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

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Acknowledgment and Disclaimer

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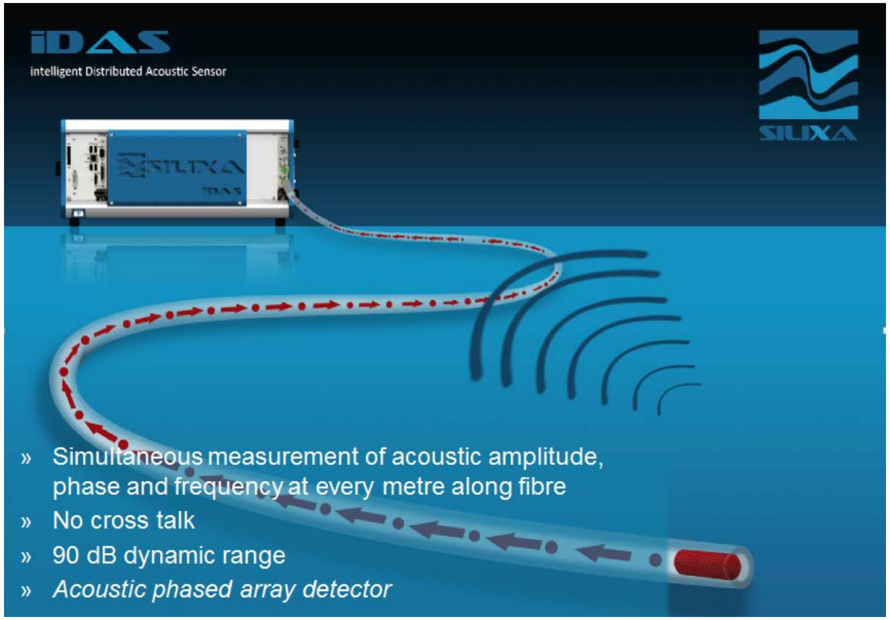
Presentation Outline

- Technical Status
- Accomplishments to Date
- Lessons Learned
- Synergy Opportunities
- Project Summary
- Appendix

Technical Status

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

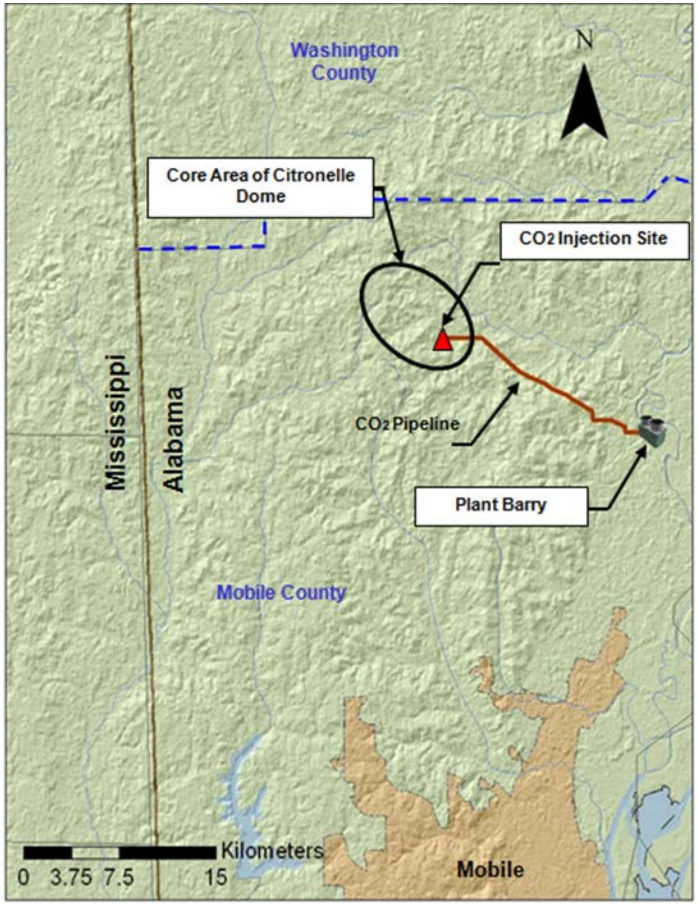
- Light emitted into a fiber is reflected throughout the fiber's length by Rayleigh scattering
- DAS system measures the modulation of the backscattered light
- An acoustic field around the fiber exerts tiny pressure/ strain changes on the fiber, resulting in changes to the backscattered light
- The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

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

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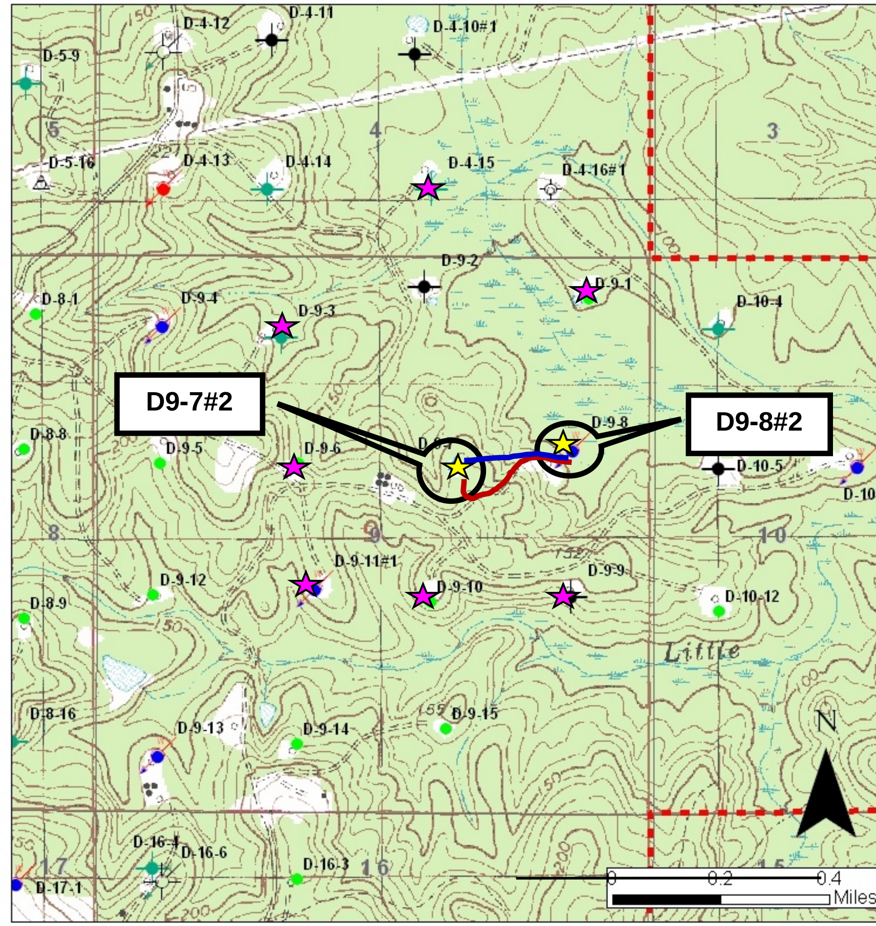
Citronelle Offers a Unique Opportunity to Compare Seismic Methods to Monitor CO_2 Plume Location

Deployment of the Modular Borehole Monitoring (MBM)

Conventional geophone array (left) and yellow flat pack containing the fiber optic based DAS array (right)

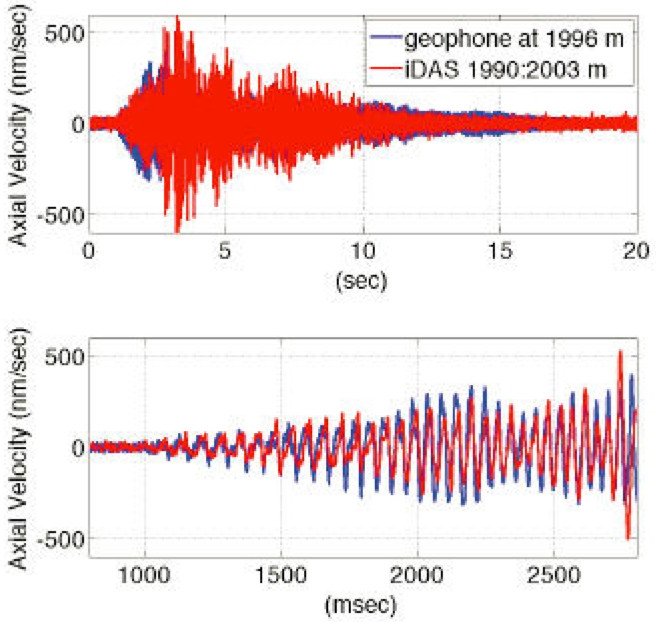


VSP source offset locations (stars), receiver locations (D9-7#2 and D9-8#2), and walk-away lines (blue and red lines)

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 2015)

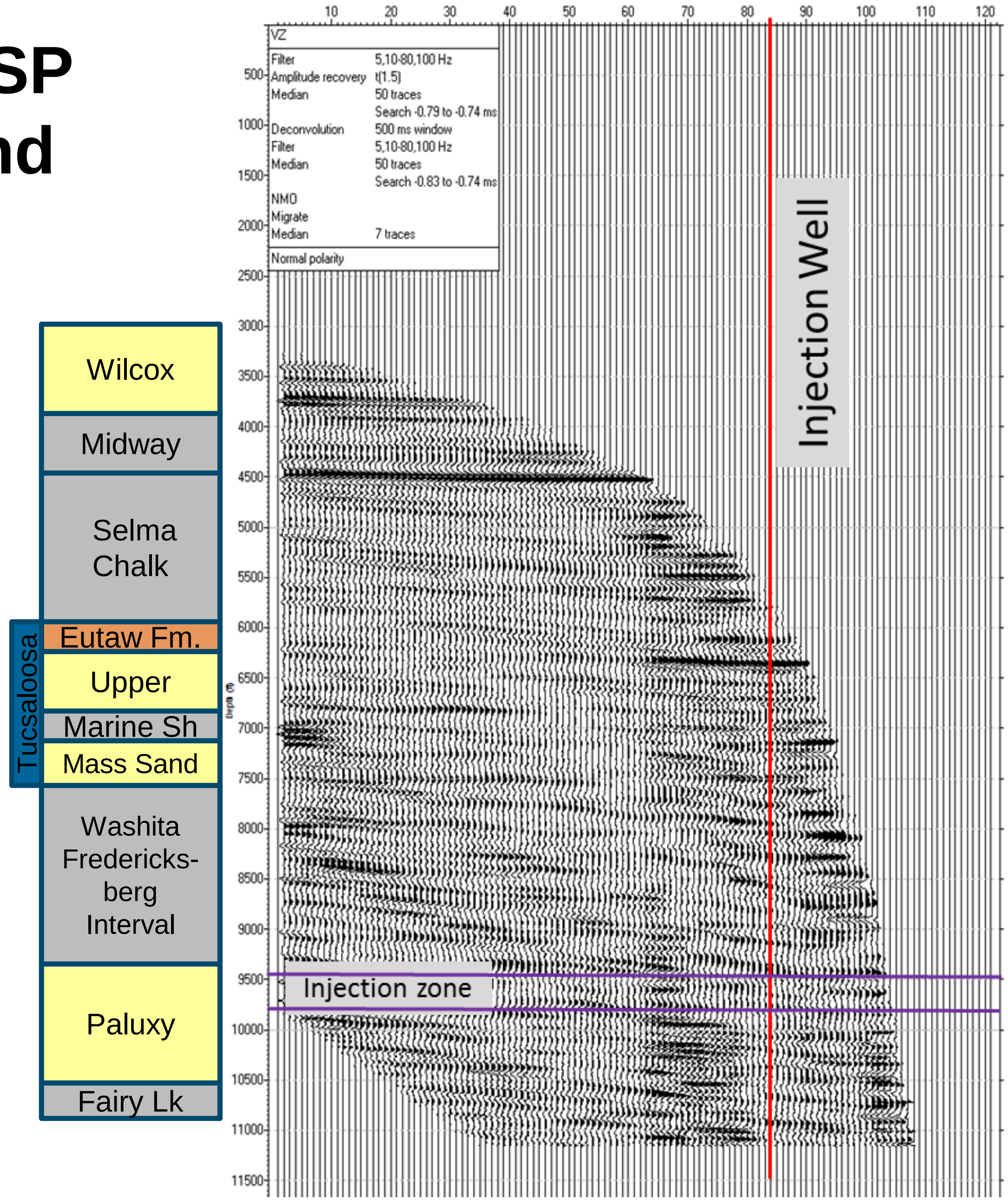
Good match between geophone and DAS response!!



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)

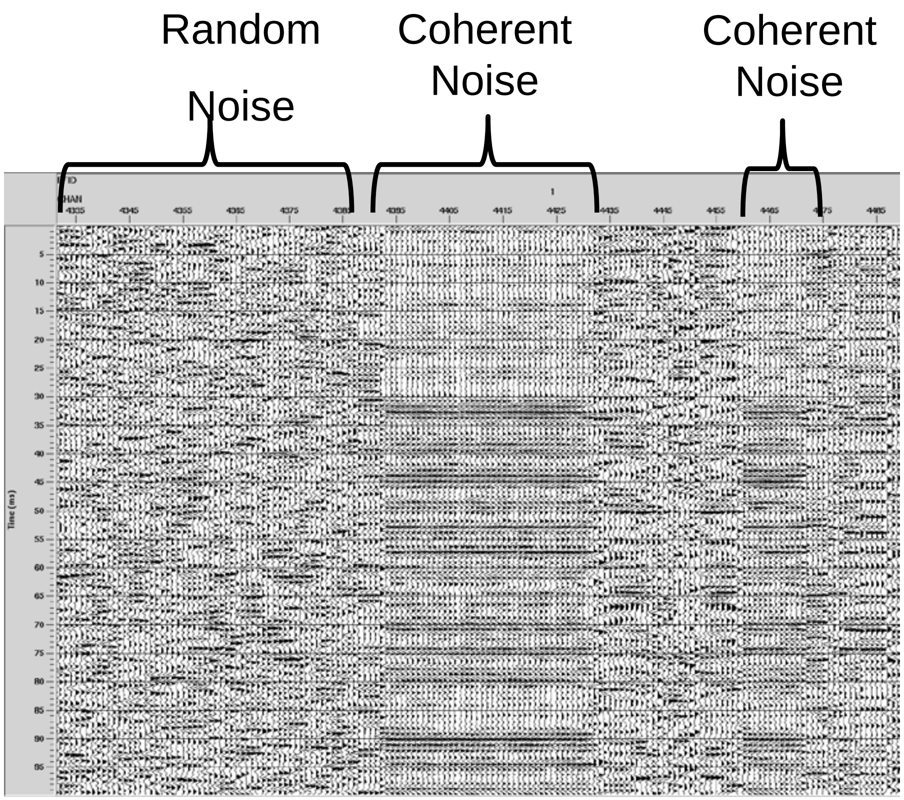
June 2014 DAS-VSP Survey Results and Conclusions

- 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



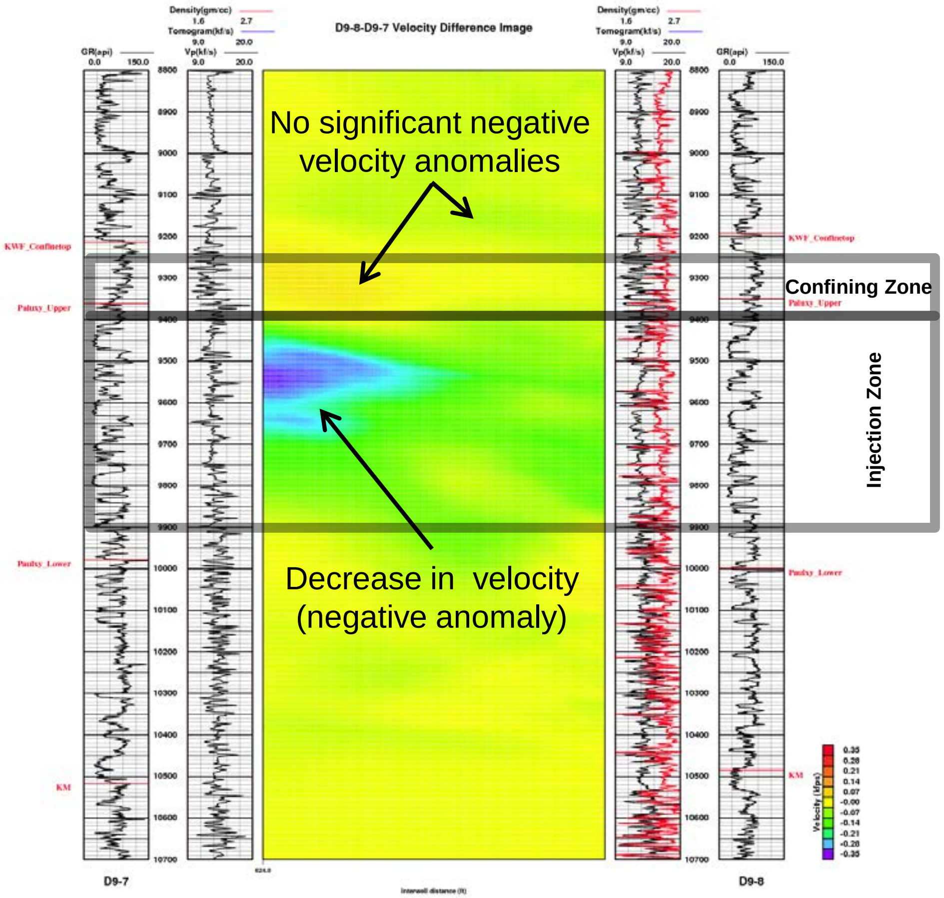
June 2014 Crosswell Survey Results

DAS



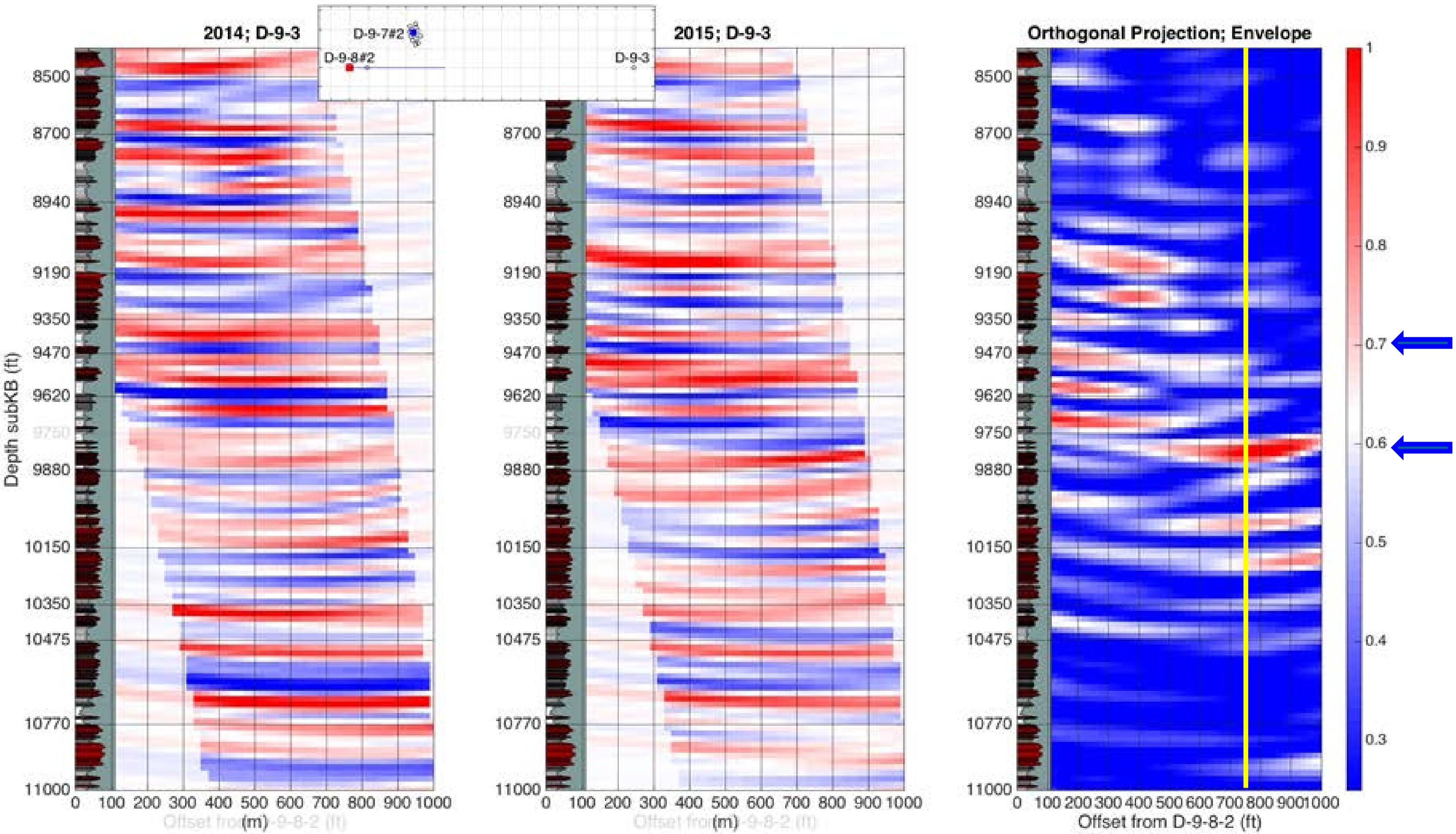
DAS Data at 9,340 ft – Only See Random Noise, Except Some Coherent Noise Not related to sweep

Conventional



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

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

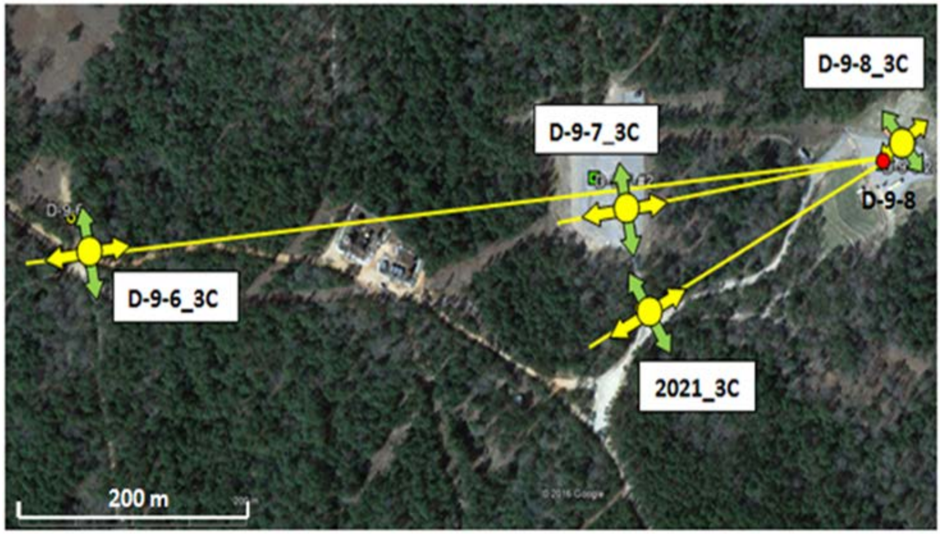


Shear-Wave DAS Survey

- Collaboration between EPRI, LBNL, Silixa and the University of Texas – Austin
- UT provided their 64,000 lb Vibroseis Truck
- “T-Rex” is capable of generating compression (P) and shear (S) source waves
- One of only a few shear-wave sources in the US

Shear-Wave DAS Survey Parameters

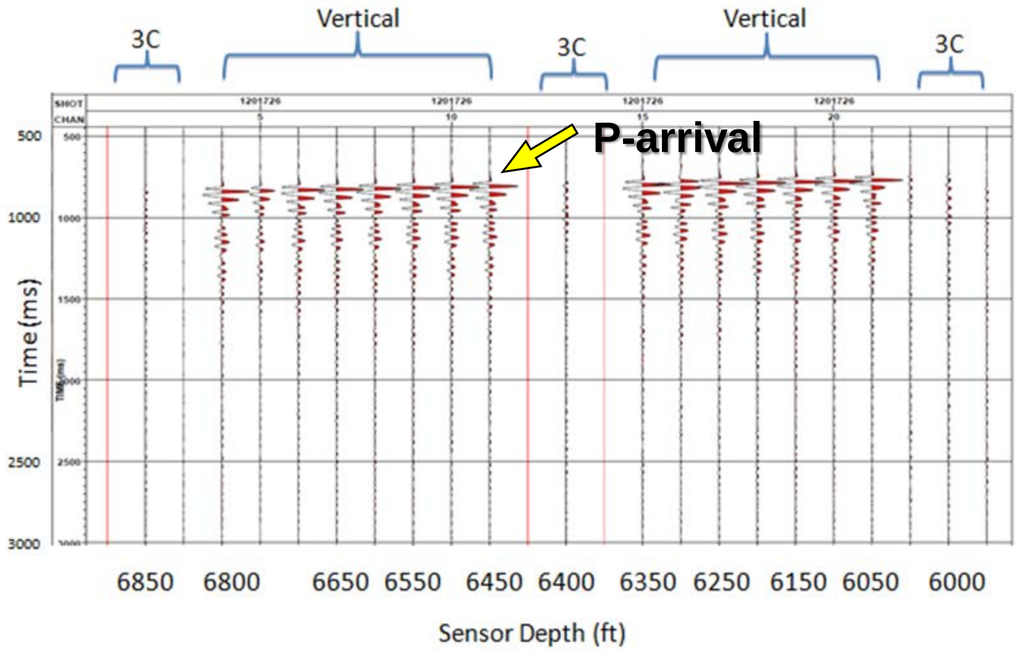
- Triggered DAS and conventional geophone data were collected at four site locations (VPs) with the following parameters (Figure)
- 5–80 Hz linear sweep with 0.5 sec cosine tapers each end
  - P-mode (vertical baseplate motion)
  - SL-mode (motion radial to well D-9-8, shear-longitudinal, or inline)
  - ST-mode (motion orthogonal to well D-9-8, shear-transverse, or cross-line)



- Sweep length 16 seconds, 4 second listen time
- 32 sweeps per mode per VP (total of 96 sweeps each VP)

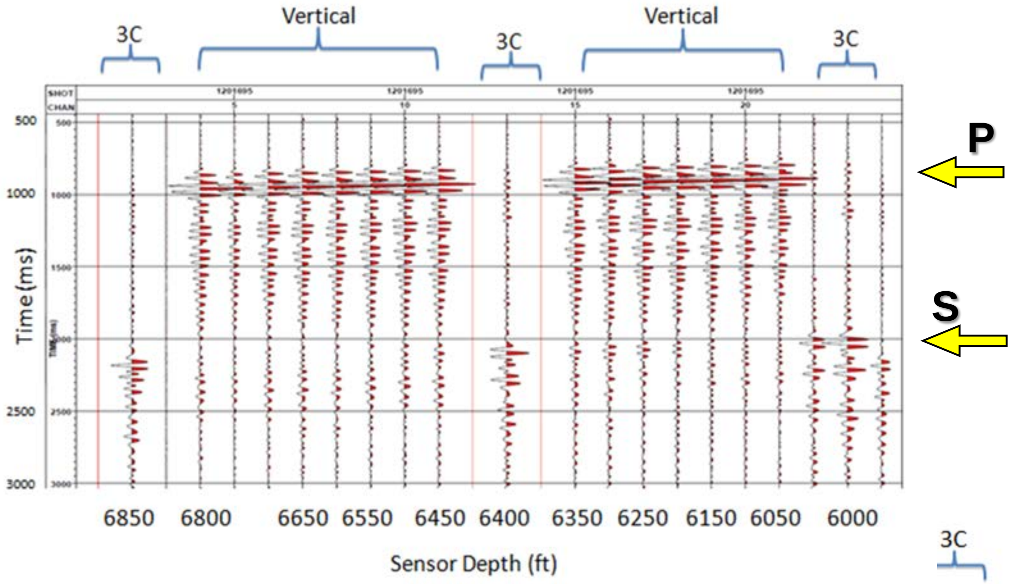
Geophone Response for Source Point 2021_3C, Correlated with the Pilot Sweep

Data were recorded at 1 kHz sample rate, 50-foot channel spacing between 6000 – 6850 ft, 20 second records

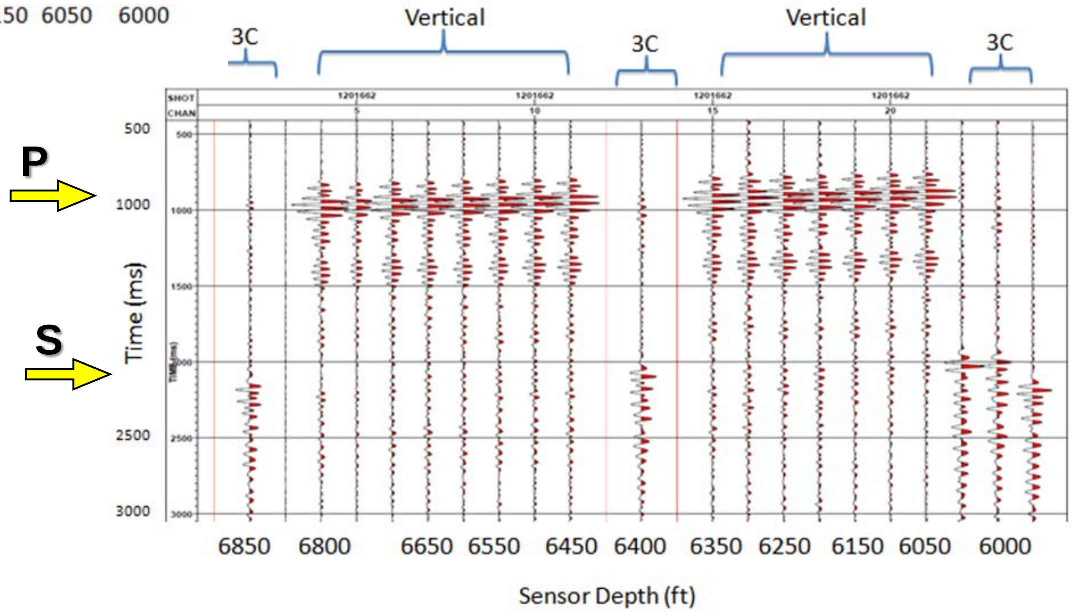


P-mode source at 2021_3C

Geophone Response for Source Point 2021_3C, Correlated with the Pilot Sweep



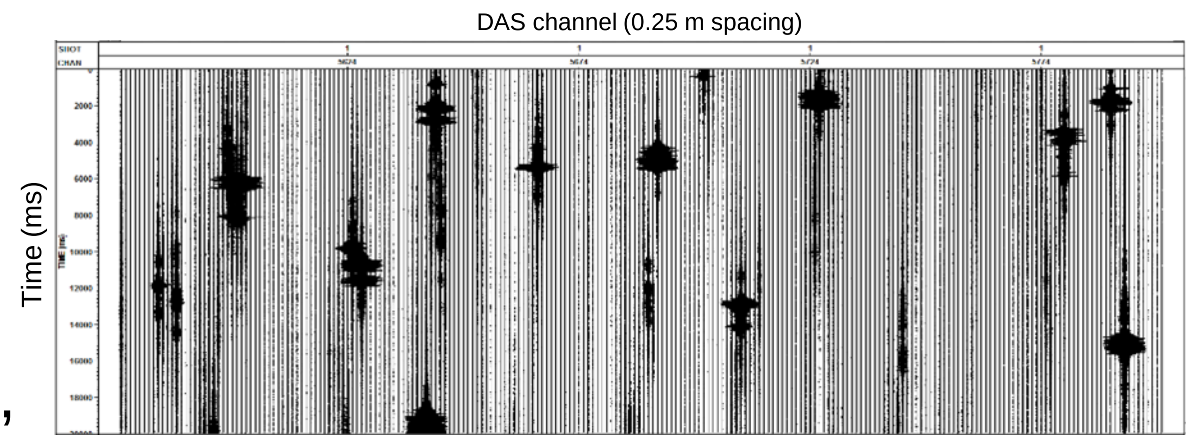
SL-mode source at 2021_3C

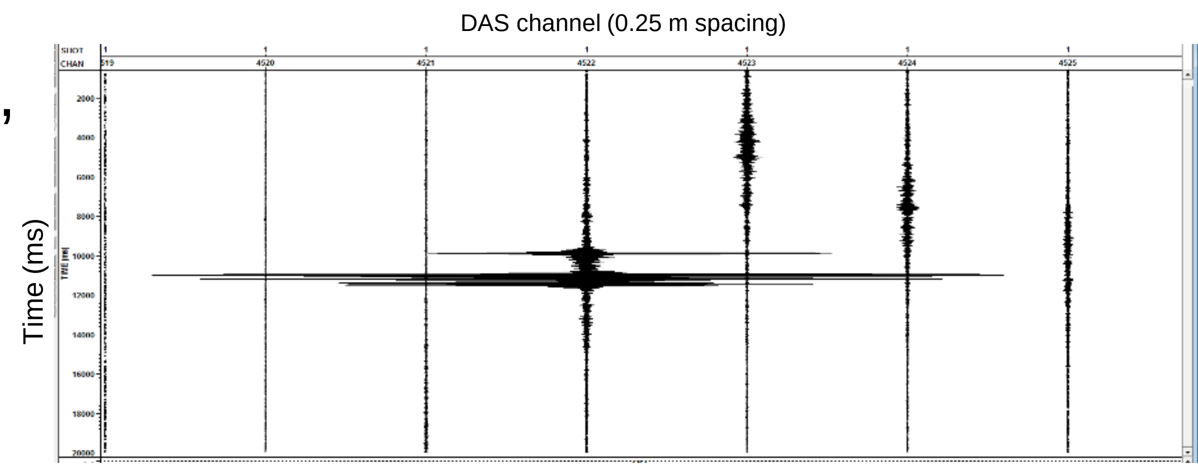


ST-mode source at 2021_3C

Non-acoustic Noise Bursts are Seen on Individual 0.25 m Channels in the Raw Data

Fiber data were recorded on a Silixa iDAS interrogator using 0.25 m spacing, 2kHz sample rate, triggered 20s records, and imaging the full fiber length.

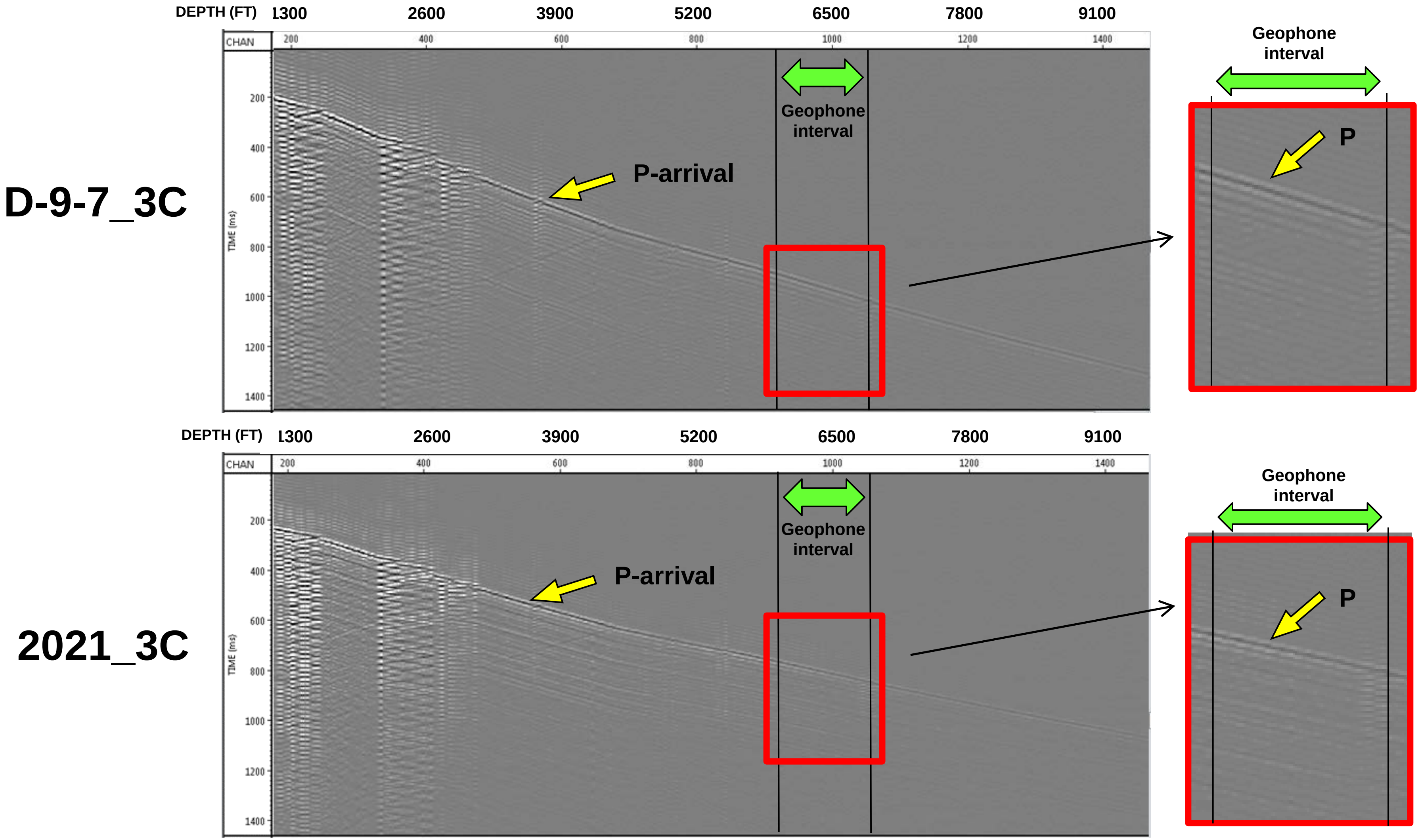




Six traces in the 20 s record showing one magnified noise burst

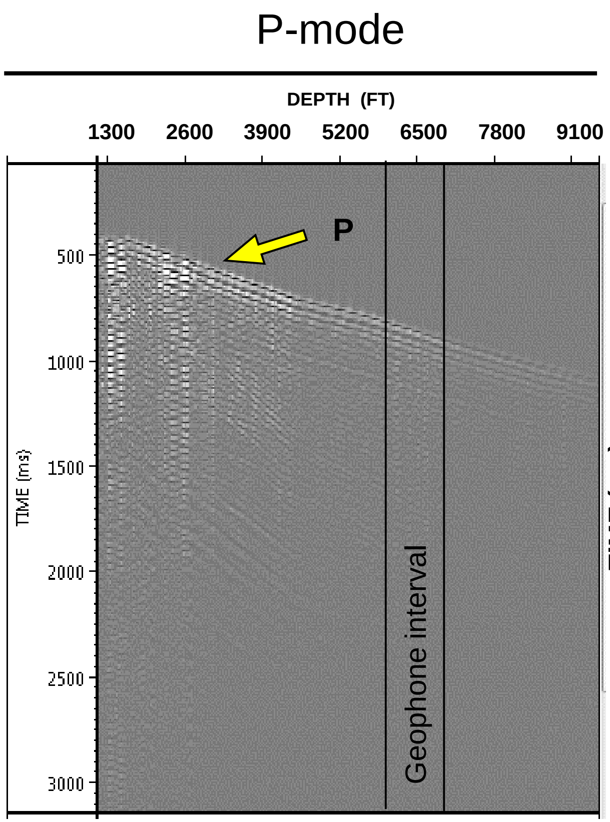
Processing of this data requires editing of noise bursts and weighted stacking

Correlated DAS data from P-mode Source Points after De-noising Pass in the Processing Flow

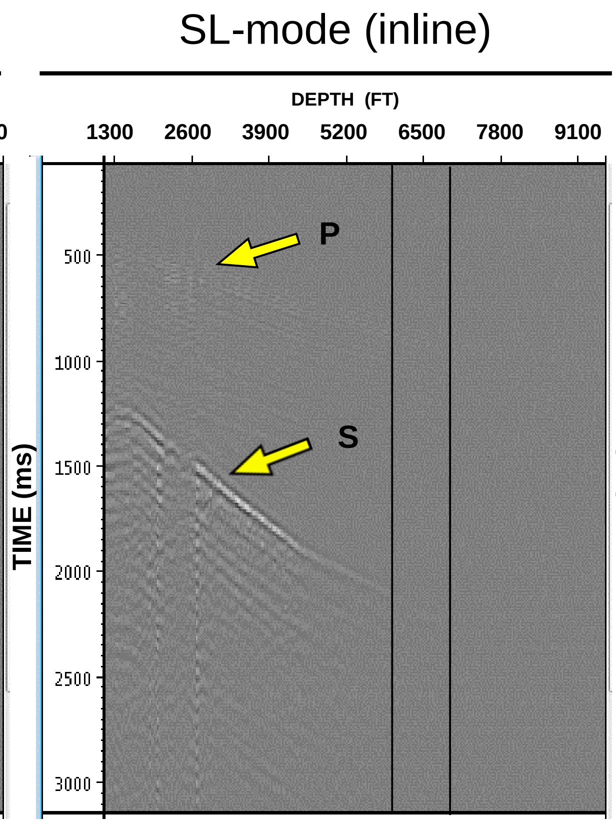


DAS traces are at 2 m spacing, stack of 32 sweeps, correlated with pilot trace.

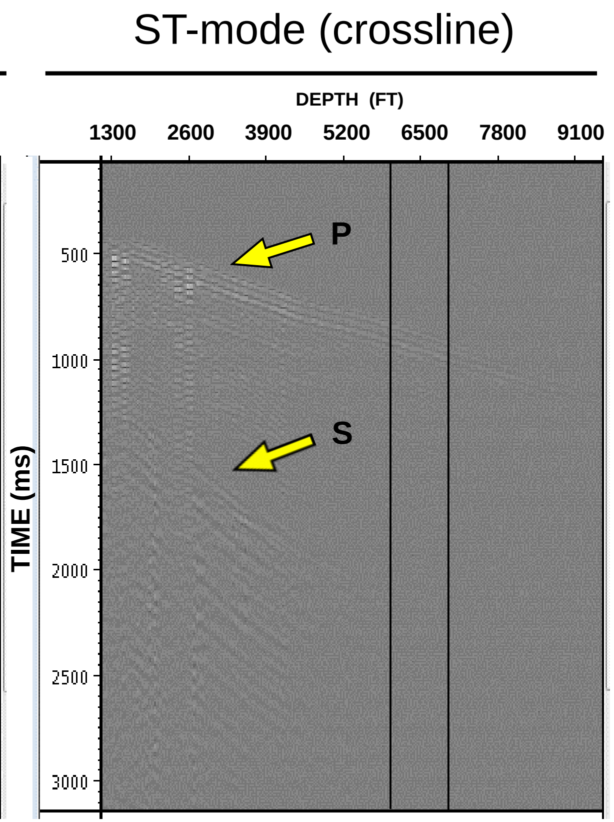
Shear-Source DAS data from Source Point D-9-6_3C after De-noising



strong P-arrival



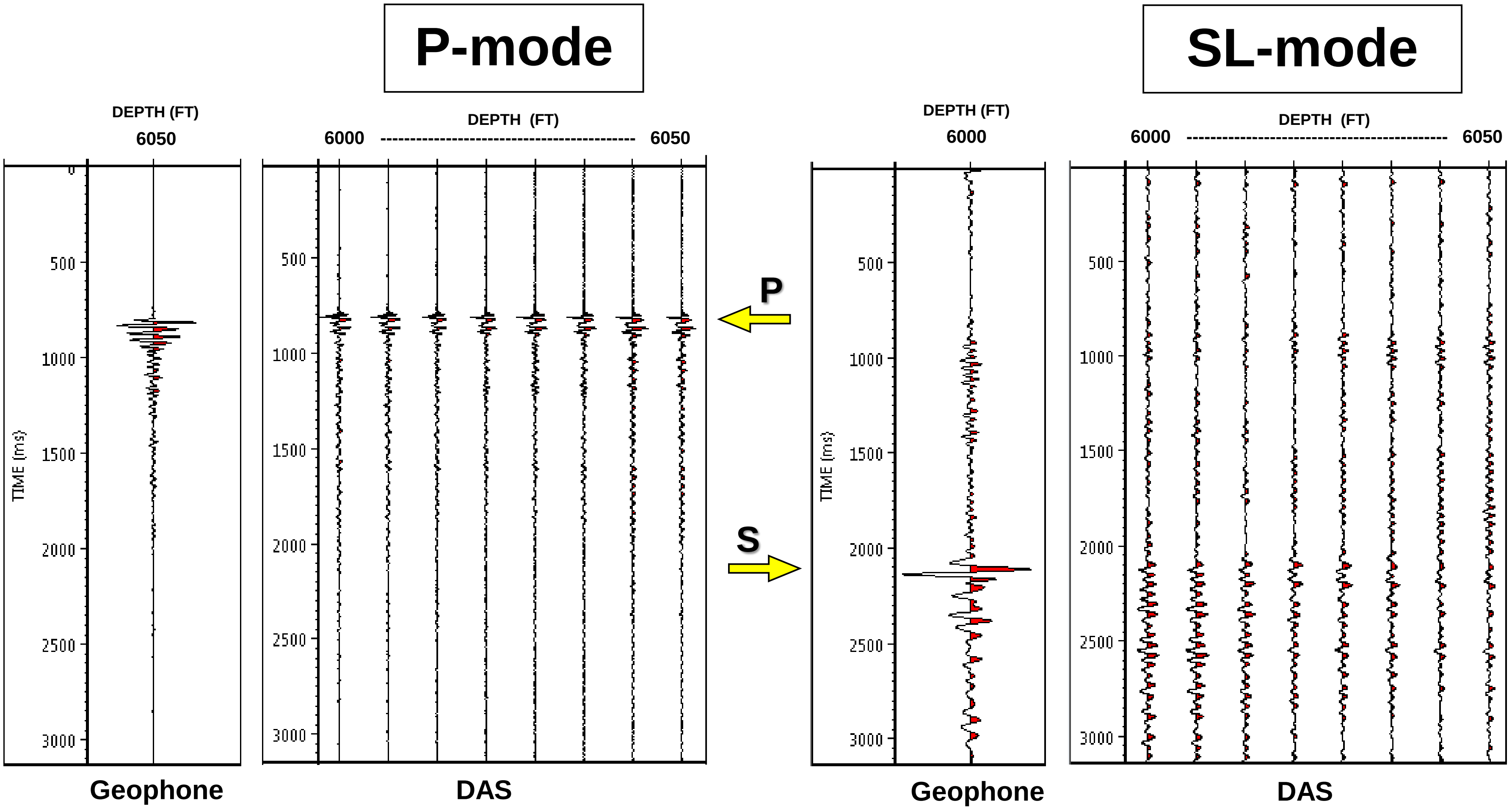
strong S-arrival to 6000ft, weak P-arrival



weak S-arrival, weak P-arrival

Traces are at 2 m spacing, stack of 32 sweeps, correlated with pilot trace. Geophone interval is from 6000 – 6800 ft.

Comparison of First Arrivals for Geophone vs. DAS at Source Point D-9-6_3C



DAS traces are at 2 m spacing, stack of 32 sweeps, correlated with pilot trace. No trace scaling applied.

Accomplishments to Date

- DAS was successfully used to acquire VSP data in time-lapse mode (2012-2014)
- Wave form acquired using stacked VSP-DAS provides good match with results from conventional geophones (2015)
- Daley et al. (2015) demonstrated geophone to DAS agreement in true units
- DAS data were too noisy to allow detection of seismic waves in the crosswell configuration (2015)
- DAS was successfully used to acquire P-, SL- and ST-wave first arrivals using a triaxial vibroseis source (2016)

Lessons Learned

- The fiber optic project has relied heavily on host sites for access to CO_2 wells for testing the DAS technology
- Our original DOE-funded host projects have been canceled or indefinitely delayed due to circumstances beyond our control

Field research plans need to flexible and readily adapt to unanticipated site conditions and site host changes/schedules

Synergy Opportunities

- Partnering with the Southeast Carbon Sequestration Partnership (SECARB), the CO_2 Capture Project (CCP) and the UT-Austin at the Anthropogenic Test at the Citronelle, Alabama provided an important testing ground for the DAS technology

Project Summary

Findings

- Fiber-optic based sensor arrays are innovative and robust
- DAS is a commercial-ready technology for monitoring CO_2 plume development in the VSP configuration
- Additional fiber development and testing is needed for DAS to be effective in the cross-well (broadside) configuration
- Good agreement between the geophone and DAS P- and S-wave first arrival times

Future Plans

- Complete processing of the shear-wave data
  - Compare geophone and DAS shear-wave forms
  - Data migration to produce final seismic image
- Possible move to the Containment and Monitoring Institute's (CaMI) Field Research Station in Alberta Canada
  - Focus will be on heat-pulse monitoring using DTS

Together…Shaping the Future of Electricity

Appendix

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

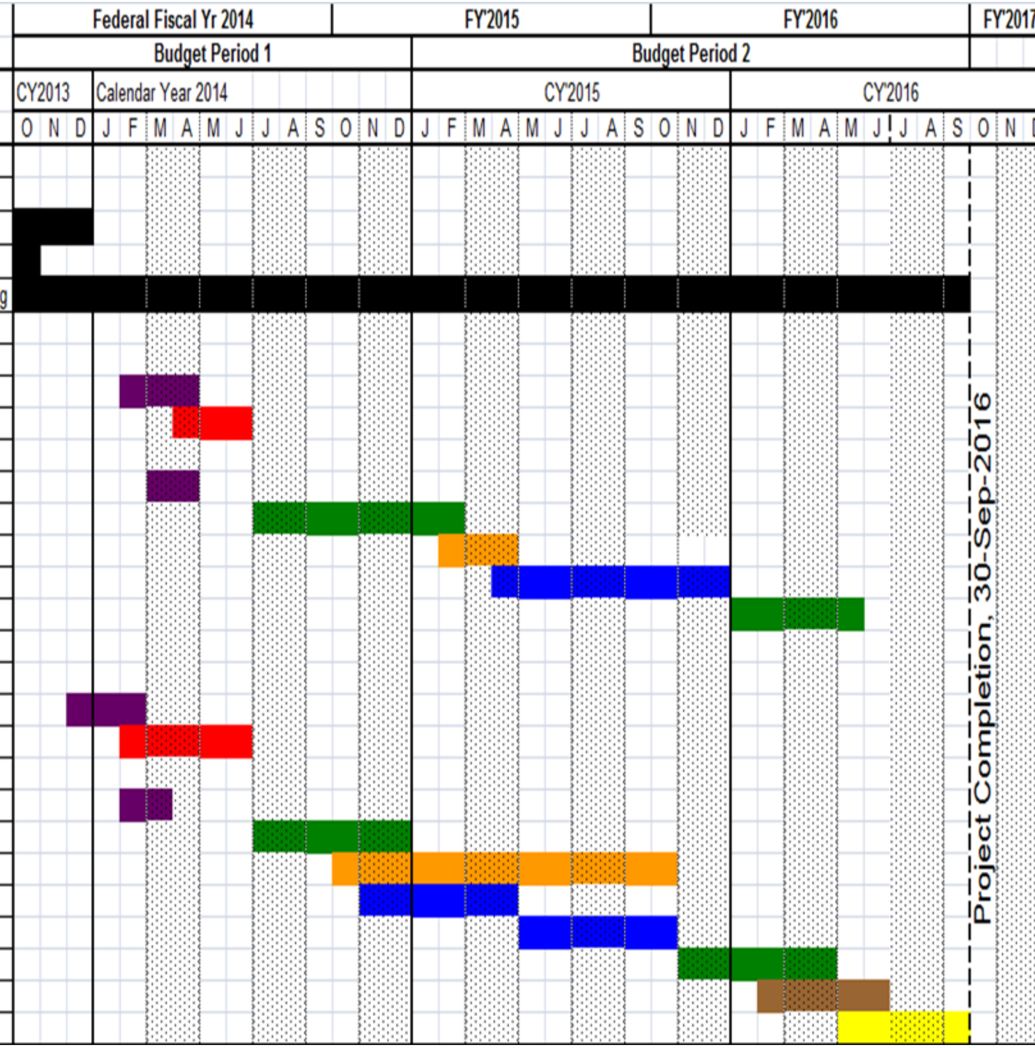
- **Overall objective**: Develop cost effective monitoring tools that can be used to demonstrate safe, permanent storage of carbon dioxide (CO_2) in deep geologic formations.
- **Specific objectives include**:
  - Make hi-res spatial measurements of the CO_2 plume using permanent distributed acoustic 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

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
- 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

- 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