Kentucky Geological Survey
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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

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Abstract

Two three-dimensional vertical seismic profiles (3D-VSP) were acquired at the KGS Marvin Blan No. 1 CO_2 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 CO_2 and then 584 m^3 of 2 percent potassium chloride water (to displace the remaining CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 and saline water) alter the local pressure regime within the host rock, as well as change the bulk density of that rock where the injected fluids displace pore fluids that are of a different density. These localized pressure and density changes alter the elastic properties of the rock body, which therefore affect the seismic response it produces. By comparing two duplicate surveys acquired immediately before and after injection (using identical source, receiver, and processing parameters), any differences in the resulting data sets can be assumed to be a product of that injection.

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 CO_2 injection test program of the Marvin Blan No. 1 well. The objective of this survey was to model the extent of the CO_2 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

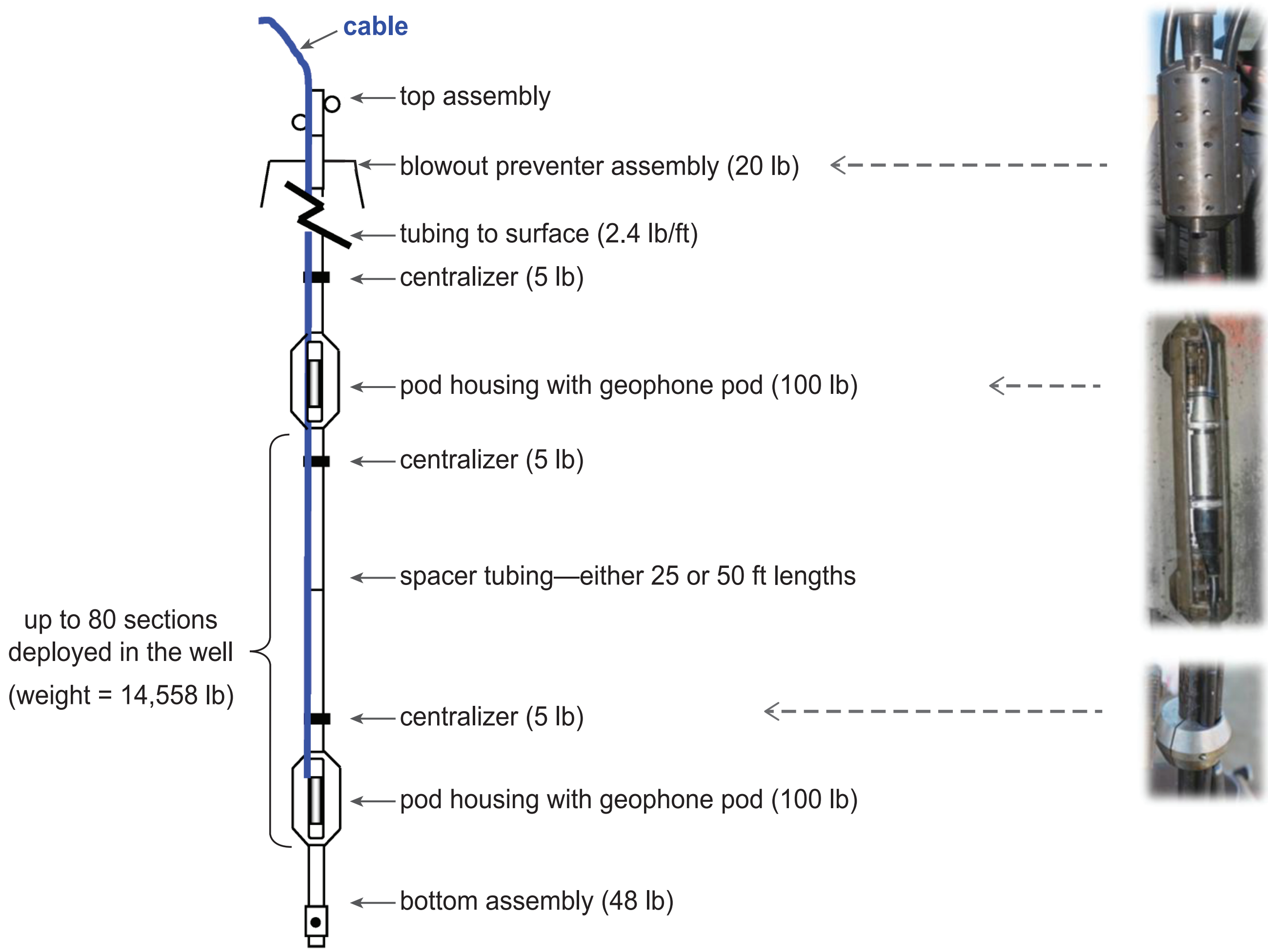


Figure 1. Mechanical component details of SeisRes-2020's downhole 80-geophone array tool. Each pod housing contains a single three-component geophone (see Figure 2).

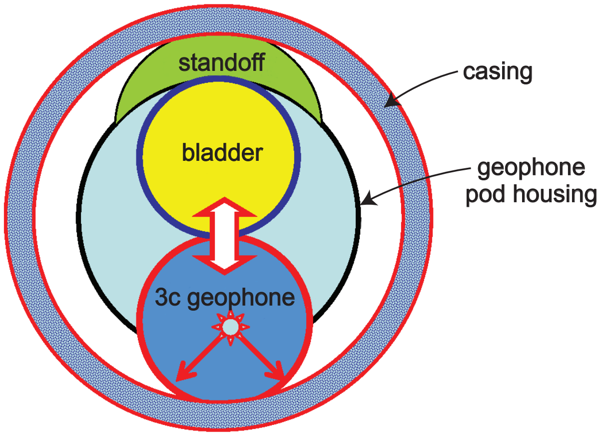


Figure 2. Schematic diagram of geophone placement in a wellbore. After air bladders were lowered to the appropriate depth, they are inflated, which secures the three-component (3C) geophones to the well casing, assuring adequate acoustical coupling to the surrounding geology.

casing at a depth of 1,115.6 m, about 457 m above the injection interval in the Gunter. This placement was recommended by SeisRes-2020 and allowed the geophone string to be placed in the well casing to ensure good acoustic coupling (there were concerns the rugosity of the wellbore below casing would negatively affect acquisition).

Initially, SeisRes-2020 recommended a source layout that consisted of a grid of 1,022 surface source locations (with 22.9-m spacing between points) within a 427-m radius of the Marvin Blan No. 1 wellhead, and two walkaway profile lines for calibration purposes that would cross at the wellhead (a 1,524-m north-south line and a 1,166-m east-west line). This plan was later modified because much of the area in the recommended 427-m radius around the well included areas with steep surface slopes or that were heavily wooded. These aspects made these areas inaccessible to the mobile seismic sources (2.4 m × 9 m vibrator trucks) required for the acquisition. The total number of available source locations was further limited by the presence of an active oil pipeline that crosses the Blan farm property just south of the Marvin Blan No. 1 wellhead. Because the operator of the pipeline was concerned that the weight and operation of the vibrator trucks could damage the pipeline, a 15-m-wide buffer zone was defined over the pipeline right-of-way where seismic-source vibrations were not permitted (Fig. 3).

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_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_2, followed by 584 m^3 of 2 percent potassium chloride water solution to displace CO_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.

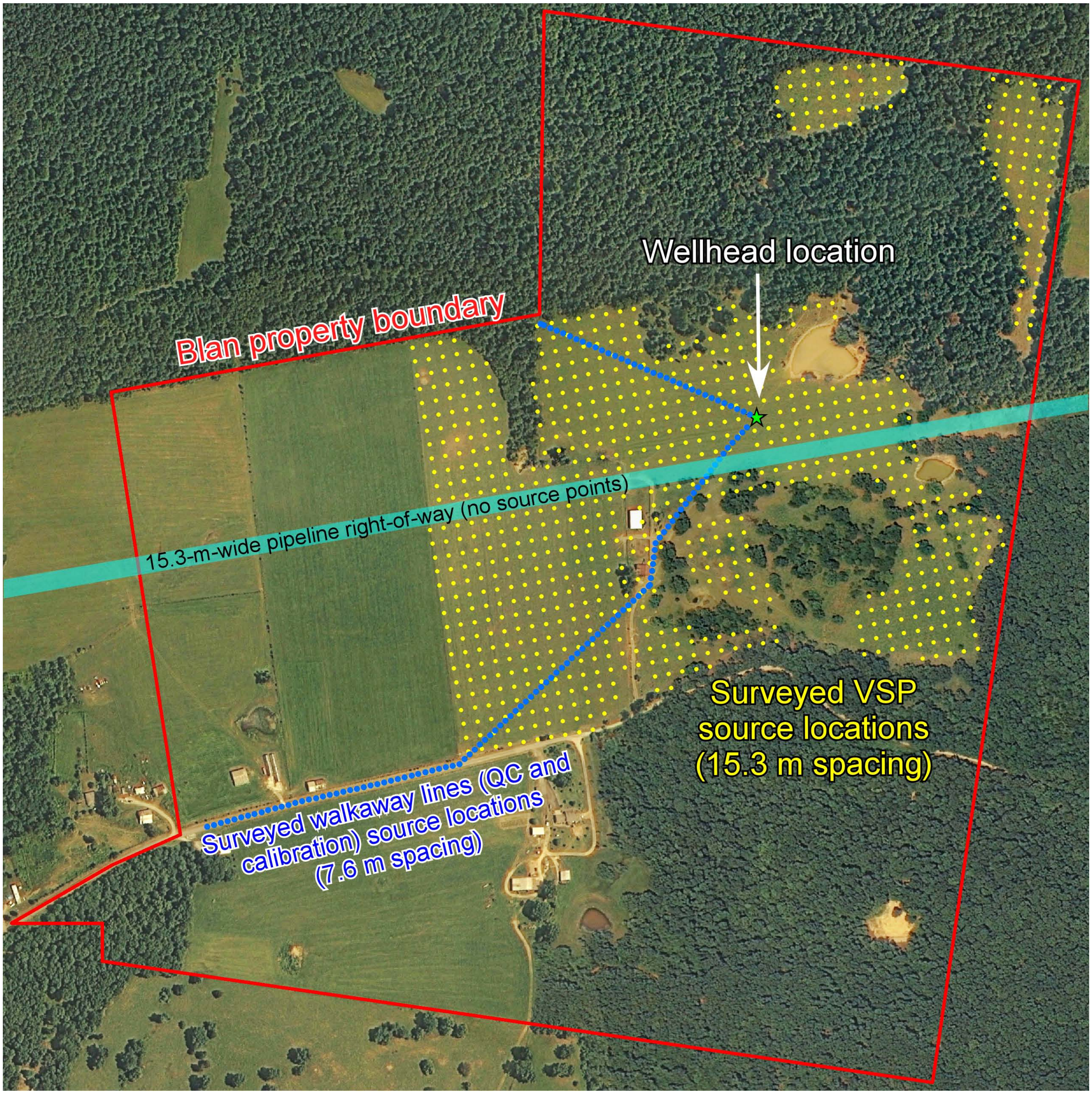


Figure 3. Blan property showing locations of seismic-source points. See Appendix 2 for additional maps. A vertical array of recording geophones was lowered into the well near the center of the group of source points (well location indicated by green star).

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.
3. Geophone orientation estimation.
4. Spectral analysis.

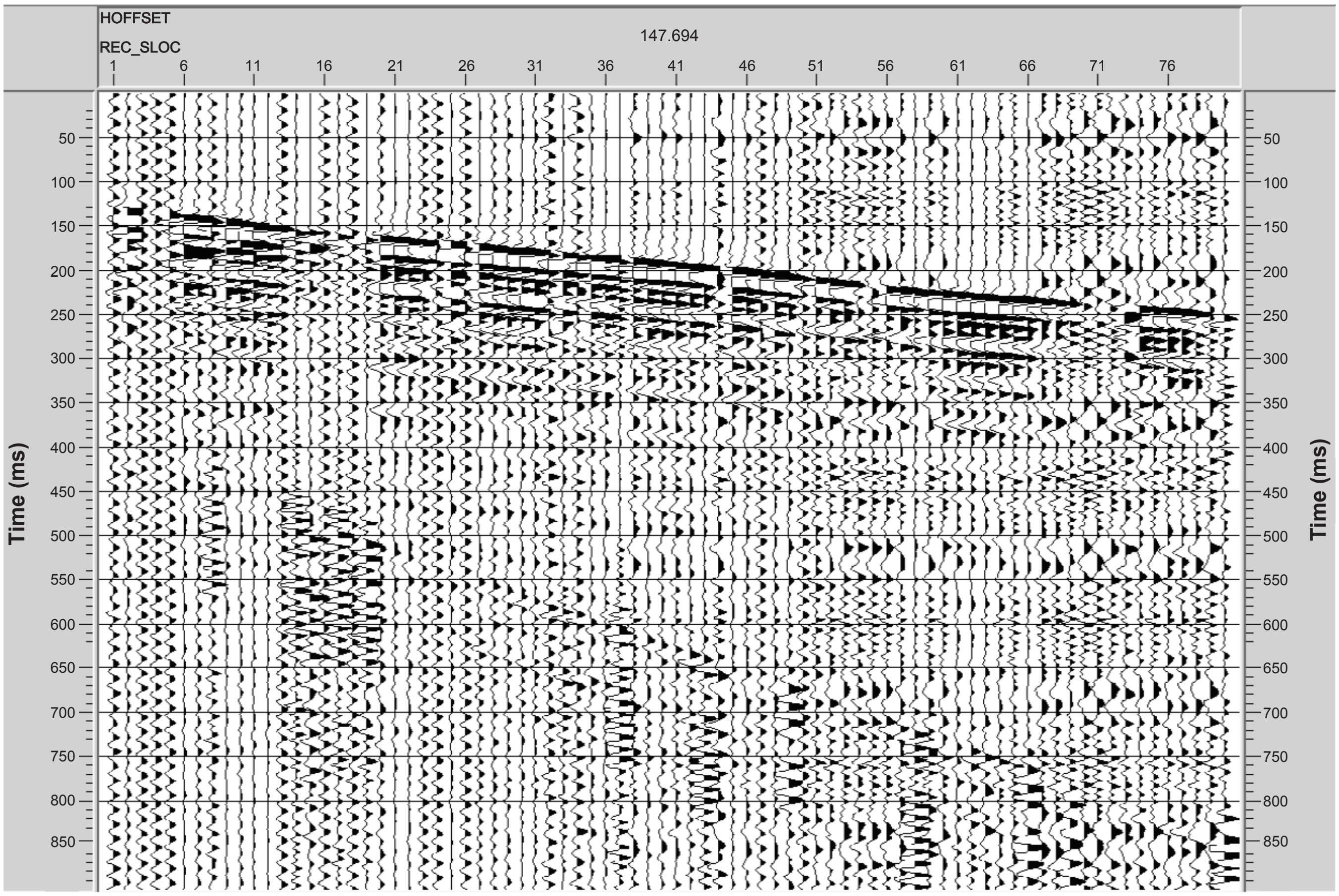


Figure 4. Sample single-event raw seismic data gather from the 80 downhole geophones. The relatively high degree of electrical 60-Hz noise will be reduced later using appropriate frequency filters.

5. Standard zero-offset processing.
6. P-wave direct-arrival inversion.
7. Zero-offset velocity profile estimation.
8. Three-dimensional velocity model extrapolation.
9. Deconvolution operator design.
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

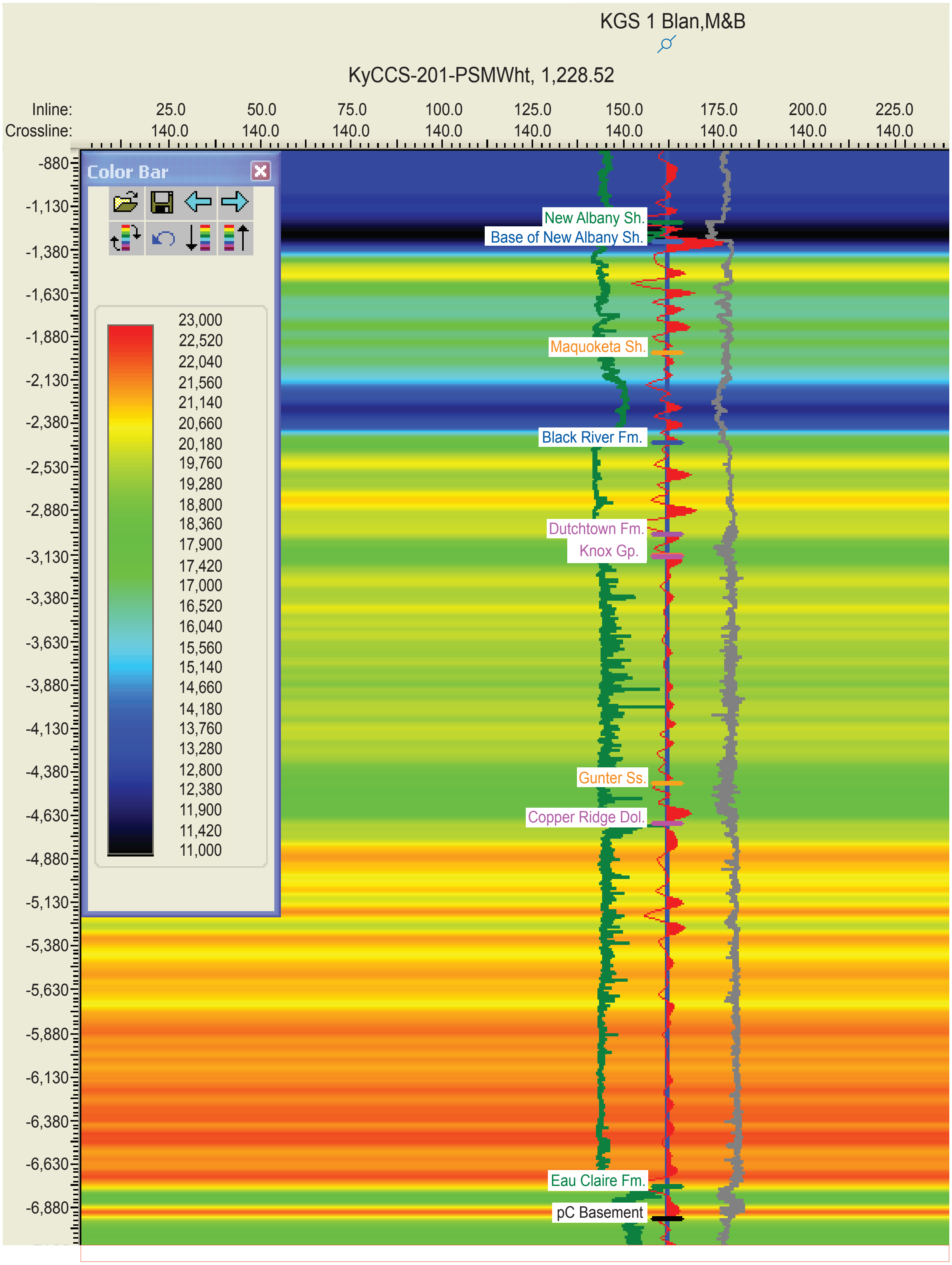


Figure 5. Sonic velocity model (ft/s) used for VSP correlation and depth conversion. Gamma-ray (green) and acoustic (gray) logs from the Marvin Blan No. 1 well are marked for reference. A synthetic seismogram wavelet produced from the well logs is overlain in red.

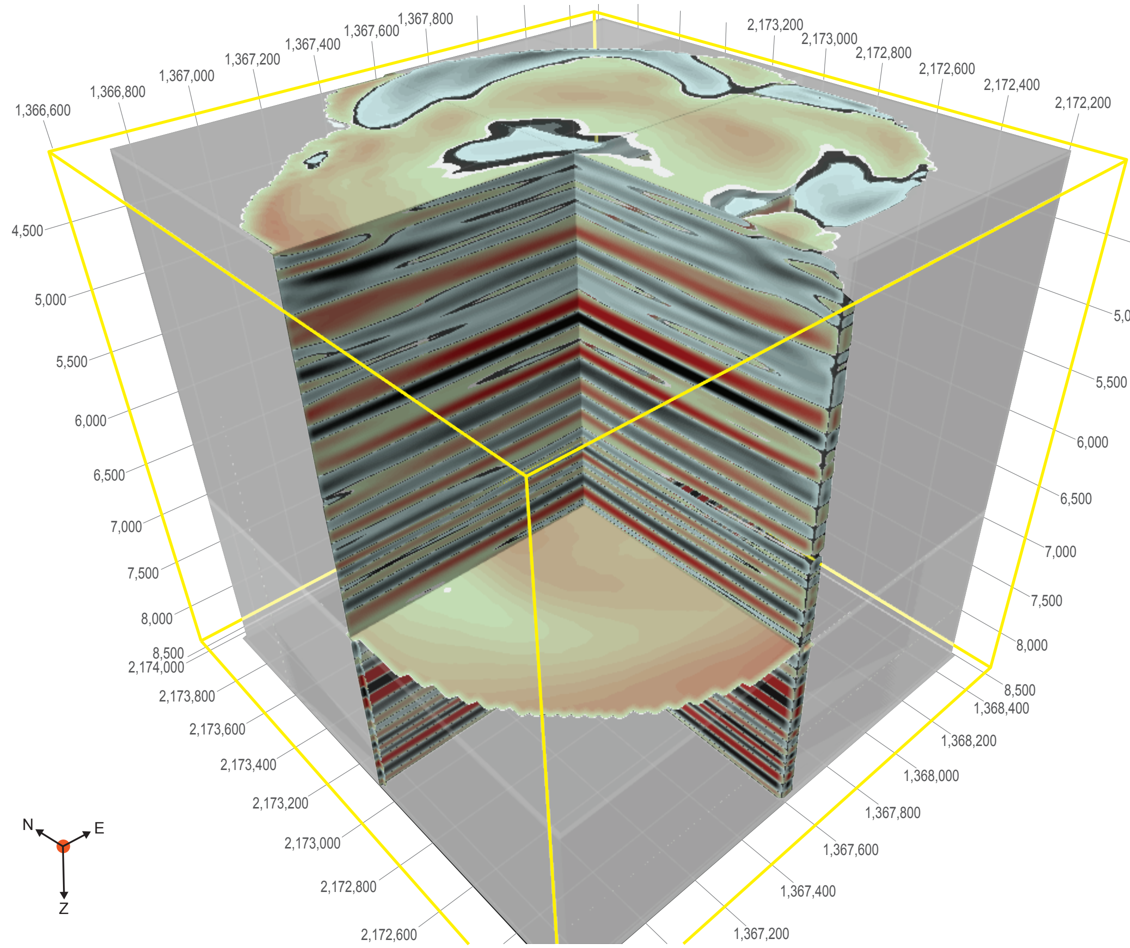


Figure 6. Processed 3D data of preinjection (baseline) VSP survey centered on well, displayed with the southwest quadrant removed to show internal reflections. Positive reflections are displayed in black and negative wavelet reflections in red. Unlike 3D surface seismic surveys, the data cube for a VSP is actually cylindrical because all of the receiving geophones are located in a vertical line in the borehole. The lateral dimensions of the data volume (yellow cube) are equivalent to the blue square in Figure 7.

injection of 333 metric tons of supercritical CO_2. The dimensions of the full VSP data volumes (Figs. 6–7) are 488 m × 488 m × 2,590 m deep (lateral extent equivalent to the blue square in Figure 8). The limited-depth-interval difference volumes encompassed a volume of 488 m × 488 m × 457 m thick. The desired intent, or best-case scenario for this task, was to image the injected plume of CO_2 in the subsurface in three dimensions, and, if successful, potentially act as a model technique for future subsurface storage verification tests. Although some changes were evident between the pre- and post-injection surveys (Figs. 9–11), the lateral and vertical extent of the plume could not be determined from these data.

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

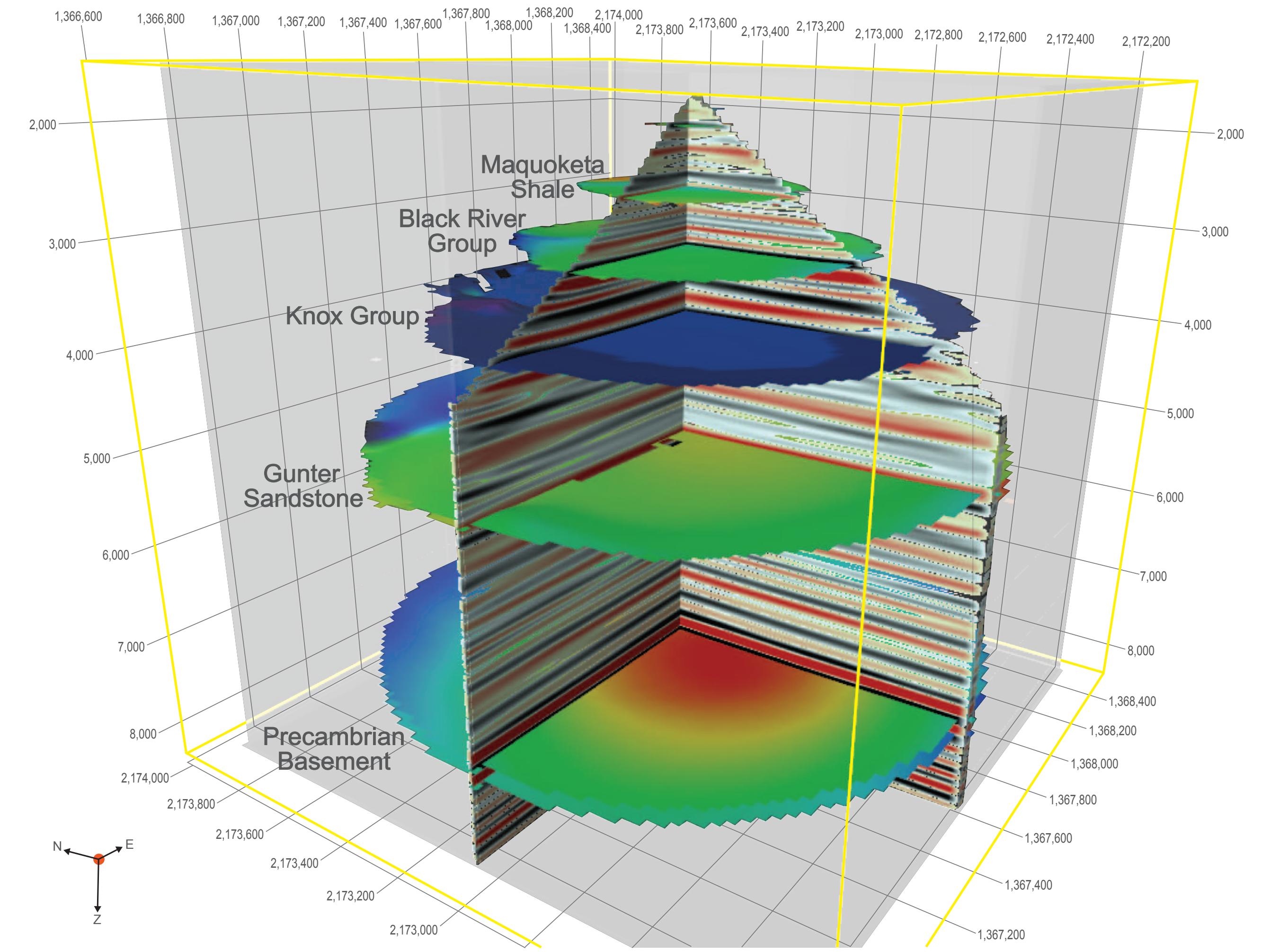


Figure 7. North-south and east-west profiles of preinjection VSP data with selected stratigraphic horizons interpreted across the 3D space. Positive reflections are displayed in black and negative wavelet reflections in red.

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 CO_2 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 CO_2 plume using the finite-difference method, some of the anomalies in the results can be explained by the presence of the supercritical CO_2. In addition to the changes in the wavelet character described above and illustrated

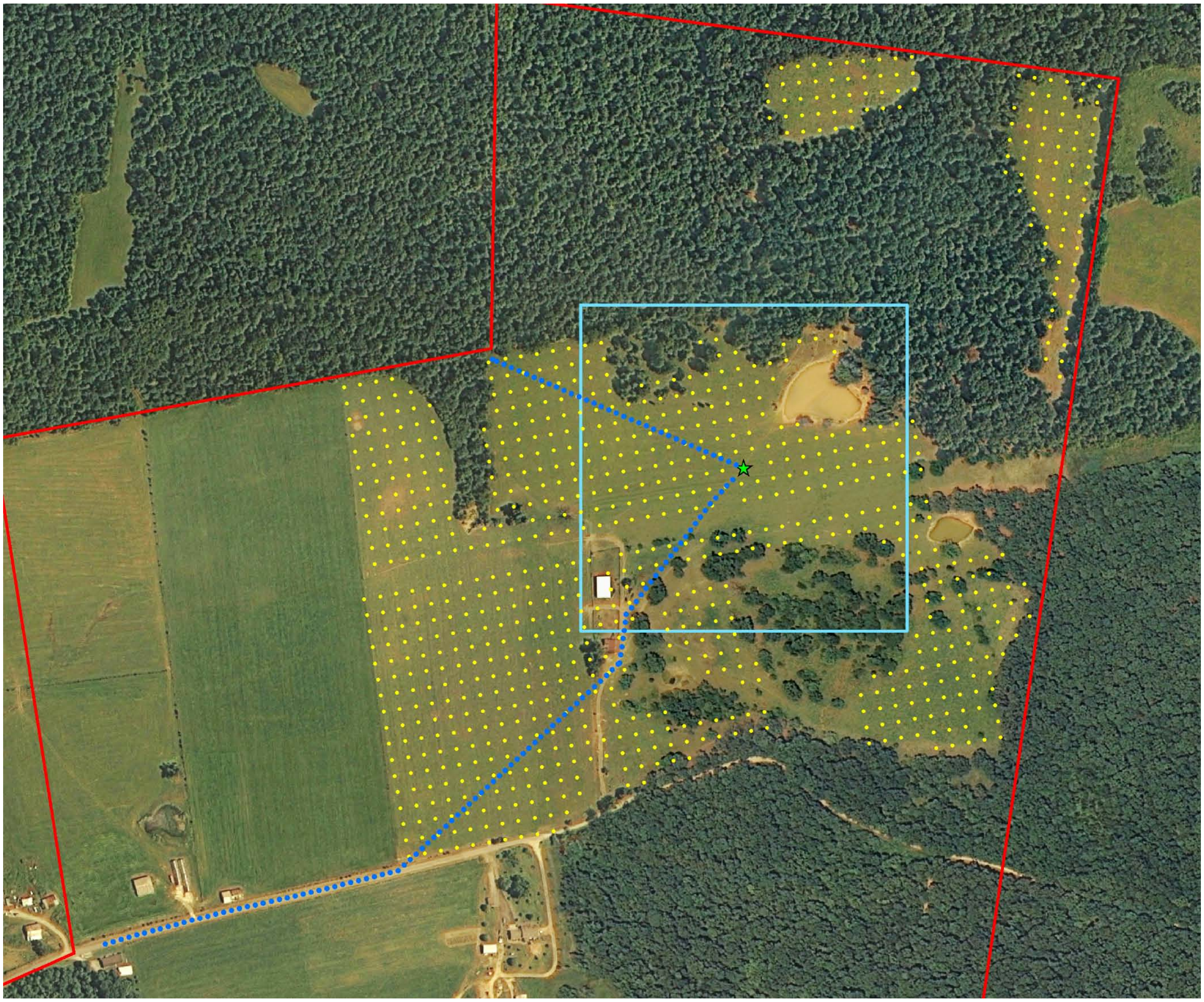
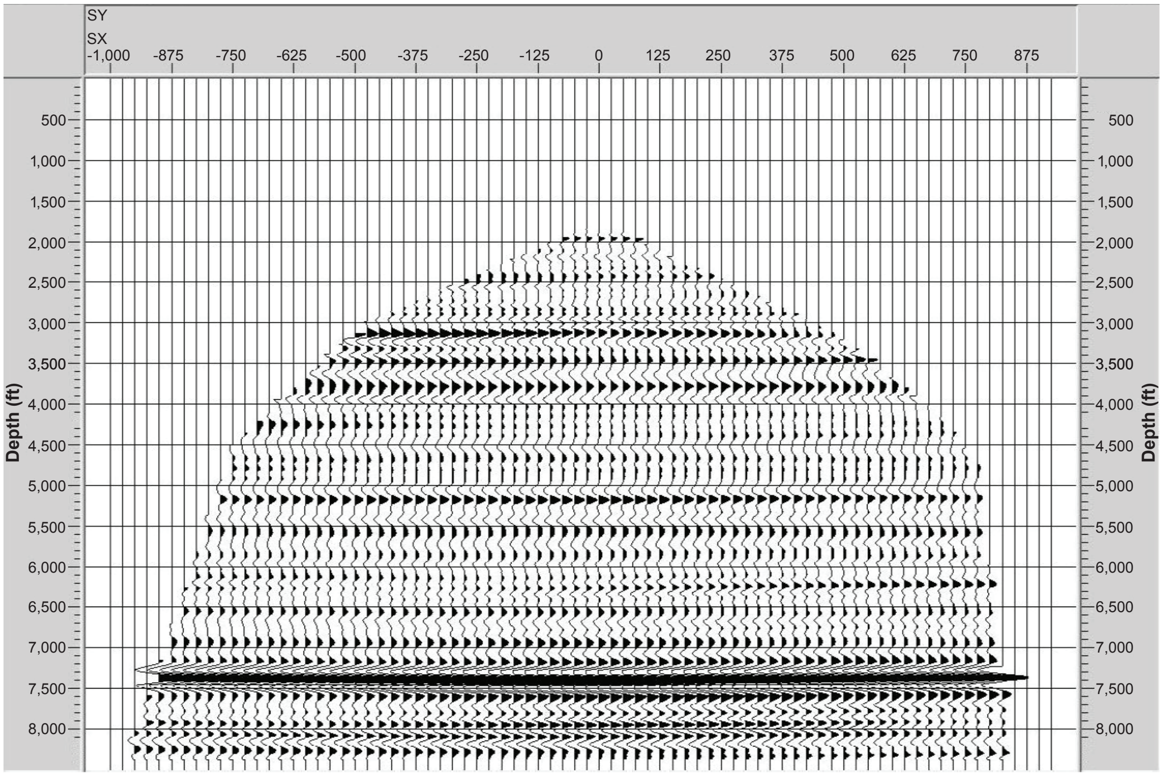


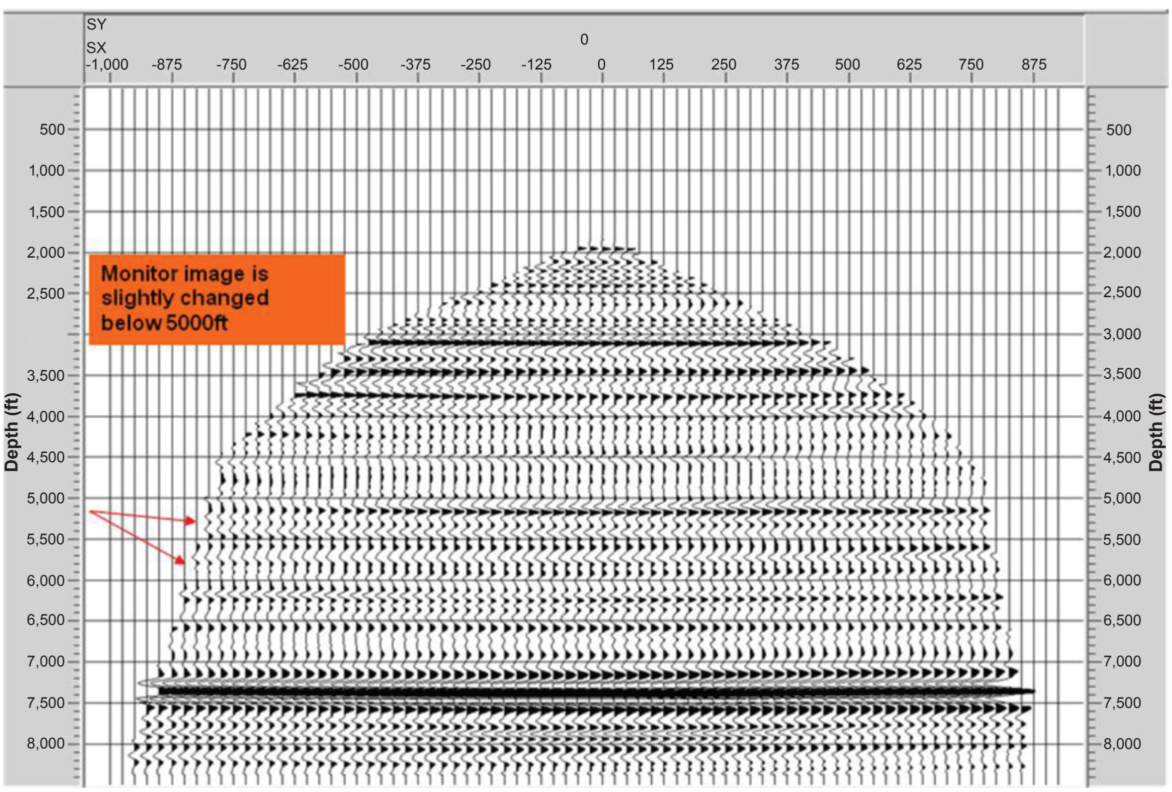
Figure 8. Areal footprint of the processed VSP data cube. Data-cube location (highlighted blue square) centered over wellhead. Yellow points are 3D acquisition source locations and the dark blue points are source locations for the two walkaway profiles used for quality control and calibration of processing techniques.

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 CO_2) 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 CO_2 (Fig. 12). In an attempt to investigate this possibility, the depth to this reflection was mapped and contoured for both the preinjection (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



Depth-migrated monitor image (west-east).



Depth-migrated monitor image (west-east).

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.

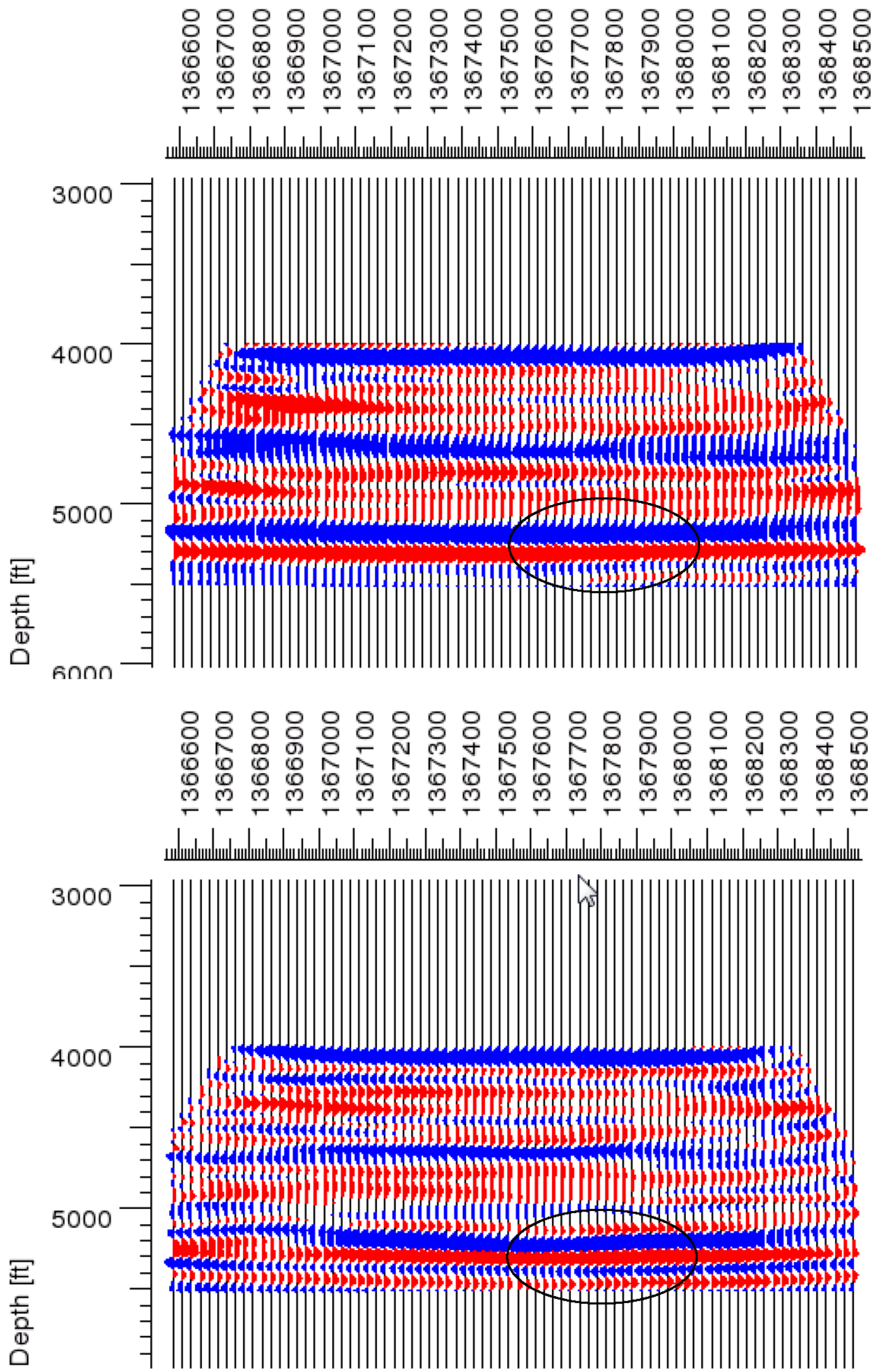


Figure 10. West-east depth-migrated image slices across well location, focused on the depths within and just above the injection zone. Upper image is from the preinjection survey and lower image is the post-injection survey of the same profile. Note the difference in wavelet character (highlighted by black oval) in the injection zone (Gunter Sandstone). Positive reflections are displayed in red and negative wavelet amplitudes are in blue.

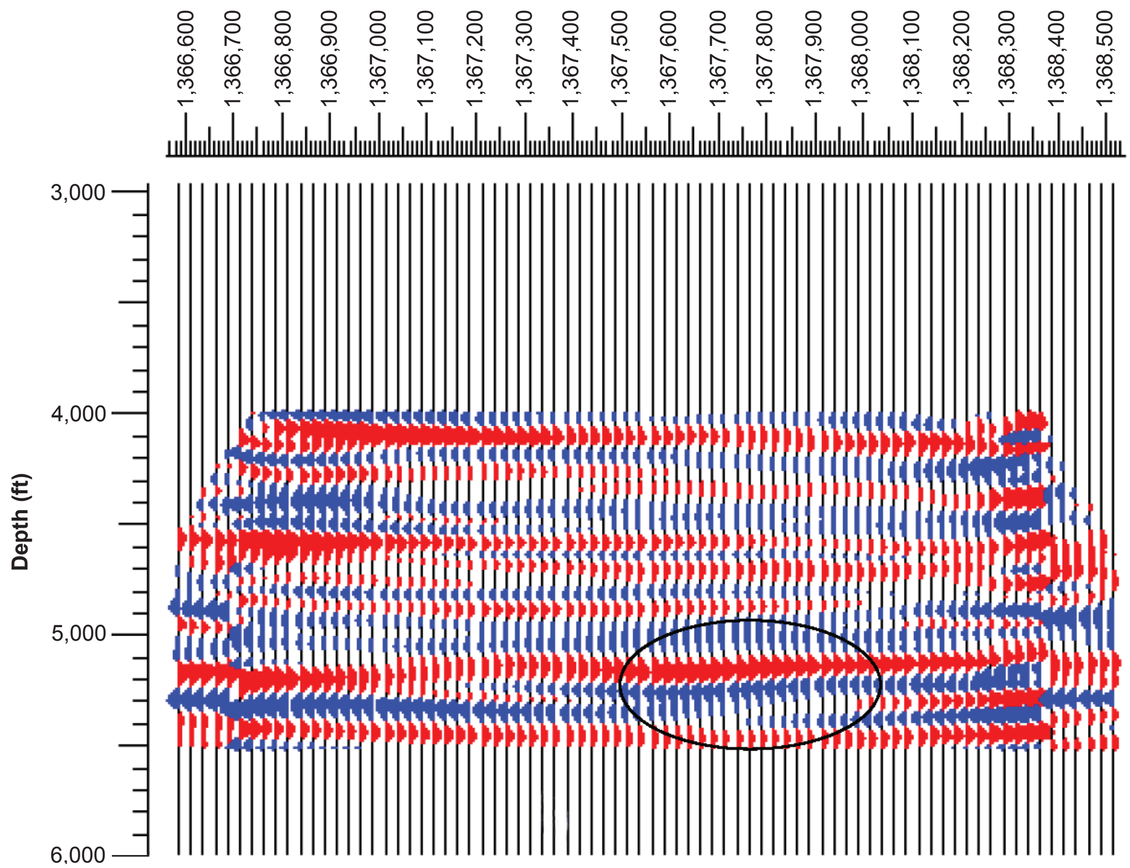


Figure 11. Depth-migrated west-east slice-difference image (post-injection seismic response subtracted from the preinjection response), focused on the injection depth. Positive reflections are displayed in red and negative wavelet amplitudes are in blue.

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 CO_2 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

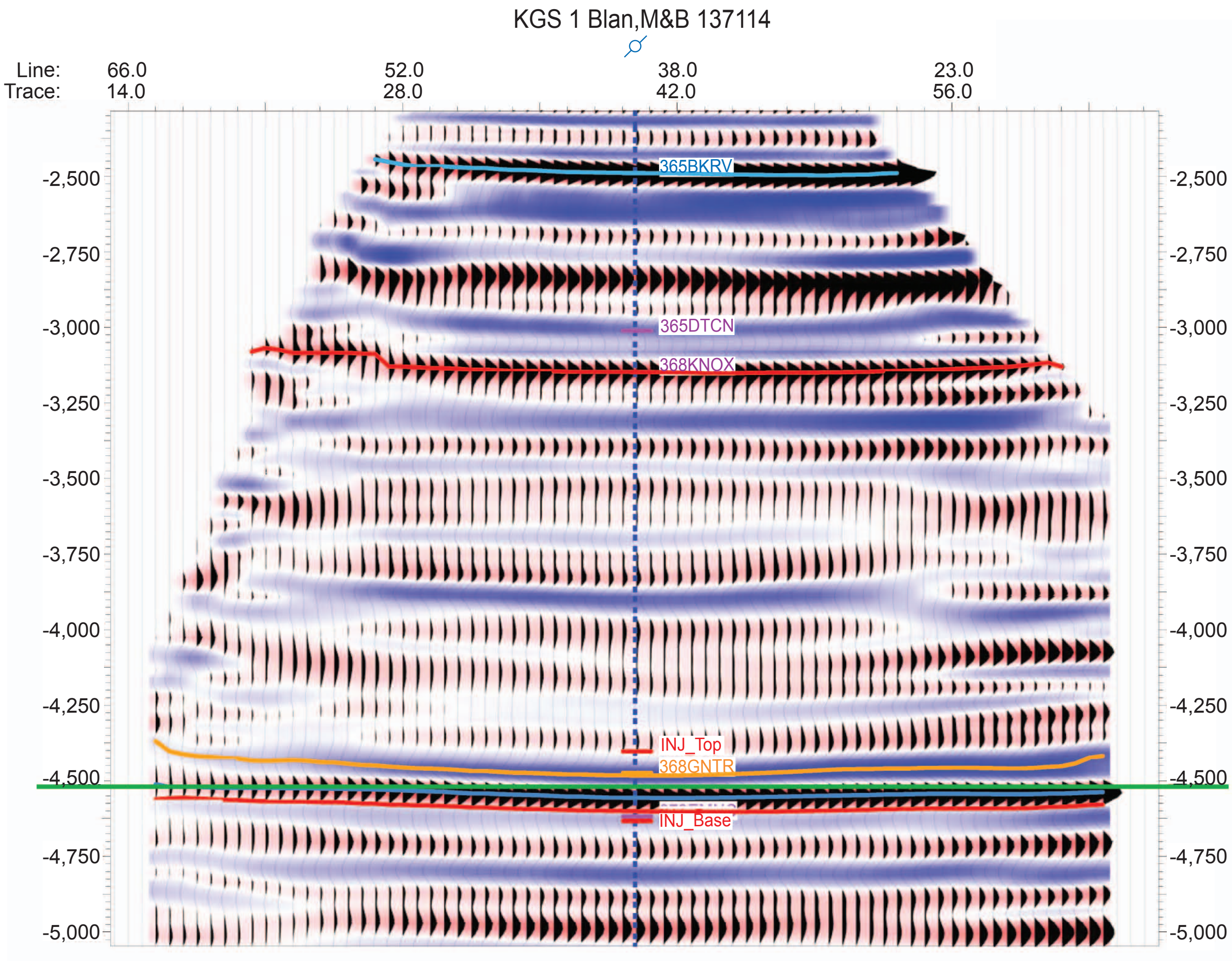


Figure 12. Northwest-southeast depth-migrated seismic-amplitude profile of the post-injection survey. Note slight apparent downwarping or pull-down of light blue horizon relative to horizontal (bold green line overlay just below –4,500 ft) near the well location (dashed blue vertical line). The top and 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.

that could affect the ability to monitor the reservoir over time using seismic data.

Acknowledgments

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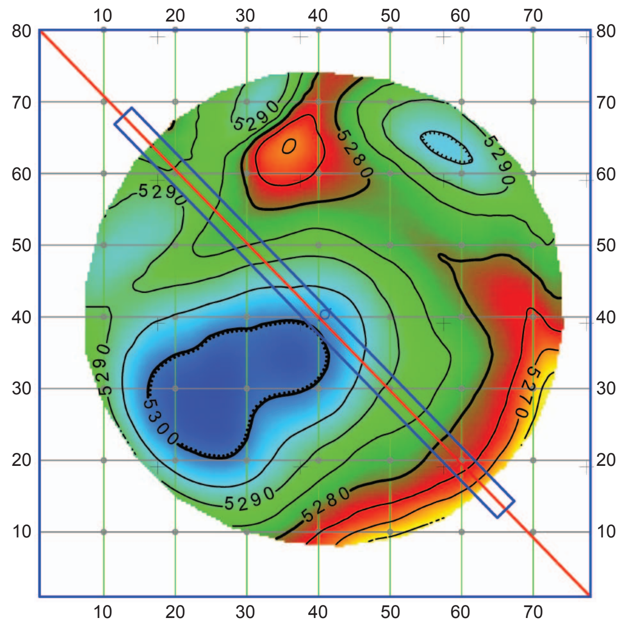

Figure 13. Calculated depth of the mid-Gunter reflection prior to CO_2 injection. Depth is in feet below the reference datum. The light blue horizon corresponds to the mid-Gunter reflection in Figure 12, and the bold red northwest-southeast line corresponds to the location of the profile shown in Figure 12.

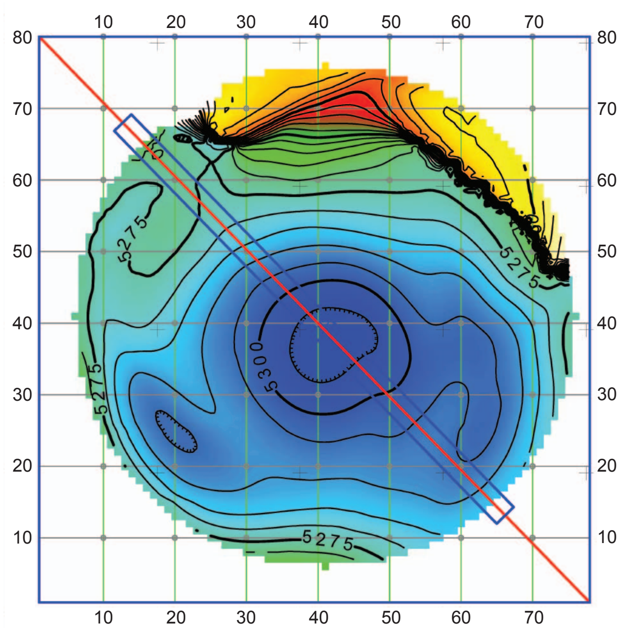

Figure 14. Calculated depth of the mid-Gunter reflection after CO_2 injection. Depth is in feet below the reference datum. The bold red northwest-southeast line corresponds to the location of the profile shown in Figure 12.

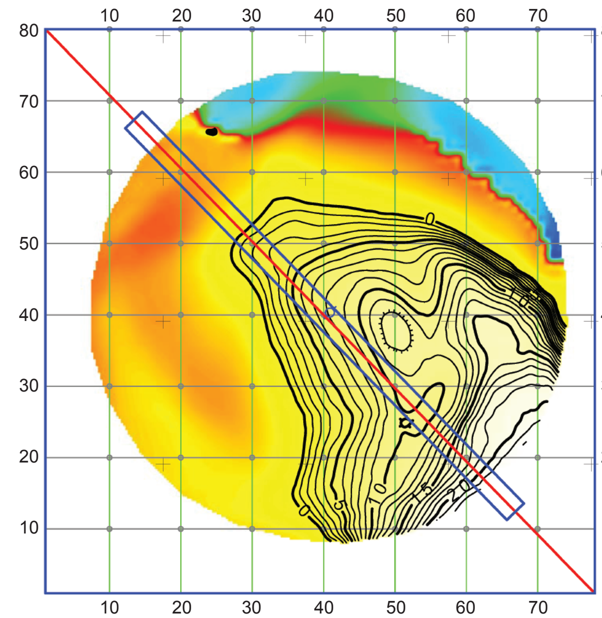

Figure 15. Calculated depth differential of the mid-Gunter reflection between the pre- and post-injection surveys. Positive values (deeper after injection) are contoured in feet.

References Cited

Dahlhaus, L., Garnett, A., Whitcombe, J., Galybin, K., and Shafiq, M., 2012, Onshore time-lapse borehole seismic project for CO_2 injection monitoring: Australian Society of Exploration Geophysicists Extended Abstracts, v. 2012, p. 1–4.

Li, G., 2003, 4D seismic monitoring of CO_2 flood in a thin fractured carbonate reservoir: The Leading Edge, v. 22, p. 690–695.

Majer, E.L., Daley, T.M., Korneev, V., Cox, D., Peterson, J.E., and Queen, J.H., 2006, Cost-effective imaging of CO_2 injection with borehole seismic methods: The Leading Edge, v. 25, p. 1290–1302.

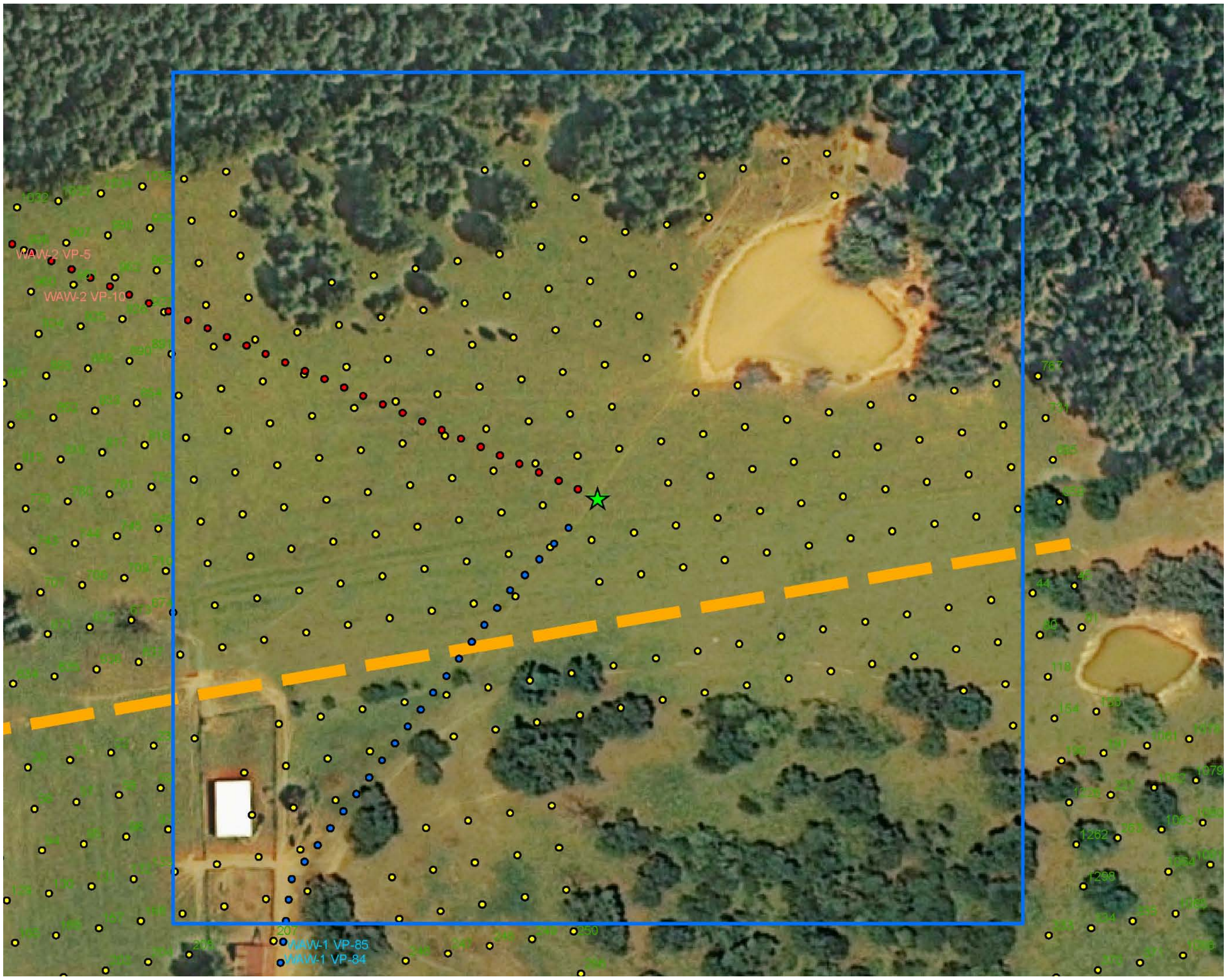

Figure 16. Detailed view of VSP survey area outlining the extent of the final data volume. The areas in Figures 13 through 15 with highly anomalous values correspond to the regions with the least amount of input data because of limited seismic source points.

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