Plains CO_2 Reduction (PCOR) Partnership
Energy & Environmental Research Center (EERC)

TIME-LAPSE MONITORING USING VERTICAL SEISMIC PROFILES (VSPs), BELL CREEK OIL FIELD, MONTANA

Plains CO_2 Reduction (PCOR) Partnership Phase III
Task 13 – Value-Added Report

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EXECUTIVE SUMMARY

The Plains CO_2 Reduction Partnership (PCOR) Partnership, led by the Energy & Environmental Research Center (EERC), is working with Denbury Resources Inc. (Denbury) to study associated carbon dioxide (CO_2) storage incidental to commercial enhanced oil recovery (EOR) at the Bell Creek oil field located in southeastern Montana, which is operated by Denbury Onshore LLC. Site characterization, modeling, simulation, and reservoir monitoring were completed as part of the PCOR Partnership's assessment of associated storage at Bell Creek. As part of this effort, several seismic data sets have been acquired, including 2-D and 3-D surface seismic, vertical seismic profiles (VSPs), and passive seismic data.[1]

A baseline and two monitor 3-D VSP data sets were collected at Bell Creek as part of the deep subsurface-monitoring program. The purpose of the surveys was to assess time-lapse changes in the reservoir due to CO_2 around two observation wells. The VSP data were processed independently by two contracted processing companies and used for time-lapse analysis. Comparison of the baseline VSP data processed by each company showed several differences in reflection characteristics. These differences were likely caused by one company using a subset of the baseline VSP data or the result of the incorrect application of the amplitude- and phase-compliant processing algorithms, which are necessary to preserve time-lapse changes.

While time-lapse VSPs have been proven to be applicable for reservoir monitoring at other sites,[2] time-lapse VSP results were inconclusive at Bell Creek. Time-lapse comparison of the VSP data produced ambiguous results that could not be used to identify time-lapse differences in the reservoir. There is uncertainty about whether these results are related to differences in acquisition parameters between the baseline and monitor surveys that were not overcome in data processing or, similarly, as with the baseline survey, incorrect application of data-processing algorithms. The time-lapse VSP results are in stark contrast to the time-lapse 3-D surface seismic results at Bell Creek which yielded outstanding results, allowing CO_2 migration to be tracked and adding value to oilfield operations by illuminating previously unknown geologic features of the reservoir.

[1] Salako, O., Livers, A.J., Burnison, S.A., Hamling, J.A., Wildgust, N., Gorecki, C.D., Glazewski, K.A., and Heebink, L.V., 2017, Analysis of expanded seismic campaign: Phase III Task 9 – Deliverable D104. Plains CO_2 Reduction Partnership Deliverable Report for U.S. Department of Energy National Energy Technology Laboratory Cooperative Agreement No. DE-FC26-05NT42592, EERC Publication EERC-10-09, Grand Forks, North Dakota, Energy & Environmental Research Center, June.

[2] O'Brien, J., Kilbride, F., and Lim, F., 2004, Time-lapse VSP reservoir monitoring: The Leading Edge, v. 23, no. 11, p. 1178–1184.

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INTRODUCTION

The Plains CO_2 Reduction Partnership (PCOR) Partnership, led by the Energy & Environmental Research Center (EERC), is working with Denbury Resources Inc. (Denbury) to study associated carbon dioxide (CO_2) storage incidental to commercial enhanced oil recovery (EOR) at the Bell Creek oil field located in southeastern Montana, which is operated by Denbury Onshore LLC. Site characterization, modeling and simulation, reservoir monitoring, and risk assessment were completed as part of the PCOR Partnership's assessment of associated storage at Bell Creek. Several seismic data sets were acquired for site characterization and monitoring, including 2-D and 3-D surface seismic, vertical seismic profiles (VSPs), and passive seismic data during the course of the PCOR Partnership's assessment efforts (Figure 1).

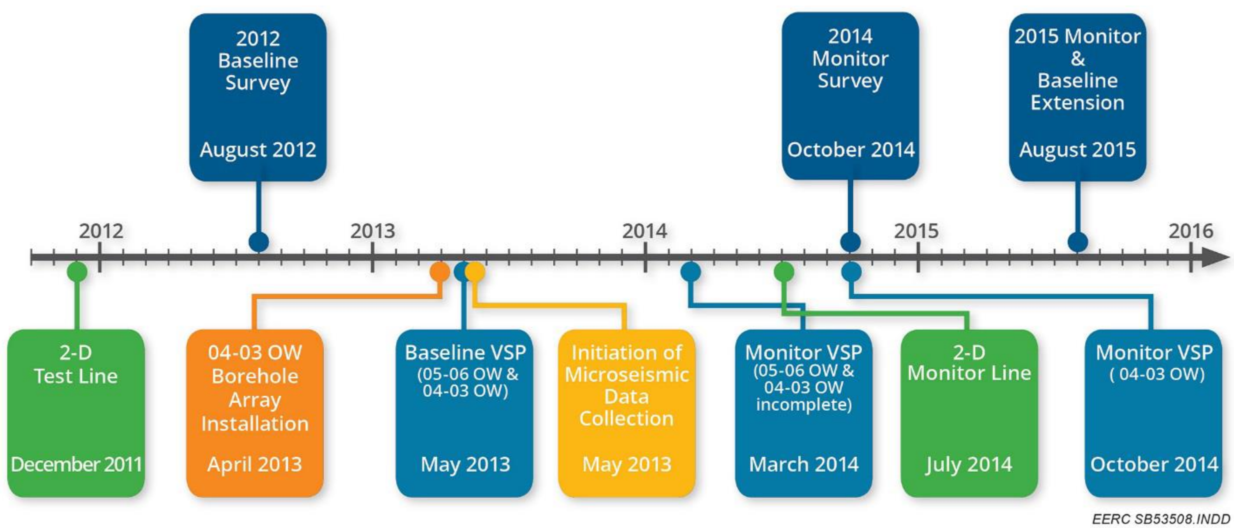

Figure 1. Time line showing the different components of the expanded seismic campaign.

Time-lapse 2-D surface seismic was instrumental in proving that CO_2 could be observed in the reservoir. A baseline 3-D surface seismic survey acquired in 2012 prior to the start of CO_2 injection provided detailed information that enhanced the characterization of the reservoir and served as a benchmark comparison for two subsequent surface monitor surveys acquired in 2014 and 2015. Time-lapse 3-D surface seismic data were used to map changes in the reservoir fluid distributions associated with CO_2 injection. Mapping these changes enabled detailed characterization of the injection zone and provided significant information on permeability barriers and flow channels that were used to update the geologic models and predictive simulations used to determine the ultimate fate of injected CO_2. Salako and others (2017) describe the results of these surface seismic studies in more detail.

As part of the monitoring efforts, a permanently installed 50-level seismic geophone array was used to record passive seismic data in order to detect microseismic events that occurred during field development and CO_2 flooding (Barajas-Olalde and others, 2018). In addition to passive data acquisition, the permanent geophone array was used to acquire 3-D VSPs. The purpose of the VSP surveys was to assess time-lapse changes in the distribution of fluids in the reservoir, the Muddy Formation, following CO_2 injection near two observation wells (OWs): 05-06 OW and 04-03 OW (Figure 2). This report discusses the results of these VSP surveys.

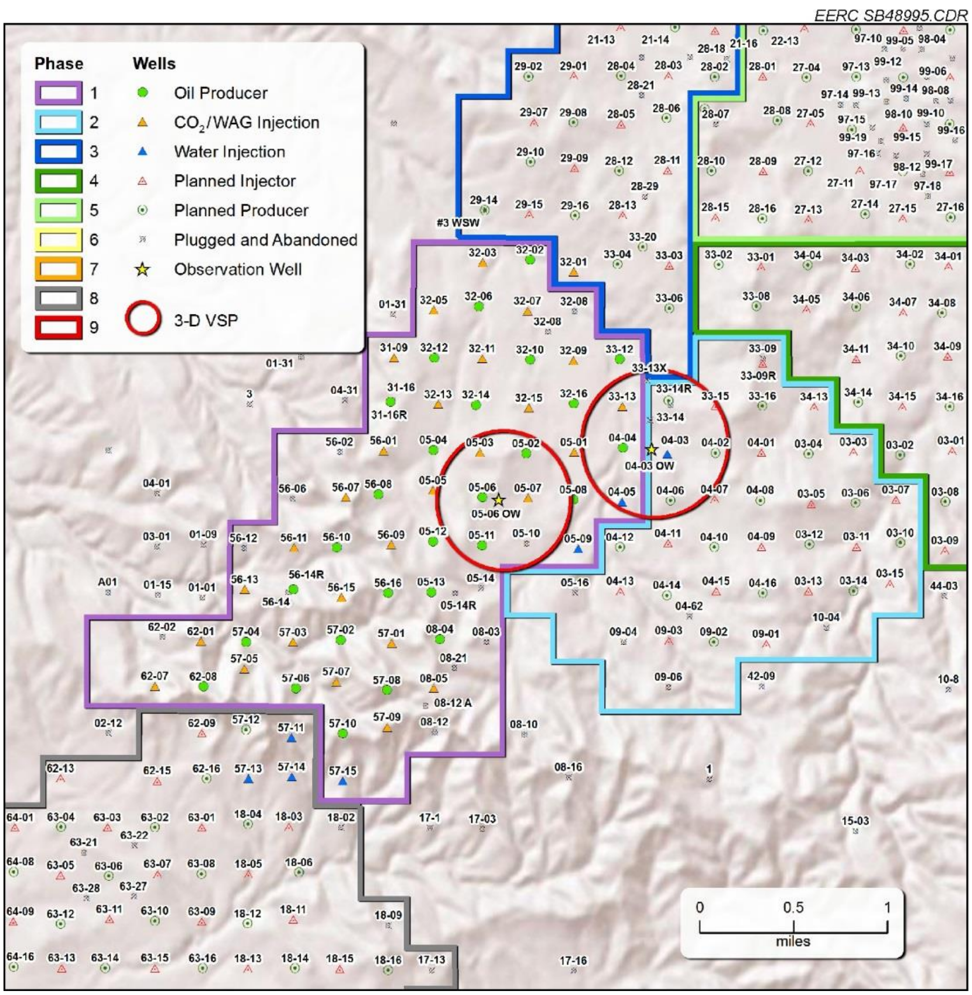

Figure 2. Location map and notional coverage of the 2013 baseline VSP survey. The area of coverage at the Muddy Formation is within the two outlined circles (Burnison and others, 2014).

3-D VSP Data Aquisition and Processing

A baseline and two subsequent monitor 3-D VSP data sets were collected at Bell Creek as part of the deep subsurface-monitoring program. Pre-CO_2 injection baseline 3-D VSPs were acquired in two observation wells (OWs): 05-06 OW and 04-03 OW. 05-06 OW employed a removable array, with the permanent geophone array in 04-03 OW. A partial monitor VSP was acquired in 2014 but was not completed because of budget considerations related to standby time caused by equipment malfunctions. A complete monitor 3-D VSP survey was acquired using the 04-03 OW array concurrent with the first surface seismic monitor survey in October 2014. Data acquisition parameters, including maps showing the source point locations for each VSP survey, can be found in Appendix A.

The 2013 baseline VSP data and the incomplete 2014 monitor VSP data were processed by a contracted processing company in 2014. In 2015, a new processing company processed the geophone data from the 04-03 OW permanent borehole array collected during the 2013 baseline VSP survey and the geophone and hydrophone data from the October 2014 monitor VSP survey. The 2013 baseline VSP data from the 05-06 OW well was not reprocessed as part of the 2015 processing efforts. Because of differences in source point locations between the 2013 baseline and the October 2014 monitor VSP survey, only data from source point locations that were common to both data sets were processed in 2015. Additional information about the processing routines used by both processing companies can be found in Appendix B.

3-D VSP Interpretation

A comparison of time-migrated images from the 2013 baseline VSP data processed in 2014 and the 2012 3-D surface seismic baseline data shows a good match in reflection characteristics on cross-sectional views (Figure 3). The processed data were clipped by the processing company to only show the areas with similar data coverage. Along the edges of the clipped VSP data shown in Figure 3 are some discontinuities in the reflections, which may be migration artifacts related to poor data coverage at those offsets.

The baseline VSP data processed in 2015 show a good match with the 3-D surface baseline data in cross-sectional view before migration (Figure 4). After migration was applied, the amplitude of the baseline VSP data no longer appears to be consistent with the surface data (Figure 5). Additionally, the migrated data contain several discontinuous reflection events across the entire data set, not just at the edges of the data, which are likely migration artifacts related to not just poor data coverage at some offsets but also to an insufficient velocity analysis or incorrect application of the migration algorithm. The processed data were not clipped by the data processing company to remove the areas with poor data coverage.

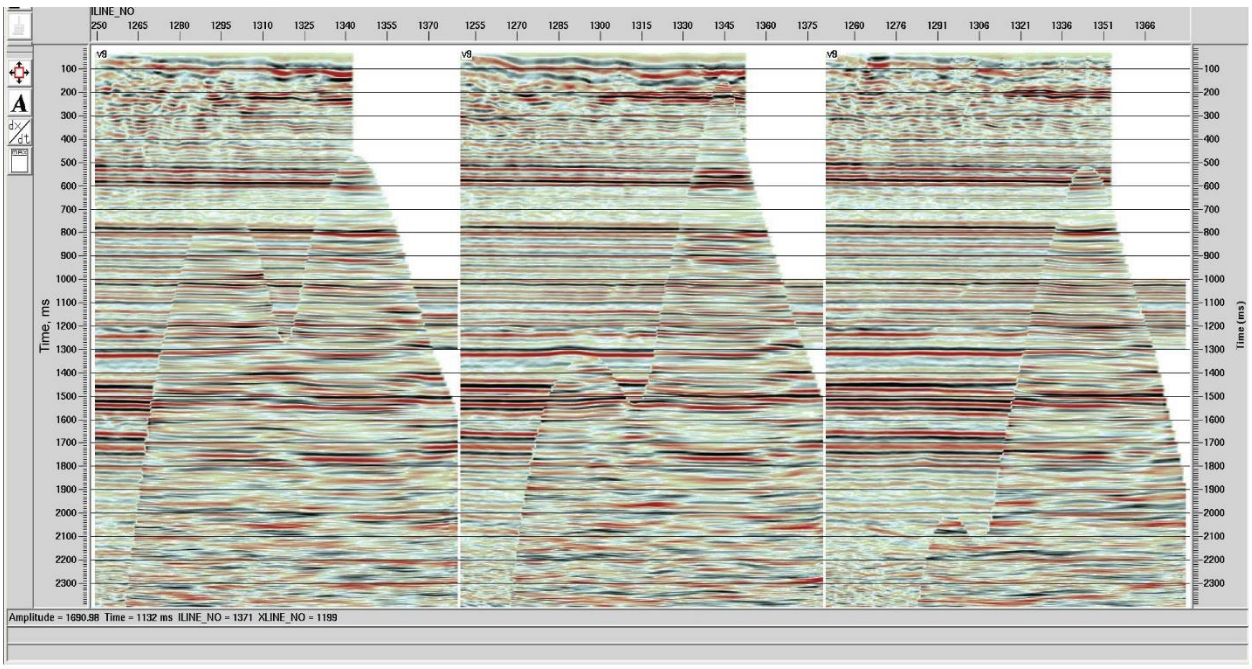

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Figure 3. Time-migrated 2012 3-D surface seismic baseline cross sections underlying the corresponding cross section from the 2013 baseline VSP data processed in 2014 (image courtesy of Apex HiPoint).

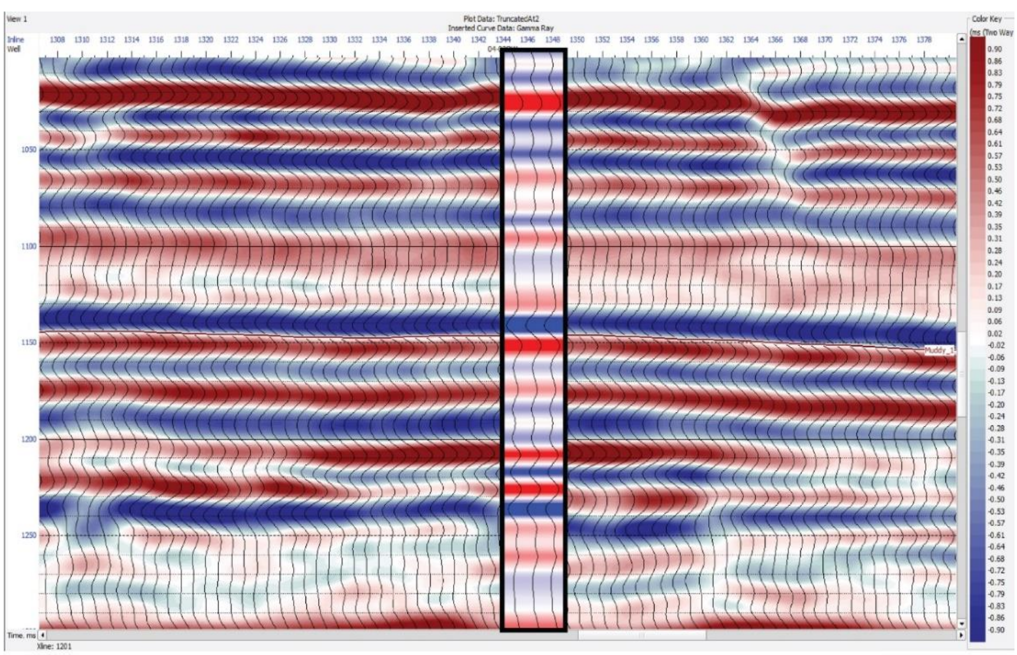

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Figure 4. Migrated 2012 3-D surface seismic baseline cross section underlying a zero offset corridor stack from the 2013 baseline VSP data processed in 2015 at well 04-03 OW (image courtesy of Paulson, Inc.).

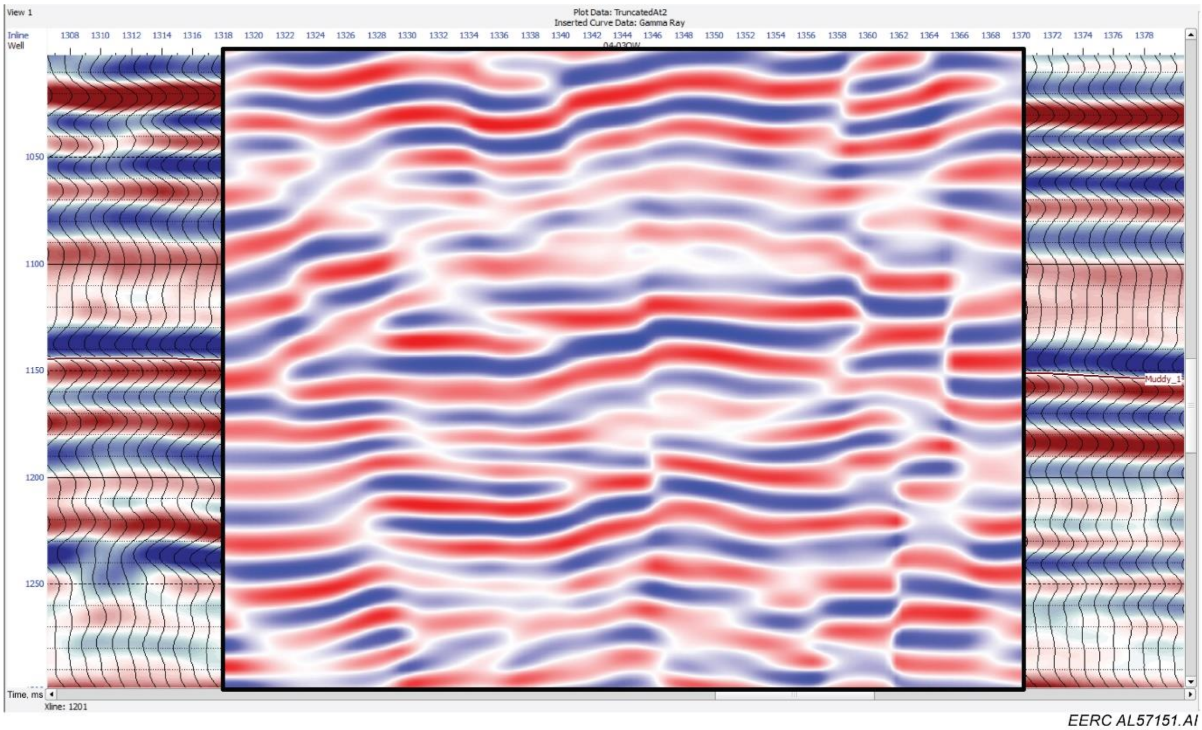

Figure 5. 2012 3-D surface seismic baseline cross section underlying the corresponding migrated cross section from the 2013 baseline VSP data processed in 2015 at well 04-03 OW (image courtesy of Paulson, Inc.).

The processed VSP data were correlated to well log data, and the reservoir horizon was picked. Root mean squared (RMS) amplitude maps of the 2013 baseline VSP data at the reservoir level were generated using a window centered on the picked horizon. The RMS amplitude maps generated from the VSP data do not show amplitude distributions similar to the baseline surface seismic data (Figures 6–8). Differences between the VSP and surface seismic data are expected, given the higher-frequency content of the VSP data. However, these amplitude maps were created after applying a high cut filter to the VSP data to filter out high-frequency data that are not present in the surface seismic data. The differences between the VSP data and the 3-D surface seismic data are likely attributed to the difference in spatial sampling of the reservoir due to differences in acquisition configurations between the VSP surveys and the 3-D surface seismic surveys.

The RMS amplitude maps show major differences between the 2013 baseline VSP data processed in 2014 and the 2013 baseline VSP data processed in 2015 (Figures 6 and 7). Some differences are expected because all the 2013 baseline VSP data were processed in 2014 while only a subset of the 2013 baseline VSP data were processed in 2015. Since the VSP data were processed for time-lapse analysis, amplitude and phase-preserving processing routines should have been used. If both processing flows were amplitude-preserving processing routines, the RMS amplitude maps should have more similarities than they do. The major differences between the 2013 baseline VSP data processed in 2014 and 2015 and the differences between the data processed in 2015 and the 3-D surface seismic data suggest incorrect application of processing algorithms in 2015.

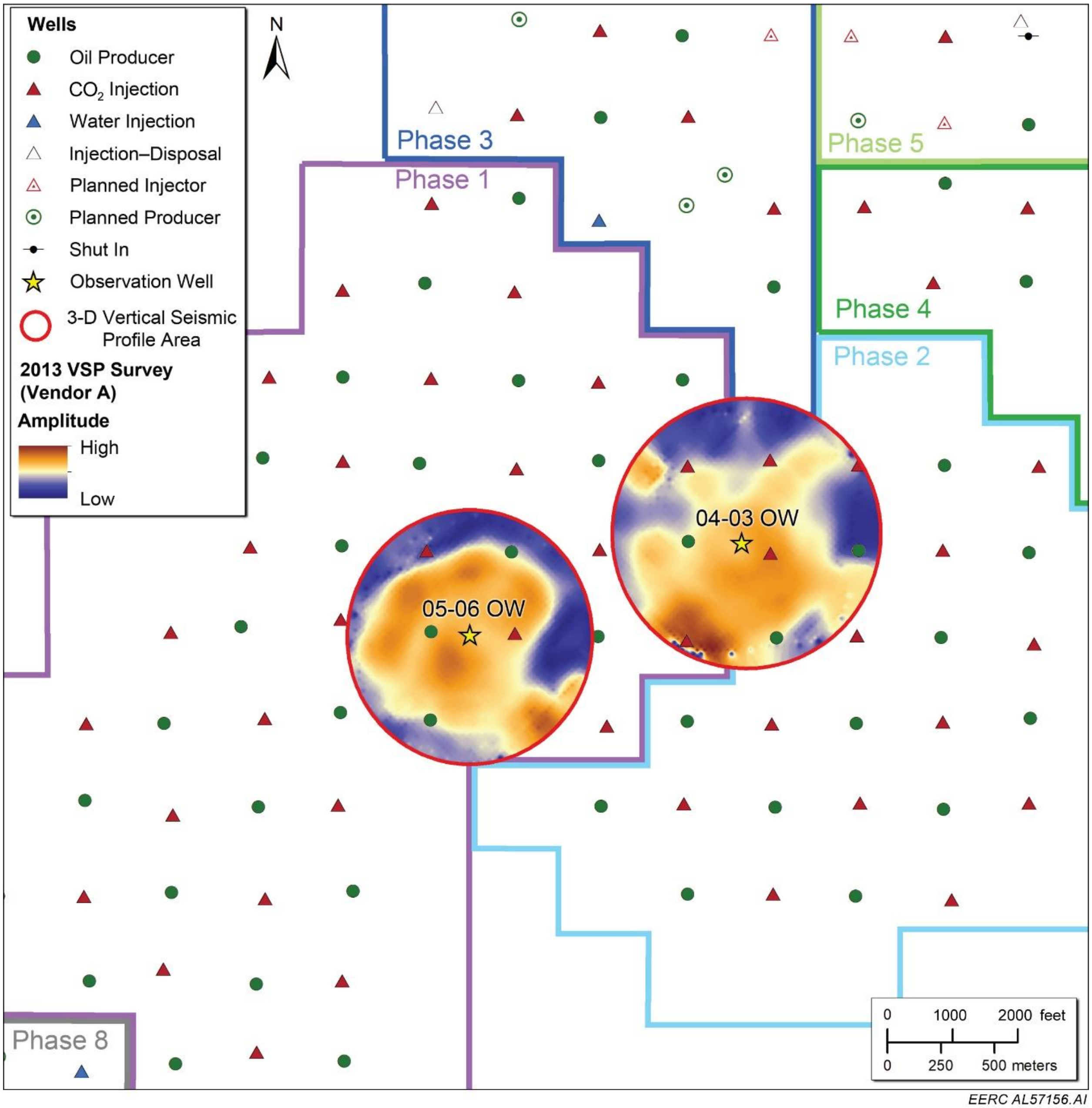

Figure 6. RMS amplitude map of the reservoir interval at Bell Creek generated using the 2013 baseline VSP data processed in 2014.

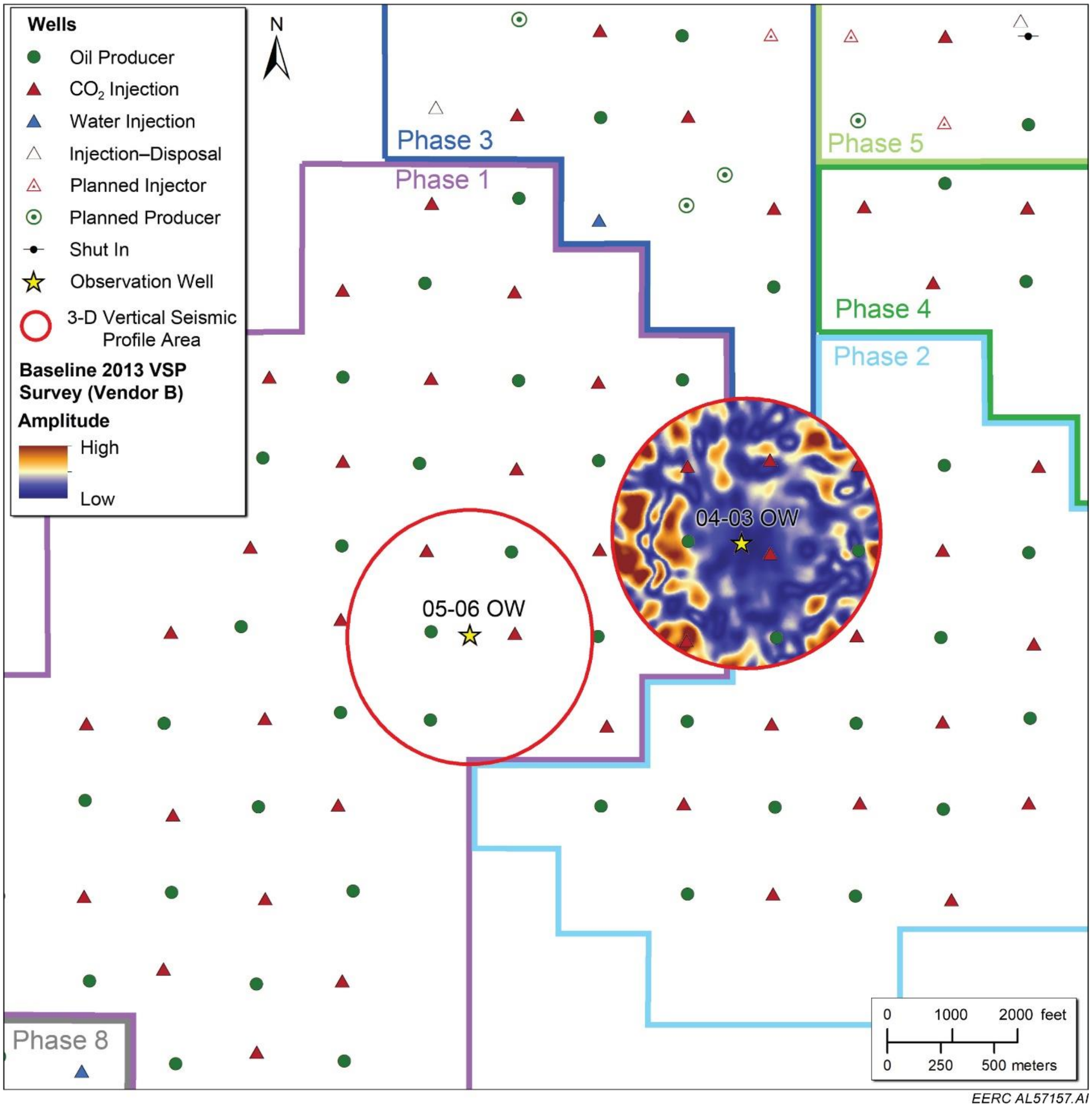

Figure 7. RMS amplitude map of the reservoir interval at Bell Creek generated using the 2013 baseline VSP data processed in 2015.

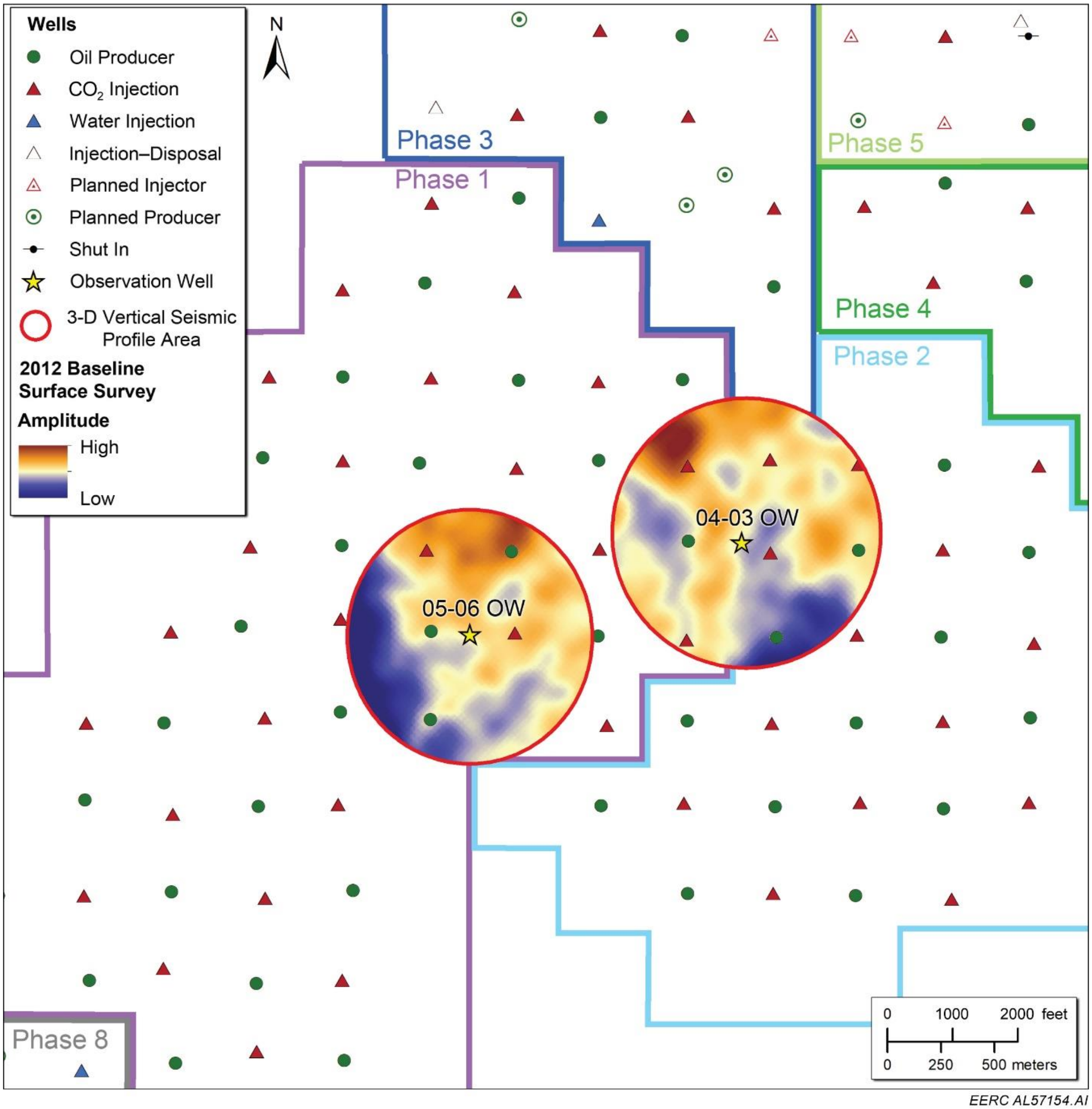

Figure 8. RMS amplitude map of the reservoir interval at Bell Creek generated using the 2012 3-D surface seismic baseline data. The data have been clipped to the area imaged by the baseline VSP data.

3-D VSP Time-Lapse Analysis

Time-lapse comparison of the 2013 baseline VSP data and the incomplete 2014 monitor VSP data was conducted using shot gathers. Shaping filters were used to minimize differences in the two data sets caused by differences in acquisition parameters and noise conditions. After conditioning the data using shaping filters, difference panels were generated by subtracting individual shot gathers from the baseline VSP survey from corresponding shot gathers from the monitor VSP survey. This time-lapse shot gather analysis produced ambiguous results that could not be used to interpret or map difference in the reservoir.

Time-lapse comparison of the 2013 baseline VSP survey and the 2014 monitor VSP survey was conducted by the second processing company in 2015. 2-D difference images were generated by subtracting the baseline data from the monitoring data. The difference images show amplitude differences within the reservoir at 4500 feet as well as above and below the reservoir (Figure 9). No data-conditioning algorithms were applied to the data prior to time-lapse analysis, which may account for these differences above the reservoir. In addition to changes above the reservoir, both an increase and decrease in amplitude in the reservoir were observed on the 2-D difference images, making results ambiguous. Given the time-lapse analysis results for the 3-D surface seismic surveys, a decrease in amplitude in the reservoir due to CO_2 injection is expected.

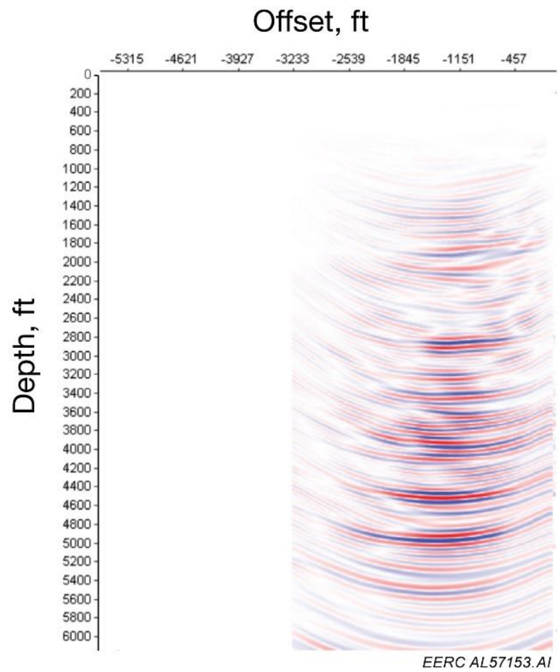

Figure 9. 2-D difference image generated by the processing company in 2015.

The EERC applied data conditioning to the VSP data processed in 2015 by the second processing company and generated an RMS amplitude difference map for the reservoir interval by subtracting the baseline data from the monitor data. The RMS amplitude difference map shows change in the reservoir in several places (Figure 10), whereas the RMS amplitude difference map generated using the 2012 and 2014 3-D surface seismic data sets shows large differences around the injection wells that illuminate a permeability barrier which intersects well 04-03 OW (Figure 11). The differences on the RMS amplitude difference map generated using the VSP data appear to be random. Additionally, there are no differences in the VSP data around two of the injection wells.

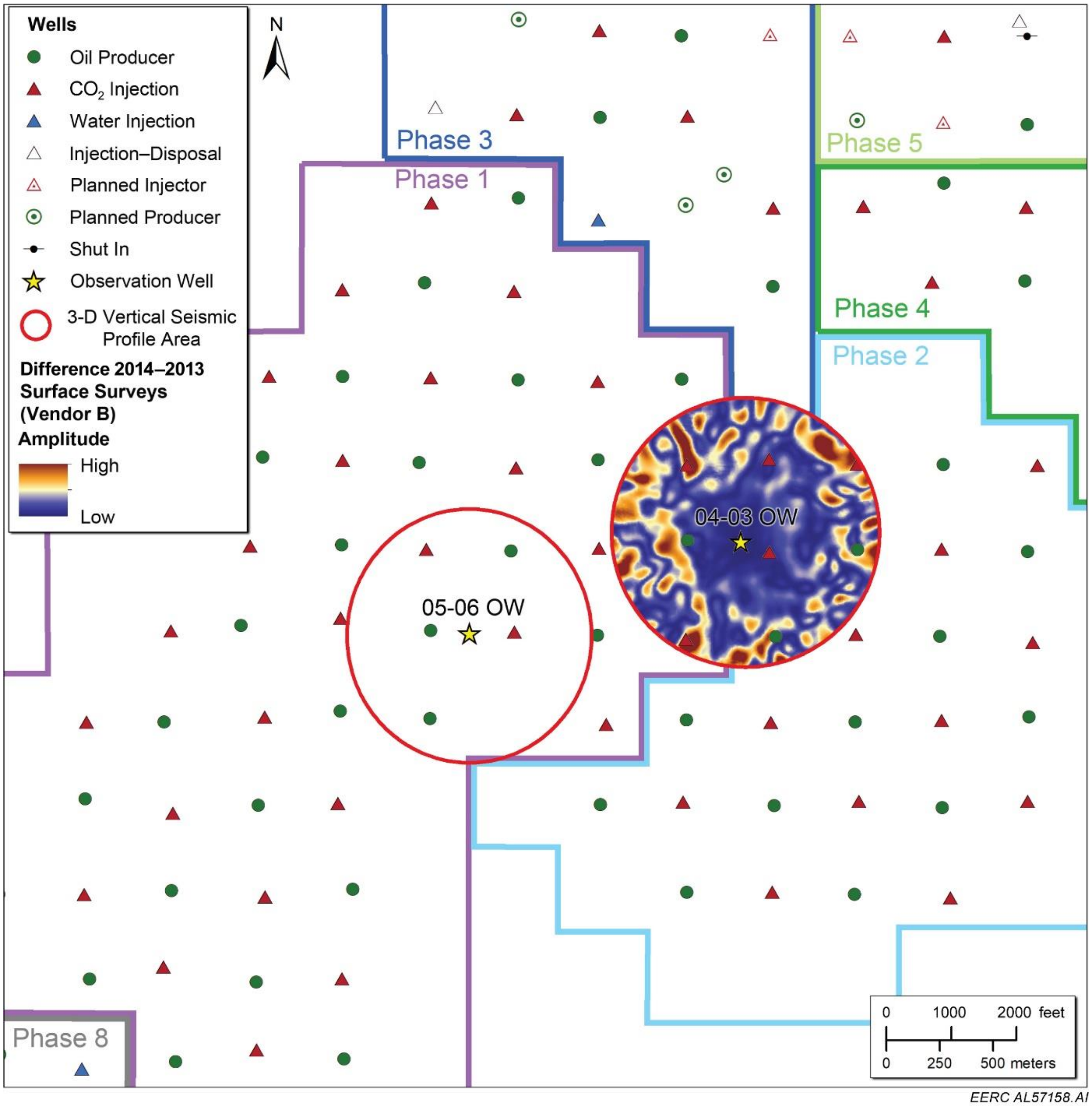

Figure 10. RMS amplitude difference map of the reservoir interval at Bell Creek generated using a difference volume calculated by subtracting the 2013 baseline VSP data processed in 2015 from the 2014 monitor VSP data processed in 2015.

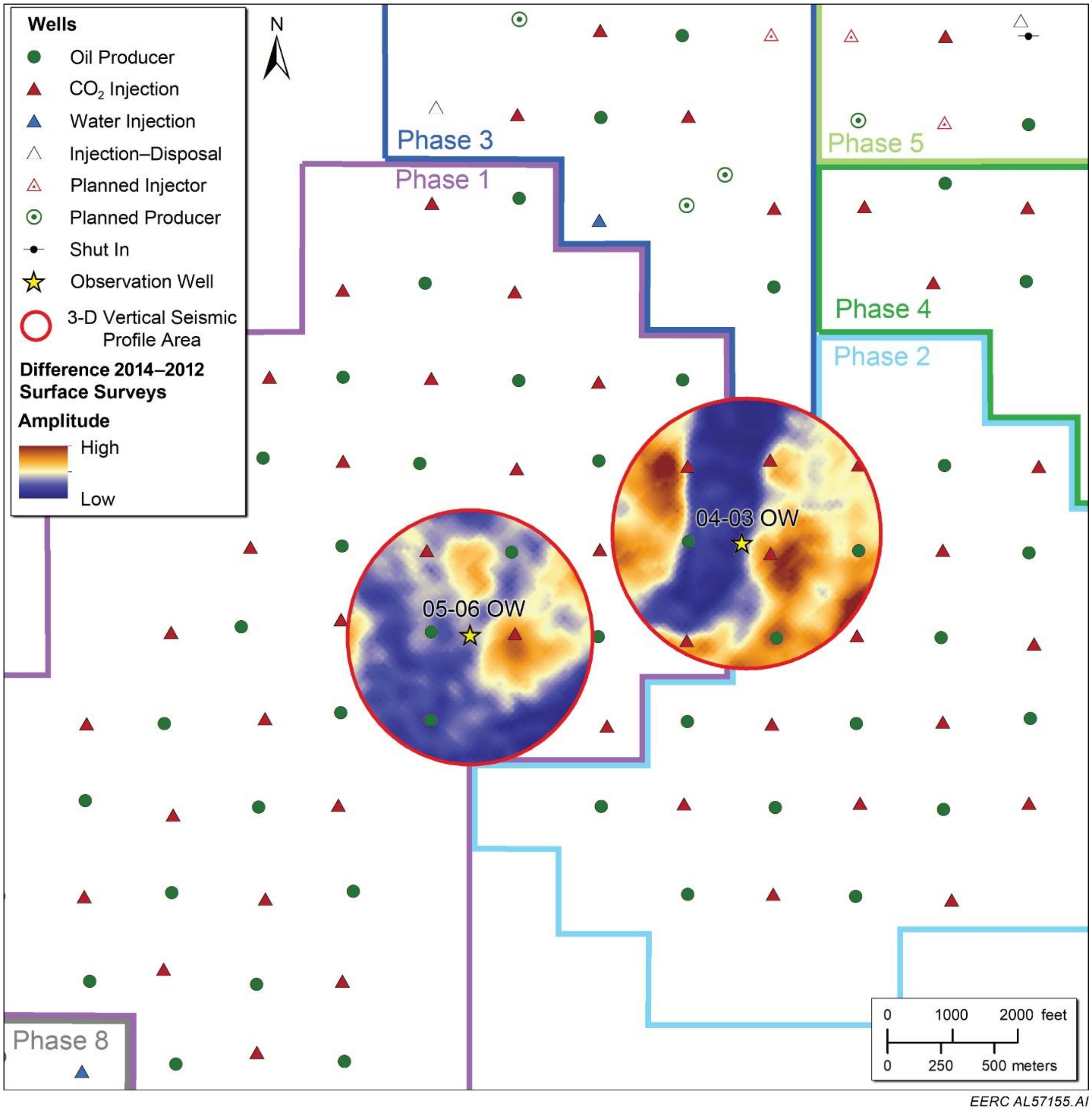

Figure 11. RMS amplitude difference map of the reservoir interval at Bell Creek generated using a difference volume calculated by subtracting the 2012 3-D surface seismic baseline data from the 2014 3-D surface seismic monitor data. The data have been clipped to the area imaged by the baseline VSP data.

CONCLUSION

Amplitude characteristics between the 2013 baseline VSP processed in 2014 and the 2012 3-D surface seismic baseline show similarities in cross-sectional views but differences in amplitude distribution on RMS amplitude maps calculated at the reservoir interval. Differences between the two data sets are likely attributed to the difference in spatial sampling of the reservoir because of differences in acquisition configurations between the VSP surveys and the 3-D surface seismic surveys. The amplitude characteristics of the 2013 baseline VSP processed in 2015 did not show similarities to the 2012 3-D surface seismic baseline data. The VSP data volumes generated in 2015 also included several discontinuous reflections likely associated with migration artifacts. Additionally, the amplitude characteristics of the original 2013 baseline VSP data and the reprocessed data show major differences, suggesting either the old or the new processing routine did not apply an amplitude and phase-preserving workflow correctly, which is necessary to preserve time-lapse changes in the reservoir and enable observation of the effects of CO_2 injection.

Time-lapse comparison of the 2013 baseline VSP data and the incomplete 2014 monitor VSP data conducted using pairs of shot gathers produced ambiguous results that could not be used to interpret difference in the reservoir. Time-lapse analysis of the 2013 baseline VSP data and the October 2014 monitor VSP data showed differences within the reservoir as well as above and below the reservoir. In addition to changes outside the reservoir, both an increase and decrease in amplitude in the reservoir were observed, making results ambiguous. An RMS amplitude difference map of the reservoir generated as part of this effort also showed ambiguous results that did not agree with results from the time-lapse analysis of the 3-D surface seismic data.

While time-lapse VSPs have proven to be applicable for reservoir monitoring at other sites (O’Brien and others, 2014; Luo and others 2018), time-lapse VSP results were inconclusive at Bell Creek. There is uncertainty about whether these results are related to differences in acquisition parameters between the baseline and monitor survey that were not overcome in data processing or incorrect application of some data-processing algorithms. The time-lapse VSP results are in stark contrast to the time-lapse 3-D surface seismic surveys at Bell Creek which yielded outstanding results, allowing CO_2 migration to be tracked and adding value to the oilfield operations by illuminating previously unknown geological features of the reservoir (Salako and others, 2017).

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APPENDIX A

3-D VSP DATA AQUISITION

3-D VSP DATA AQUISITION

2013 BASELINE VSP SURVEY

The baseline VSP survey was collected by Apex HiPoint during a 5-day campaign from May 15–19, 2013. The receiver arrays were the 50-level permanent borehole array in 04-03 W and a 60-level retrievable array deployed in 05-06-OW. The borehole array parameters can be found in Tables A-1 and A-2. The energy source was two 64,000-lb AHV-IV vibrators operating in unison. The total number of shot points was 961 (Figure A-1). Data were recorded normally with a time break. The hydrophone data from the 04-03 OW borehole array were not recorded; however, the data from the three orthogonal OMNI-2400 15-Hz geophones were recorded.

Table A-1. 04-03 0W Borehole Array Parameters

Receiver Type	Digitized 4C Sensor Module (one Deepender™ 5000-X hydrophone and three orthogonal OMNI-2400 15-Hz geophones)
Total Sondes	50
Total Interconnects	50
Total String Length	2460 feet
Sonde Spacing	49.2 feet
First Level	60 feet
Bottom Depth	2461 feet
Coupling Method	Attached to a cemented downhole pipe by bracket

Table A-2. 05-06 0W Borehole Array Parameters

Receiver Type	DS 150 3-C 15-Hz Geophone
Total Sondes	60
Total Interconnects	60
Total String Length	2953 feet
Sonde Spacing	49.2 feet
Bottom Depth	3002 feet
First Level	19.2 feet
Coupling Method	Magnets on the receiver casing and pressure buildup using gas

MARCH 2014 MONITOR VSP SURVEY

A monitor survey was started by Apex HiPoint in March 2014. The acquisition equipment and parameters were the same as the 2013 baseline VSP. After 125 shots were collected, the survey team was placed in standby mode because of operator error and equipment malfunctioning that required review. After several days of standby, the survey was aborted for budgetary considerations. Figure A-2 shows the shot points that were successfully acquired.

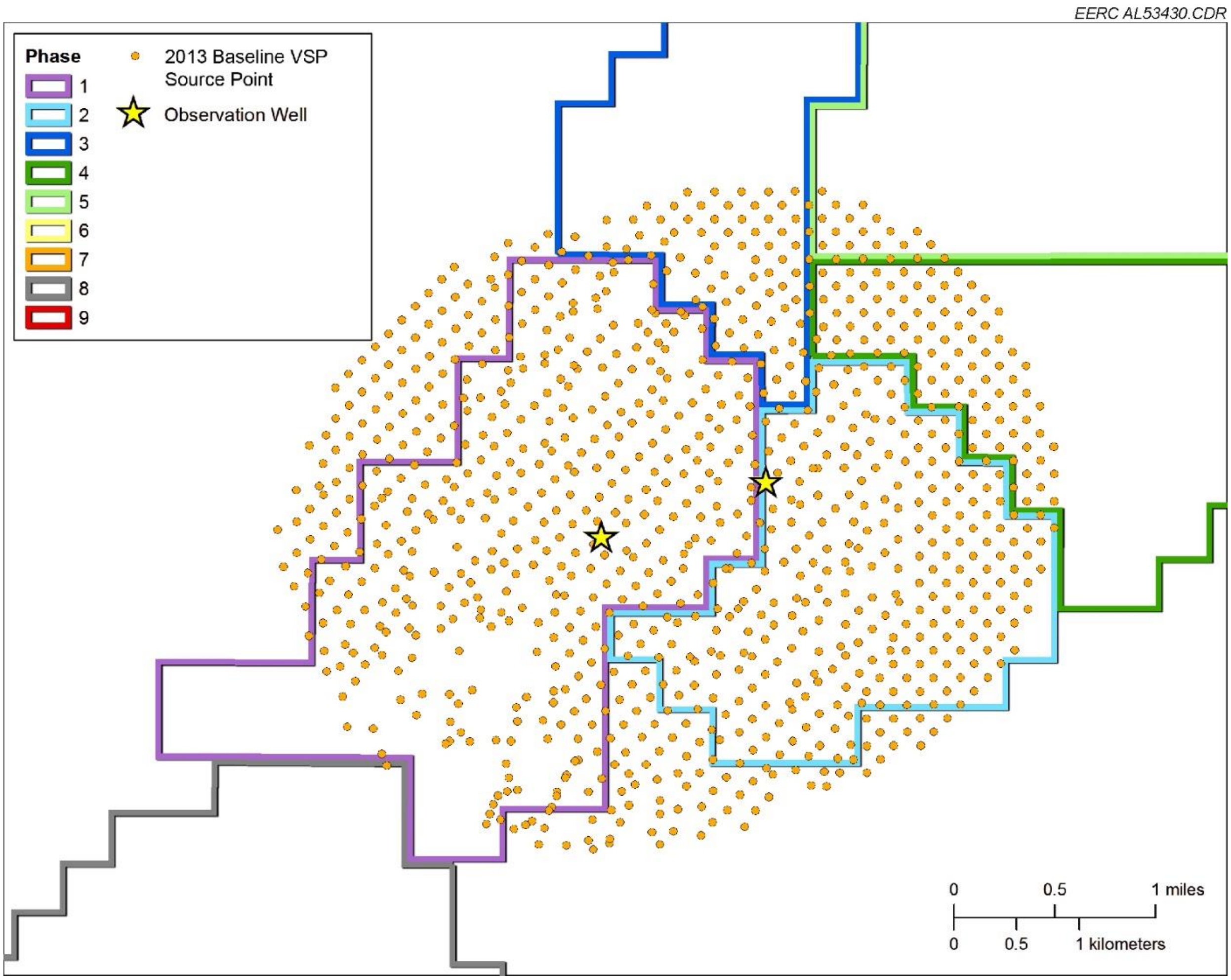

Figure A-1. Map showing source points for a 2013 baseline VSP survey acquired in the Bell Creek Field.

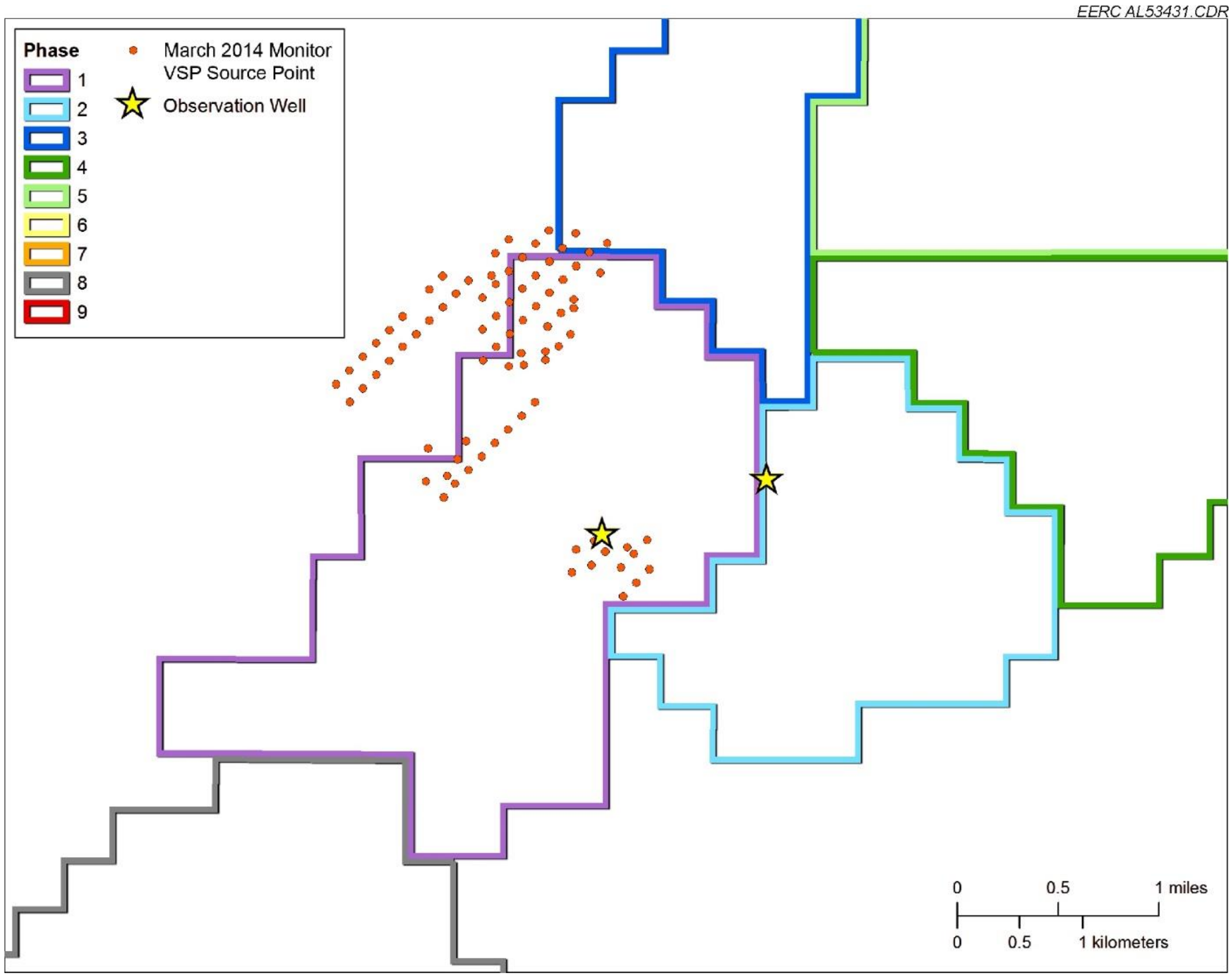

Figure A-2. Map showing source points for a March 2014 monitor VSP survey acquired in the Bell Creek Field.

OCTOBER 2014 MONITOR VSP SURVEY

In October of 2014 during the 2014 3-D surface seismic monitor survey, Dawson Geophysical Company collected a monitor VSP survey. This VSP survey utilized the permanent borehole array in 04-03 OW and shot points collected as part of the 3-D surface survey that overlaid shot point locations from the baseline VSP. 442 shots were selected from the 3-D surface seismic survey shot lines, and an additional 238 shots were specifically collected for the VSP survey, for a total of 680 shots (Figure A-3). The energy source was two 64,000-lb AHV-IV vibrators operating in unison. No repeat VSP data were collected for 05-06 OW with a retrievable array because of budgetary constraints. No time break was used for data collection, as the main focus of this data acquisition was for the 3-D surface seismic survey. Active shot records were extracted from the continuous data recorded by the 04-03 OW array using GPS (global positioning system) time stamps. All of the data from the permanent array were recorded, including the hydrophone data.

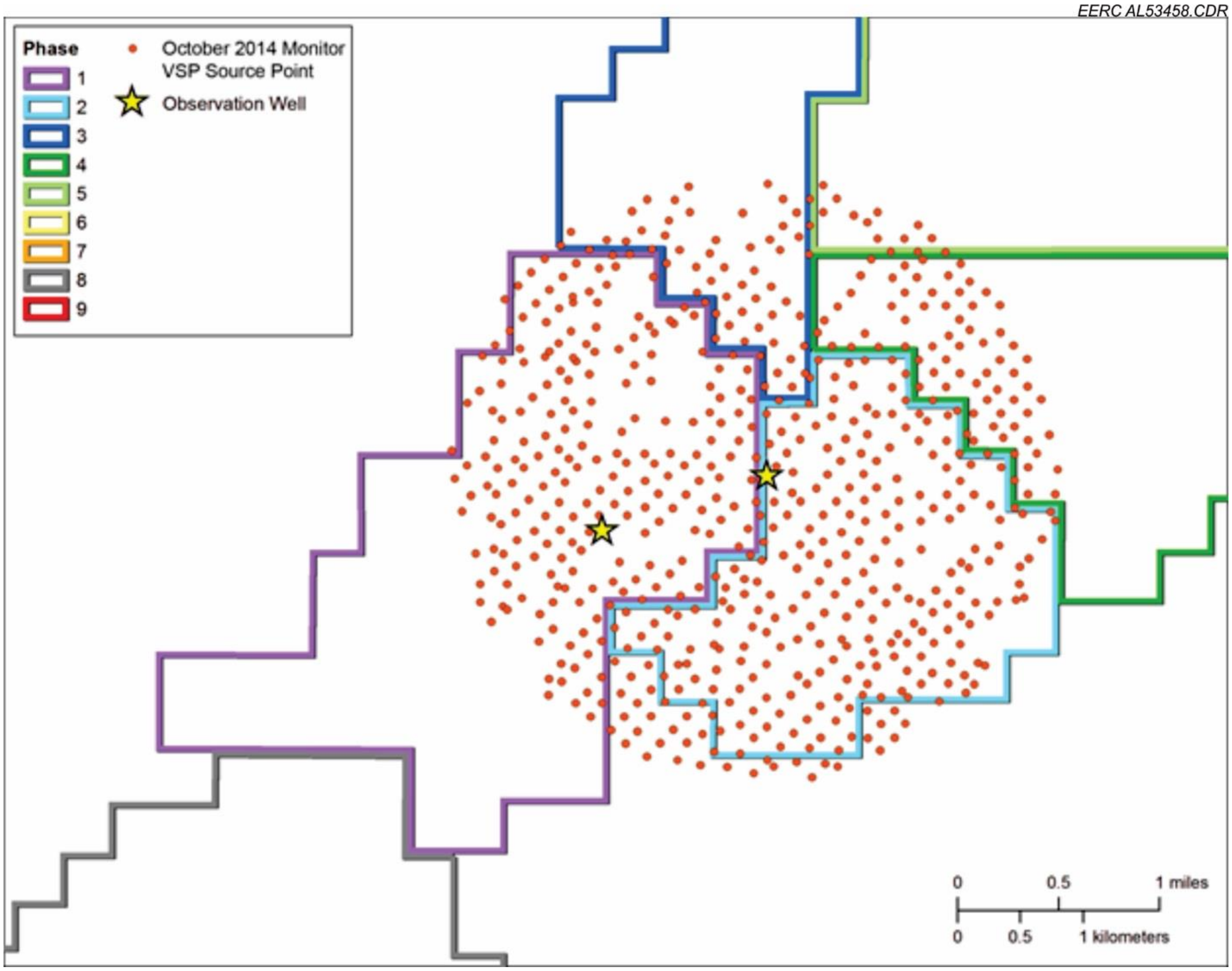

Figure A-3. Map showing source points for an October 2014 monitor VSP survey acquired in the Bell Creek Field.

APPENDIX B

3-D VSP DATA PROCESSING

3-D VSP DATA PROCESSING

A contracted processing company processed the 2013 baseline VSP survey data with the following summarized sequence (greater detail is provided in Salako and others [2017]):

- Reformatting and geometry assignment
- Geophone orientation analysis and rotation
- First arrival picking
- Time-variant rotation
- Spherical divergence correction
- Removal of downgoing energy
- Upward continuation to pseudo-receivers at surface
- Surface consistent scaling and deconvolution
- 3-D gridding, CMP (common midpoint) sort and stack
- Surface consistent scaling and deconvolution, trace balancing
- Velocity analysis and residual statics
- Kirchoff PSTM (prestack time migration)
- NMO (normal moveout correction), mute, stack, and filter
- Datum statics

In 2014, the same company processed the shot points from the 2013 baseline and March 2014 monitor VSP survey data that were repeated with the following summarized sequence (greater detail is provided in Salako and others [2017]):

- Reformatting and geometry assignment
- Geophone orientation analysis and rotation
- First arrival picking
- Time-variant rotation
- Spherical divergence correction
- Match filter
- Source wavelet estimation and wavelet deconvolution
- Removal of downgoing energy
- Linear moveout correction (LMO)
- Filter and shift to final datum

In 2015, a new processing company processed the geophone data from the 04-03 OW permanent borehole array collected during the 2013 baseline survey and October 2014 monitor VSP survey with the following summarized sequence (greater detail is provided in Salako and others [2017]):

- Geometry assignment, geometry QC, data subset selection, and trace editing
- Geophone orientation analysis and rotation
- First arrival picking
- Datum statics
- Source wavelet estimation and wavelet deconvolution

- Velocity analysis
- Update receiver locations using well deviation and first arrivals
- Spherical divergence correction and surface consistent scaling
- Removal of downgoing energy
- Surface consistent scaling, and statics
- Kirchhoff prestack depth migration (PSDM)
- Residual statics and refined velocity analysis
- Spectral balancing
- Anisotropic velocity analysis and anisotropic Kirchhoff PSDM

The second processing company included the hydrophone data from the October 2014 monitor VSP survey in its processing routine. The 2013 baseline data from the 05-06 OW well were not processed as part of this effort.

REFERENCE

Salako, O., Livers, A.J., Burnison, S.A., Hamling, J.A., Wildgust, N., Gorecki, C.D., Glazewski, K.A., and Heebink, L.V., 2017, Analysis of expanded seismic campaign: Phase III Task 9 – Deliverable D104, Plains CO_2 Reduction Partnership Deliverable Report for U.S. Department of Energy National Energy Technology Laboratory Cooperative Agreement No. DE-FC26-05NT42592, EERC Publication EERC-10-09, Grand Forks, North Dakota, Energy & Environmental Research Center, June.