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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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
  - Time-lapse seismic results (June 2014 and Dec 2015)
  - Shear-wave seismic source survey (Dec 2015)
- Task 3 – Containment and Monitoring Institute Field Research Station (CaMI)
  - Heat-pulse monitoring to determine flow allocation
  - Continue DAS geophysical monitoring

Benefit to the Program

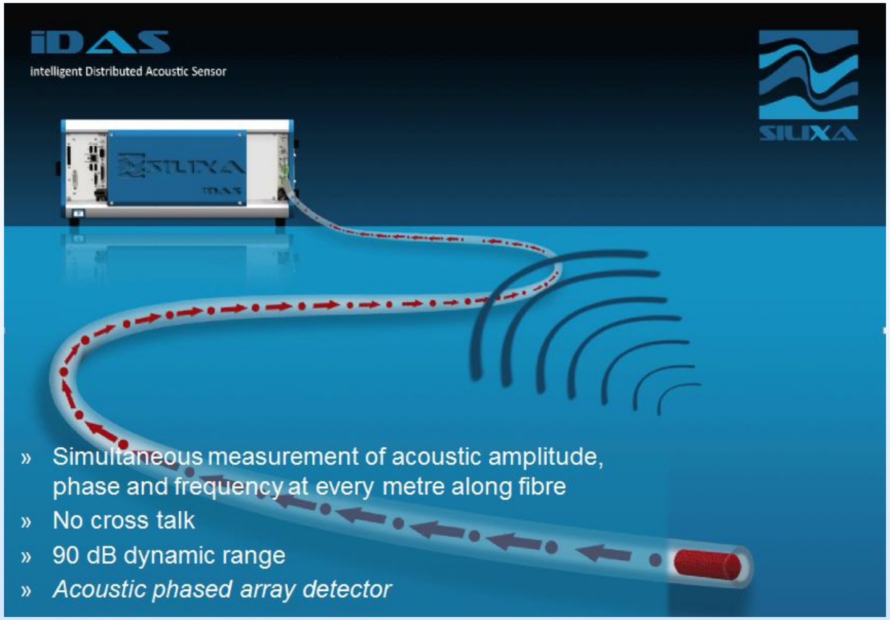
- Program goals
  - Develop and validate technologies to ensure 99 percent storage permanence.
- Benefit Statement
  - The project uses Distributed Acoustic Sensor (DAS) arrays to detect and image the CO_2 plume using seismic methods
  - Heat-pulse monitoring using Distributed Temperature Sensing (DTS) 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

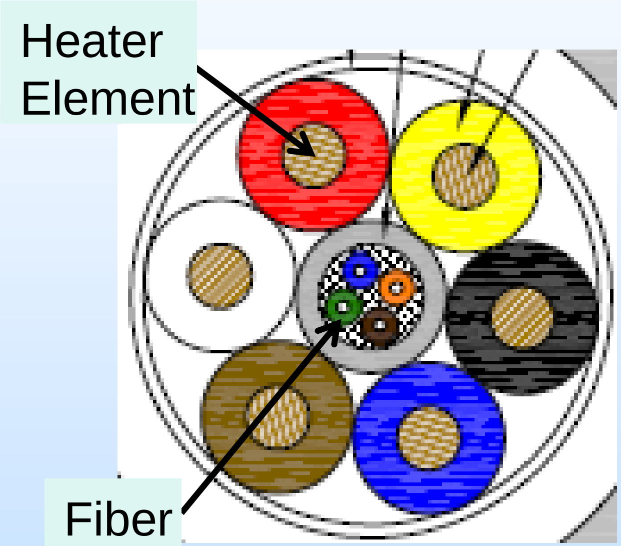
- Light emitted into a fiber is reflected throughout the fiber's length by Rayleigh scattering
- DAS system measures the modulation of the backscattered light
- An acoustic field around the fiber exerts tiny pressure/ strain changes on the fiber, resulting in changes to the backscattered light
- The 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

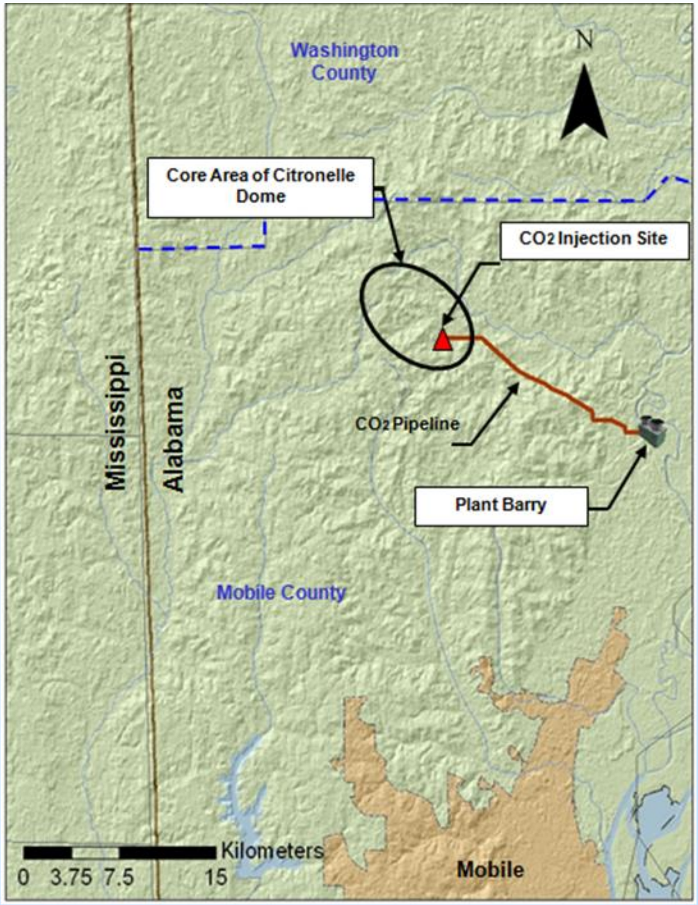
- Measurement of Raman backscattering combined with Optical Time-Domain Reflectometry (OTDR) are used to determine distributed temperatures along the fiber length
  - DTS used for past 20 years
  - 5 km fiber: spatial resolution 25 cm, temperature resolution 0.01°C measurement time 1 s
- Copper heater 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

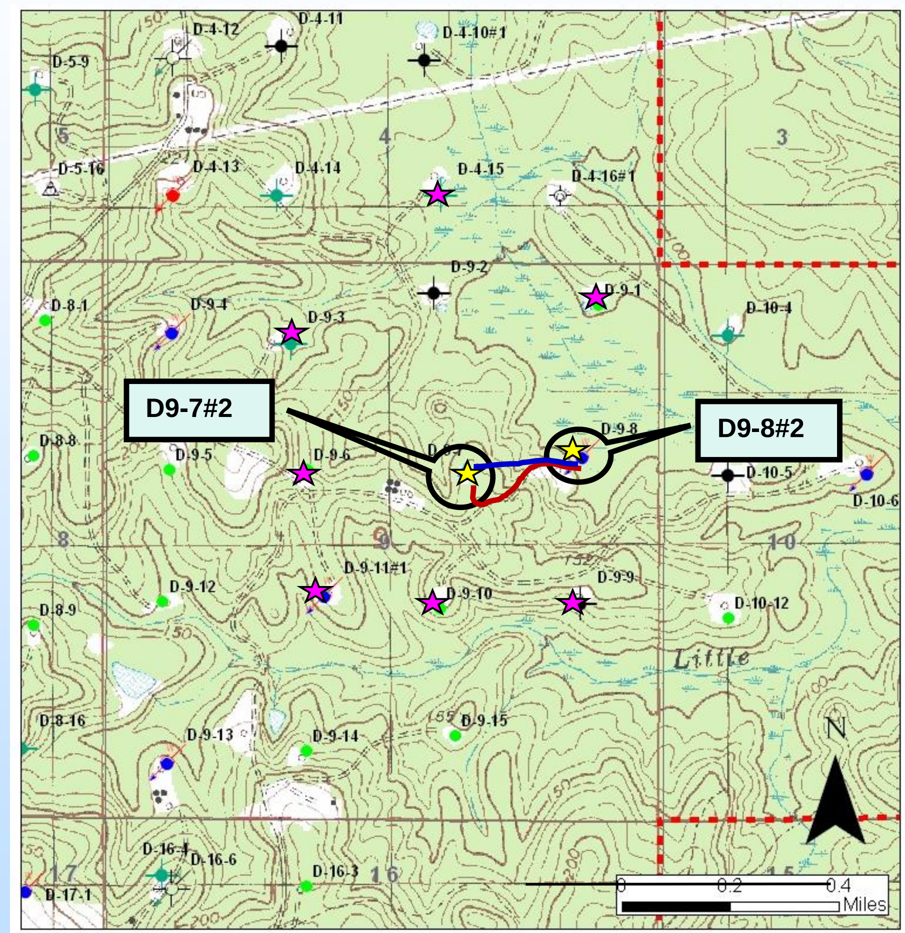
- First integrated CO_2 capture, transportation and storage project on a coal-fired power station using advanced amines in the U.S.
- Southern Co. and MHI captured over 210,000 tCO_2
- Denbury Resources transported, injected and stored over 114,104 tCO_2 in the Paluxy Formation
- Project stopped injecting and entered the Post Injection Site Care period September 1, 2014



Plant Barry, CO_2 pipeline and Citronelle storage site near Mobile AL

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

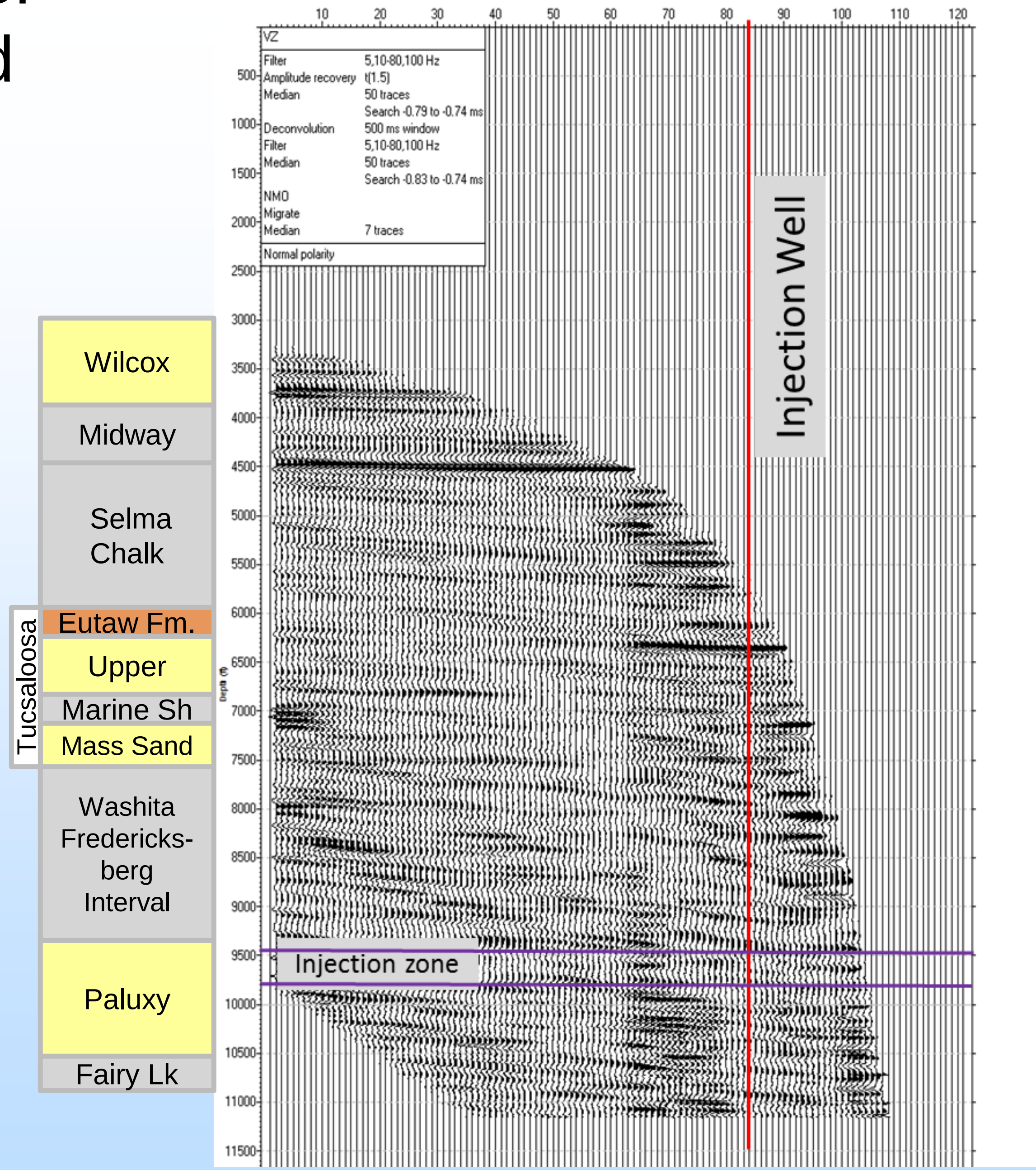
Deployment of the Modular Borehole Monitoring (MBM) Conventional geophone array (left) and yellow flat pack containing the fiber optic based DAS array (right)



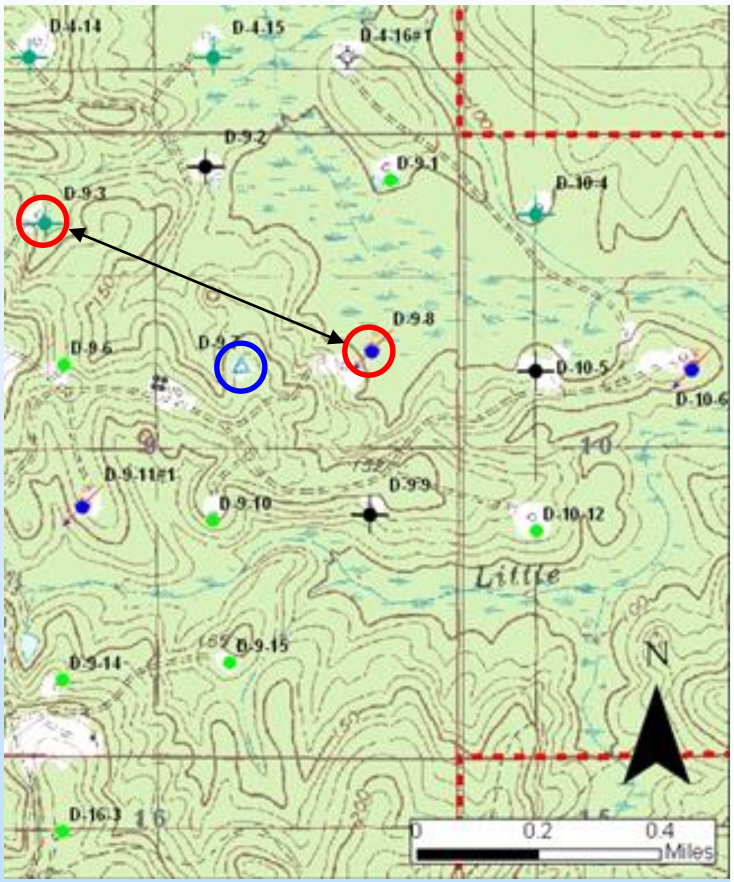
VSP source offset locations (stars), receiver locations (D9-7#2 and D9-8#2), and walk-away lines (blue and red lines)

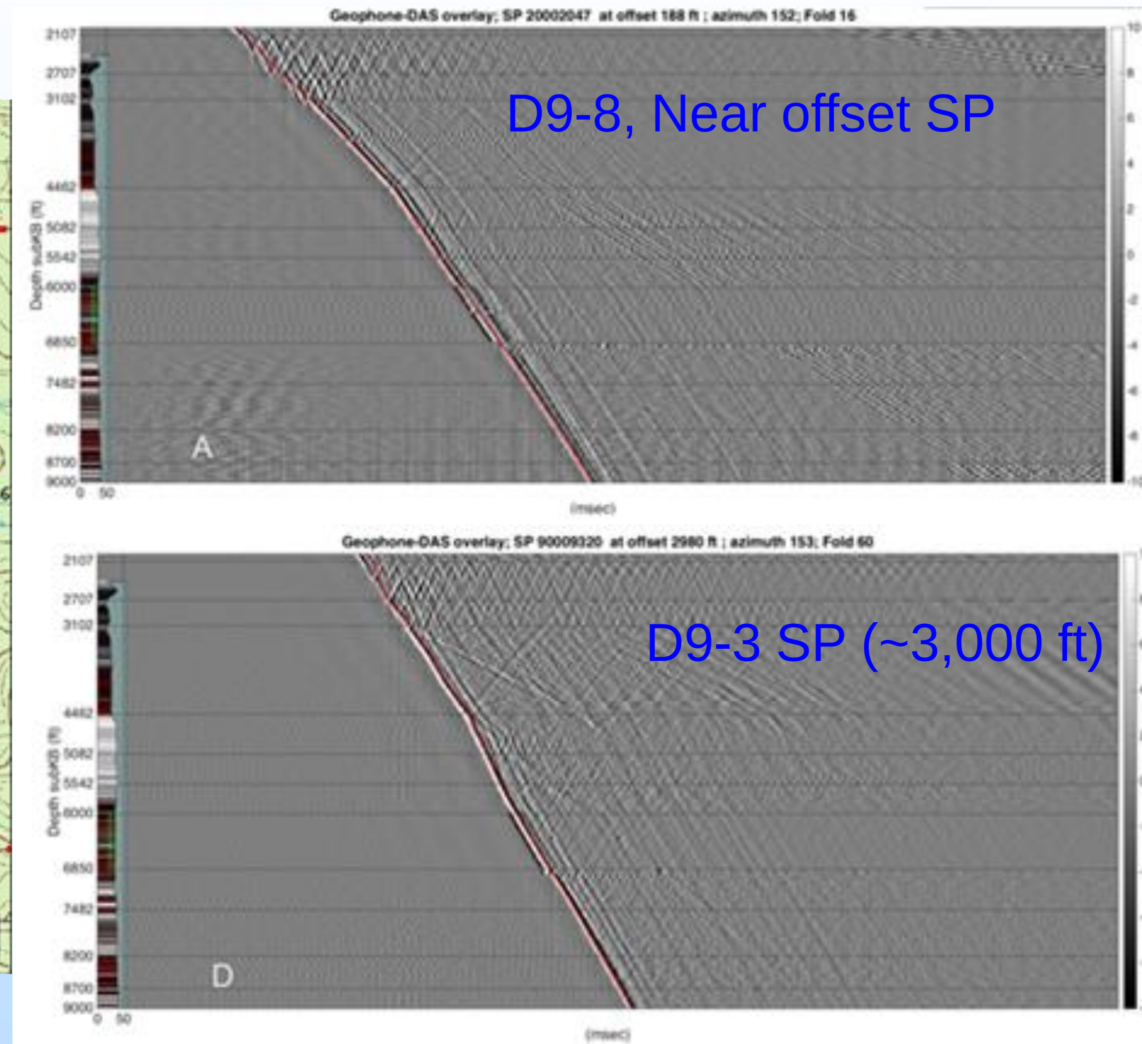
June 2014 DAS-VSP Survey Results and Conclusions

- Migrated image →
  - Observed strong reflectors
  - Good tie to formation logs (e.g., Selma Chalk)
- Image has sufficient quality to conduct time-lapse analysis using results from the second (final) survey



December 2015 Final DAS-VSP Survey

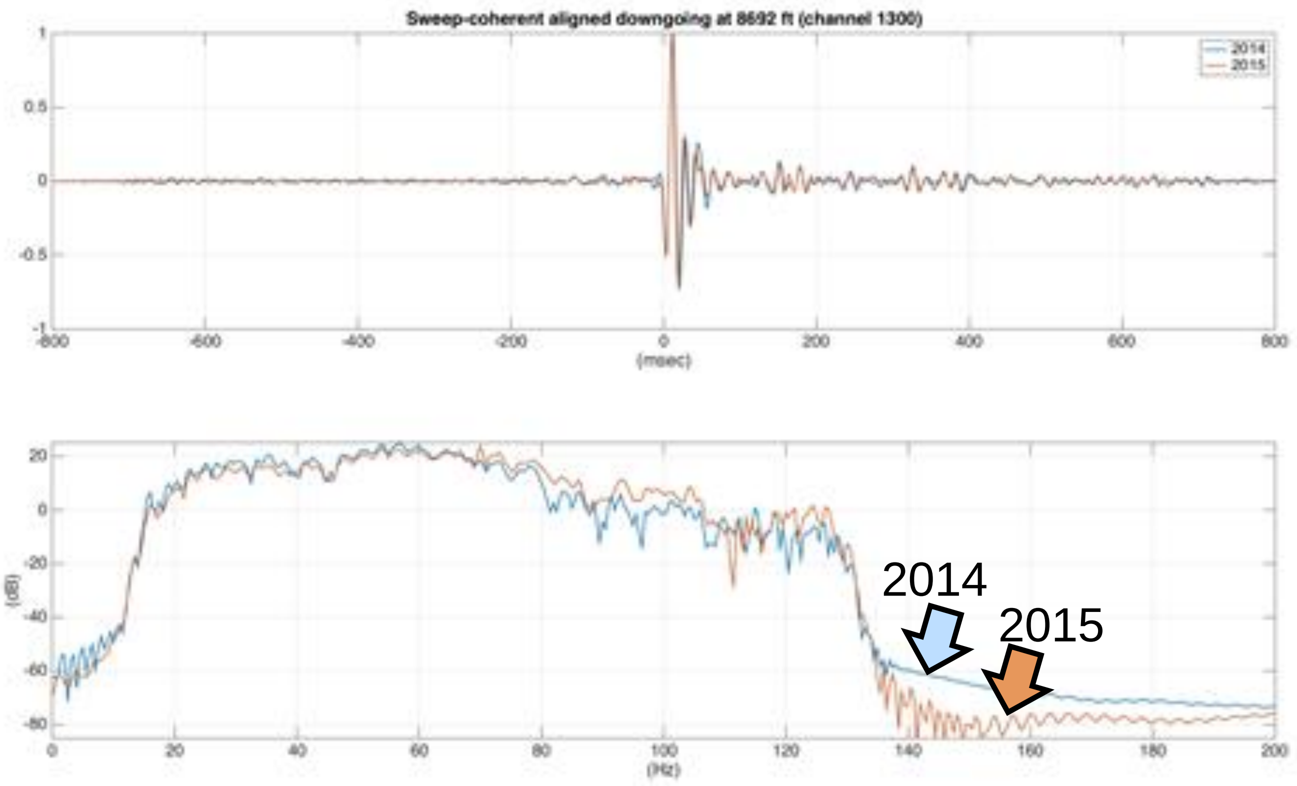




Good Repeatability Between 2014 and 2015 Surveys
DAS Technology Improvements Result in Lower Noise Floor

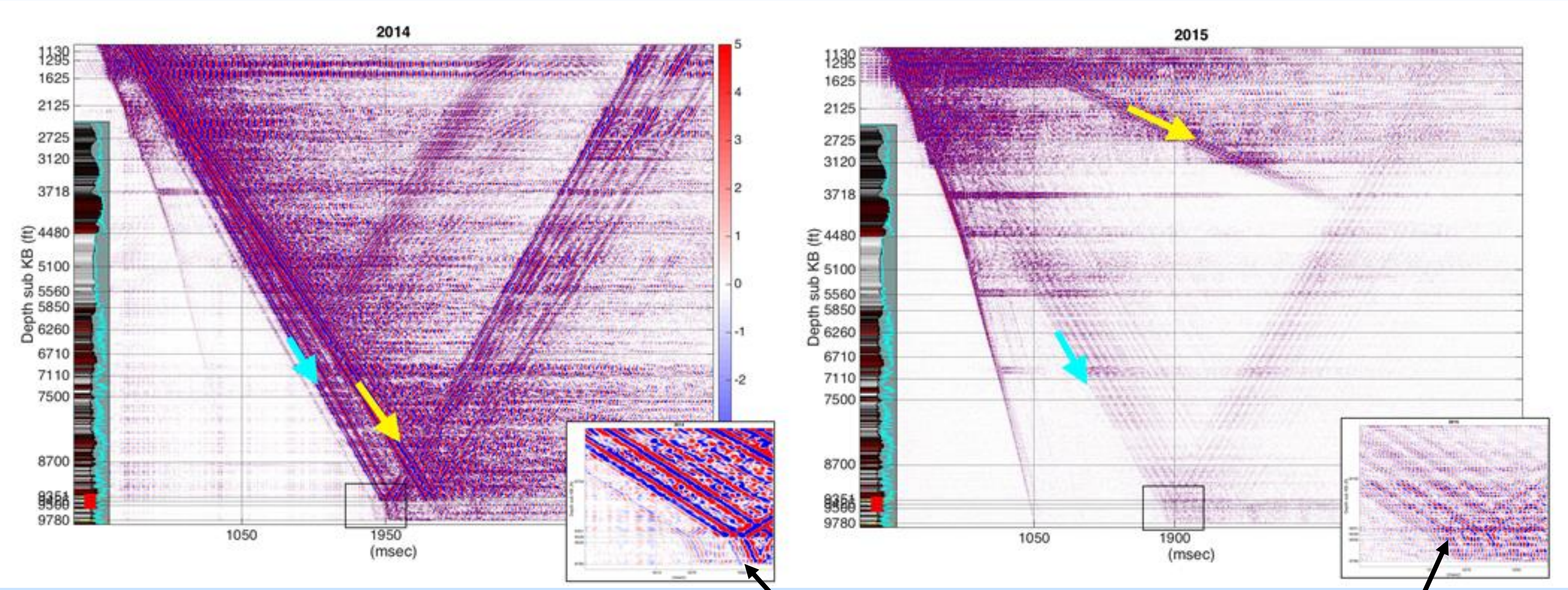
Good agreement between 2014 and 2015 downgoing wave forms at 8,592 ft depth

Comparison of 2014 and 2015 power spectrum



Comparison of Surveys Indicates Changes in Coupling and Tube Wave Response at Near Offset SP

Well Annulus Contained CO_2 in December 2015



June 2014

Dec 2015

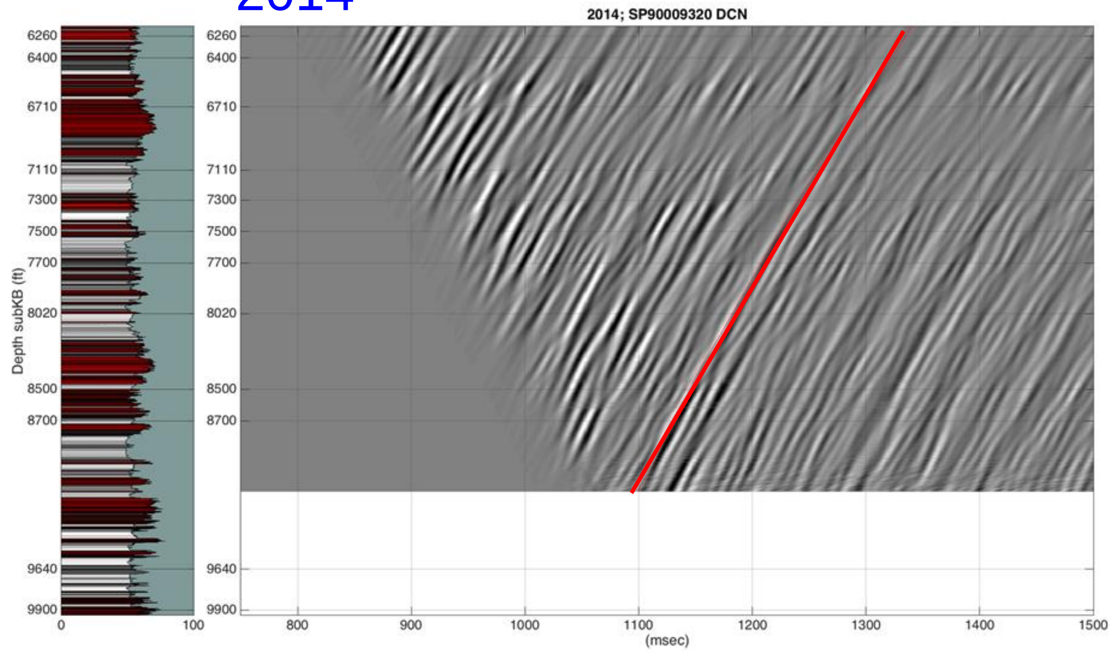
Primary tube wave inside tubing (in fluid)
Secondary tube wave in annuuls (gas to fluid)

Insets show strong tube wave reflection from the packer at 9,400 ft

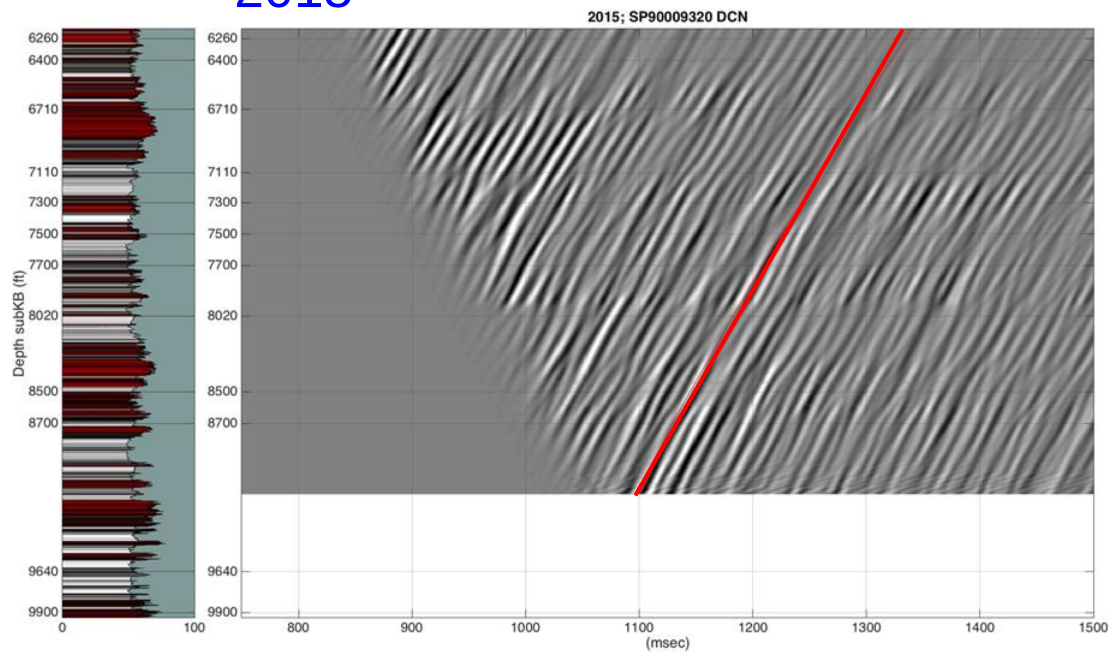
Deconvolved Upgoing Signal

- Processing by Doug Miller (Silixa)
- Red curve superimposed on the data shows the computed up going reflection time for a flat reflector at 9640 ft
- Processed data were used as input to the migration (next slide)

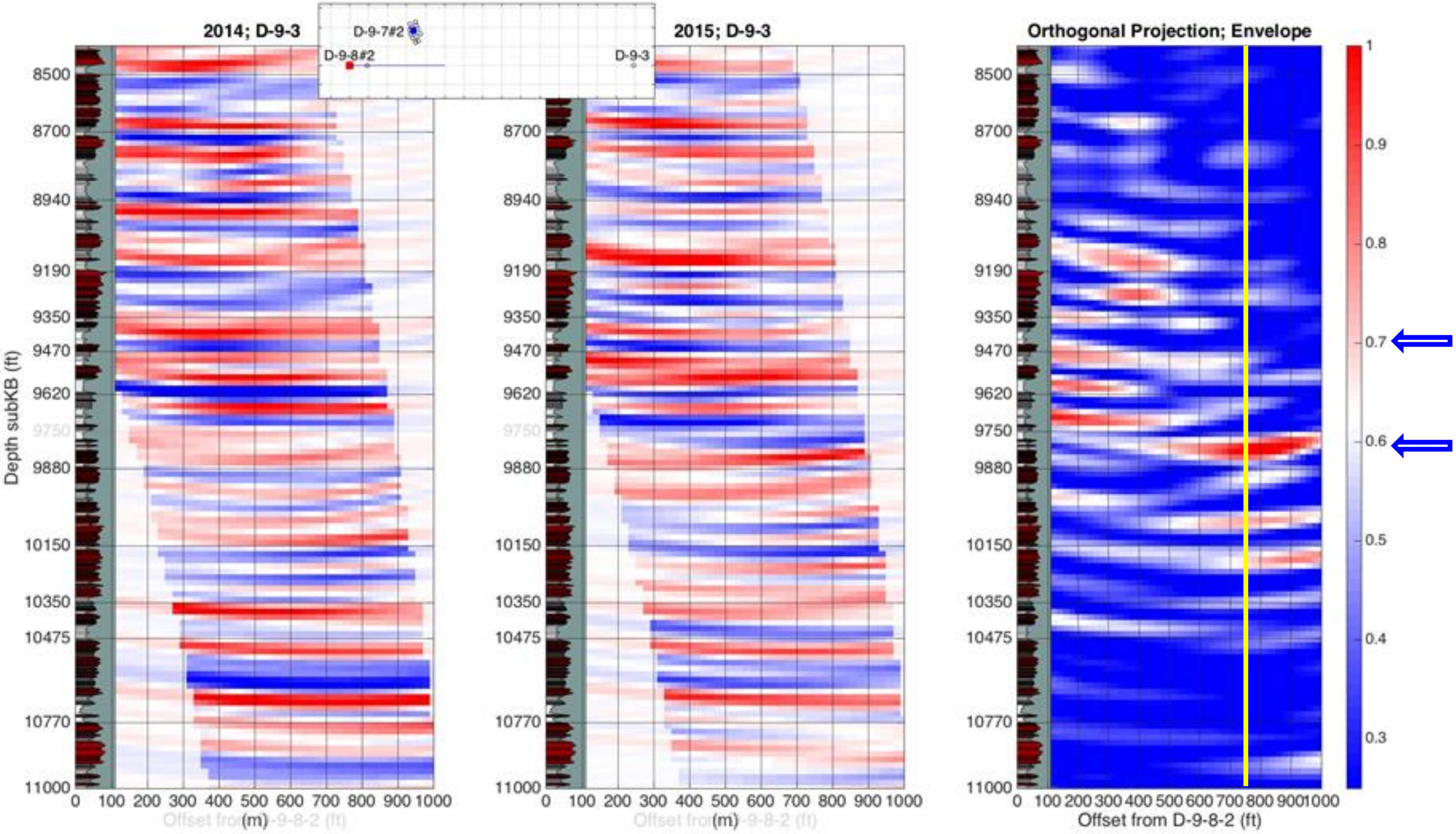
2014



2015



DAS Migrated Images from 2014 (left), 2015 (center) and Time Lapse Difference (right)

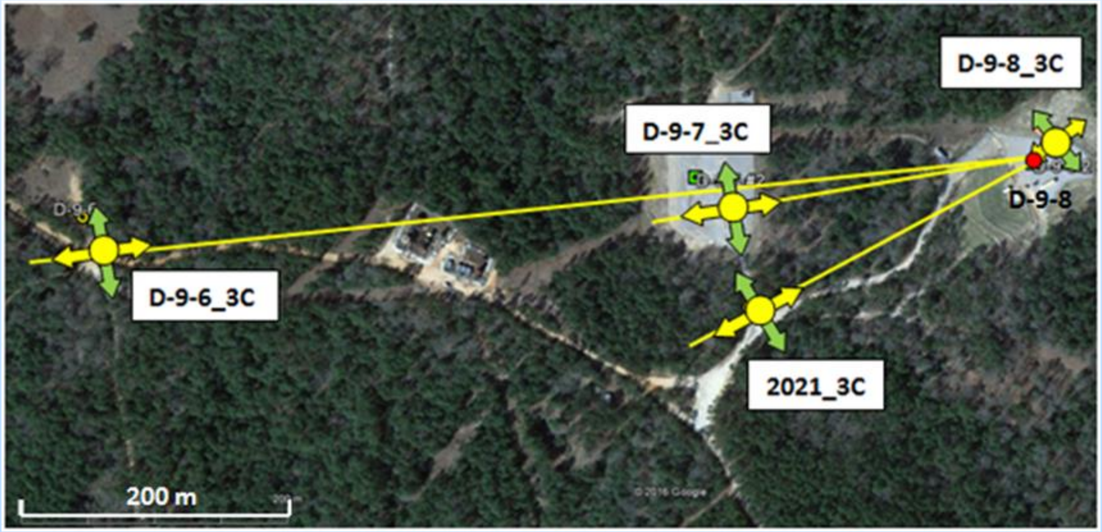


DAS Shear-Wave Source Pilot Test

UT-Austin's T-Rex triaxial vibroseis source

T-Rex
64,000 lbs
Vibroseis
Truck

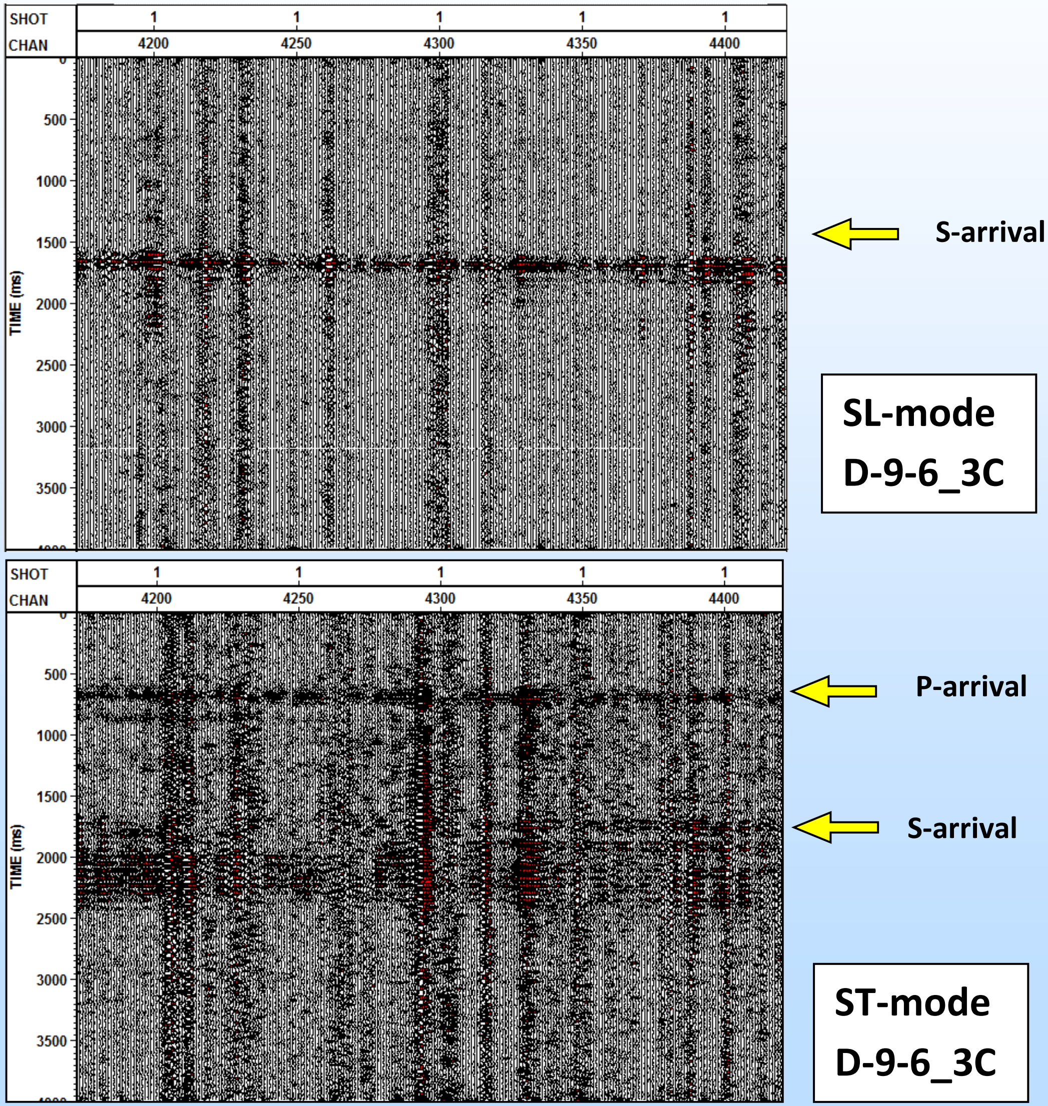
T-Rex
Footprint



Shear
Components
SL (yellow arrows)
ST (green arrows)

Preliminary Correlated DAS Data from Shotpoint D-9-6_3C After One De-Noising Pass

- Processing by Michelle Robertson (LBNL)
- Traces are at 0.25m spacing (2 kHz sample rate) along entire well length
- Single sweep, 4 second record
- Data selection is from ~3420–3625 ft in the observation well
- Data in this figure are plotted above geophone level due to weak signals at depth without stacking
- Yellow arrows identify possible P-wave and S-wave arrivals



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 and DAS repeatability
  - Demonstrated that time-lapse imaging of the CO_2 is possible using DAS technology
    - Use of different sources at Citronelle will complicate interpretation
  - Demonstrated that DAS can be used to record shear-wave data at high spatial resolution

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
  - Daley et al. (2015) demonstrated geophone to DAS agreement in true units
  - DAS data noise was too large in the sweep bandwidth to allow detection of seismic waves in the crosswell configuration
  - DAS is a promising technology for monitoring CO_2 plume development in the VSP configuration

Future Plans

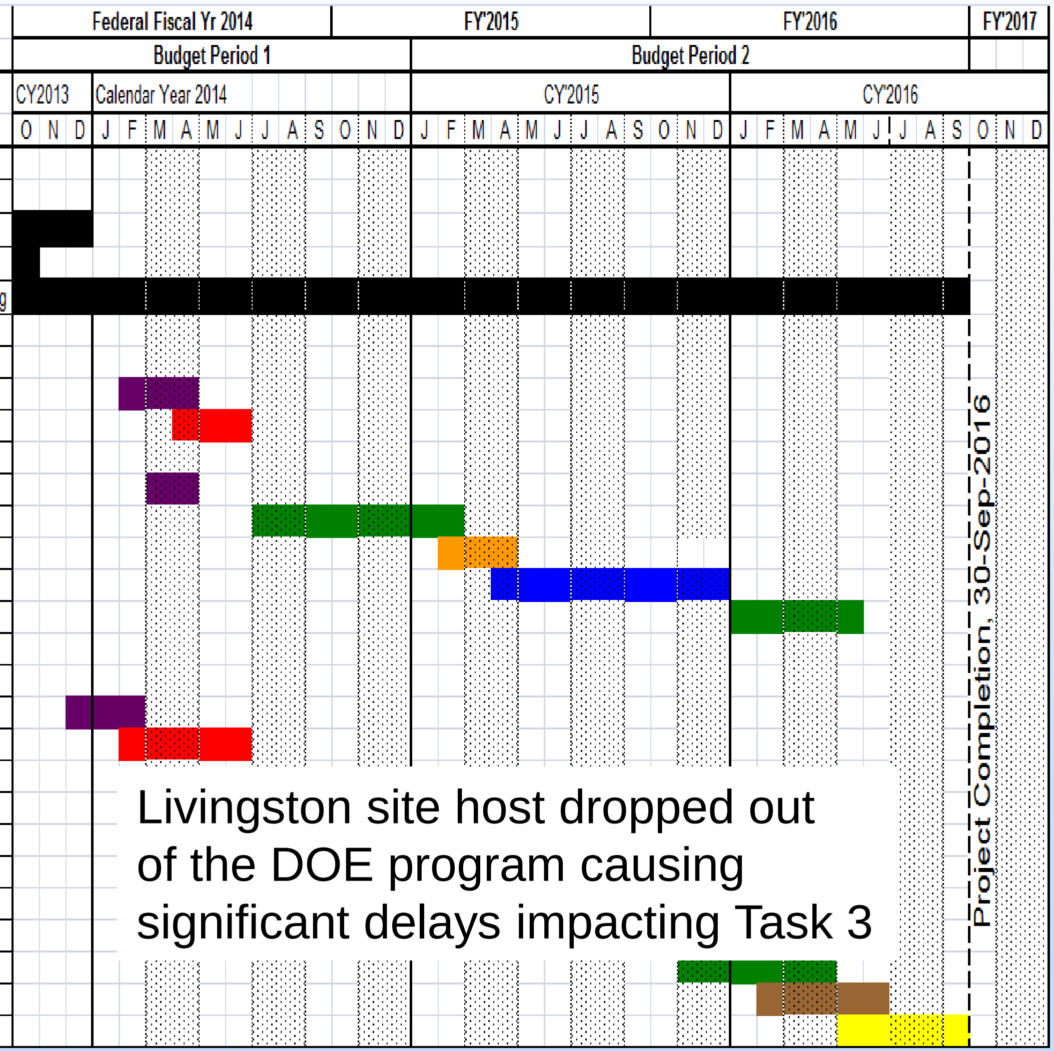
- Continue processing shear-wave data set
- Livingston project host cancelled its contract with DOE causing FO project delays
- Path forward is to move the FO project to the Containment and Monitoring Institute's (CaMI) Field Research Station in Alberta Canada pending DOE approval
- Requires re-scoping and no cost contract extension

Appendix

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

- Daley, T.M., Miller, D.E., Dodds, K., Cook, P. and Freifeld, B.M. (2015), Field testing of modular borehole monitoring with simultaneous distributed acoustic sensing and geophone vertical seismic profiles at Citronelle, Alabama. Geophysical Prospecting. doi: 10.1111/1365-2478.12324