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Geophysical Monitoring Using Active Seismic Techniques at the Citronelle Alabama CO_2 Storage Demonstration Site

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ABSTRACT

Between August 2012 and September 2014, about 114,000 metric tonnes of CO_2 was captured from the coal-fired Plant Barry Power Station at Bucks Alabama and injected into the Paluxy Formation above the oil pool in the southeast unit of the Citronelle Oilfield. Various monitoring methods were deployed at land surface and in project wells to measure system performance, comply with permit requirements and test new and innovative monitoring tools. The monitoring program relied heavily on active seismic methods for subsurface imaging of geologic structure and time-lapse seismic techniques to track the CO_2 migration in the injection interval. Both conventional geophone/hydrophone and fiber-optic based Distributed Acoustic Sensing (DAS) arrays were deployed and tested, allowing a side by side comparison of the equipment and techniques.

Geophysical imaging of the subsurface was successful using DAS in the offset vertical seismic profile (OVSP) survey configuration. A high resolution OVSP image of the subsurface was obtained in 2014 with DAS, which exceeded project expectations in comparison to a lower resolution image obtained in 2012 using a conventional 80-level geophone array. A time-lapse image of the redistribution of CO_2 after injection ended in September 2014 was obtained with two DAS OVSP surveys from June 2014 and December 2015, thus successfully demonstrating its proof-of-concept. Unfortunately, a pre-injection baseline survey with DAS, which was in its initial stage of technology development in 2012, did not have sufficient quality for use, making it difficult to interpret the acquired DAS time-lapse difference. Additional research in this area has since demonstrated the utility of time-lapse DAS OVSP. DAS data were also acquired during a cross-well seismic survey conducted in 2014. Unfortunately, the DAS technique was not success in the cross-well survey configuration because the system noise level was too high in the crosswell frequency output range (100–1,200 Hz) of the piezoelectric source (increasing by a factor of ten compared to VSP frequency band). Additionally, the cross-well geometry causes sub-horizontal (broadside) incidence on the vertical DAS fiber cable, which is known to be problematic. Current research is focused on improving the DAS cable response to broadside acoustic energy.

Time-lapse seismic surveys using commercially available conventional arrays were also acquired. In contrast to the DAS acquired data, the cross-well seismic results obtained with the conventional array was highly successful and clearly showed the CO_2 remained in zone at the end of injection. Time-lapse differencing of the OSVP surveys acquired with the conventional arrays proved to be inconclusive. Changes in wellbore conditions between surveys and unavoidable changes in equipment (the array used for the baseline survey was retired) affected data quality, making it difficult to interpret the OVSP results.

KEYWORDS

CO_2 Storage, CO_2 Monitoring, Borehole Geophysics, Distributed Acoustic Sensing

INTRODUCTION

The SECARB Anthropogenic Test was the first fully integrated carbon capture and storage (CCS) demonstration project in the United States (U.S.) on a coal-fired power station using advanced amines for capture (Koperna, et al., 2013). Funded by the U.S. Department of Energy (DOE), Southern Company, and the Electric Power Research Institute (EPRI), the research project demonstrated the feasibility of capturing CO_2 emissions from the James M. Barry Electric Generating Plant in Bucks, Alabama, owned by Alabama Power Company (**Figure 1**). The CO_2 was safely transported 12 miles (19 km) via pipeline to the Citronelle Oilfield, where the CO_2 was injected (Esposito, et al., 2013). The amount of CO_2 captured was equivalent to the emissions produced when generating 25 megawatts of electricity, or about 550 metric tonnes of CO_2 per day (tCO_2/d). CO_2 injection started in August 2012 and ended in early September 2014 after injecting 114,104 tCO_2. Injection was intermittent because Alabama Power Company shut down the coal-fired units during the winter months when the demand for electricity was low.

Figure 1. Study location showing the CO_2 capture facility at Plant Barry and Storage site at Citronelle Oilfield, Alabama (color figure).

The Citronelle Oilfield is contained within a large, gently dipping, salt-cored anticline that has four-way closure, making it ideal for commercial-scale CO_2 storage (Esposito et al., 2008). CO_2 was injected into eight sand layers within the Paluxy Formation at depths ranging from 9,436 to 9,800 ft (2,876–2,987 m), which stratigraphically lies about 3,000 ft (900 m) above the oil producing zone. The Paluxy Formation was deposited during the Lower Cretaceous Period and consists of alternating shale/mudstone and high permeability, high porosity sandstone containing high salinity brine. Lying above the Paluxy Formation is the basal shale of the Washita-Fredericksburg Group, which forms the primary seal containing the CO_2, and the 1,000 ft (305 m) thick Selma Chalk, which provides a secondary seal.

Two Class V Experimental Injection Wells, designated D9-7#2 and D9-9#2, and one observation well D9-8#2 (**Figure 2**) were drilled by SECARB at existing drill pads where former oil wells were once located (now plugged and abandoned). The D9-7#2 served as the project's primary CO_2 injection well and D9-9#2 was drilled for additional injection capacity, which was never needed.

SECARB developed a robust monitoring, verification, and accounting (MVA) program as part of the Underground Injection Well (UIC) permits to track the CO_2 plume (Koperna, et al., 2014). This included multiple time-lapse seismic surveys designed to image the CO_2 as it migrated through the Paluxy Formation. SECARB originally proposed conducting seismic surveys using commercial vendors to acquire the data. Seismic surveys acquired with DAS were added to the original MVA program and accepted by state regulator as a legitimate research need, thus justifying issuance of the UIC Class V "experimental well" permit. Time-lapse differencing of the pre- (baseline) and post-CO_2 injection surveys were planned to observe changes in acoustic impedance associated with CO_2 migration in the subsurface (and the associated pore-fluid substitution of CO_2 for brine).

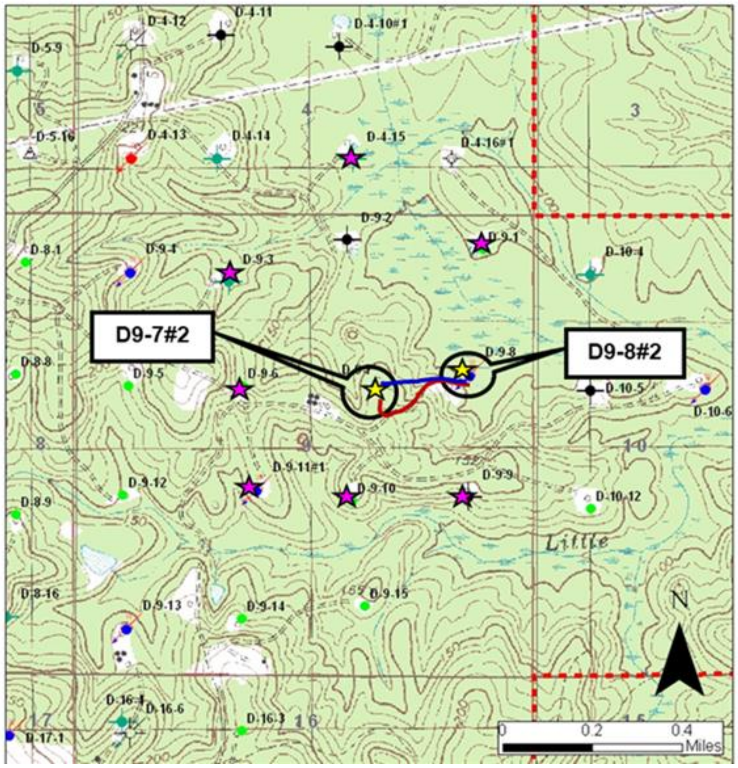

Figure 2. Topographic map showing the location of the primary injection well (D9-7#2), observation well (D9-8#2), offset shot points (magenta stars), receiver arrays (yellow stars), and walk-away transects (blue and red curves). (color figure)

Shell Canada reportedly performed the first downhole DAS field trial in 2009 to assess its application in the oil and gas industry to monitor hydraulic fracture performance (Molenaar et al., 2011, Kimbell, 2013). A field trial of the DAS technology was initiated soon there-after in April 2012 at the SECARB Anthropogenic Test site to determine the efficacy of using DAS to monitor the performance of CO_2 injection projects. Since 2012, the DAS technology has undergone considerable testing and refinement related to CO_2 monitoring at the SECARB site, CO2CRC Otway Project in Australia (Dou et al, 2016; Yavuz et al., 2019), Ketzin pilot site in Germany (Götz et al, 2018) and AquiStore Project in Saskatchewan, Canada (Harris et al., 2016) to name a few. This paper summarizes the seismic methods used and survey results obtained at the SECARB site, thus providing future CCS project developers with valuable lessons learned.

1.0 MATERIALS - Seismic Survey Equipment

The survey equipment included a combination of borehole geophone/hydrophone arrays, fiber optic distributed acoustic sensors (DAS), data acquisition equipment and vibroseis and piezoelectric sources.

1.1 Conventional Geophone/Hydrophone Arrays

Commercially available geophone/hydrophone arrays were used to acquire conventional survey data. Schlumberger (SLB) supplied a 10-level hydrophone array for the cross-well surveys and SR2020 provided two 80-level analog geophone arrays for the offset vertical seismic profile surveys described in the paper. The hydrophone spacing was 10 ft (3 m) and the two 80-level geophone arrays had 25 to 50 ft spacing between sensors. Compared to shorter commercial arrays, the 80-level array allowed for fast data acquisition and interleaving but took longer to deploy in the well. The 80-level arrays were only used for the pre-CO_2 injection baseline survey because SR2020 sold the business and retired the arrays before the final post-CO_2 injection survey was performed. OptaSense performed the final survey using a Weatherford digital 2-level array and fewer data points were acquired over the same depth range as the baseline survey. The conventional arrays were temporarily deployed in the wells and removed after completing each survey.

1.2 Modular Borehole Monitoring (MBM) System

The project installed a tubing deployed modular borehole monitoring (MBM) system, a novel integrated monitoring design described by Freifeld et al., (2014) and Daley, et al, (2015). The fiber optic cables in the MBM were then used as a field trial for testing fiber optic (FO) distributed sensor arrays. Compared to the temporary deployment of the conventional arrays, the MBM system was semi-permanently installed in observation well (D9-8#2) offset from the primary injection well (D9-7#2) by approximately 850 ft (259 m) at land surface (**Figure 2**).

The FO monitoring cable contained two high-temperature acrylate single mode fibers for subsurface seismic imaging using distributed acoustic sensing (DAS) and distributed temperature sensing (DTS). (Refer to Freifeld et al, 2015a and 2015b for more information on DTS monitoring). The fibers were installed from land surface 0 ft (0 m) to a depth of approximately 9,800 ft (2,987 m), which by design spanned the Washita-Fredericksburg confining unit, the top and upper section of the Paluxy Formation, and the entire perforated CO_2 injection interval. Silixa's intelligent Distributed Acoustic Sensor (iDAS™) was used to digitally record both the amplitude and phase of the acoustic field at sampling rates up to 10 kilohertz (kHz). While DAS systems have fundamentally different physics than conventional geophones (e.g. Daley, et al, 2015), the system specifications provide nominal one-meter spatial resolution with a wide dynamic range of more than 90 dB with no cross-talk.

A semi-permanent 18-level geophone array was also incorporated into the MBM system, initially as the primary seismic monitoring system, and then as a means of checking the performance and sensitivity of the DAS array. Geophones were selected for the final design (rather than hydrophones) based on lower overall cost, and ability to limit tube-wave noise (clamped sensors have lower tube-wave amplitude than fluid coupled sensors, White, 2000). The clamped geophone array contained fifteen, 1-component (i.e., vertical) geophones and three, 3-component geophones, giving a total of 18 geophone pods. The 3-component geophones were placed at the top, bottom and middle of the array. A spacing of 50 ft (15.24 m) was chosen between pods, which were identical for both the vertical and 3-componenet geophones. The geophone array spanned the interval 6,000–6,850 ft (1,829–2,088 m) below ground level. The use of geophones required positive mechanical coupling to the cemented casing, and thus needed a novel clamping system, described in Daley, et al, 2015.

1.3 Acoustic Sources

Several vibroseis trucks were used during the study to generate the acoustic energy recorded with conventional receivers, DAS, and the MBM 18-level geophone array. The vibroseis units ranged in output from 24,000 to 65,000-pound force (lbf; 107 to 289 kilonewtons; kN) and, except for one survey (see Appendix A), generated 10 to 160 Hz compression (p-) waves. A 60,000 lbf (267 kN) triaxial source named T-Rex, owned and operated by The University of Texas—Austin, was used during the final DAS survey in December 2015. While it would be ideal to use the same source for all time-lapse monitoring surveys (as well as the same sensors), financial and other factors necessitated the use of varying sources. A commercial downhole piezoelectric vibratory source with 100–1,200 Hz output was used for the cross-well surveys.

2.0 METHODS - Seismic Survey Configurations

Two types of seismic survey configurations were used to monitor CO_2 migration in the subsurface, including time-lapse Offset Vertical Seismic Profile (OVSP) and cross-well surveys. The operational goal was to use periodic lower cost surveys with the MBM system to limit the use of expensive surveys with the commercial geophone arrays. **Appendix A** provides a summary of the cross-well and VSP surveys performed using conventional receivers provided by SLB and SR2020, and 18-level geophone receivers and DAS array deployed in well D9-8#2 as part of the MBM system.

2.1 Zero and Offset VSP Surveys

Only one conventional pre-injection (baseline) and one post-CO_2 injection OVSP survey were planned and performed by SECARB because of high cost. The baseline OVSP survey was performed in February 2012, prior to CO_2 injection, using the 80-level geophone arrays deployed in D9-7#2 and D9-8#2 covering a 2,000 ft (610 m) aperture. The locations shown with magenta-colored stars on **Figure 2** are the offset shot points where the vibroseis trucks were positioned. The D9-7#2 and D9-8#2 well pads also served as zero-offset shot point locations (yellow stars). The far-offset shot points were arranged around the D9-7#2 injection well to provide azimuthal coverage for optimum CO_2 detection in all directions surrounding the center injection point. Table 1 provides a summary of the approximate distance from the offset shot points to the two receiver wells.

Table 1. Approximate horizontal distance from the receiver wells (D9-7#2 and D9-8#2) to the far offset shot points measured at land surface.

Well Designation	Distance to Injection Well D9-7#2, ft (m)*	Distance to Observation Well D9-8#2, ft (m)*
D9-7#2	0 (0)	850 (259)
D9-8#2	850 (259)	0 (0)
D9-9#2	1,835 (559)	1,390 (424)
D9-10	1,170 (357)	1,575 (480)
D9-11	1,675 (511)	2,390 (728)
D9-6	1,550 (472)	2,400 (732)
D9-3	2,175 (663)	2,900 (884)
D4-15	2,925 (892)	3,105 (946)
D9-1	2,175 (663)	1,810 (552)

*Distances are reported to the nearest 5-foot increment and then converted and reported to the closest 1 meter.

A two-level digital geophone sensor array was used in 2017 for the final post-injection OVSP survey. The well operator had to “kill” the CO_2 injection well with a heavy drilling mud before the well could be entered safely. In addition, a pressure control lubricator was used with the two-level array to guard against an unexpected CO_2 blowout. A similar lubricator could not have been used for the 80-level array had the array been available due to the length of the longer array (about 2,000 ft (610 m)).

After the baseline surveys were conducted, observation well D9-8#2 was completed with the Modular Borehole Monitoring (MBM) system described above. A limited baseline OVSP survey was attempted in April 2012 with DAS equipment as an early proof-of-concept to determine how well the DAS system would perform. This survey was one of the first publicly reported DAS surveys. Unfortunately, synchronization problems with the vibroseis source made the results difficult to interpret, and four vibroseis sweeps per shot point proved to be insufficient energy for the first-generation DAS system.. Nonetheless, the observation of seismic waves (tube-waves) did encourage the further testing and development of DAS (Daley, et al, 2013).

2.2 Walk-Away OVSP Surveys

Given the fact that the conventional OVSP surveys were limited to only two snap shots of the CO_2 plume in time (i.e., 2012 pre- and 2017 post-CO_2 injection surveys) covering a 2-year injection period, it was decided to perform walk-away (WAW) OVSP surveys at intermediate times using the DAS and MBM geophone arrays to help lower the overall cost of seismic monitoring. The semi-permanent DAS and MBM geophone arrays deployed in the observation well eliminated the added cost and risk of pulling the packer and production tubing to deploy the 80-level geophone array used by SR2020. The cost savings came from not having to workover the well to remove and reinstall equipment each time a survey was performed.

SECARB conducted two walk-away transects shown by the red and blue curves connecting wells D9-8#2 and D9-7#2 in **Figure 2**. After the initial walk-away survey, the “blue” transect (most direct route between the wells) was abandoned because a steep hill and no road created a safety hazard for the vibroseis operator, especially during wet weather conditions. The more circuitous “red” transect was adopted because it follows an existing oil-field lease road. Up to 70 shot points along this transect could be performed in a single day. WAW surveys were conducted every 6–12 months to provide greater time-lapse coverage and each survey took only one day to acquire.

2.3 Cross-Well Seismic Surveys

Cross-well surveys were performed by deploying the piezoelectric source in the D9-7#2 injection well and the hydrophone receiver array inside the tubing in the D9-8#2 observation well (**Figure 2**) along-side the DAS cable. SLB performed the baseline cross-well seismic survey in February 2012 prior to CO_2 injection by deploying the source and hydrophones in the open wells. Delivery of the 18-level geophone array was delayed preventing the MBM system from being installed until late March; therefore, no baseline pre-CO_2 injection cross-well surveys were attempted with MBM geophones or DAS.

Schlumberger performed a second repeat cross-well survey in June 2014, after approximately 100,000 tCO_2 had been injected by SECARB and only two months prior to stopping CO_2 injection in September 2014. The CO_2 injection well was killed for the survey with a dense drilling mud for safety reasons, the injection tubing removed, and the piezoelectric source was deployed in the open well. The hydrophones were deployed inside the production tubing in the observation well using a pressure control lubricator. SECARB also recorded the 2014 cross-well survey with the DAS system. The DAS survey was completed in one day compared to the hydrophone survey that required five days to complete. The 10-level hydrophone array had to be moved multiple times in the observation well for each shot point in the injection well to cover the depth range (approximately 8,160–10,500 ft; 2,487–3,200 m). In comparison, only the source had to be moved for the DAS survey, thus significantly reducing the data acquisition time.

3.0 SURVEY RESULTS

3.1 Time Lapse Cross-Well Survey Results

In June 2014, Silixa LLC acquired DAS data at the same time that Schlumberger (SLB) acquired cross-well survey data from the SLB high-frequency piezoelectric seismic source. Silixa’s iDAS™ optical interrogator recorded the full set of 26 cross-well fans generated from the piezo-source in injection well D9-7#2.

Silixa transferred a small sample of the cross-well data to team member Lawrence Berkeley National Laboratory for initial processing. The initial data set included uncorrelated sweeps recorded on the DAS in the observation well from two shot points including 9,000 and 9,340 ft (2,743 and 2,846 m); 128 sweeps were acquired at each depth. The deepest shot point lies approximately 60 ft (18 m) above the top of the Paluxy Formation at a depth of 9,400 ft (2,865 m). The data were acquired at 0.82 ft (0.25 m) spatial resolution and 0.25 ms sample rates.

An example of the DAS cross-well data, correlated with a synthetic sweep, is shown in **Figure 3**. Unfortunately, the correlated sweep data show no evidence of first arrivals, only coherent and random noise, suggesting that the acquired seismic data from this interval represents random noise. The coherent noise shown on **Figure 3** has no moveout and delayed arrival time (~30 ms versus the expected ~5-10 ms) and, therefore, is considered some type of DAS system noise such as interrogator vibration, which has coherent correlation with our sweep over multiple channels.

To investigate evidence for useful data in the uncorrelated records, a spectral analysis was performed on one of the two data sets and then compared to a synthetic spectrum generated using the same parameters used for the actual sweep (100 to 1200 Hz, linear, 2.6 s). **Figure 4 (top)** shows the expected spectral response from the synthetic sweep. We are looking for evidence of signal above noise in some part of the sweep spectrum within the field data. The synthetic spectrum shows a relatively flat response of -5 dB from ~200 Hz to ~1200 Hz. In comparison, the spectral response for a stack of 200 uncorrelated DAS field recordings collected at the 9,340 ft (2,847 m) depth (**Figure 4, bottom**) show that data noise is too large in the sweep bandwidth to allow detection of seismic waves. The noise is increasing with frequency from 10 to 1,000 Hz by a factor of about 20 dB, and is then level to about 2,000 Hz. In general, DAS noise is expected to increase linearly with frequency due to integration of raw strain measurement to strain-rate output (Daley, et al, 2015), which makes high-frequency crosswell data more problematic. Additionally, the directional sensitivity of DAS data is not optimal for most crosswell geometries. Despite this initial negative result, the use of DAS cables for cross-well monitoring remains a research goal because of the potential for greatly reduced acquisition time and cost.

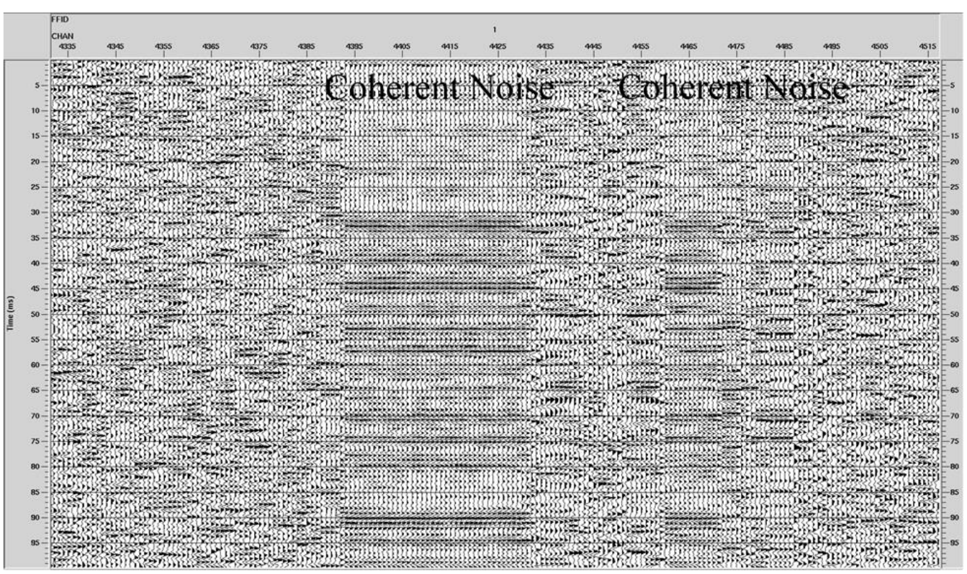

Figure 3. Correlated DAS data collected from 9,340 ft (2,847 m). Channels labeled 'coherent noise' have no moveout and non-physical arrival times. (black & white)

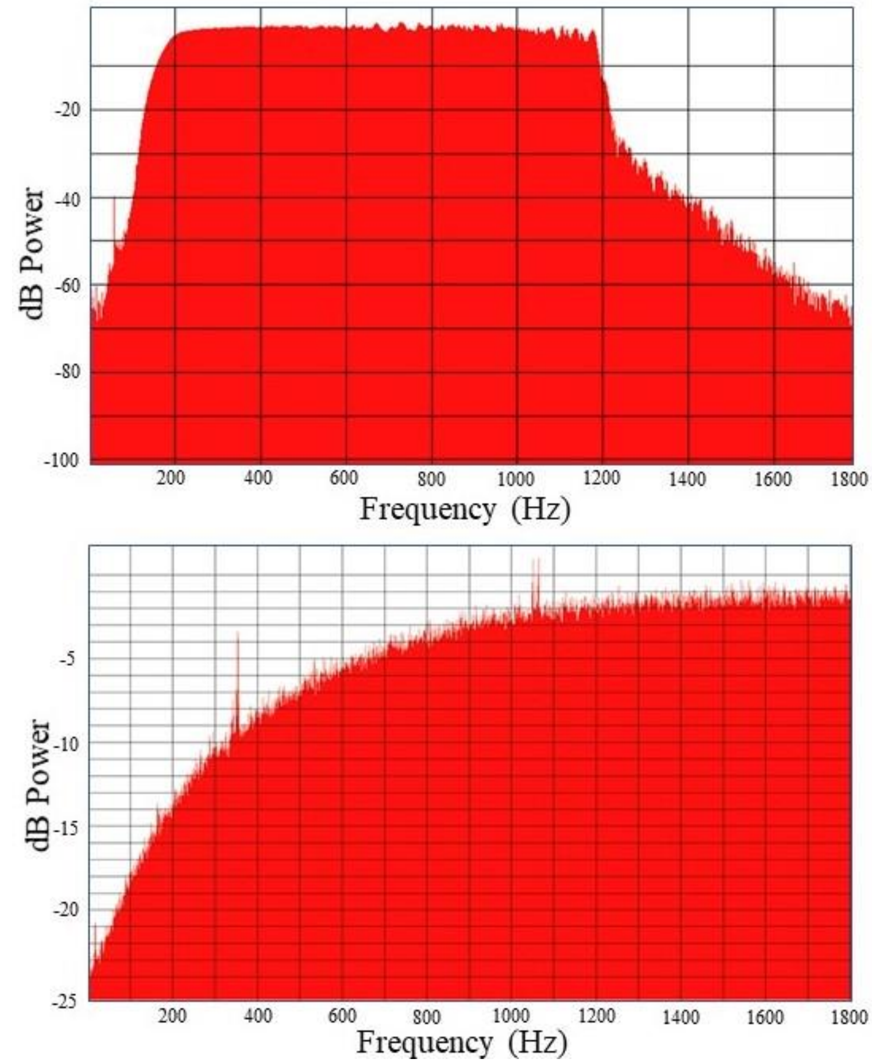

Figure 4. (Top) Synthetic power spectrum generated with actual sweep parameters and (Bottom) raw power spectra for the acquired DAS data (200 traces recorded over 164 ft (50 m) of cable stacked together). Note difference in vertical scales. (black & white)

SLB also acquired cross-well data in February 2012 (baseline) and June 2014 (repeat) survey using the piezoelectric source and borehole hydrophones deployed in the injection/production tubing. **Figure 5** shows the resulting combination of velocity tomograms from the first arrivals and migrated reflection images for the two surveys. Strong reflections were observed during the baseline survey but not during the repeat survey likely caused by signal attenuation from the stiffness of the injection/production tubing. The well completion had changed between baseline and repeat, as the baseline survey was performed in the cased well without tubing. Although the reflections from the repeat survey were weak, time-lapse differencing of the velocity tomograms (based on first arrivals, not reflections) from the two hydrophones surveys was successful, providing an approximate image of the CO_2 plume (**Figure 6**).

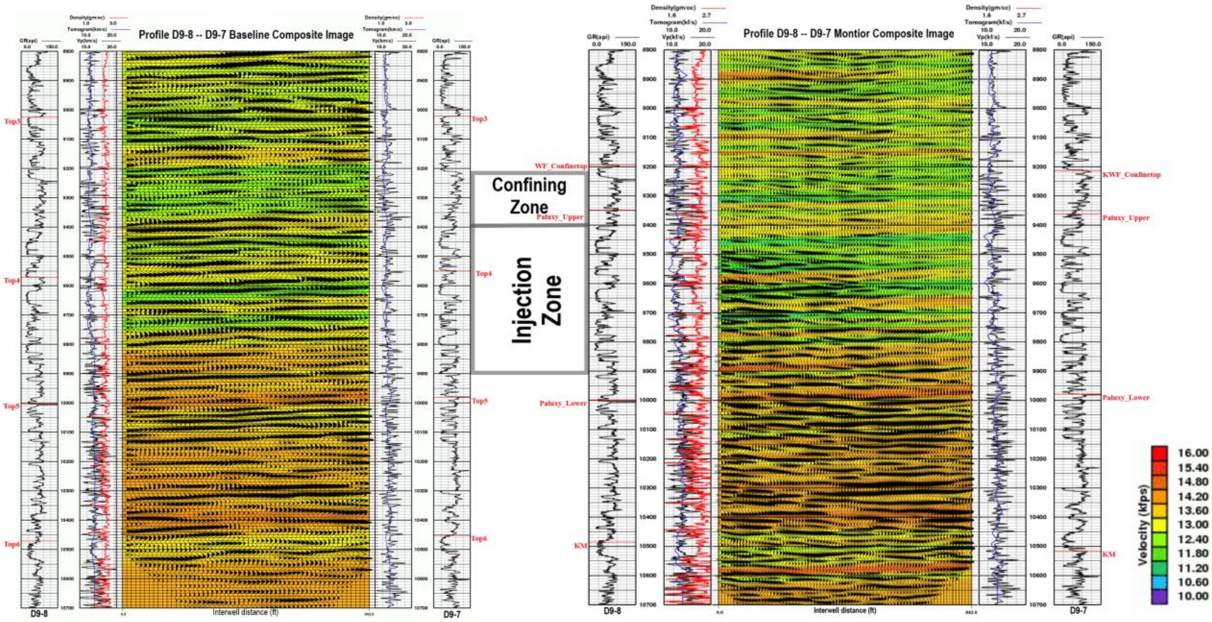

Figure 5. 2012 baseline (left) and June 2014 (right) cross-well velocity tomograms acquired with conventional hydrophone receivers. The observation and injection well are shown on the left and right side of each image, respectively. (color figure)

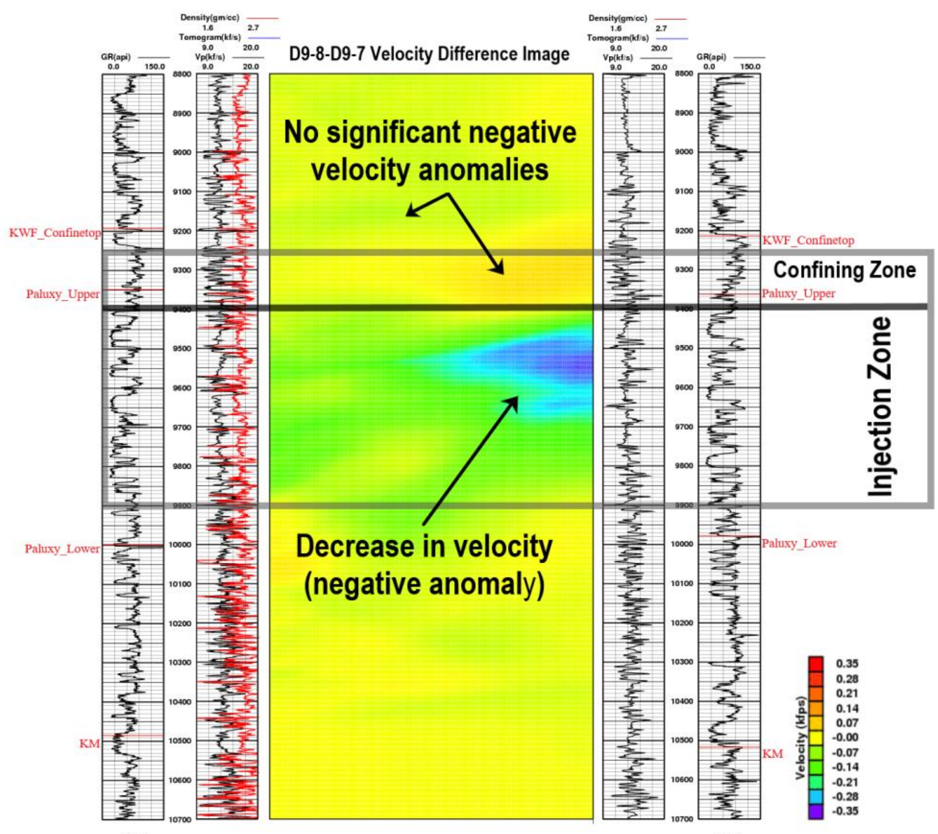

Figure 6. Time-lapse velocity difference from the conventional survey showing a velocity anomaly corresponding to the approximate location of the CO_2 plume in June 2014. (color figure)

In conclusion, the DAS data cross-well noise was too large in the sweep bandwidth to allow detection of seismic waves from the DAS cross-well survey. This result is understandable due to the noise characteristics of current DAS acquisition. DAS system noise is approximately linearly increasing with frequency from 10 to 1,000 Hz, by a factor of about 10, and then is level to about 2,000 Hz. The cross-well source was higher frequency (100–1,200 Hz) than the OVSP sources (10–160 Hz), and therefore required much higher signal levels (or greater noise reduction). Attempts to investigate 'true' ground motion signal levels and acoustic noise levels from SLB hydrophone data for comparison to DAS data, and thus to allow calculation of the number of sweeps required to overcome the noise, were unsuccessful due to lack of true ground motion calibration available for the SLB hydrophone recordings.

3.2 DAS WAW Survey Results—April 2012 and August 2013

The initial DAS data acquisition using the single-mode fiber deployed as part of the MBM system in the D9-8#2 observation well occurred in April 2012 and is described by Daley *et al.*, 2013. The survey consisted of a walk away OVSP (**Figure 7)** recorded with an early version of the Silixa iDAS™ optical interrogator paired with a 35,000-lbf vibroseis source. The initial survey results were somewhat disappointing in that, although the DAS was found to record seismic energy, there was insufficient signal-to-noise ratio (SNR) to observe p-waves below approximately 1,600 m (**Figure 8, upper inset in right image labeled 2012**). In contrast, p-wave energy was easily detected by the MBM geophones at 6,000 ft (1.8 km) to 7,000 ft (2.1 km).

Results from this initial April 2012 test were sufficiently successful to move forward with improving the data acquisition plan for a second field campaign. The second DAS survey described by Daley et al., 2015 occurred in August 2013 and involved a rigorous source effort. The goal was to determine the number of sweeps needed to obtain signal-to-noise ratios comparable to those obtained with the MBM geophone data. The primary focus for testing was on source location SP2021 (**Figure 7**). The maximum number of sweeps at each shot point was determined in the field, based on near real-time analysis of stacked data, which was not possible during the 2012 survey. Testing also involved modifying the iDAS™ optical interrogator settings, requiring 280 total sweeps at SP 2021 alone.

Improvements in noise reduction and data processing techniques with an increased number of sweeps per source point resulted in significantly improved SNR for the August 2013 survey, with first-arrival energy observable along the full length of the borehole fiber (**Figure 8**). The very high-quality data obtained in this survey was a breakthrough in demonstrating the utility of DAS OVSP acquisition.

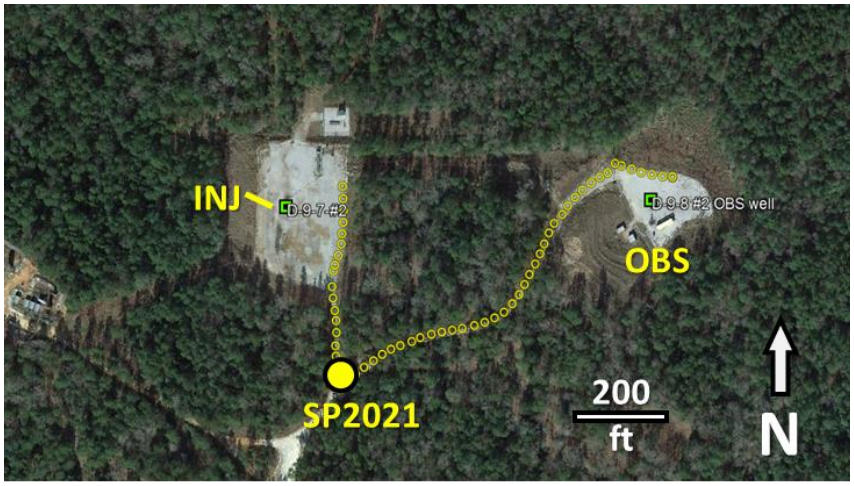

Figure 7. Map view of the D9-8 #2 observation well, D9-7 #2 injection well (green squares), and source points (yellow circles) from the April 2012 walkaway OVSP survey. DAS and geophone data from source point SP2021 (yellow dot) are shown in Figure 8. (color figure)

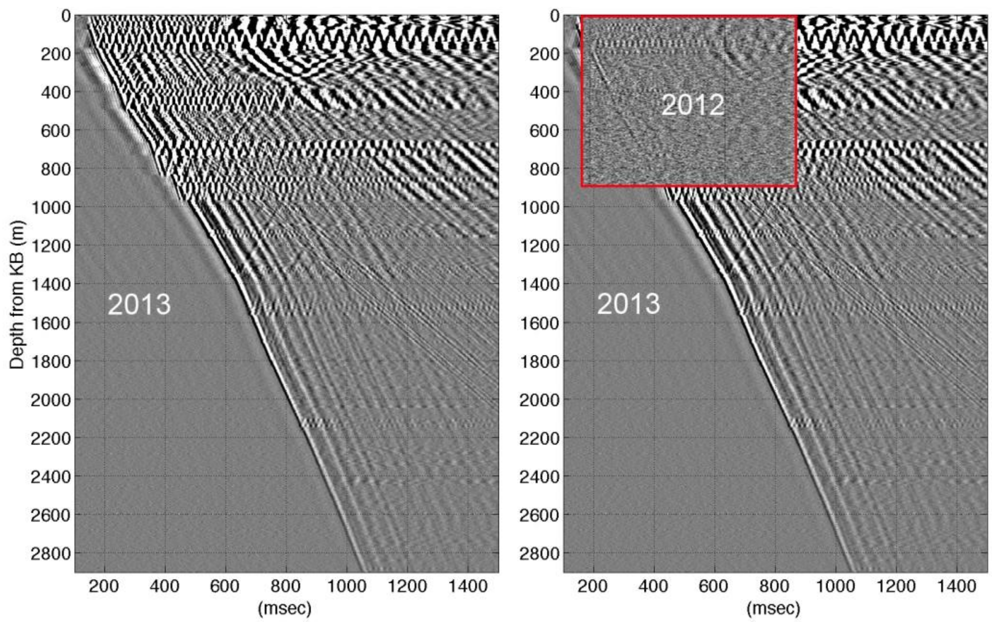

Figure 8. DAS results from vibroseis source station SP2021 offset approximately 700 ft (213 m) from the D9-8#2 observation well. The base image is from the August 2013 DAS survey, resulting from stacking 16 sweeps with denoising showing clear first arrivals along the full length of the fiber (from Daley et al., 2015 and Daley 2015). Top inset in right figure is from the April 2012 DAS survey, resulting from stacking only four sweeps. While the signal-to-noise ratio levels are low, Daley et al. (2013) determined that two arrivals were visible in the 2012 image. The 2012 results were encouraging, which led to improvements in DAS data acquisition and processing methods, reflected by the better quality 2013 image.

3.3 Time-Lapse OVSP Survey Results

3.3.1 June 2014 OVSP Survey

In June 2014, DAS data were recorded from a zero offset and seven far offset VSP source points centered on observation well D9-8#2 (**Figure 2**). Collection of the zero and far offset data allowed for acquisition of a baseline survey for a subsequent time-lapse OVSP. The data from shot point D9-6 are highlighted herein, which is approximately 1,550 ft (472 m) from injection well D9-7#2 (**Figure 9**). Shot point D9-6 represents the location most likely to result in the detection of the top of the CO_2 injection zone with the DAS fibers installed in D9-8#2. The data were depth corrected, correlated and noise suppressed. The noise suppression was done with a Silixa designed diversity filter which exploited the physics of DAS acquisition.

Figure 9. Physical location of the far offset shot point D9-6 (left) relative to the injection well D9-7#2 (center) and the DAS array in D9-8#2 (right). (color figure)

The zero offset VSP and a far offset VSP were processed to investigate the ability of DAS technology to identify a velocity anomaly associated with the CO_2. The zero offset VSP from well D9-8#2 suffered from tube wave noise, however, the data were useful in producing a velocity model for subsequent processing of the offset shot point data. Ray tracing was used to verify the velocity model by comparing model predictions to actual first break arrival times.

The OVSP data did not suffer from tube wave noise. **Figure 10** shows the depth-migrated reflections for shot point D9-6 acquired with the DAS system. The image quality is good. Processed results of the far-offset VSP show a clear reflection response from the top of the Selma Chalk, Tuscaloosa Marine Shale, and the zones where CO_2 was injected at depths ranging from 9,436–9,800 ft (2,876–2,987 m). Compared to the baseline VSP survey performed in 2012 using the 80-level geophone array (**Figure 11**) and shot point D9-7#2, the DAS image has reasonably comparable resolution. This was an encouraging result because it showed that DAS had the resolution needed to potentially image CO_2 in the subsurface.

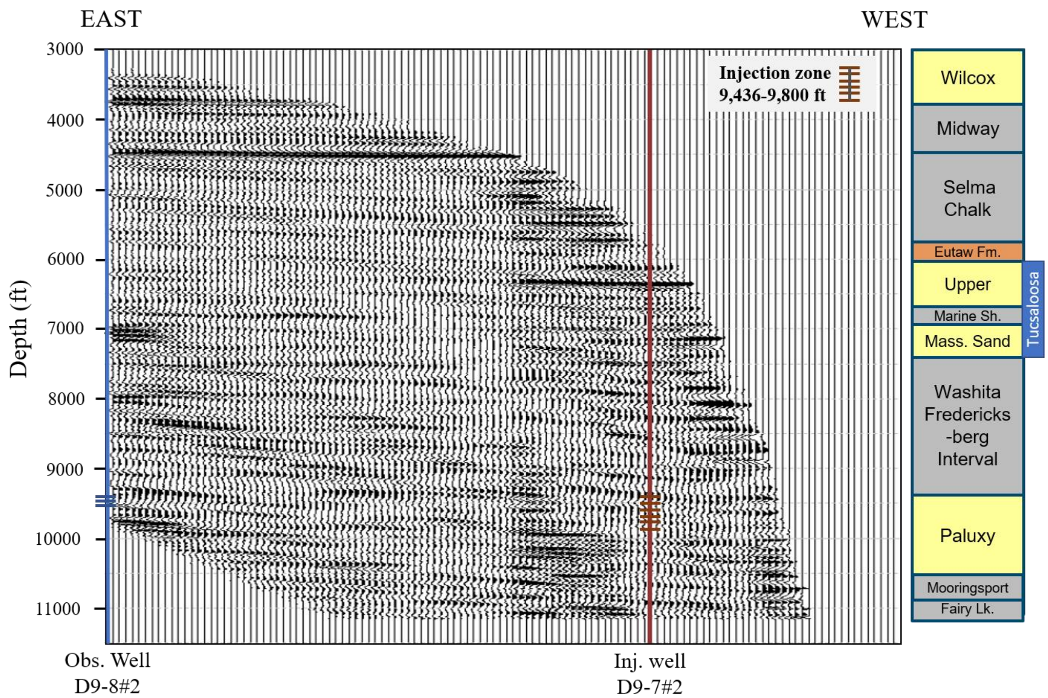

Figure 10. Depth migrated image showing the reflections for shot point D9-6 recorded with DAS deployed in observation well D9-8#2. 2014 CO_2-injection survey. In general, the DAS resolution compares favorably to the 2012 conventional baseline OVSP survey shown in Figure 11. (color figure)

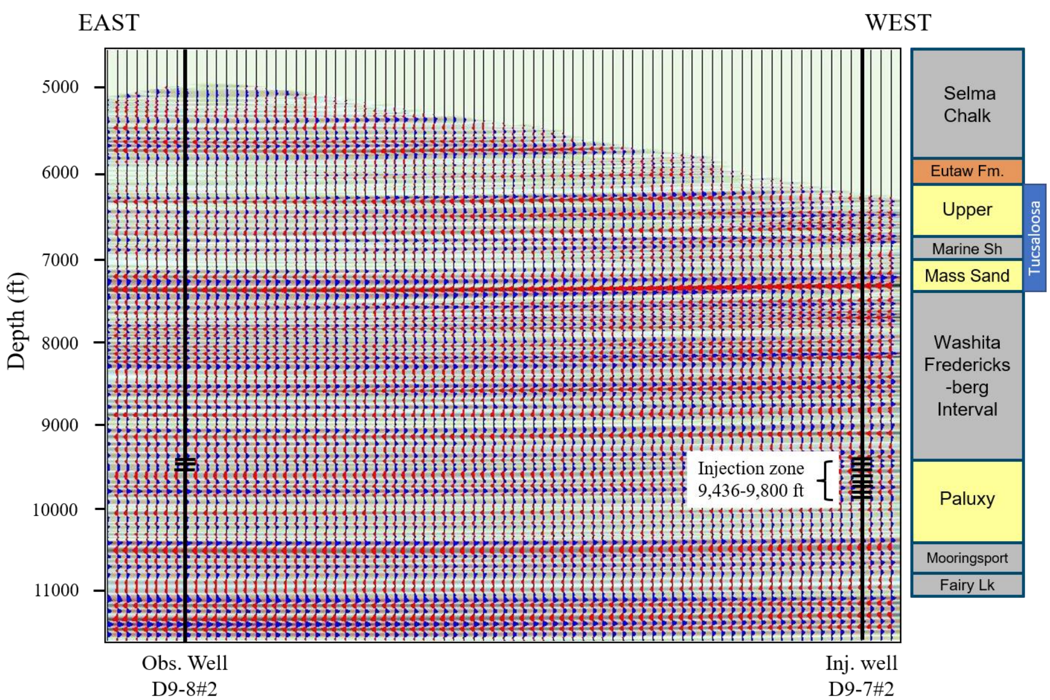

Figure 11. Depth migrated image showing reflections for shot point D9-7#2 recorded with the 80-level geophone array deployed in observation well D9-8#2. 2012 pre-injection baseline survey. Note difference in vertical and horizontal scale compared to Figure 10. (color figure)

<u>3.3.2 December 2015 OSVP Survey</u>

The goal of the December 2015 DAS survey was to determine if time-lapse differencing using the June 2014 survey results could be used to determine if the CO_2 continued to move after injection ended in early September 2014. Data from the zero and far offset shot points recorded in June 2014 were repeated in December 2015 with a larger 65,000 lbf (289 kN) triaxial vibroseis source and 16 sweeps recorded at each location. Silixa's iDAS™ system and LBNL's MBM geophones recorded all source points.

Adaptive noise-reduction described by Daley, et al, 2015was applied resulting in a better signal to noise ratio compared to prior surveys. **Figure 12** shows correlated 2015 data from four shot points: (A) Near offset at observation well D9-8 #2; (B) injection well D9-7 #2; (C) D9-6; and (D) large offset at D9-3. (Refer to **Figure 1** and **Table 1** for location and distances between shot point). Each plot is overlain with geophone recordings between 6,000 and 6,850 ft (1,829–2,088 m) depth as well as modeled arrival time. There is generally good agreement between DAS and geophone recordings. To date, only the DAS data have been fully processed and only the large-offset position (D) has been processed to a time-lapse migrated image.

Figure 13 compares near-offset data from 2014 and 2015. The insets show detail near 1,950 ms at 9,426 ft (2,873 m). The most striking difference is the dramatic change in the tube-wave response. A tube-wave is a type of seismic guided wave which propagates in a borehole and is sensitive to borehole conditions including fluids. The 2014 data show a double tube wave (marked with the arrows). The faster tube wave marked in cyan on each panel shows a similar propagation speed (about 5,000 ft/s = 1,500 m/s) for both surveys. It is interpreted as signal carried mainly in the fluid-filled central bore which is open at the packer. The slower tube wave is marked in yellow on each panel. In the 2014 survey, it can be seen to reflect strongly from the packer at 9,426 ft (2,873 m). In the 2015 survey, it is evidently replaced by the slow (1,300 ft/s = 400 m/s) signal that was absent below 4,000 ft (1,219 m). This seems to be signal carried mainly in the annulus between the tubing to which the fiber optic cable is strapped and the outer well casing. This suggests that the annulus contained a significant amount of free gas above 4,000 ft (1,219 m) in December 2015. We note that ambient noise in boreholes is likely dominated by tube-waves (e.g. White, 2000), and that ambient noise processing of DAS data has been successful (Ajo-Franklin, et al, 2015). Therefore, it is likely that continuous monitoring of this signal (with the DAS system to track the system response to ambient tube-wave noise) would have given early detection of free gas in the annulus sometime between June 2014 and December 2015.

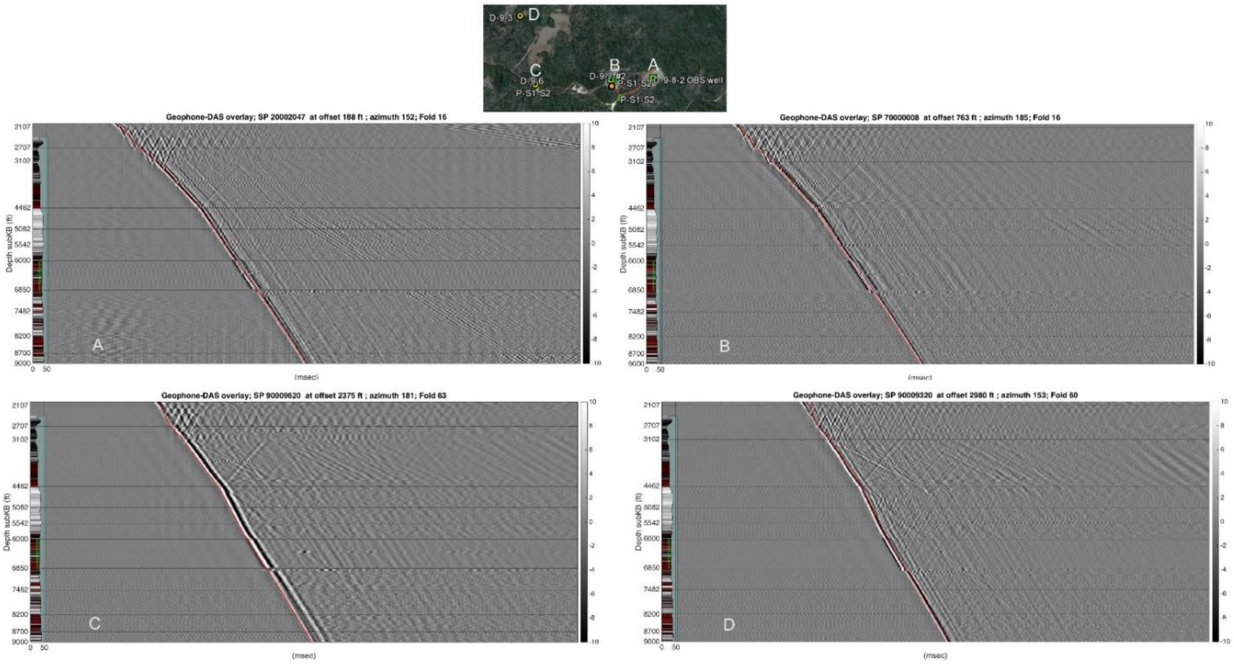

Figure 12. Correlated DAS data results from far- and zero-offset VSP source points with clear first-arrivals along the full length of fiber. Each plot is overlain with geophone recordings between 6,000 ft and 6,850 ft (1,829 and 2,088 m) as well as a modeled arrival time. (color figure)

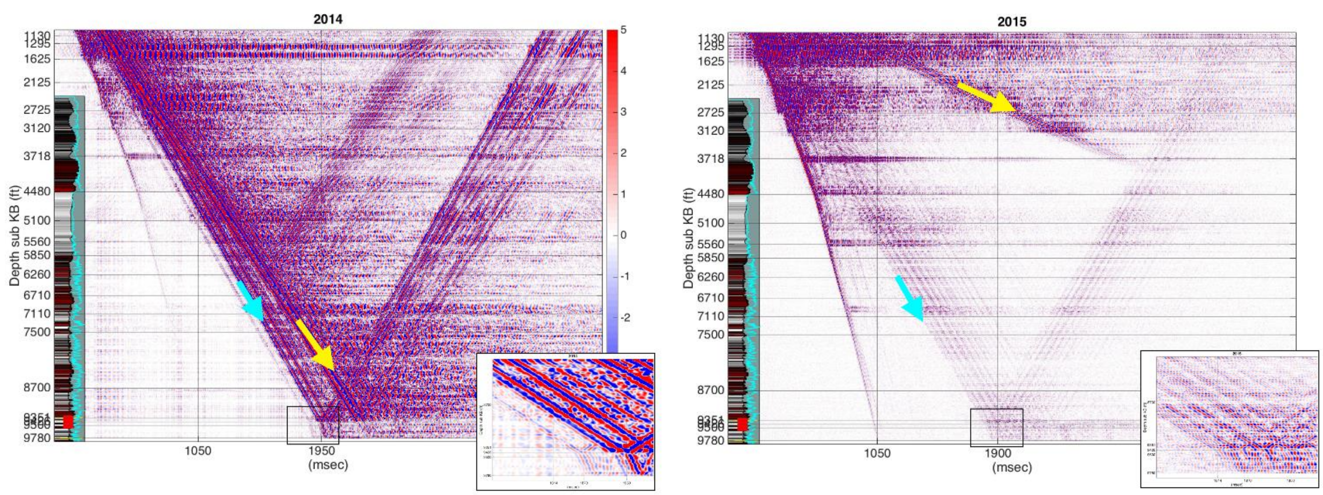

Figure 13. Near offset data taken from a shot point located on the observation well D9-8 #2 drill pad. The change in velocity of the tube waves (shown by arrows) from 2014 (left) to 2015 (right) indicates that the annulus contained free gas in December 2015. (color figure)

Figure 14 shows migrated images from the D9-3 offset position (**Figure 12D**). The inset in Figure 14 shows a map view of the shot point and wells in a coordinate system rotated clockwise 153 degrees to align the x-axis to the vector from the observation well D9-8#2 to the shot point D9-3. Gridlines are at 200 ft (61 m) intervals. The image extends about 1,000 ft (305 m) along the line connecting D9-8#2 and

D9-3. The injection well is close to coordinate [750 ft, 200 ft] (229 m, 61 m). The rightmost panel was made by subtracting from the 2015 image at each image-offset column, a scaled copy of the corresponding 2014 image column and then forming the envelope of the resulting time-lapse difference. The left two panels (Figure 14) show the image windowed to the illumination aperture for reflections from flat reflectors superposed on their continuation outside the specular aperture. The ovals mark the region of interest at 750–800 ft (229–244 m) offset from D-9-8#2 at 9,740 ft (2969 m) depth where a bright spot reasonably coincides with the maximum CO_2 concentration.

In summary, the strongest effect was a change in coupling and a dramatic change in tube wave response due to invasion of CO_2 into the annulus of observation well D9-8 #2. In a difference image made from 2D VSP migrations from the large offset shot point (D9-3) a bright spot reasonably coincides with the base of the CO_2 injection zone at 9,800 ft (2,987 m).

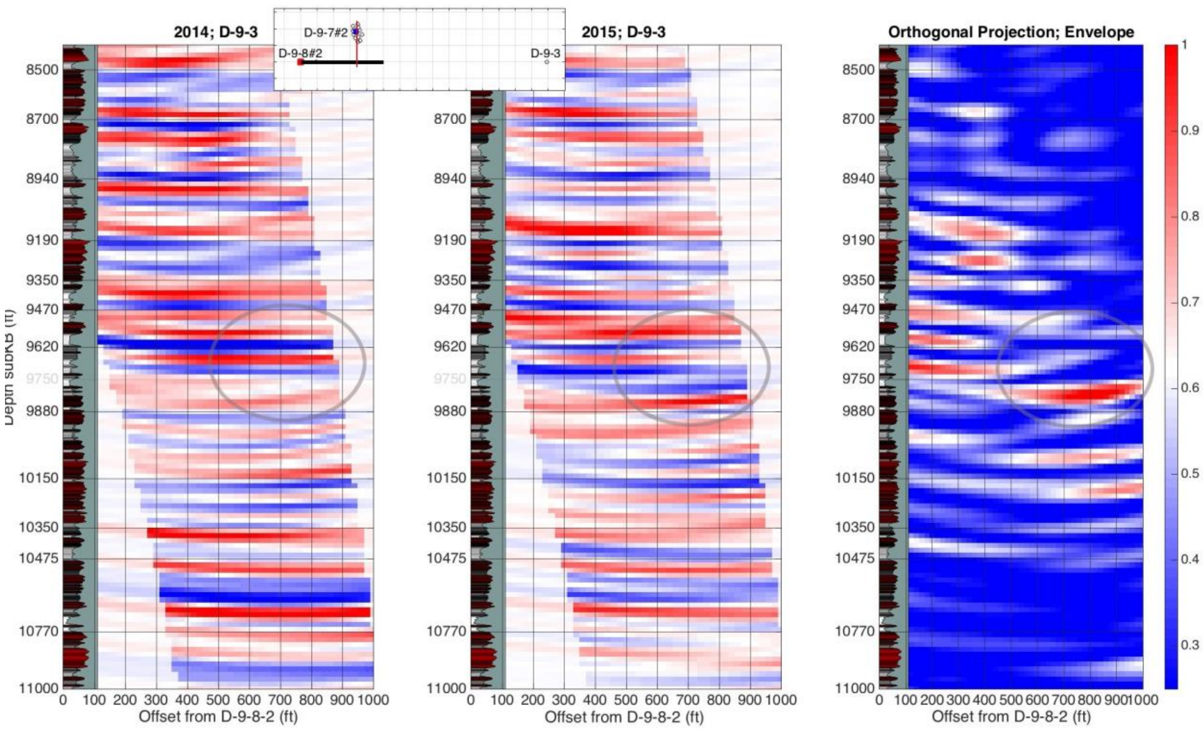

Figure 14. Depth migrated images of the amplitude response obtained collected from source location D9-3 in 2014 (left) and 2015 (center). The time lapse difference between these two surveys is shown on the right panel. (color figure)

4.0 CONCLUSIONS

This study developed and utilized a unique downhole tool referred to as the modular borehole monitoring system, deployed as a semi-permanent monitoring system. In addition to conventional seismic monitoring and geochemical and temperature monitoring, the MBM was used to successfully demonstrate the benefits of fiber optic sensing for leak detection and CO_2 monitoring (Freifeld et al, 2015a and 2015b). Large cross-well and VSP data sets using conventional borehole geophone and DAS arrays were acquired for CO_2 plume detection and method comparison. Survey results include:

- The cross-well survey produced a high-resolution image of the CO_2 plume acquired with conventional hydrophones and a piezoelectric source. In comparison, only random noise was recorded with the DAS array in the cross-well configuration, although the acquisition of DAS cross-well data was demonstrated in a deep well for perhaps the first time.
- In contrast, DAS was successfully used to acquire high quality images of the subsurface by employing the VSP survey method that had good correlation with the log data. The DAS acquired images had comparable resolution to the data acquired with the 80-level geophone array.
- We attribute the poor quality of the cross-well survey results to the DAS system noise levels at higher frequencies. The system noise increases approximately linearly with frequency from 10 to 1,000 Hz, by a factor of about 10, and then is level to about 2,000 Hz. The cross-well piezoelectric source output bandwidth is in the frequency range of 100–1,200 Hz much higher frequency (100–1,200 Hz) compared to the VSP sources (10–160 Hz), and therefore, requires higher signal levels, increased number of sweeps or greater noise reduction, than the VSP surveys.
- A time-lapse image of the post-injection CO_2 plume was successfully obtained with the DAS OVSP data acquired in 2014 and 2015 after CO_2 injection ended. No attempt was made to interpret the image because it represents a short period of CO_2 re-distribution after CO_2 injection stopped and, therefore, cannot be used to determine the plume position. However, it did demonstrate, to our knowledge for the first time in public data, that DAS time-lapse differencing is possible. Permanent DAS arrays have consistent coupling and sensor location, in addition to near total well coverage, providing significant advantages over mobilizing temporary sensor arrays for each survey.
- In contrast, time-lapse imaging with the OVSP data collected by SECARB using the conventional geophone array deployed in the injection well was not possible, even though there was a pre-injection baseline survey available. This was due to the large changes in survey conditions, including equipment (source strength and receiver type) and changing borehole conditions (kill fluid, drilling mud, etc) that created artifacts unrelated to fluid substitution that could not be corrected or removed.
- The signal to noise ratio of the DAS system can be dramatically improved by collecting multiple sweeps and stacking the DAS data at each shot point.
- Significant improvements in Silixa's optical interrogator used to record the DAS data have resulted in improved signal to noise ratios over time. Other DAS interrogators have similarly improved.

Future recommendations for research include improved fiber designs to increase the signal to noise ratio in the cross-well configuration where the acoustic wave arrives broadside to the fiber and field testing of alternative corrosion resistant materials in the construction of the capillary tubes used to house the fibers.

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6.0 DATA AVAILABILITY

DAS and conventional survey data sets are available to interested researchers through the U.S. Department of Energy, National Energy Technology Laboratory, Energy Data eXchange (EDX), https://edx.netl.doe.gov/.

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Appendix A—Summary of seismic surveys conducted at the Citronelle field site from 2012 to 2016 using DAS and conventional receiver arrays (DAS related activities and surveys are shown in bold).

Survey	Date	Vendor(s)	Active Source	Data Acquired	Comments
1	2012 Jan	Schlumberger (SLB)	Piezo-electric borehole source • 100 – 1200 Hz linear sweep • 2.6 s sweep length	Cross-well baseline survey	Survey between injection well D9-7#2 (source) and observation well D9-8 #2 (receiver), acquired on 10-level hydrophone receiver array with 10 ft (3 m) sensor interval
2	2012 Feb	SR2020	Vibroseis • 35,000 lbf (156 kN) • 12 – 160 Hz linear sweep • 16 s sweep length	Zero Offset VSP (ZOVSP), Offset VSP (OVSP) + 2 Walkaway (WAW) baseline surveys	- Baseline ZOSVP and OVSP acquired on an 80-level geophone array with 25 ft (7.6 m) spacing deployed in D9-7#2 and 80-level geophone array with 50 ft (15.2 m) spacing in D9-8#2. - OVSP was acquired at seven shot points including well locations D4-15, D9-1, D9-3, D9-6, D9-9#2, D9-10, D9-11. - WAW surveys were conducted along: 1) the powerline (PWAW) and 2) lease road (RWAW) with 25 ft (7.6 m) spacing between shot points
--	**2012 Mar**	**Denbury Resources / LBNL**	--	Installed LBNL's MBM system in observation well D9-8 #2	The MBM array includes the 18-level geophone array, DAS and DTS fibers, and copper heater elements
3	**2012 Apr**	**SR2020 / Silixa**	Vibroseis • 35,000 lbf (156 kN) • 10 – 160 Hz linear sweep • 16 s sweep length	OVSP + RWAW + DTS	- Acquired on LBNL MBM 18-level geophone permanent array in D9-8#2, and DAS - Repeat walkaway on the lease road (RWAW), same points as Feb 2012 - DAS was acquired at WAW shot points 2003, 2021 and 2054 - Problems with the vibroseis sweep electronics resulted in poor quality results

Survey	Date	Vendor(s)	Active Source	Data Acquired	Comments
4	2012 May	SR2020	Vibroseis • 35,000 lbf (156 kN) • 12–160 Hz linear sweep • 16 s sweep length	ZOSVP + OVSP + RWAW	- Acquired on LBNL MBM 18-level geophone permanent array in D9-8#2 - DAS data were not acquired during this campaign - Offset shot points and RWAW are repeats of the Feb. 2012 baseline survey - ZOVSP performed at D9-7#2
--	2012 Aug	--	--	--	Start of CO_2 injection
5	2013 May	SR2020	Vibroseis • 35,000 lbf (156 kN) • 12–160 Hz linear sweep • 16 s sweep length	OVSP + RWAW	- Acquired on LBNL MBM 18-level geophone permanent array in D9-8#2, without DAS acquisition - Offset shot points and RWAW are repeats of the Feb. 2012 baseline survey
6	**2013 Aug**	**SR2020 / Silixa**	Vibroseis • 35,000 lbf (156 kN) • 12–110 Hz linear sweep • 16 s sweep length	OVSP +RWAW + DAS test at 3 shot points	- Acquired on LBNL MBM 18-level geophone permanent array in D9-8#2, including DAS - Offset shot points and RWAW are repeats of the Feb. 2012 baseline survey - DAS was acquired for three test shot points (2003, 2021 and 2040/2041) along RWAW with active triggering
7	2014 Apr	SR2020	Vibroseis • 64,000 lbf (267 kN) • 12–130 Hz linear sweep • 16 s sweep length	OVSP + RWAW	- Acquired on LBNL MBM 18-level geophone permanent array in D9-8#2 - Offset shot points and RWAW are repeats of the Feb. 2012 baseline survey

Survey	Date	Vendor(s)	Active Source	Data Acquired	Comments
8	**2014 Jun**	**SLB / SR2020 / Silixa**	Piezo-electric borehole source for crosswell survey • 100–1200 Hz linear sweep • 2.6 s sweep length Vibroseis for VSP, WAW • 64,000 lbf (267 kN) • 12–130 Hz linear sweep • 16 s sweep length	Crosswell + ZOVSP + OVSP + RWAW + D9-7 Grid	- Repeat of Jan. 2012 cross-well baseline survey - Acquired on LBNL MBM 18-level geophone permanent array in D9-8#2, including DAS - Offset shot points and RWAW are repeats of the Feb. 2012 baseline survey - Dense grid of VSP shot points taken at wellpad D9-7#8 - DAS recorded all VSP and piezo cross-well source points + 1-hour noise record
--	2014 Sept	--	--	--	CO_2 injection ends. Cumulative amount injected was 114,104 tCO_2.
9	**2015 Dec**	**Silixa / UT Austin**	Vibroseis • 64,000 lbf (267 kN) • 12–130 Hz linear sweep • 16 s sweep length	ZOVSP + OVSP + RWAW + D9-7 Grid	- Acquired on LBNL MBM 18-level geophone permanent array in D9-8#2, including DAS - Same source points as June 2014 survey except no cross-well survey - DAS recorded all source points
10	2016 Jan	Optasense (ex-SR2020)	Vibroseis • 64,000 lbf (267 kN) • 12–130 Hz linear sweep • 16 s sweep length	ZOVSP + OVSP	- The baseline ZOSVP and OVSP were acquired using a Weatherford 2-level digital geophone array with 50 ft (15.2 m) spacing deployed in D9-7#2. - Limited data were acquired over the same 2,000 ft (610 m) interval recorded in 2012