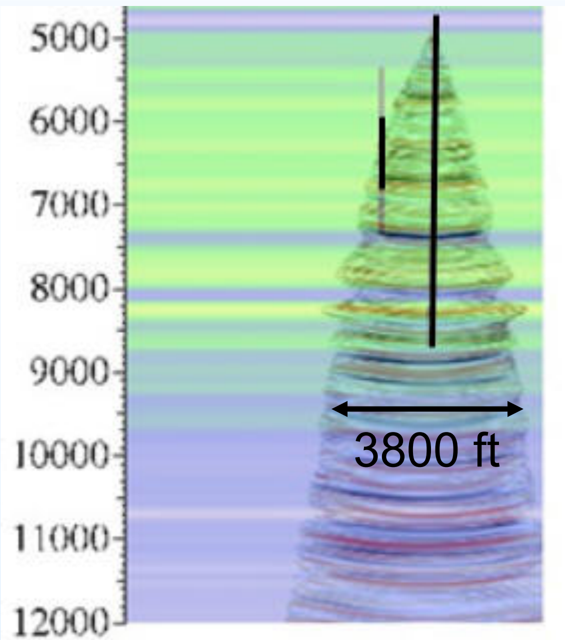
Deployment of the Modular Borehole Monitoring (MBM) Conventional geophone array (left) and yellow flat pack containing the fiber optic based DAS array (right)



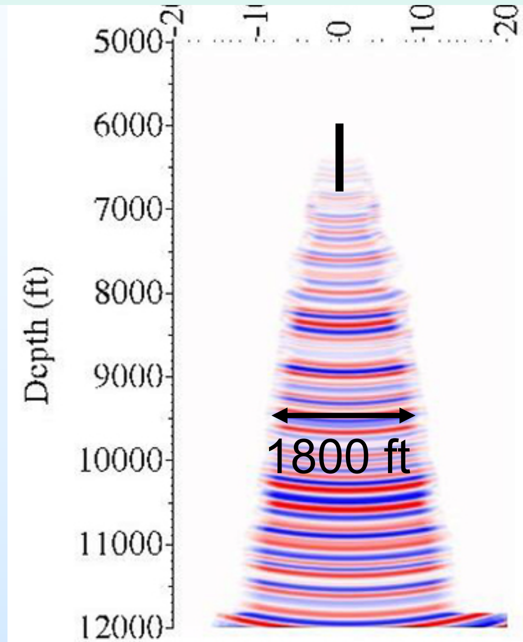
VSP source offset locations (stars), receiver locations (D9-7#2 and D9-8#2), and walk-away lines (blue and red lines)

Survey Configuration Summary Using Conventional (Conv.) Geophones and DAS

80-Level long string receiver array (Conv.)
- 1x pre-injection (2012)
- 2x walkaway (2012)



Short string MBM surveys
- 4x Conv., 7 far offset pts.
- 2x Conv. walkaways
- 1x DAS, 7 far offset pts. (2014)
- 2x DAS select walkaways



Crosswell Surveys
- 1x Conv. Pre-inj. (2012)
- 1x Conv. Repeat (2014)
- 1x DAS (2014)

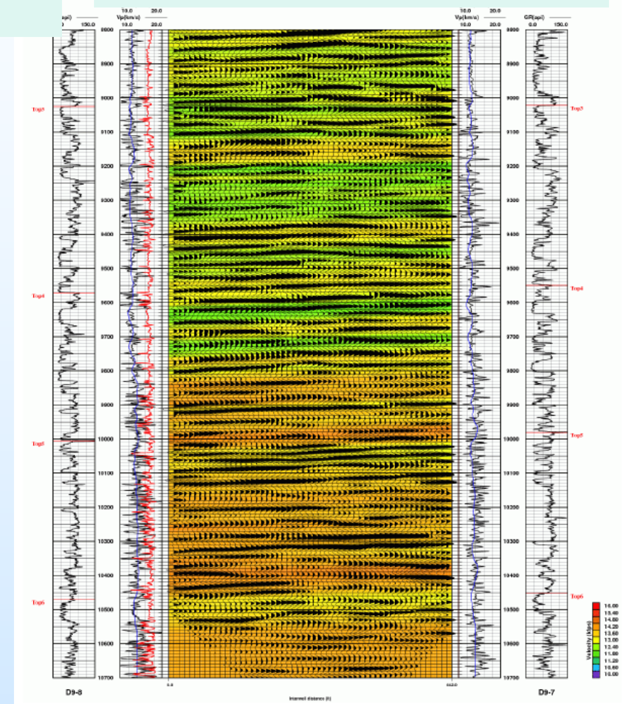
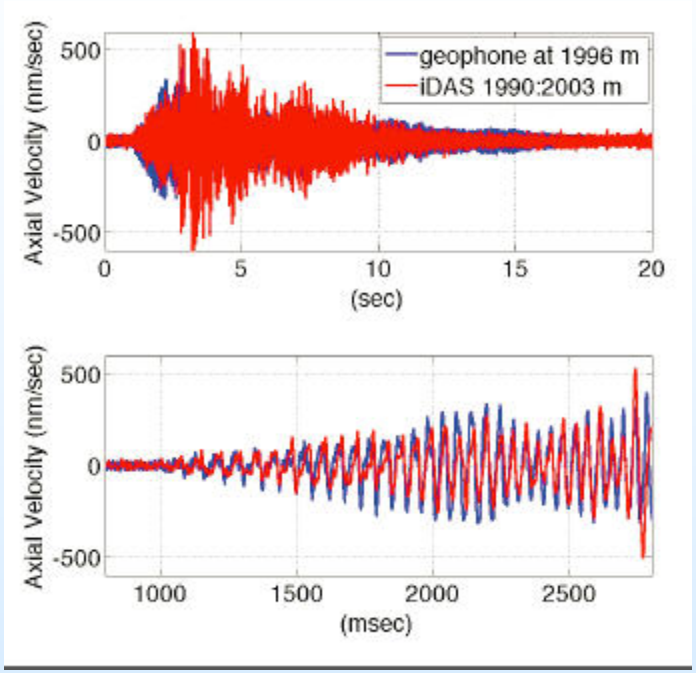


Figure I-4. Profile D-9-8 – D-9-7 baseline composite image

Post-CO_2 injection long-string, crossswell and DAS repeat surveys are planned

Comparison of Geophone to DAS Response

- 2013 implemented a large source effort (64 sweeps per shot point)
- Processed the results using adaptive stacking and spectral rebalancing to improve SNR
- DAS native measurement is strain rate
- Converted strain rate to particle velocity (Daley, et al in press)

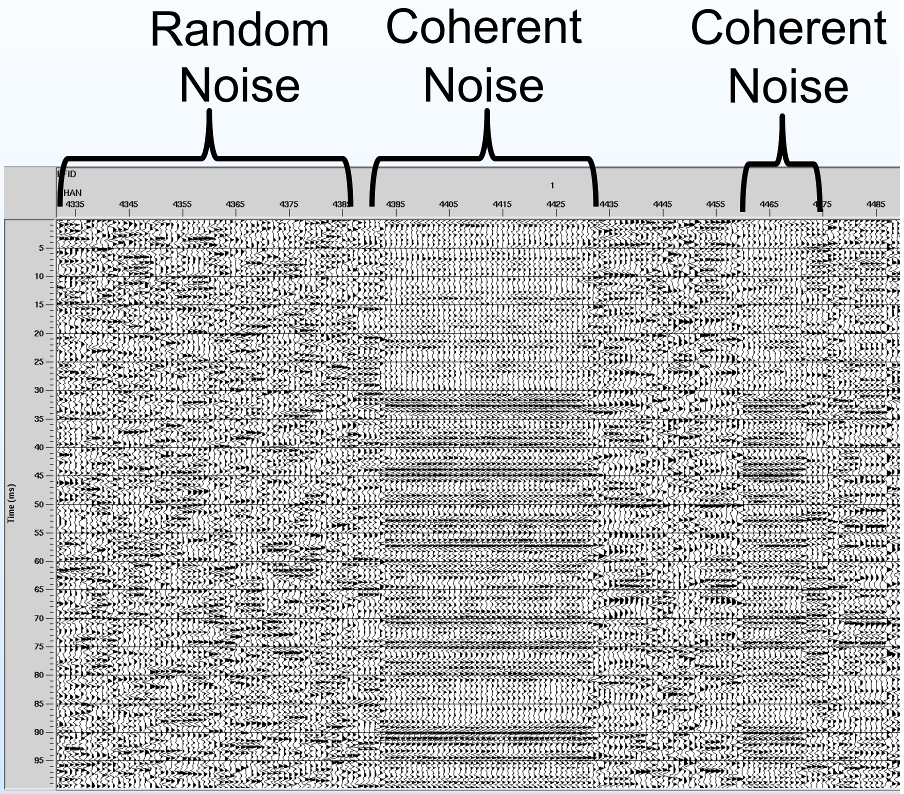


Daley, T.M., et al. Field Testing of Modular Borehole Monitoring with Simultaneous Distributed Acoustic Sensing and Geophone Vertical Seismic Profiles at Citronelle, AL, Geophy. Prosp. (in press)

Good match between geophone and DAS response!!

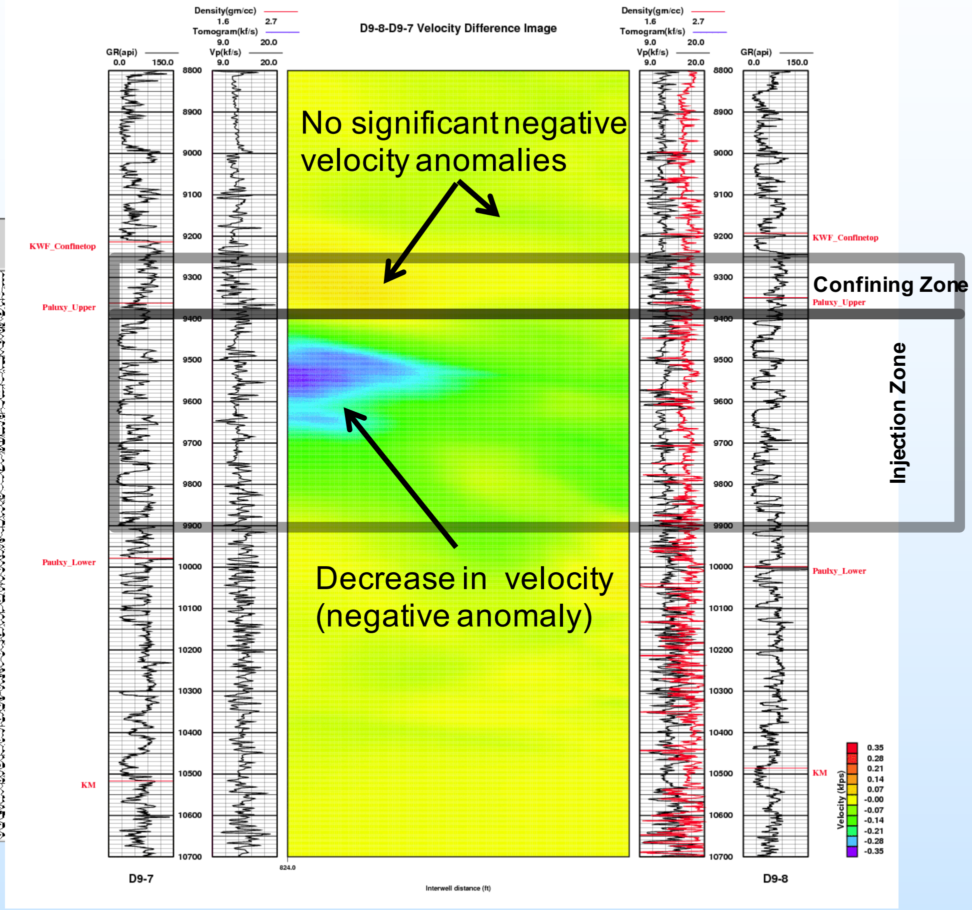
June 2014 Crosswell Survey Results

DAS



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

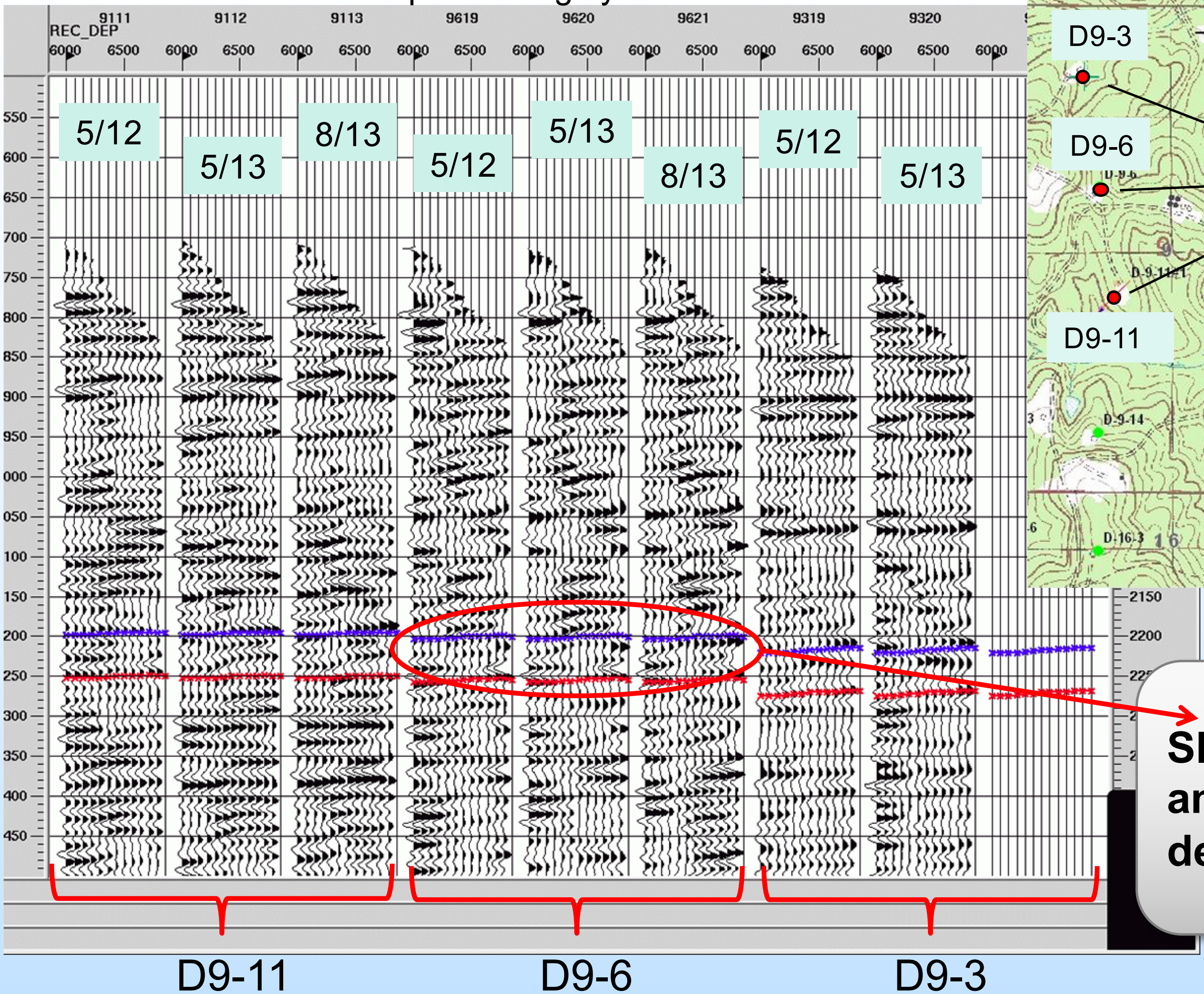
Conventional

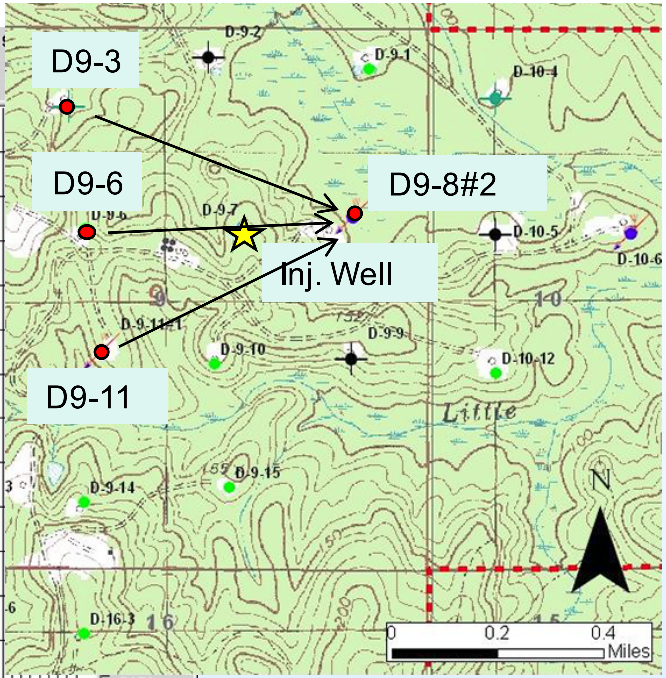


Pixelized difference tomography results without seismic reflection overlay showing positive velocity differences in warm colors and negative differences in cool colors

Time-Lapse Comparison of Baseline (5/2012) to CO_2 Injection Repeat VSP Surveys (2013) is Inconclusive for Conventional Geophones acquired using MBM

Seismic processing by SR2020

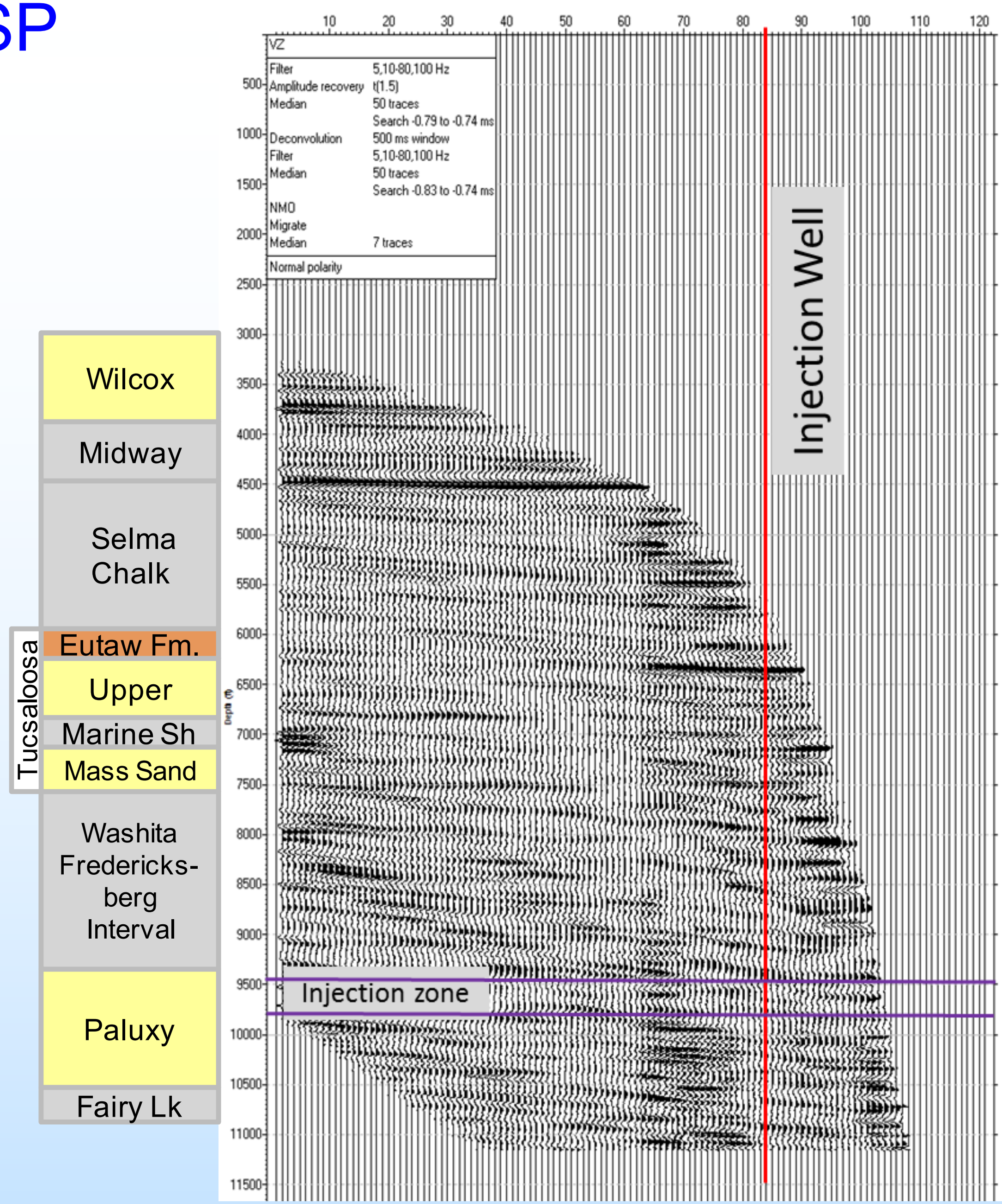




Slight change in amplitude at target depth

June 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
- Image has sufficient quality to conduct time-lapse analysis using results from the second (final) survey



Synergy Opportunities

– Collaboration with UT-Austin on the second (final) DAS seismic survey at Citronelle
  - "T-Rex" p- & s-wave vibroseis source
  - First survey to use DAS to acquire s-wave data

UT-Austin's "T-Rex" Vibroseis Truck

Accomplishments to Date

- **SECARB Citronelle Site**
  - Collected large crosswell and VSP data sets using DAS and conventional geophones for method comparison
  - Increased source effort combined with improved processing methods results in better SNR
  - Showed that DAS can be used to acquire good quality data in the VSP survey configuration
  - First cross-well survey performed using DAS in the public domain

Summary

Findings

- Fiber-optic based sensor arrays are innovative and robust
  - Wave form acquired using stacked VSP-DAS provides good match with results from conventional geophones
  - DAS data noise was too large in the sweep bandwidth to allow detection of seismic waves in the crosswell configuration
  - DAS appears promising for monitoring CO_2 plume development in VSP configuration

Future Plans

- Final VSP survey at Citronelle will take place Fall 2015
- Our Livingston site host cancelled their DOE contract. In contact with alternative site hosts including:
  1. Pinnacle reefs in Northern Michigan (Core Energy/Battelle)
  2. Arbuckle Formation in Wellington Field Kansas (KGS/Borexco)

Appendix

Crosswell Hyrdophone Array Data Acquisition Parameters at D9-8#2 – June 2014

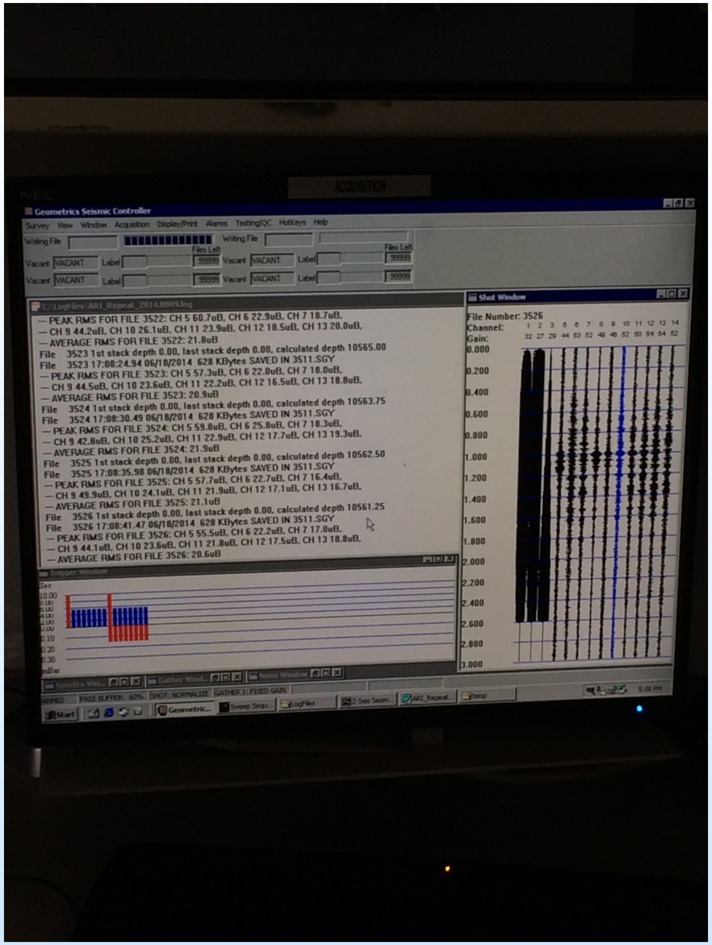
- Schlumberger Carbon Services
- Receiver array deployed inside tubing
- Receiver type: TARS Hydrophone – 10 levels
- Sample Rate: 0.25 ms
- Stack:
    - 8 sweeps for each fan
- Receiver spacing: 10 ft
- Receiver start depth: 10,590 ft
- Receiver end depth: 8,170 ft
- Data acquisition time: 5 days

Crane set up on well D9-8#2 containing hydrophone array. Photo by Michele Robertson (LBNL).

Crosswell DAS Array Data Acquisition Parameters at D9-8#2 – June 2014

- Silixa, LLC
- Fiber cable clamped to production tubing
- Receiver type: fiber optic Tubing Encased Cable
- Sample rate: 4kHz
- Stack:

  8 sweeps were recorded for multiple ‘fans’
- 128 sweeps at 9,000 and 9,340 ft depth
- Receiver spacing: 0.25 m
- Data acquisition time: <1 day



Geometrics data screen, SLB doghouse, during collection of 26 crosswell fans

Offset and Walkaway Data Acquisition Parameters for the VSP Survey - June 2014

- Walkaway survey between the injection & observation wells
- Seven far offset points located
- Source: vibroseis truck
  - ~60 shot locations
  - 6-8 sweeps per location
  - Sweep duration: 16,000 ms; recording 4,000 ms
  - Sweep frequency range: 12-160 Hz
- 18-level MBM geophone array in D9-8#2
- DAS fiber optic array in D9-8#2

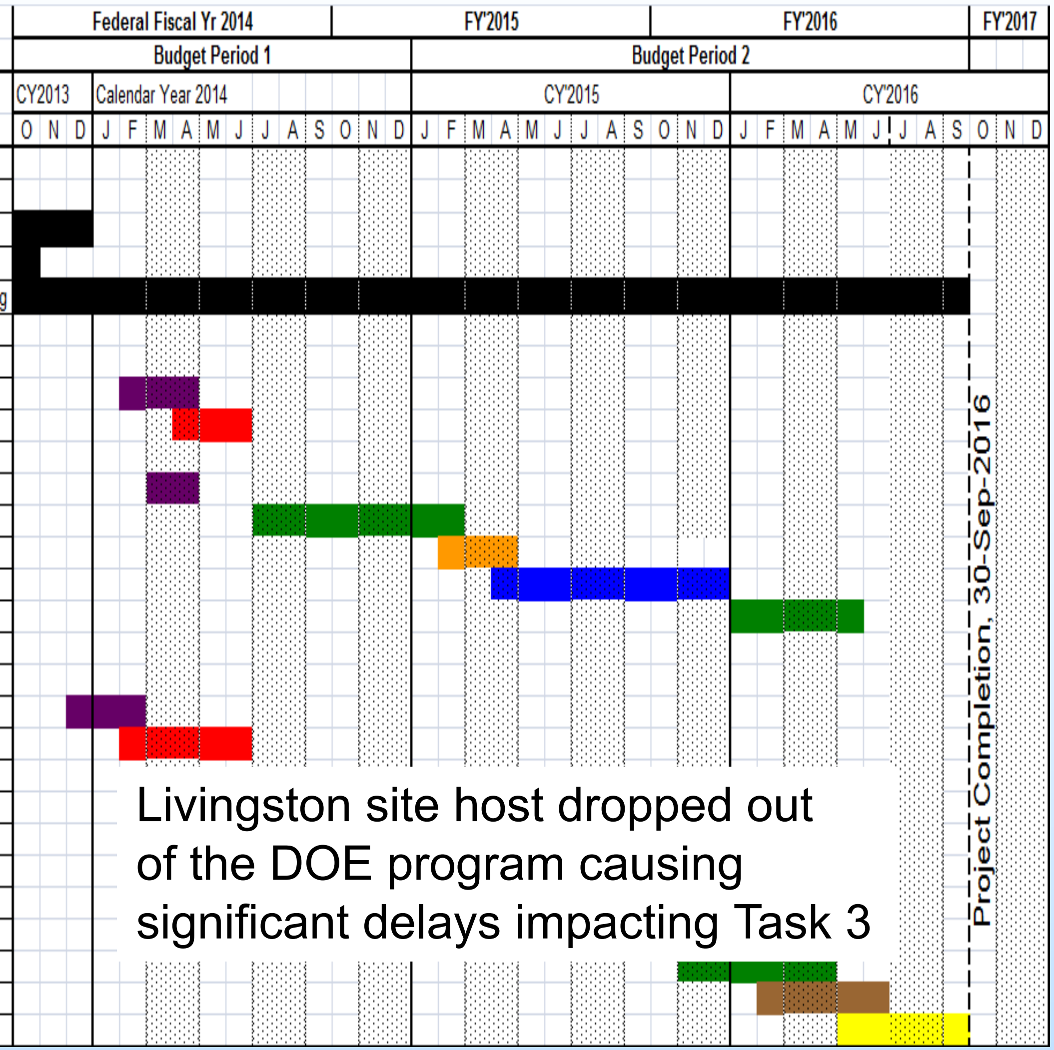
Map showing position of the individual shot locations (yellow dots) for the walkaway and dense grid coverage at injection well D9-7#2 (left well pad). The receiver array and DAS are located in the observation well D9-8#2 (right well pad). Far offset shotpoints not shown.

Organization Chart

- Department of Energy, NETL
  - Andrea Dunn, PM
- Electric Power Research Institute, Project Lead
  - Rob Trautz, PI
- Lawrence Berkeley National Laboratory, Geophysical & Hydrologic Modeling & Analysis
  - Tom Daley, Co-PI
  - Barry Freifeld, Co-PI
- Sandia Technologies, LLC, Field Site Engineering
  - Dan Collins, Co-PI
- Silixa, LLC, Fiber Optic Data Acquisition
  - Joe Greer, Co-PI

Gantt Chart

Description	Start Date	End Date	Dur. Mos.
Task 1.0 Project Management			
Revise Project Management plan	10/1/2014	12/31/2013	3
NEPA field study preparation/submittal	10/1/2014	11/30/2013	1
Project management	1/1/2014	9/30/2016	Ongoing
Task 2.0 – Vertical Well – Citronelle Alabama			
Subtask 2.1 – Sensor Design and Fabrication			
Design	2/1/2014	4/30/2014	3
Purchase, fabrication and equipment delivery to site	2/1/2014	6/30/2014	5
Subtask 2.2 – Field Testing			
Survey design & planning	3/1/2014	4/30/2014	2
Baseline seismic acquisition and processing	3/1/2015	3/31/2016	6
Heat-pulse monitoring	9/1/2014	8/31/2015	12
CO2 injection*	4/1/2015	12/31/2015	9
Post-injection seismic acquistion and processing	1/1/2016	5/31/2016	5
Task 3.0 Horizontal Well – Livingston Field Louisiana			
Subtask 3.1 – Sensor Design and Fabrication			
Design	10/1/2014	1/31/2014	3
Purchase, fabrication and equipment delivery to site	2/1/2014	6/30/2014	5
Subtask 3.2 – Field Testing			
Survey design & planning	2/1/2014	3/31/2014	2
Baseline seismic acquisition and processing	7/1/2014	12/31/2014	6
Heat-pulse monitoring	10/1/2014	10/31/2015	13
CO2 injection*	11/1/2014	4/30/2015	6
Foam injection*	5/1/2015	10/31/2015	6
Post-injection seismic acquistion and processing	11/1/2015	5/31/2016	6
Task 4.0 – Data Analysis	1/1/2016	6/30/2016	5
Task 5.0 – Final Sensor Performance Report	5/1/2016	9/30/2016	5



Bibliography

List peer reviewed publications generated from project per the format of the examples below

- None