2014

Using Time-Lapse Three Dimensional Vertical Seismic Profiling to Monitor Injected Fluids During Geologic Carbon Sequestration

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Using Time-Lapse Three-Dimensional Vertical Seismic Profiling to Monitor Injected Fluids During Geologic Carbon Sequestration

John B. Hickman
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Technical Level

General Intermediate Technical

ISSN 0075-5591
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Using Time-Lapse Three-Dimensional Vertical Seismic Profiling to Monitor Injected Fluids During Geologic Carbon Sequestration

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Abstract

Two three-dimensional vertical seismic profiles (3D-VSP) were acquired at the KGS Marvin Blan No. 1 CO₂ sequestration research well outside of Cloverport in Hancock County, Ky. The initial (preinjection) survey was performed September 15–16, 2010, and was followed by the injection of 361.2 metric tons of supercritical CO₂ and then 584 m³ of 2 percent potassium chloride water (to displace the remaining CO₂ in the wellbore) on September 22, 2010. After injection, the well was shut in with a downhole pressure of 17.5 MPa at the injected reservoir depth of 1,545.3 m. A second 3D-VSP was acquired September 25–26, 2010. These two surveys were combined to produce a time-lapse 3D-VSP data volume in an attempt to monitor and image the subsurface changes caused by the injection.

Less than optimum surface access and ambient subsurface noise from a nearby active petroleum pipeline compromised the quality of the data, preventing imaging of the CO₂ plume in the subsurface. Some changes in the post-injection seismic response (both wavelet character and an apparent seismic pull-down within the injection zone) are interpreted to be a result of the injection process, however, and imply that the technique could still be valid under different circumstances.

Objectives

The objectives of time-lapse 3D-VSP at the Marvin Blan No. 1 research well were to test the feasibility of using well-based 3D-VSP’s to verify the CO₂ plume emplacement location (both vertically and horizontally) within the Gunter Sandstone reservoir, Cambrian-Ordovician Knox Group, as well as attempt to monitor any initial local migration of those injected fluids into high-permeability zones or fractures.

Introduction and Background

In order for future industrial-scale carbon capture and storage projects to succeed safely, verification of CO₂ emplacement within the target reservoir and monitoring of the injected reservoir intervals will be required. One possible method of monitoring these subsurface reservoirs is through the differential analysis of repeated seismic surveys (Li, 2003; Majer and others, 2006; Dahlhaus, and others, 2012). Fluids injected into a reservoir (supercritical CO₂ and saline water) alter the lo-
Experimental Procedures

General Methodology for 3D Vertical Seismic Profile Design

A three-dimensional vertical seismic profile survey was conducted in conjunction with phase 2 of the CO₂ injection test program of the Marvin Blan No. 1 well. The objective of this survey was to model the extent of the CO₂ plume migration in the Gunter. Reports discussing data acquisition and processing methods and results of this task are in Appendices 1 through 3. The vendor, SeisRes-2020 Inc., was chosen to provide and operate the 3D-VSP downhole survey tools, and to process the acquired digital seismic data. The seismic receiver array tool consisted of 80 three-component geophones (X-, Y-, and Z-axis sensors), spaced 7.6 m apart vertically along production tubing (Fig. 1). Once the receivers were lowered into place, expandable bladders were inflated that stabilized and coupled the geophone sensors to the sides of the wellbore (Fig. 2). For this project, the base of the geophone string was placed at the bottom of
Experimental Procedures

Following discussions with SeisRes-2020, a revised source survey was designed to accommodate these survey acquisition issues. To compensate for the reduced survey area, a source grid with tighter spacing between source points (15.3 m) was defined for the main survey, along with a tighter spacing between sources along the two walkaway lines (7.6 m). Figure 3 shows the final survey layout design details. Appalachian Geophysical Services of Killbuck, Ohio, was chosen as the vendor to provide three Vibroseis source vehicles for the seismic survey. The Vibroseis source inputs used for both surveys were 12-s linear sweeps through 12- to 130-Hz frequencies.

Seismic Survey Acquisition

In an attempt to monitor the effects of CO\textsubscript{2} injection, a time-lapse 3D-VSP survey was conducted. This was accomplished by performing adaptive subtraction of a preinjection 3D-VSP’s seismic response from the post-injection VSP’s seismic-response data set. Prior to the VSP acquisitions, SeisRes-2020’s proprietary downhole VSP tool was installed in the wellbore. SeisRes-2020 personnel operated the downhole equipment, monitored the seismograph recordings, and synchronized the hydraulic vibrators (seismic sources on board the Appalachian Geophysical Services source trucks) during both acquisitions. During the acquisition stage of the two surveys, multifrequency seismic waves were input into the subsurface at more than 700 surface locations surrounding the Marvin Blan No. 1 research well (yellow points in Figure 3). For each of these source-location points, raw seismogram data recordings (Fig. 4) were made by each of the 80 geophones in the well. These data were then compiled and processed by SeisRes-2020 staff.

The initial, preinjection survey was performed at the Marvin Blan No. 1 well September 15–16, 2010. This was followed on September 22, 2010, by the injection of 333 metric tons of supercritical CO\textsubscript{2}, followed by 584 m\textsuperscript{3} of 2 percent potassium chloride water solution to displace CO\textsubscript{2} in the reservoir. After injection was completed, the well was shut in with a downhole pressure of 17.5 MPa at the injected reservoir depth of 1,545.3 m. The second 3D-VSP was acquired September 25–26, 2010, after the reservoir pressure falloff test was completed.

Figure 2. Schematic diagram of geophone placement in a wellbore. After air bladders were lowered to the appropriate depth, they are inflated, which secures the three-component (3C) geophones to the well casing, assuring adequate acoustical coupling to the surrounding geology.
**Seismic Data Processing**

Seismic data processing was performed using a proprietary model developed by SeisRes-2020 for monitoring CO$_2$ plume migration at sequestration well sites. After examining the data recordings taken from both VSP acquisitions, SeisRes-2020 selected records from 719 source locations that contained acceptable results from both VSP surveys for final data processing. The VSP data were processed by SeisRes-2020 using the following steps:

1. Data quality checks on raw VSP data.
2. Geometry assignment.
4. Spectral analysis.
Results and Discussion

5. Standard zero-offset processing.
6. P-wave direct-arrival inversion.
8. Three-dimensional velocity model extrapolation.
10. Three-component (X, Y, and Z) P-reflection wave field separation.
11. Prestack depth migration.
12. Time-lapse comparisons.

In order to depth-migrate the seismic data, a 3D subsurface sonic-velocity model was created (Fig. 5). The input data for this model was constructed from both the Marvin Blan No. 1 geophysical well logs along with the near-well recorded VSP data travel times. The process of depth-migrating the seismic data (which are originally recorded in units of time) results in a data volume for which all three axial dimensions are in units of distance. Depth-migrated seismic data thereby allow for direct comparison with conventional drillhole data (see geophysical log overlay on Figure 5).

**Results and Discussion**

After processing the data, 3D data volumes for the preinjection and post-injection VSP’s, along with the 3D velocity model used for seismic processing, were made available to the Kentucky Geological Survey by SeisRes-2020 in January 2011. In addition, two limited-depth-interval 3D difference volumes were provided: one at the injection level (1,534.6–1,605.6 m depth) and one at a shallower marker horizon level (762–1,219 m depth). The 3D difference data volumes were created by subtracting the preinjection seismic response from the post-injection seismic-response data sets. Theoretically, this difference method should isolate only the changes in seismic response, in this case the...
Figure 5. Sonic velocity model (ft/s) used for VSP correlation and depth conversion. Gamma-ray (green) and acoustic (gray) logs from the Marvin Blan No. 1 well are marked for reference. A synthetic seismogram wavelet produced from the well logs is overlain in red.
injection of 333 metric tons of supercritical CO$_2$. The seismic amplitudes and waveforms changed slightly in the injection zone below 1,534.6-m depth (Fig. 9). There are also subtle changes throughout the data set, however, even at depths in intervals that were too distant or stratigraphically compartmentalized to be affected by the injection. This is especially apparent in the 3D difference volume (Fig. 11). If the technique had worked as designed, the areas without injected CO$_2$ should have amplitudes approaching zero (after subtracting the post-injection seismic amplitudes from the preinjection amplitudes). Subdued seismic responses relative to those within the injection zone are present in the interval away from the injection zone (see black oval in Figure 11), and
both positive and negative wavelet amplitudes are present in the data set.

The lack of a single region of post-injection amplitude anomalies made defining the extent of the plume (with only these seismic data) impossible. The most probable reasons for the lack of resolution in these VSP’s were low data density and poor data quality. Because of the uneven terrain and the inability to place seismic source points along the pipeline right-of-way, or anywhere outside of the Blan farm property boundaries (Fig. 3), the data density was less than optimal, especially north and east of the well. In addition, the presence of an active pipeline in close proximity to the well (vibrational noise), along with active domestic and well-site equipment (electrical noise), led to relatively low signal/noise ratio conditions in the data (Fig. 4). It is possible that a larger plume of CO₂ would have been easier to image, but the ambient noise and limited surface access would still have led to uncertainties in the exact extent of the subsurface plume.

Although we were unable to define the exact lateral extent of the CO₂ plume using the finite-difference method, some of the anomalies in the results can be explained by the presence of the supercritical CO₂. In addition to the changes in the wavelet character described above and illustrated...
in Figures 9 through 11, there appears to be an anomalous pull-down of a reflection in the Gunter injection interval on the post-injection survey. Theoretically, the introduction of a lower-density fluid (supercritical CO₂) into pore spaces and open fractures would lower both the bulk density and the average seismic velocity of the host rock. If this new injection-interval seismic velocity is significantly lower than that of the velocity model used to process and depth-migrate the data (Fig. 5), the seismic reflections will take longer to travel back to the recording geophones. This delayed reception of the seismic signal would result in the reflections within and below that horizon being plotted at a greater depth than is appropriate.

The concave-upward shape of high-amplitude reflection in the Gunter on the depth-migrated post-injection survey can be interpreted to be a pull-down effect from the introduction of the seismically slower CO₂ (Fig. 12). In an attempt to investigate this possibility, the depth to this reflection was mapped and contoured for both the pre-injection (Fig. 13) and post-injection (Fig. 14) surveys. For the majority of the area, the post-injection horizon does indeed plot deeper than the same horizon before injection (Fig. 15). The regions to the
Figure 9. Example profiles across the VSP survey illustrating subtle changes within and below the injection zone of the waveform amplitudes following injection. Positive reflection amplitudes are colored black.
Figure 10. West-east depth-migrated image slices across well location, focused on the depths within and just above the injection zone. Upper image is from the preinjection survey and lower image is the post-injection survey of the same profile. Note the difference in wavelet character (highlighted by black oval) in the injection zone (Gunter Sandstone). Positive reflections are displayed in red and negative wavelet amplitudes are in blue.
north-northeast and southeast in the post-injection survey with highly anomalous calculated depths in Figures 14 and 15 correspond to the areas with much lower data densities (Fig. 16), and therefore are probably artifacts of the data processing and not a true result of the injection. Although this apparent agreement of the data with seismic theory is encouraging, separating the effects of the plume from the effects of the low data density and quality was not possible with this data set.

## Conclusions and Recommendations

Although the technique of using time-lapse 3D-VSP’s for finite-difference analysis appears to be a useful and valid tool for subsurface CO₂ storage verification and monitoring, physical limitations such as limited surface access and ambient noise sources can make it impractical and thus not useful for all situations. In industrial sequestration operations, the area available for seismic surveying would likely be larger than was available on the Blan farm, and thus have more potential seismic-source locations (producing a greater signal/noise ratio). However, the steep-walled, incised creek valleys that prevented access of the seismic-source trucks to some of the areas on the Blan farm are a common feature in much of Kentucky, so having a larger survey footprint would not necessarily provide all of the access needed for VSP surveys with sufficient resolution for plume imaging. In light of this, sequestration site selection in the future should consider not only the quality and appropriateness of the reservoir in the subsurface, but also the surface conditions and restrictions present.
that could affect the ability to monitor the reservoir over time using seismic data.

**Acknowledgments**


The first phase of this project was funded in part by the Commonwealth of Kentucky, University of Kentucky, and Kentucky Geological Survey, and additional funding was provided by the Western Kentucky Carbon Storage Foundation, the Illinois Department of Commerce and Economic Opportunity–Office of Coal Development, and the U.S. Department of Energy–Office of Fossil Energy–National Energy Technology Laboratory. Drill-site access was graciously granted by Marvin and Brenda Blan, Hawesville, Ky.

Figure 12. Northwest-southeast depth-migrated seismic-amplitude profile of the post-injection survey. Note slight apparent downwarping or pull-down of light blue horizon relative to horizontal (bold green line overlay just below −4,500 ft) near the well location (dashed blue vertical line). The top and base of the injection zone in the wellbore are indicated by red dashes at −4,403 and −4,633 ft, respectively. Positive reflections are displayed in red and negative wavelet amplitudes are in blue.
Figure 13. Calculated depth of the mid-Gunter reflection prior to CO₂ injection. Depth is in feet below the reference datum. The light blue horizon corresponds to the mid-Gunter reflection in Figure 12, and the bold red northwest-southeast line corresponds to the location of the profile shown in Figure 12.

Figure 14. Calculated depth of the mid-Gunter reflection after CO₂ injection. Depth is in feet below the reference datum. The bold red northwest-southeast line corresponds to the location of the profile shown in Figure 12.

Figure 15. Calculated depth differential of the mid-Gunter reflection between the pre- and post-injection surveys. Positive values (deeper after injection) are contoured in feet.

References Cited


Figure 16. Detailed view of VSP survey area outlining the extent of the final data volume. The areas in Figures 13 through 15 with highly anomalous values correspond to the regions with the least amount of input data because of limited seismic source points.
Appendix 1:
KGS 3D VSP Modeling: 3D Illumination

Appendix 2:
3D VSP Shotpoint Map

Appendix 3:
Processing Report for Kentucky Geological Survey Blan No. 1
Basic survey information

- Client: *KGS*
- Client Rep:
- Field: *Marvin Area:*
- Survey dates: *August 15-25 2010 tentative*
- Seismic datum: *500 ft AMSL*
- Well name: *Blan 1*
- Surface source line interval: *75 ft*
- Number of shot points modeled: *1022*
- Maximum Horizontal offsets: *1400 ft*
- Target Depth: *5000 ft*
- Receiver array: *81 levels at 25 ft spacing*
- Receiver depths (Depths below datum): *3000-5000 ft*
3D VSP Pre-Survey Modeling

• Velocity model building is conducted using existing VSP velocities for a 1D stratigraphy

• The current modeling examines the effect of an 80 level receiver array with 25ft spacing.

• Bottom receiver is positioned slightly above at target depths so a direct (depth-time) tie can be achieved during the survey

• Sources are located with maximum offsets of ~2700ft (SW corner)

• Target illumination horizon is at 5000 ft
1D velocity model

- The client has provided a VSP report for the Blan 1 well in PDF format.
- No numeric velocity values were given.
- A 1D velocity function was obtained after rough digitizing of figure 3.5 from the report.
- Only major layers were digitized.
- This velocity model was used as initial 1D profile for the modeling.
3D Source Spacing Effects

- A regular spaced grid with maximum offset of 1400 ft was analyzed
- The grid itself was not regular however. Deeply forested area does not allow for a regular grid. Only shots located in a wide open area could be used during acquisition, and therefore only those shot points were modeled
- Also two 2D lines were suggested:
  - NS line at 25 ft spacing with maximum offset of 2500 ft
  - EW line at 25 ft spacing with maximum offset of 2500 ft to the West and 1325 ft offset to the East
Shot Points Lay Out

3D map: 75 ft spacing, 1022 shots

2D lines: 25 ft spacing, 146 shots (EW) 201 shots (NS)
1D velocity function was smoothed over 350 ft to satisfy 3D Norsar requirement. The it was extrapolated into a 3D cube. A flat horizon at 5000 ft was used as a illumination target.
NORSAR 3D Illumination Ray Tracing

- NORSAR 3D modeling software is used for illumination ray tracing
- The ray tracing is conducted using the wavefront construction method
- For ray-tracing stability the velocity model was previously smoothed in the vertical direction over 350 ft
- To perform ray-tracing more rapidly, the receiver array was used as the sources and the source array was used for the receivers
3D velocity model and survey geometry import in Norsa...
Wavefront tracing trough the model
Wavefront tracing through the model
Wavefront tracing through the model
Wavefront tracing through the model
Ray tracing provides several different reflection attributes on the target horizon.

The most important of these reflection attributes are the hitcount, which is a measure of the fold, and the angular aperture, which indicates the range of angles available for illuminating a particular bin position.
Illumination Attributes

- **Hit Count** maps indicate the area where reflections from the survey geometry would be available. The logarithmic scale indicates the number of hits that are available at each bin location.

- **Angular Aperture** is a determining factor on the final image quality. For better resolution in the image a wide range of angles, arriving at a particular reflection point, is required for proper stacking of the information. Wider angular apertures are indicative of a robust survey that will provide a wide range of angles.
Hit count on target horizon. PP waves

Illumination includes all reflections in the data including supercritical ones.

Triangle is location of the Blan1
Dots are 3DVSP sources

The fold is decreasing with the offset

Maximum image offset is ~400 ft due to target depth of ~4200 ft and max offset of ~1400 ft
Min and Max incidence angle on target horizon. PP waves

Due to small offsets comparably to target depth, angular aperture is narrow
Angular Aperture on target horizon. PP waves

The image beyond 45 degree max incidence angle contour is subject to supercritical reflections, lower fold and potential wavelet distortion.

Due to small offsets again, no supercritical reflections are expected.
Amplitudes are decreasing with offset.
Min and Max offset on target horizon. PP waves

All offsets are contributing to the map.
Hit count on target horizon. PS waves

Illumination includes all reflections in the data including supercritical ones.

Triangle is location of the Blan 1
Dots are 3DVSP sources

The fold is decreasing with the offset
Maximum image offset is 250 ft due to target depth of ~4200 ft and max offset of ~1400 ft
Min and Max incidence angle on target horizon. PS waves

Due to small offsets comparably to target depth, angular aperture is narrow
The image beyond 45 degree max incidence angle contour is subject to supercritical reflections, lower fold and potential wavelet distortion.

Angular aperture is very narrow.
Min and Max offset on target horizon. PS waves

All offsets are contributing to the map
Image Diameter and Fold

- Given that the target horizon is flat and velocity model is in general smooth, the image diameter is about 400 feet including areas with low fold (hit count)
- High contrasts in velocity and variations in topography and target horizons will alter the image extend
- Mode dense source grid would provide higher fold
- Bigger offsets might be suggested to increase the image size and to increase high fold areas diameter
Summary Remarks

- Velocity changes in the field at some depths and it would be preferable to place the receivers in such a fashion that they capture these changes. The longest the VSP array the more optimal the velocity control will be.

- Going closer to the target provides a wider angular coverage and the quality of the image would be enhanced.

- The velocity model exhibits significant changes that cause significant bending of the rays. The ray-bending effectively would reduce the illuminated area. These changes in velocity associated to high velocity layers control the wave kinematics and guide the image’s final diameter of illumination.

- Maximum source offsets were modeled out to 1,400 ft
  - If the source offset was to decrease there would be a decrease on image radius
NOTE: 5,000 WAS ADDED TO THE POINT NUMBERS STAKED IN THE FIELD FOR THE ELEVATION POINTS ON THE GRID. SO POINT #64 STAKED IN THE FIELD IS THE SAME AS POINT #5064 SHOWN HEREON.
Processing Report

For

Kentucky Geological Survey
Blan#1

November, 2010

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Disclaimer
SR2020 Inc. cannot and will not guarantee a certain outcome in the enclosed report. There are many factors that affect the processing of the data and the quality of the images that are outside SR2020’s control. Examples of these factors include the quality of the input model the velocity information, and geological and velocity complexities. All processing is performed on a reasonable commercial effort basis only. However, SR2020 will perform the processing to our highest professional standards, which we believe meet or exceed the industry processing standards.
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Executive Summary

SR2020 recorded a time-lapse 3D VSP for the CO2 injection project in Blan1 well as part of the DOE Grant #3048107146 entitled “An Evaluation of the Carbon Sequestration Potential of the Cambro-Ordovician Strata of the Illinois and Michigan Basins”. SR2020’s main partner was the Kentucky Geological Survey which designed and carried out CO2 injectability tests in the Blan1 well. The seismic borehole data acquisition was carried out before and after injection period.

During the pre-survey modeling a full areal source layout and a dense receiver array was designed for best capturing the small subsurface changes due to the CO2 injection. However, due to permitting, accessibility issues and deployment in cased hole only sections of the well, the acquired data set was sparser than desired. The source layout shows large patches of inaccessible areas while the receiver array was approximately 1000 ft above the injection zone. So illumination at the injection level is not uniform and only a few lines well sampled offsets exist. The velocity model below the deepest receiver had to be incorporated from prior surveys and well logs. Thus, no independent before and after VSP measurement exists at that depth level coincident with the injection test.

The velocity model was estimated on Baseline and Monitor survey from near offset shots. Slight overburden variations exist and are caused most likely by different noise conditions between the time-lapse surveys. The local 3D model around well fits the 3D direct arrival times from the areal source pattern very well. Source static variations were estimated from the averaged differences of pick versus computed arrival times. Generally the statics variations and statics difference variations are small except for some source locations located at the outer edge of the source pattern. Although the proper statics compensations have been applied those source locations can still anomalous due to different source coupling or other environmental factors that changed between the two surveys.

Baseline and Monitor survey processed identically using the same noise suppression, as well as deconvolution parameters and wave field separation parameters. Electrical noise trains were removed from raw data gathers by a multichannel adaptive filter on both data sets. The deconvolution recovered the expected source spectrum. Separation extracted the up-going wave field, subsequent radon filtering suppressed the converted waves and enhanced the up-going P-waves.

Depth migration in an accurate velocity model emphasizes consistent signals and reduces random or incoherent noise. Pre-stack depth migration was carried out in the overburden and injection zone. In order to maintain consistent illumination, only source locations that exist in both baseline and monitor survey are processed and imaged. However, the imaging capability is limited due to limited accessibility resulting in a limited coverage area, as well as limited repeatability due to varying noise conditions at the well site. The time-lapse analysis concentrated on depth migrated image volumes, due to the increased signal to noise ratio. A RMS amplitude scaling factor was to be applied before differencing the images. Characteristic changes are visible below 5000 ft depth correlating to the injection zone. However, due to the limited coverage the exact outline is difficult to interpret. Based on the adaptive subtraction, most changes seem to occur near the well and in the North-East direction.
1 Introduction

KGS lead a research effort for CO2 sequestration and performed a CO2 injection test in the Blan1 well. SR2020 collected a 3DVSP immediately before and after the injection period.

The following summary report outlines the processing steps to achieve the velocity model estimation and imaging performed to obtain time-lapse images. All processing results were presented to the client in the form of PowerPoint presentations and digital data files. Displays in this report represent an exemplary subset of the material already presented. For more detailed information, the PowerPoint presentations and digital files are listed in the appendix and are attached to this report.

2 Summary of Survey Parameters

Field: Kentucky Geological Survey
Area: KY Hancock County (NAD 83)
Date of survey: September, 2010
Data Type: VSP
Source type: Vibroseis
Source Parameters: linear sweep 12-130Hz, sweep length 12 seconds
VSP well: Marvin Blan#1
Well KB: well ground level elevation: 620.3ft relative to MSL
Well Location: X=1367587.938ft, Y=2173048.083ft
Downhole receivers: 80-level 3C
Receiver spacing: 24.98 ft
Receiver depths: 1653.28 – 3626.7ft below datum
Injection depth: ~5, 070 ft below datum
Recording sample rate: 2.0 ms / 1.0 ms
Record length: 4 sec
TimeLapse Source Points: 719
3 Data Processing

3.1 Data Input, Geometry Assignment and QC

The time-lapse borehole seismic data were acquired in September 2010 before and after the CO2 injection operation. SR2020 used information from observer logs and header entries to complete geometry assignment for the VSP. Vibroseis sources were employed for the entire VSP survey. A full range of 80 downhole receiver locations was recorded.

Figure 1 shows the planned source layout with a dense 3D VSP indicated with blue dots, and two walk-away lines to farther offsets. The red circle indicates a 1 mile radius for reference. The initial desired layout of uniform source coverage around the injection well could not be achieved due to a variety of permitting reasons (infrastructure, agricultural, ownership) and access issues in densely wooded areas. So the final acquired source layout differs substantially from the desired modeled scenario. Details of the illumination modeling and ideal survey design can be found in the previous modeling reports listed in the appendix.

Figure 1. Areal picture of location of Blan1 well with planned source points overlay.
Figure 2. Baseline source map with color coded elevation.

Figure 3. Monitor source map with color coded elevation.
Figure 2 and 3 show the source maps acquired for baseline and monitor survey with the elevation color coded. There are 719 source locations that were reoccupied identically in a time-lapse fashion. As is visible on the maps the only completely contiguous source recording is a line of sources extending roughly West-East following the access road traversing the well slightly to the East. Other azimuthal directions show significant missing sources at various offsets from the well, such that a full 3D image is impossible to obtain without footprint. Thus, many tests were carried out and documented in detail on the West-East line before applying it to the entire time-lapse data set.

3.2 VSP Processing Flow

The VSP data were processed starting with the raw data files and observer logs using the following main steps:

1. Data QC on Raw VSP data
2. Geometry Assignment
3. Geophone Orientation Estimation
4. Spectral Analysis
5. Standard ZO processing
6. P direct Arrival Inversion
7. ZO Velocity Profile Estimation
8. 3D Velocity Model Extrapolation
9. Deconvolution Operator Design
10. P-Reflection 3C Wave Field Separation
11. Pre-stack Depth Migration
12. Time-lapse Comparisons

Each of those steps was applied to all the VSP data and the following sections shows selected displays for each of those steps.

3.3 Raw Data Views

Figure 4 and 5 show a single shot gather of one component of the total wave field recorded at an identical source location. As can be seen, there is significant coherent and random noise present in the data. This being a relatively near offset source location a down-going tube wave can be observed. Figure 6 and 7 show similarly gathers at various offsets from the borehole. The noise level is similar for both baseline and monitor, with signal to noise ratio slightly increasing for the monitor survey. However, these noise conditions present a challenge in the further processing, where the aim is to enhance the up-going target time-lapse signal.
Figure 4. Baseline data exhibits electrical noise influence.

Figure 5. Monitor data exhibits electrical noise influence, but has slightly higher signal to noise ratio.
Figure 6. Baseline vertical component data across and West-East spread.

Figure 7. Monitor vertical component data across and West-East spread.
Figure 8. Baseline vertical component data spectrum near offset.

Figure 9. Monitor vertical component data spectrum near offset.
Figure 10. Baseline vertical component data spectrum far offset.

Figure 11. Monitor vertical component data spectrum far offset.
Figure 12. Baseline First Break picks on vertical component data on east west spread.

Figure 13. Monitor First Break picks on vertical component data on east west spread.
Figure 8-11 show the corresponding spectral displays. The raw data exhibits electrical noise, as can be seen in the raw data as well as in their amplitude spectra. These noise patterns will be suppressed in later processing through appropriate Notch filters and adaptive noise filters.

However, in order to perform the estimation of geophone orientation angles such filters have not been applied at this point in order to be able to focus purely on the first arrival p-wave energy. Figure 12 and 13 show the First Breaks overlaid on the shot gathers for both baseline and monitors. The FB picks for the baseline and monitor are consistent.

3.4 Geophone Orientation Estimation

Since the SR2020 receiver tools do not provide geophone orientation on their own, the geophone orientation has to be derived from a circular subset of shots around the borehole or using all source location simultaneously. In this case an approximate circle covering many azimuthal directions was used. Since the tool was removed and redeployed for the second data acquisition, the orientation of geophones does not remain constant between the baseline and monitor acquisition. The geophone orientation estimation had to be carried out for baseline and monitor independently. Figure 14 and 15 shows the hodogram display of a typical receiver level. The hodogram linearity for the incoming direct p-wave is of good quality for both baseline and monitor. While the linearity is comparable, the actual hodogram angles are different between baseline and monitor survey.

Figure 16-18 shows the same baseline seismic gather with various receiver rotations applied. Figure 16 shows all three components of a baseline seismic gather as it was recorded in the field. In Figure 17 all receivers have been rotated to the same EW-NS-V (XYZ) coordinate system. The line-up of downgoing energy on the various components becomes coherently aligned. While the (XYZ) rotated data is the starting point for all further processing, in Figure 18 the receiver is tilted in such a way that it points roughly towards the known source location. This particular orientation is useful for estimating and extracting the downgoing wave field, as for refined FirstBreak picking and deconvolution operator estimation.

Figure 19 – 21 repeats the display of those data rotations for the monitor survey. Qualitatively the same behavior can be observed. After rotating all receivers to a common coordinate system, energy becomes coherently visible on certain data components as we expect.

This TrueXYZ data set (EW-NS-V) is the basis for all further processing and has been stored as the reference data set for both baseline and monitor.
Figure 14. Baseline hodogram example, receiver 20.

Figure 15. Monitor hodogram example, receiver 20.
Figure 16. Baseline raw 3C data for mid offset.

Figure 17. Baseline trueXYZ data for mid offset.
Figure 18. Baseline V-to-Source data for mid offset.
Figure 19. Monitor raw 3C data for mid offset.

Figure 20. Monitor trueXYZ data for mid offset.
The downgoing wave field might incorporate a variety of wave field effects that are related to source location, source mechanism and source near surface effects. To remove such effects we design a deterministic deconvolution operator on the isolated downgoing wave fields, and then apply this deconvolution operator to the upgoing wave field after separation. The deconvolution operator is designed in a deterministic manner, such that only effects that are present in the downgoing wave field are taken into account. Since no statistical spectral enhancement or spiking is applied, this deconvolution operator is safe for any of the subsequent time-lapse processing steps.

Figures 22-25 show that an operator length of 800 msec is able to collapse the downgoing energy into a compact zero phase wavelet for both the baseline and monitor seismic gathers at various distances from the well. Although the baseline and monitor survey were collected within days of each other, differences in the downgoing wave fields are visible, mainly due to compaction of the near source area or other environmental changes. Thus, for each source location in the baseline and monitor survey a unique optimal source deconvolution operator filter is designed, that can be applied to the up-going reflected wave field in subsequent steps.
Figure 22. Baseline far offset Deconvolution filter 6,12,100,130Hz with 400,600 and 800 msec length.

Figure 23. Monitor far offset Deconvolution filter 6,12,100,130Hz with 400,600 and 800 msec length.
Figure 24. Baseline near offset Deconvolution filter 6,12,100,130Hz with 400,600 and 800 msec length.

Figure 25. Monitor near offset Deconvolution filter 6,12,100,130Hz with 400,600 and 800 msec length.
3.6 Velocity Model Construction

First break picking and QC on all gathers was performed using an automatic First Break picker followed by manual editing of individual picks. A set of picks was determined and an initial velocity model was estimated using nonlinear iterative least squares estimation.

A near well gather served as a basis for the velocity model inversion within the geophone array. Figure 26-27 show the baseline and monitor gather with the FirstBreak arrival overlaid. The wave forms as well as the picks are very consistent between the Baseline and Monitor, thus, picked direct arrival times are nearly identical.

Since the receiver array was located in a depth range that did not have any injection present, we do expect hardly any change to be present in the velocity function. Figure 29 shows the resulting velocity curves, the yellow and blue curves are inverted from the same source location for baseline and for the monitor, respectively. Their shape is nearly identical and in many places on the graph overlay each other. The slight discrepancy is likely to be within the picking error while the noise conditions were different.

Thus, a stable velocity function has been inverted within the array length. However, the depth range beneath the array does not provide direct transmission time measurements due to not having receivers present. Therefore, we used a scaled version of the p-wave sonic log to augment the velocity curve beneath the array. The sonic log samples velocity measurements at much higher frequencies than a VSP. However, since the smoothed and up-scaled sonic log is very similar in character to the VSP velocity curves that have been inverted, we estimate it be a good representation of the velocity model from the receiver array down to the injection zone and beyond.

In order to see if the general 1D velocity model can be extrapolated into a 3D model that is representative of the small region around the well under investigation, direct arrival times have been computed for all the source location into baseline and monitor survey. The reference elevation for this velocity model is 750 ft AMSL and all subsequent images are reference to that same datum.

Figures 32 and 33 show the computed versus picked direct arrival times for various baseline and monitor gathers respectively. In most cases the red picked curve overlays the blue computed curve with only minor discrepancies. Slight overall mismatches can arise if a near source effect has not been incorporated into the velocity model. In this case an overall slight shift is visible as a static shift. These static shifts will be analyzed subsequently in detail.
Figure 26. Baseline source at offset 166ft used in velocity estimation.
Figure 27. Monitor source at offset 166ft used in velocity estimation.

Figure 28. Baseline source at offset 59ft used in velocity estimation.
Figure 29. Estimated p-wave velocity profiles: yellow baseline at 166ft, blue monitor at 166ft. In most depth ranges the two velocity curves completely overlay.
Figure 30. Estimated p-wave velocity profile augmented by up-scaled sonic velocities.
Figure 31. 3D velocity volume with top at 750 AMSL.
Figure 32. First Break Pick and Predicted overlay on seismic Baseline data (West–East).

Figure 33. First Break Pick and Predicted overlay on seismic Monitor data (West–East).
3.7 Source Statics

Extensive data QC had been necessary, incorporating seismic header information and auxiliary observer logs, thus ensuring correct assignment of the source points. During the acquisition the near surface environment can be affected by local weather conditions, such as rain. The Baseline and Monitor acquisition occurred several days apart, during which local source coupling conditions could have changed.

Source statics estimation aims to remove any time shifts that might have been caused by a source specific timing effect. In this processing step we estimate source static values for Baseline and Monitor survey separately and compare their differences.

Using the available velocity model direct arrival times are computed from each source location to all receiver locations. This arrival is compared to the FirstBreak pick times and a model based source static value is computed. The overlays in Figure 32 and 33 show how well the FirstBreak picks match the computed arrival times, where the red and blue curve should overlay each other nearly identically for each source gather.

Figure 34 shows the estimated source static values as computed. The left hand side shows an interpolated view that exaggerates some of the features, while the right hand displays show the static value color coded while plotted at the actual individual source locations. Small source static values are near white color coded, while extreme positive or negative are blue and red respectively. The source statics values are generally small. There are several larger values, but they are generally located at the boundary of the source pattern, limiting the influence of such a source on the interior image.

Figure 35 shows the statics difference values between Baseline and Monitor surveys. In general the discrepancies are small indicated by the very pale colors. Nevertheless, these differences need to be compensated for. Some of the larger statics values at the edge of the acquisition can differ from Baseline to Monitor, since the source locations are acquired at different times and thus might have significantly different near surface conditions.

In preparation for the following processing steps, the source static values have been applied individually to both Baseline and Monitor data in order to remove any predictable source static effects.
Figure 34. Top) Baseline statics map, bottom) Monitor statics map; left) gridded, right) on source locations.
3.8 Wave Field Separation

Figures 36-37 show the wave field after noise suppression and deconvolution, while Figures 38-46 show the separated and enhanced up-going wave fields. Since the survey geometry is dominated by near vertical reflection geometry, the separation has been carried out using a median filter, in combination with a Radon filter to pass up-going P-wave reflections only.

These up-going wave fields contain the reflected P-wave field. Although the processing steps were identical for Baseline and Monitor surveys, there are differences visible in the up-going wave fields. Wave field differences can be caused by changing noise conditions and would manifest themselves ultimately in variations in the up-going wave fields.
Figure 36. Baseline gathers after noise suppression and deconvolution (west-east).

Figure 37. Monitor gathers after noise suppression and deconvolution (west-east).
Figure 38. Upgoing baseline gathers East of well.

Figure 39. Upgoing monitor gathers East of well.
Figure 41. Upgoing baseline gathers South of well.

Figure 42. Upgoing monitor gathers South of well.
Figure 43. Upgoing baseline gathers West of well.

Figure 44. Upgoing monitor gathers West of well.
Figure 45. Upgoing baseline gathers North of well.

Figure 46. Upgoing monitor gathers North of well.
3.9 Imaging

All up-going wave field data, at coincident source point locations both Baseline and Monitor, were pre-stack depth migrated using an amplitude preserving Pre-stack Kirchhoff Depth Migration algorithm using the identical velocity model, as shown in Figure 31.

The depth migration was conducted with the following set of parameters:

- Maximum incidence angle: 45 degrees
- Maximum operator dip: 10 degrees
- True-amplitude compensation
- Maximum length: 8500ms
- Baseline and Monitor use only identical source locations

The resulting image volumes are depth volumes where the reference top elevation is given as 750 ft AMSL. The images are limited by the available source pattern. The source location impact is visible on both Baseline and Monitor images. However since both footprints are identical for Baseline and Monitor survey, we can still attempt to extract the relative time-lapse change. Amplitudes are preserved in the migration algorithm and amplitude values are normalized, such that low and high fold areas show consistent amplitudes. Both Baseline and Monitor data use the same velocity for depth migration.

Figure 47 shows an up-going wave field with the expected reflection time and depth labeled. Such as reflection signal will map into a subsurface depth image with amplitude and character changes.

Figures 48-51 show West-East and South-North image slices of the Baseline and Monitor through the borehole location. When comparing Baseline and Monitor images the shallow and deep marker horizons are clearly visible and correlatable. Key features match in Baseline and Monitor as they should, while detailed responses vary due to different noise conditions during Baseline and Monitor survey. Such noise conditions can cause variations of smaller scale reflection responses. Although the velocity model did not incorporate any subsurface dip in the vicinity of the borehole, a very small general up-dip to the North East is visible on all those slices.

Figure 52 and 52 show slices in the time domain and incorporate Zero Offset corridor Stacks. However, the nearest offset shot that was used to generate the corridors tended to have tube wave and other noise present which impacts the correlation of reflectivities with the images. In low noise areas the ties are visible.

The image character above 5000 ft is consistent between Baseline and Monitor, while below 5000 ft differences are more pronounced.
Figure 47. Approximate expected target reflection in monitor gather.

Reflection of injection depth at 5070ft, upgoing about 650ms
Figure 48. Depth migrated baseline image (South-North).

Figure 49. Depth migrated monitor image (South-North).
Figure 50. Depth migrated monitor image (West-East).

Figure 51. Depth migrated monitor image (West-East).
Figure 52. Depth migrated baseline image in time with corridor stack.

Figure 53. Depth migrated monitor image in time with corridor stack.
4.0 Time-Lapse Observations

During the deconvolution process we had applied the optimum deconvolution operator as estimated on the Baseline and the Monitor individually. The following Figure show the deconvolution operators for an identical set of the source points in comparison for Baseline and Monitor. As Figure 54 shows below, in general the Baseline source deconvolution operators (left) exhibit a greater variability than the Monitor deconvolution operators (right). Slight variations in deconvolution filter responses are visible for corresponding Baseline and Monitor pairs, but generally are consistent as applied.

Figure 54. Decon operators for left) Baseline right) Monitor for each individual source location.
In an attempt to alleviate amplitude differences that might arise due to different noise patterns, source or near surface conditions, both Baseline and Monitor depth images were equalized by normalizing their RMS differences in a marker window above the injection zone. The estimated scale was applied to the Monitor, and subsequently the Baseline was subtracted from the Monitor. An additional residual image static shift was estimated, but the correlation based approach did not find any significant applicable shifts to be necessary to get a more accurate Baseline to Monitor image alignment.

While the previous Figures 48-53 show the overall slices, the following Figures focus on a smaller image window that includes the injection zone. Amplitude responses are continuous in the interior region of the image. As the edges of the images are approached, the low fold and limited source distribution causes inconsistent amplitudes at the edges. This is particularly visible on the left and right hand side of the difference image slices in Figure 57 and 60. Figure 55-57 show image slices extending from South to North, while Figures 58-60 show the corresponding West to East slices. The well is located at x=1367587 and y=2173048, roughly in the center of the slices.

After image subtraction the near-well amplitude residual extends in the north–easterly direction away from the injection well. The feature is highlighted on Figure 55-60 and corresponds to the depth slice as extracted at approx. depth 5170 in Figure 61, in close proximity to the CO2 injection interval.

Due to having limited and non-uniform source layout around the injection well due to permitting, environmental and logistical restrictions, and due to the receiver array restrictions to be placed safely high in the well, the incidence angle range for the depth imaging was limited. The depth image is constructed using near vertical reflection responses, and thus limits the lateral resolvability. The vertical resolution however is maintained.
Figure 55. Depth migrated baseline image South-North slice in depth.
Figure 56. Depth migrated monitor image South-North slice in depth.
Figure 57. Depth migrated difference image South-North slice in depth.
Figure 58. Depth migrated baseline image West-East slice in depth.
Figure 59. Depth migrated monitor image West-East slice in depth.
Monitor-Base Image WE

CDP_Y: 2173048

78 traces plotted

Figure 60. Depth migrated difference image West-East slice in depth.
5.0 Conclusions

A spatially limited time-lapse VSP data set was collected before and after CO2 injection into a storage formation. Although the data exhibited noise conditions that were not ideal, the subsequent processing steps tried to minimize those effects and isolated the up-going reflected signal for imaging purposes. Using a consistent 3D velocity model for imaging both the Baseline and Monitor data set ensured that the kinematics of the overburden were identical for the data sets. In and around the injection zone the velocities and thus the images are expected to differ. After imaging both Baseline and Monitor survey, the respective image volumes were normalized based on a marker window above the injection zone, such that RMS amplitude values were consistent between the two data sets. The difference image shows amplitude variations in and around the injection window with a slight up-dip to the NE direction.
Appendix A. Delivered Digital Data.

1) KGS_3DVSP_Blan1_TrueXYZBaseline.segy (Baseline VSP data, SEGY)
2) KGS_3DVSP_Blan1_TrueXYZMonitor.segy (Monitor VSP data, SEGY)
3) Velocity Model (SEGY)
4) KGS_3DVSP_Blan1_Baseline_Depth-122010.segy (Baseline Image, SEGY)
5) KGS_3DVSP_Blan1_Monitor_Depth-122010.segy (Monitor Image, SEGY)

6) Summary Report