Technical Progress Report, Year 2, and Plan for Year 3:
4-D High-Resolution Seismic Reflection Monitoring
of Miscible CO_2 Injected into a Carbonate Reservoir

Type of Report
Technical Progress Report

Reporting Period Start Date
9/1/04

Reporting Period End Date
8/31/05

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Date of Report
September 2005

DOE Award Number
DE-FC26-03NT15414

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KGS Open-file Report 2005-32

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Abstract

The objective of this research project is to acquire, process, and interpret multiple high-resolution 3-D compressional wave and 2-D, 2-C shear wave seismic data to observe changes in fluid characteristics in an oil field before, during, and after the miscible carbon dioxide (CO_2) flood that began around December 1, 2003, as part of the DOE-sponsored Class Revisit Project (DOE #DE-AC26-00BC15124). Unique and key to this imaging activity is the high-resolution nature of the seismic data, minimal deployment design, and the temporal sampling throughout the flood. The 900-m-deep test reservoir is located in central Kansas oomoldic limestones of the Lansing-Kansas City Group, deposited on a shallow marine shelf in Pennsylvanian time. After 18 months of seismic monitoring, one baseline and six monitor surveys clearly imaged changes that appear consistent with movement of CO_2 as modeled with fluid simulators.

4-D High-Resolution Seismic Reflection Monitoring of Miscible CO_2 Injected into a Carbonate Reservoir

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Technical Progress Report, Year 2

EXECUTIVE SUMMARY

Efficiency of enhanced oil recovery (EOR) programs relies heavily on accurate reservoir models. Movement of miscible carbon dioxide (CO_2) injected into a thin (~5 m), shallow-shelf, oomoldic carbonate reservoir around 900 m deep in Russell County, Kansas, was successfully monitored using high-resolution 4-D/time-lapse seismic techniques. High-resolution seismic methods show great potential for incorporation into CO_2-flood management, highlighting the necessity of frequently updated reservoir-simulation models, especially for carbonates. Use of an unconventional approach to acquisition and interpretation of the high-resolution time-lapse/4-D seismic data was key to the success of this monitoring project.

Interpretations of geologic features from seismic data have provided location-specific reservoir properties that appear to strongly influence fluid movement in this production interval. Lineaments identified on seismic sections likely (based on time-lapse monitoring and production data) play a role in sealing and/or diverting flow through the reservoir. Distribution and geometries associated with similarity seismic facies and seismic lineament patterns are suggestive of a complex ooid shoal depositional environment. By incorporating these features, using properties consistent with core data, a more realistic reservoir simulator results, honoring the production and core properties. Flow models after simulator updating (sealing lineaments and preferential permeability manifested by faster progression of the CO_2 bank) show improvement in detail and provide correlation with the material balance.

Amplitude envelope attribute data possess changes in texture generally consistent with expectations and CO_2 volumetrics. Arguably, a multitude of different boundaries could be drawn to define the shape of the CO_2 plume, but the shapes suggested match the physical restraints, based on engineering data and the estimated amplitude response. Focusing on the injection well area and continuity of the characteristics defining the anomalous area, it is not difficult to identify a notable change in data character and texture likely associated with the displacement of reservoir fluids with CO_2.

Advancement of the CO_2 from the injector seems to honor both the lineaments identified on baseline data and changes in containment pressures. Overlaying the amplitude envelope attribute map with the lineament attribute map provides an enhanced view, and therefore perspective, of the overwhelming variability in the reservoir rocks and the associated consistency and control these features or irregularities have on fluid movement.

Increased northerly movement of the CO_2, as interpreted on seismic data and inferred from production data, after several months of CO_2 injection and oil production, stimulated an increase in injection rates at the water flood wells. After several months of

increased water injection, the CO_2 advancement to the northwest was halted and some regression was observed on seismic data.

Shortness of turnaround time of time-lapse seismic monitoring in the Hall-Gurney field provided timely support for reservoir-simulation adjustments and flood-management of the pilot study. Initial reservoir flow simulations utilized models based on pre-CO_2 oil production history, measured rock properties from core, water injectivity testing, and interwell testing. These data did not completely constrain the possible permeability architecture in the reservoir and CO_2-flood performance did not match pre-CO_2 injection predicted performance. 4-D seismic data, obtained and interpreted while the CO_2 flood was ongoing, was interpreted independent of simulations updated with the most current production data; therefore, to a limited extent, the interpretations of CO_2 movement based on seismic data were performed without field production input. Seismic predictions of CO_2 breakthrough at well 12 and the delay at well 13 were based on seismic data alone after the second monitor survey. Following initial seismic prediction, seismic and flood performance data were integrated to both validate the 4-D interpretation and confirm it was not inconsistent with flood performance, and to provide seismic input of flood progress to the flood management process. In general, seismically predicted changes in the CO_2 plume and measurements at production wells have been consistent throughout the flood.

Interpretations of time-lapse seismic data are consistent with and have assisted understanding of field response for the pilot. In a similar fashion, 4-D seismic have provided input to reservoir simulations investigating full-field EOR-CO_2 floods. Key observations from seismic data include

- accurate indication of solvent “CO_2” breakthrough in well 12,
- predicted delayed response in well 13,
- interpretation of a permeability barrier between wells 13 and CO2I#1, and
- consistency with reservoir simulation prediction of CO_2 movement and volume estimated to have moved north, outside the pattern.

Time-lapse seismic monitoring of EOR-CO_2 can reveal weak anomalies in thin carbonates below temporal resolution and can be successful with moderate cross-equalization and attention to consistency in acquisition and processing details. Most of all, methods applied here avoid the complications associated with inversion-based attributes and extensive cross-equalization techniques. Spatial textural, rather than spatially sustainable magnitude, time-lapse anomalies were observed and should be expected for thin, shallow carbonate reservoirs. Non-inversion, direct seismic attributes proved both accurate and robust for monitoring the development of this EOR-CO_2 flood.

Weak-anomaly enhancement of selected non-inversion, 4-D seismic attribute data represented a significant interpretation development and proved key to seismic monitoring of CO_2 movement. Also noteworthy was the improved definition of heterogeneities affecting the expanding flood bank. Among other findings, this time-lapse seismic feasibility study demonstrated that miscible CO_2 injected into a shallow, thin carbonate reservoir could be monitored, even below the classic temporal seismic resolution limits.

Project Overview: Seismic Activities During Funding Year 2 (September 1, 2004 to August 31, 2005)

Project Goal

A primary goal of this project has been and continues to be to seismically delineate the movement of a miscible CO_2 floodbank through this thin oomoldic limestone petroleum reservoir with sufficient resolution to identify reservoir heterogeneities and their influence on sweep uniformity and efficiency. A secondary goal is the evaluation of the high-resolution seismic method as a highly repeatable tool for monitoring the long-term stability of the CO_2 volume and in so doing develop a cost-effective, reliable approach for routinely appraising the nature and distribution of sequestered CO_2 and thus providing the assurance of CO_2 sequestration that may be required in future sequestration efforts.

This project has addressed questions that independently and together are relevant to the CO_2 flood management and CO_2 sequestration. These questions include:

Flood Management

Where is CO_2 moving?
Is CO_2 leaving the flood pattern area?
What is the sweep efficiency?
Are there areas of bypassed oil?
If CO_2 is moving, what is the mechanism?
How can the injection and production program be improved in near real-time to optimize the sweep or recovery?

CO_2 Sequestration

Where is CO_2 moving?
What is the nature (phase properties, saturation, dissolved concentration) and distribution of CO_2?
Is CO_2 leaving the flood pattern area?
If CO_2 is moving, what is the mechanism?
How does CO_2 in the reservoir change with time?
Can high-resolution seismic reflection provide the assurances necessary to accurately monitor CO_2 distribution?

Benefits

Continued success seismically monitoring CO_2 movement through this reservoir will reveal critical components and considerations necessary for routine incorporation of 3-D high-resolution seismic monitoring with CO_2 EOR programs in thin, relatively shallow, mature carbonate reservoirs. Changes in production schemes possible by incorporating nearly real-time monitoring data into CO_2 injection EOR programs could dramatically impact both the efficiency and economics of that technology in many midcontinent fields. Refinements to 3-D high-resolution reflection imaging coming from this study could provide assurances essential for routine sequestration of CO_2 in depleted oil/gas reservoirs or brine aquifers.

Background
Over the last decade, time-lapse 3-D (or 4-D) seismic reflection profiling has proven to be an effective tool for evaluating conventional EOR programs. Consistency and repeatability of 3-D surveys has been the most persistently identified problem associated with time-lapse monitoring of reservoir production. Seismic monitoring has been considered viable only for the most prolific fields, which possess the greatest potential for significant returns from identification of stranded reserves. The vast majority of midcontinent reservoirs would not be considered candidates for 4-D monitoring using historical criteria.

The potential of seismically monitoring the injection of miscible CO_2 into thin carbonate reservoirs has only recently been studied. Field tests to date of this technique have used conventional approaches with limited evaluation of the economics of routine application or spatial and temporal sampling necessary for application to most midcontinent-size reservoirs. Changes in reservoir characteristics between baseline and one, or at most two, monitoring surveys have previously assumed linearity and not been designed to be incorporated into the production scheme.

Technical Progress
Seismic data acquisition and preliminary processing on the six 3-D reflection surveys proposed for budget periods 1 and 2 have been completed on schedule. Consistent with the proposed timeline, evaluation of various interpretation approaches continues and has produced images with agreement to production models, volumetrics, and observations that provide a ground truth for interpreted results in this study. Data acquisition continues on schedule with significant effort given to ensure the highest possible data quality and field data-acquisition efficiency. Preliminary data processing on all seismic volumes is complete with secondary processing underway to enhance data resolution and interpretation potential beyond any documented studies at these depths. Due to the nature of the signal-to-noise ratio resulting from the frequency, pressure, depth, and CO_2 concentrations at the study site, processing and interpretation is challenging, is still crude, and processed data are still being optimized for resolution and signal-to-noise ratio. A variety of unexpected data and reservoir characteristics have been identified and methods of compensation developed. As part of the ongoing evaluation task, unique and consistent anomalies in both amplitude and frequency data provide images of the presence of CO_2 in the rock at these depths and with these reservoir characteristics; as key aspects of the data are identified and enhanced with specialized processing methods, images of the CO_2 plume should become vivid.

Project Results
The efficiency of enhanced oil recovery (EOR) programs relies heavily on accurate reservoir models. Movement of miscible carbon dioxide (CO_2) injected into a thin (~5 m), shallow-shelf, oomoldic limestone reservoir around 900 m deep in Russell County, Kansas, was successfully monitored using high-resolution 4-D/time-lapse seismic techniques. High-resolution seismic methods exhibit good potential for incorporation into CO_2-flood management. Use of an unconventional approach to acquisition and interpretation of the high-resolution time-lapse/4-D seismic data was key to the success of this monitoring project.

Weak-anomaly enhancement of selected non-inversion, 4-D-seismic attribute data represented a significant interpretation development and proved key to seismic monitoring of CO_2 movement. Also noteworthy was the improved definition of heterogeneities affecting the expanding floodbank. Among other findings, this time-lapse seismic feasibility study demonstrated that miscible CO_2 injected into a shallow, thin carbonate reservoir could be monitored, even below the classic temporal seismic resolution limits.

Presentations and Publications of Results During Year 2

<u>Presentations</u>

2004 SEG annual meeting in Denver (publication cited below).

2005 AAPG Midcontinent section meeting in Oklahoma City:

Miller, R.D., A.E. Raef, A.P. Byrnes, and W.E. Harrison, 2005, 4-D seismic—Application for CO_2 sequestration assurances [Abs.]: American Association of Petroleum Geologists Mid-Continent Section meeting, Oklahoma City, Oklahoma, September 10-13.

2005 Sixteenth Oil Recovery Conference in Wichita:

Miller, R.D., 2005, Time-lapse high-resolution 3-D seismic imaging to monitor a CO_2 flood in a thin carbonate reservoir, Hall-Gurney field, Kansas: Sixteenth Oil Recovery Conference, Wichita, Kansas, April 6.

2005 AAPG annual convention in Calgary, Alberta, Canada (2 posters):

Byrnes, A.P., R.D. Miller, and A.E. Raef, 2005, Evolution of reservoir models incorporating different recovery mechanisms and 4-D seismic—Implications for CO_2 sequestration assurances [Abs.]: Poster presented at the annual conference of the American Association of Petroleum Geologists, June 19-22, Calgary, Alberta, Canada.

Raef, A.E., R.D. Miller, A.P. Byrnes, W.E. Harrison, and E.K. Franseen, 2005, Time-lapse seismic monitoring of enhanced oil recovery CO_2-flood in a thin carbonate reservoir, Hall-Gurney field, Kansas, U.S.A.: Poster presented at the annual meeting of the American Association of Petroleum Geologists, Calgary, Alberta, Canada, June 22: Kansas Geological Survey, Open-file Report 2005-24.

<u>Publications</u>

KGS Project website: www.kgs.ku.edu/Geophysics/4Dseismic.

Miller, R.D., A.E. Raef, A.P. Byrnes, J.L. Lambrecht, and W.E. Harrison, 2004, 4-D high-resolution seismic reflection monitoring of miscible CO_2 injected into a carbonate reservoir in the Hall-Gurney field, Russell County, Kansas [Exp. Abs.]: Society of Exploration Geophysicists, p. 2259-2262.

Miller, R.D., A.E. Raef, A.P. Byrnes, and W.E. Harrison, 2004, Progress Report Year 1: 4-D high-resolution seismic reflection monitoring of miscible CO_2 injected into a carbonate reservoir: Kansas Geological Survey, Open-file Report 2004-45.

Miller, R.D., A.E. Raef, A.P. Byrnes, and W.E. Harrison, 2004, Project Facts: 4-D high-resolution seismic reflection monitoring of miscible CO_2 injection into a carbonate reservoir; *in* DOE Fact Sheet CO_2 EOR Technology: Technologies for Tomorrow's E&P Paradigms: U.S. Dept. of Energy, Office of Fossil Energy, National Energy Technology Laboratory, Strategic Ctr. for Natural Gas and Oil, 2 p.

Raef, A.E., R.D. Miller, A.P. Byrnes, and W.E. Harrison, 2004, 4-D seismic monitoring of the miscible CO_2 flood of Hall-Gurney field, Kansas: *Leading Edge*, v. 23, no. 11, p. 1171-1176.

Raef, A.E., R.D. Miller, E.K. Franseen, A.P. Byrnes, W. L. Watney, and W.E. Harrison, 2005, 4-D seismic to image a thin carbonate reservoir during a miscible CO_2 flood: Hall-Gurney field, Kansas, USA: *Leading Edge*, v. 24, no. 5, p. 521-526.

Project Summary

- Seismic data acquisition and preliminary processing on the six 3-D reflection surveys in budget periods 1 and 2 have been completed on schedule.
- Time-lapse seismic monitoring can reveal weak anomalies in thin carbonates below temporal resolution and can be successful in monitoring a miscible CO_2 flood using moderate cross-equalization and with attention to consistency in acquisition and processing details. Most of all, methods applied here avoid the complications associated with inversion-based attributes and extensive cross-equalization techniques.
- Time-lapse seismic monitoring provided timely support for flood-management in the CO_2 flood pilot project.
- Spatial textural, rather than spatially sustainable magnitude, time-lapse anomalies were observed and should be expected for thin, shallow-carbonate reservoirs. Non-inversion, direct-seismic attributes proved accurate and robust for monitoring CO_2 movement.
- Distribution and geometries associated with similarity seismic facies and seismic-lineament patterns are suggestive of a complex ooid shoal system.

Current Status

Beginning in June, the CO_2 Pilot began the first water injection cycle. A total of five 3-D reflection surveys were acquired in the initial CO_2 slug injection phase; since onset of water injection another survey has been acquired and several are scheduled during this water injection portion of the project. Anticipated changes in seismic signature interpreted within the Lansing-Kansas City (L-KC) Group 'C' zone should provide enhanced opportunities to better refine and sharpen the seismic image of the CO_2.

	Budget Period I	Budget Period II	Budget Period III	Budget Period IV	Budget Period V	Budget Period VI
Task	Year 1 2003-04	Year 2 2004-05	Year 3 2005-06	Year 4 2006-07	Year 5 2007-08	Year 6 2008-09
1. Seismic survey design						
2. Pre-injection 3-D survey						
3. Compare simulation to survey (CO_2 flood begins)						
4. First time-lapse 3-D survey						
5. Second time-lapse 3-D survey						
6. Third time-lapse 3-D survey						
7. Fourth time-lapse 3-D survey						
8. Fifth time-lapse 3-D survey						
9. Sixth time-lapse 3-D survey						
10. Seventh time-lapse 3-D survey						
11. Eighth time-lapse 3-D survey						
12. Evaluation of flood efficiency						
13. Ninth time-lapse 3-D survey						
14. Tenth time-lapse 3-D survey (CO_2 flood ends)						
15. Eleventh time-lapse 3-D survey						
16. Final project evaluation and report writing						

Progress Report on Intermediate Processing and Preliminary Interpretation of Baseline (November 2003) and the First Three Monitor 3-D Surveys (January, March, June 2004)

Processing data from each of the different surveys followed as near the same procedures as possible, only changing parameters as necessary to accurately compensate for surface changes and equipment performance. No standardized equalization approach was used, the only changes unique to each survey were in response to variations in statics related to changes in soil conditions. A standard 3-D processing flow was used, minimizing applications that were influenced by data characteristics, and focused on processes that act more uniformly on the different data sets. In general, the last four sweeps at each station were correlated, noise unique to each sweep removed, geometry assigned, and vertically stacked to provide the greatest signal-to-noise enhancement possible. These four-shot vertical stacks at each shot station were then muted to remove first arrivals, air-coupled wave, and ground roll. Prior to binning, these shot gathers were spectrally enhanced through deconvolution and digital filtering. Next the traces from each shot gather were sorted into their assigned bins, corrected to vertical incidence as a result of the different source-to-receiver offsets, and adjusted for trace-specific static irregularities. A variety of other processing operations were tested and some proved beneficial and will be used during final processing. Once the data were appropriately processed, they were CMP stacked to produce a seismic volume.

After production of a suitable seismic volume, any 2-D line can be extracted and viewed as a seismic cross section (Figure 1). In a 2-D format subtle differences in wavelet character can be recognized both horizontally (trace to trace) and vertically (as a function of depth). Because time-lapse techniques are being used on these data, subtle changes in wavelet characteristics are also readily recognizable over time (survey-to-survey). Changes appearing consistent throughout the time-depth interval on a single survey are likely related to the near surface. However, if changes are observed in reflection wavelets across a limited number of traces and within a small vertical time-depth window on different surveys, it is reasonable to suggest those changes are in response to variation in the rock properties somewhere within the subsurface volume. In some cases changes in seismic signature can be tracked to anomalous zones elsewhere in the section; shadow zones or dim outs are a common example.

Comparing and contrasting 2-D cross line 87 from both the baseline and third monitor (June 2004) surveys, changes in seismic character are evident (Figures 1 and 2). Clearly with a dominant frequency of only around 60 Hz, much is still needed to enhance the higher frequency component of these data present on shot gathers. However, even with this preliminary lower resolution data, a change in the reflection wavelet amplitude is likely related to reflectivity, and therefore the presence of CO_2 is evident. This change in amplitude and wavelet character between the baseline and third monitor survey can be observed across a zone approximately centered beneath X-line 71 and near the top of what is interpreted as the Lansing-Kansas City (L-KC) reflection at around 560 ms. This difference is quite pronounced considering that there has been no interval-specific processing done to these data specifically targeting the L-KC interval and this type of anomaly. Other changes in amplitude can be distinguished between the two surveys, but they are not consistent with theoretical expectation nor do they have a geometry that would lend itself to this kind of change in rock properties.

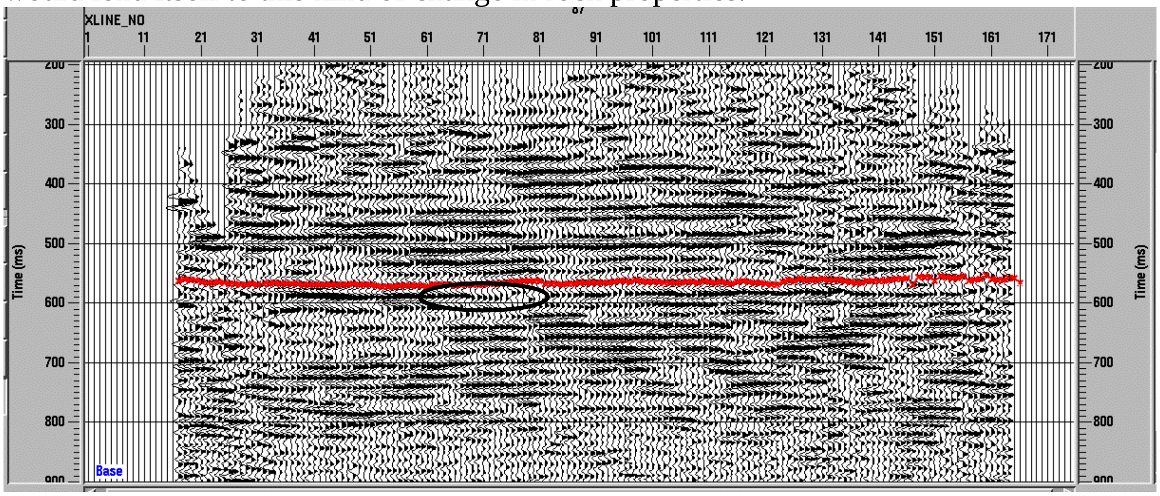


Figure 1. A 2-D slice from the baseline survey during November 2003 with the approximate top of the L-KC interval interpreted in red and an ellipse defining the area immediately below the L-KC appearing to change most dramatically when contrasted with the same 2-D cross line slice of the June 2004 survey.

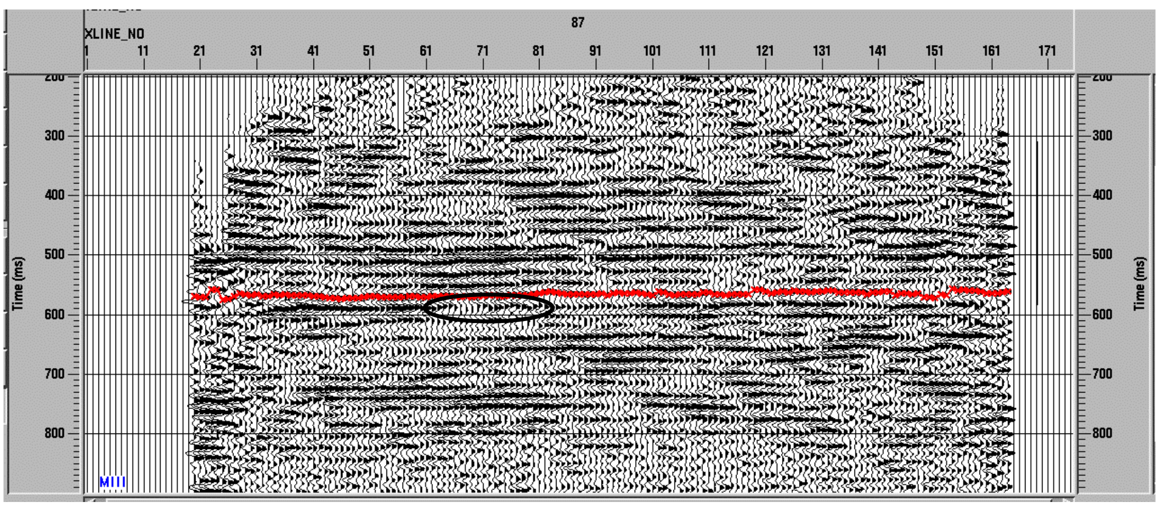


Figure 2. The same 2-D slice as Figure 1, except from the third monitor survey acquired in June 2004. As with the equivalent 2-D cross line slice, the approximate top of the L-KC interval is interpreted in red with an ellipse defining a zone where a marked change in reflection character can be observed between the baseline and third monitor survey.

Careful study of differences between the two vertical slices through the seismic volume reveals other differences below the interpreted top of the L-KC that are not directly related to the CO_2 (there is some possibility that a few of these could be indirect indicators of changes in fluid properties). For example, differences such as beneath X-line 81 at about 650 to 700 ms appear different between the two data sets. However, the depth of this anomalous zone beneath the L-KC (almost 100 ms) and its apparent isolation (that is, vertical connectivity as would be the case for a "shadow zone" related to increased attenuation or reflectivity due to the CO_2) rule out this relative difference between the two surveys as related to the CO_2 invasion. As well, intervals with differences in amplitude between the two surveys such as that visible between about 650 ms and 730 ms beneath station 111 are related to differences in source energy, coupling, cultural and natural noise, and other acquisition mismatches between the two surveys. Some data processing operations will effect slight changes in data characteristics unrelated to reservoir-specific change, as might be the case when noise levels change or soil conditions result in altered reflected wavelets.

Seismic Modeling and Rock Physics

In this thin layer pilot case study, it is essential to take into consideration that complex seismic responses to change in seismic velocity introduced by variations in pore fluid composition and therefore rock properties are similar to the apparent "velocity change" due to thickness change. Seismic modeling of a thinning layer (Figure 3) indicates that seismic amplitude may increase or decrease depending on whether thickness increases render layer thicknesses less than or greater than half the dominant seismic wavelength. We therefore took notice that the CO_2-related amplitude dimming might be weakened or enforced by thickness-related effects, depending on the region of thickness variability.

Nonuniform pore-fluid acoustic-property changes resulting from associated changes in reservoir pressures and facies within the pilot study area (pressure changes ranging from 11.7 - 106 N/m2 [1700 psi] at the injection well to 2.7 - 106 N/m2 [400 psi] near wells 12 and 13) and the associated continuum of CO_2 proportions in the pore-fluid composition significantly complicate calculations of the effective pore-fluid properties, generalized over the entire flood-pattern. Consequently, we have attempted to get an approximate bulk snapshot of the effects of pore-fluid composition changes.

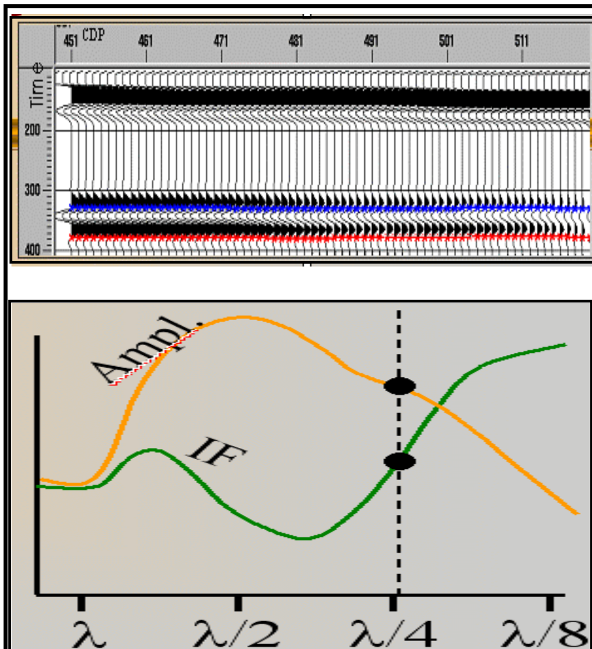
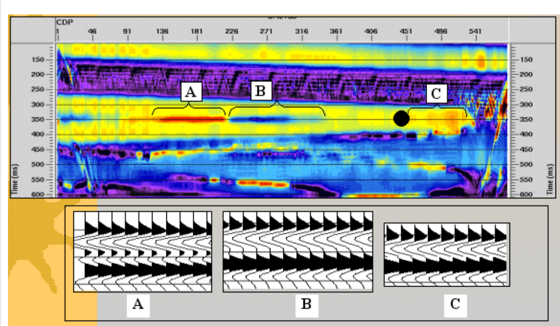


Figure 3. Synthetic seismic for a thinning layer (left); Amplitude and instantaneous frequency attributes variations with thickness in units of wavelength (lower left); Instantaneous frequency section of the thinning-layer synthetics and amplitude variations in time-window of the layer (lower right).



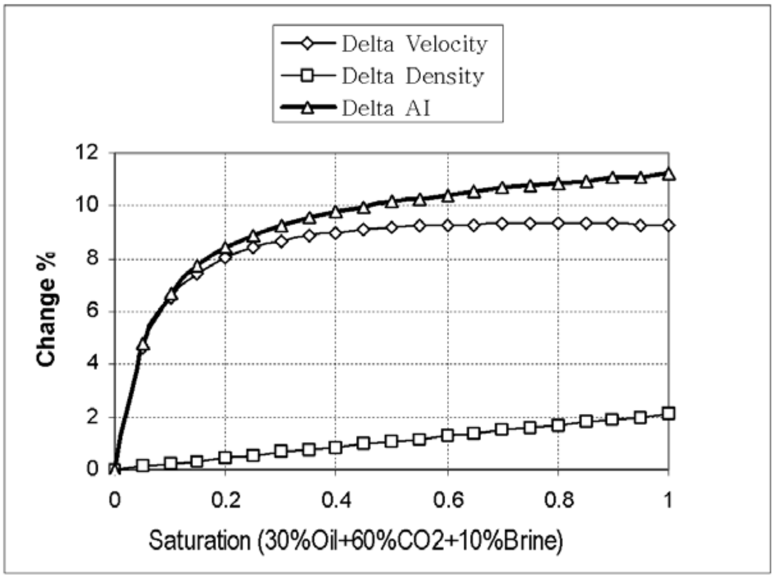


Figure 4. Gassman modeling. Percentage of property change equivalent to effective fluid (30% Oil + 60% CO_2 + 10% Brine) compared to 100% (30% Oil + 70% Brine) (pressure of 11 Mpa and temp. of 35°C).

Gassmann's relations can be used to estimate rock-bulk modulus change for the two (effective fluid) pore-fluid compositions in proximity to the injection well. For our case, the two-fluid composition includes the combination of oil-water and miscible CO_2-oil-water (Figure 4).

Unlike many carbonate reservoirs where significant facies changes can occur over very short distances, the relative lateral uniformity of petrophysical and lithological properties in the target oomoldic limestone interval should allow the use of Gassmann's type of fluid-replacement modeling. CO_2-induced acoustic-impedance changes of up to 11% are expected based on these calculations.

Amplitude Envelope Attribute Analysis

Instantaneous frequency attributes provided a gross image of the areal extent of the CO_2 early in the program (previous web updates). With the need for horizon-based interpretations and a higher resolution image of the CO_2 plume as it expands across the site, a more detailed processing flow involving reflection specific enhancements and amplitude analysis was initiated. After the horizon interpreted as the L-KC "C" was identified on all 3-D seismic cubes (baseline and first three monitor surveys), the amplitude envelope attribute was calculated for the L-KC horizon. Amplitude envelope or reflection strength seismic attribute was selected because of its insensitivity to small phase shifts. This is especially important for this data set because the vibrator used for this study was not phase locked; minor variations in wavelet phase should be expected from survey to survey and shot to shot. Seismic reflection data for this study are all recorded uncorrelated, providing the opportunity during the later years of this study to apply phase compensation filters prior to correlation. This will allow defensible comparison of phase-sensitive attributes in the future.

Amplitude envelope falls in the category of instantaneous attributes, which are based on the complex trace concept. A complex trace *F(t)* is given by:

$$F(t) = f(t) + jf_{\perp}(t) = A(t)e^{j\theta(t)}$$

Where $f(t)$ = Real trace data, $f_{\perp}(t)$= Hilbert transform of real trace (quadrature trace), $A(t)=|F(t)|=\sqrt{f^2(t)+jf_{\perp}^2(t)}$ = Amplitude Envelope or reflection strength, and $\theta(t)$= Instantaneous phase. Those complex trace attributes provide instantaneous and quantitative description of seismic waveform.

Average amplitude envelope is phase and frequency independent and more stable in terms of susceptibility to noise contamination when compared to many other seismic attributes. Those characteristics, besides the intrinsic property of being instantaneous, suggest that the average "median" amplitude envelope may be a robust candidate for time-lapse studies and enable a higher level of tolerance to imperfection in cross-equalization practices. For our application we used a "median value" of five samples around the time horizon. From analysis of synthetic examples, amplitude envelope has proven to be one of the most tolerant and robust properties to noise-effects and phase fluctuations.

PPB Interpretation Technique

Considering the necessity to image a weak (in the vicinity of background noise) EOR-CO_2 change, it was essential to apply an interpretation approach that avoided differencing time-lapse (TL) data or attribute with the corresponding baseline data or attribute. Our approach uses parallel progressive blanking (PPB), color balancing and color focusing of both baseline and TL amplitude envelope attributes, and analysis of resulting textural differences (Figure 5). With the PPB method of interpretation, no differencing is applied; PPB is applied to both the baseline and the TL-amplitude envelope maps, and a comparison/search for TL-textural reservoir signature is carried out. We applied the PPB method to balanced and normalized amplitude envelope maps of one baseline and three monitor amplitude envelope maps.

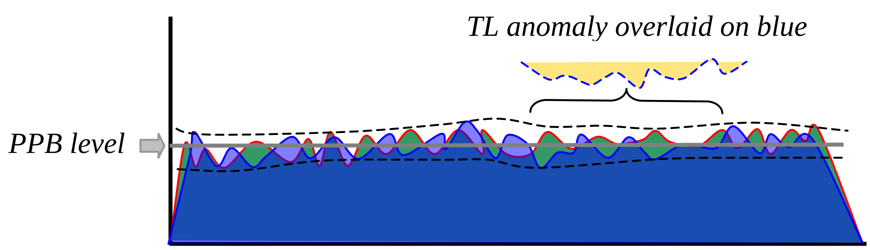


Figure 5. Schematic of the PPB approach of revealing below-background TL anomalies.

The PPB concept is based on the observation that differencing alone does not highlight reservoir anomalies if the change in magnitude of the seismic response is less than the amplitude of non-repeatable background noise. A background color is assigned to all values outside a narrow range within which the full color spectrum is focused to increase the sensitivity to fine details (Figure 6). In so doing, spatially significant textural differences can be enhanced at the highest level of resolution where otherwise the coarseness of the scale would have made these differences indistinguishable from noise. Using PPB, the sensitivity of the seismic signature to changes in the reservoir appears to be far greater than has previously been demonstrated using more conventional approaches.

The PPB approach can be illustrated (Figure 5) by placing a very weak TL attribute anomaly over a TL attribute profile from a seismically innocuous area (blue). Based on modeling, the expected change in amplitude from the incursion of CO_2 is very low (below noise fluctuations). A textural interpretation approach is a much more effective way of distinguishing areas with such small changes in amplitude compared to differencing approaches (baseline survey [green] with a TL dataset [blue]). Delineating weak reservoir signatures by their textural characteristics is effective because of the inherent reduction in sensitivity to background noise and heightened resolution potential of the data.

For this seismic imaging program, PPB proved sensitive to weak time-lapse signatures that otherwise would have been concealed by noise and remnants of balancing/cross-equalization techniques. These textural differences are relatively stable over a range (two-three color steps) of scanned levels, suggesting their origin is production and/or EOR effects. These observations were verified with production simulation, production data, and consistency in multiple surveys.

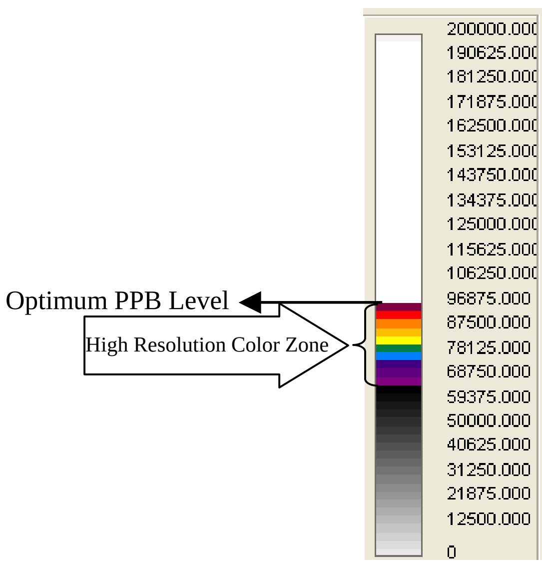


Figure 6. Sample color bar demonstrating how the fine sampled zone of data values can be presented in the highest resolution format possible.

As applied here, this newly developed 4-D-seismic interpretation approach allows better focusing of color scales within the critical textural-difference range on time-lapse attribute maps, thereby enhancing apparent resolution within the critical range. Below the temporal resolution in thin heterogeneous stiff reservoirs, signatures of reservoir change are encoded in and interfered with by main events. Contribution of small changes in fluid saturation will manifest themselves as subtle spatial changes in texture rather than monotonically increasing or decreasing horizon attributes.

The PPB method is an alternative to TL-map differencing when targeting low S/N TL anomalies and can be described succinctly using the following expressions.

$$B(x, y) = S_T(x, y) + N_b,$$

where *B(x,y)* is the baseline survey attribute horizon map and a monitor survey (acquired at some later time) attribute horizon map

$$M_1(x, y) = S_T(x, y) + S_{TL}(x, y) + N_m,$$

where N_b and N_m are random noise in baseline attributes and TL attributes respectively, and S_{TL} is the change in attributes due to a change in physical properties. The anomaly (S_{TL}) is not distinguishable over the background signal/noise levels on difference maps (B-M_1), when N_b - N_m is equal to or greater than S_{TL}. The extremely subtle S_{TL} imprinted on the S_T, combined with the non-geologic, highly variable N_m results in textural differences between baseline and monitor horizon attributes at "optimum" PPB-level. This textural change is only observable when PPB-levels for the baseline horizon are selected near background levels. Intrinsic with this approach is the need to suppress background noise so a larger color range is available within this critical variability range of TL and baseline attribute maps.

Preliminary Interpretations of January, March, June 2004 Surveys (M1, M2, M3)
With the expected small change in seismic response relative to the change in fluid during the CO_2 flood at the Hall-Gurney field, the utilization of the PPB method for interpretation of the presence of CO_2 is believed to provide accurate results (Figure 4). Because this method does not involve differencing, PPB can be applied to amplitude envelope maps of baseline and monitor data without equalization operations. Unlike differencing, PPB allows more control (determining the PPB range and scale segmentation) on the part of the interpreter, placing a more significant emphasis on matching display characteristics with the geologic setting.

Most data were of good quality, providing an excellent match between seismic cross-sections and synthetic traces (Figure 7). The target seismic horizon (gray) is at about 570 ms two-way travel time and for this project is defined as represented by a peak amplitude value.

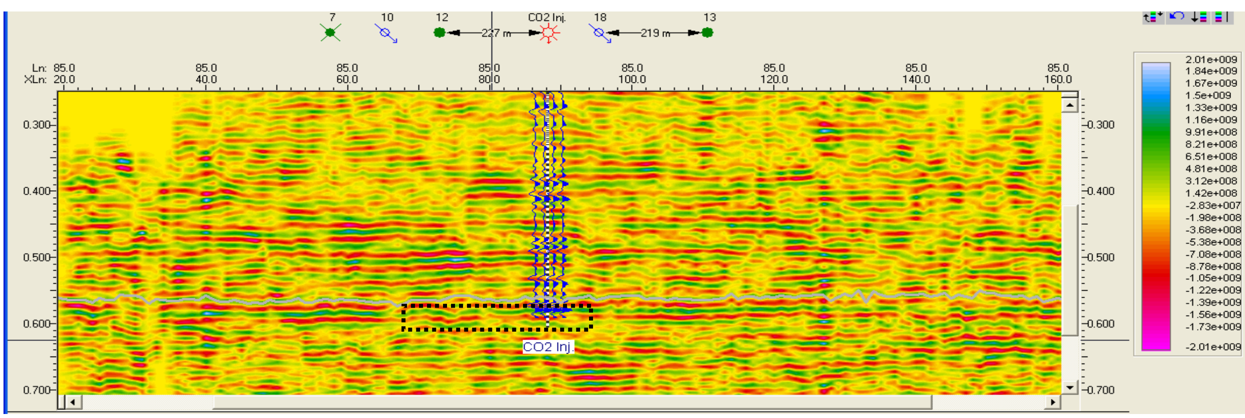


Figure 7. Seismic amplitude section, interpreted target top horizon (gray), and seismic synthetics at well CO2I#1. Gas shadow effect is evident below time horizon in the vicinity of the injection well.

Expansion of the CO_2 plume within the pilot area was successfully monitored seismically and tested against field production data (Figure 8a, b, c, d). Amplitude envelope attribute for the L-KC "C" was extracted from the horizon interpreted independently throughout each seismic volume. Synthetics generated from the sonic log of the CO_2 injection well were a principal guide in consistently identifying the appropriate wavelet. Comparison of the four different amplitude envelope attribute maps of data acquired over an eight-month period clearly shows the subtle nature of the anomaly associated with the CO_2 plume. However, using reasonable constraints on interpretations the affected area can be identified with reasonable confidence for each of the unique TL images.

Flood pressure distribution and consequent CO_2 movement are strongly influenced by the presence of boundaries interpreted to exist in the pilot region. These have been discussed in previous progress reports. Previous field performance and modeling had indicated the presence of a permeability barrier south of well 18. Seismic data clearly show the presence of an anomaly consistent with this production response. A N-S seismic anomaly has also been identified to the east of CO2I#1 and lying between CO2I#1 and well 13. This is discussed below.

Due to the weak signal-to-background seismic response, the boundary of the region identified as having CO_2 is not precise or unique. Given that CO_2 originates from a single location (CO2I#1), it is logical to assume that areas indicating consistent seismic response change, and interpreted to exhibit the presence of CO_2, would be connected with the injection source and exhibit a continuous invasion path from any CO_2-occupied area back to CO2I#1. Regions not exhibiting a continuous connection to CO2I#1, but that exhibit what might be interpreted as a change in seismic response and the presence of CO_2, are assumed to not contain CO_2 but are noted (Figure 8). For the most part, the anomalous seismic region interpreted as having CO_2 has exhibited a continuous and contained shape through all the time surveys. To verify how the region identified as containing CO_2 agreed with the material balance of CO_2 volume injected, volumetric analysis based on total injected fluid and mapped reservoir properties was performed to determine the reservoir conditions necessary to obtain the interpreted CO_2 plume size and distribution. Volumetric analysis indicates that insufficient CO_2 has been injected to have CO_2 sweep through the entire thickness of the L-KC “C” zone for the areas defined seismically. However, the interpreted areal extent of CO_2 is consistent with a volumetric model where CO_2 migration is restricted, in some portion of the flood area, to a thin (1-2 ft thick) higher-permeability interval within the “C” zone. This was premised on assumed three-phase relative permeability relationships. This model for L-KC “C” zone permeability distribution vertically is consistent with permeabilities observed in CO2I#1.

Production data are consistent with the interpreted change in the CO_2 plume area. The January 2004 and March 2004 surveys are interpreted to indicate that the CO_2 plume reached well 12 very near the time of the March 2004 survey. Production data recorded increases in CO_2 concentration in well 12 in March 2004. The June 2004 survey interpretation indicates CO_2 approaching well 13 but not reaching the well. Production data show traces of CO_2 reaching well 13 in October 2004.

Seismic mapping of the progression of the CO_2 plume away from the CO2I#1 injector provides a consistent picture of plume development. In addition, observed changes in the CO_2 plume through time are consistent with changes in field injection and production rates (Figure 9).

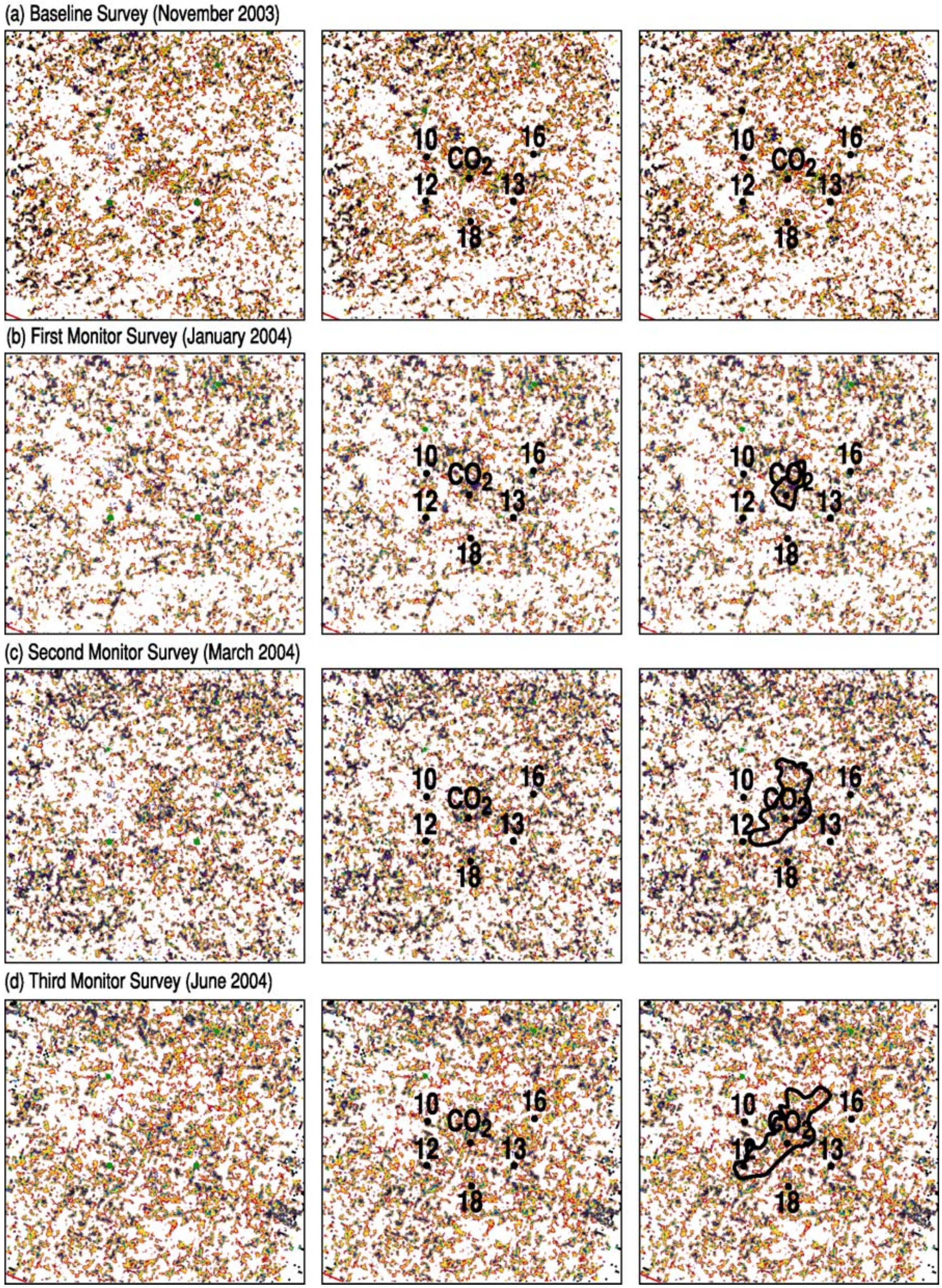


Figure 8. Amplitude envelope horizon map of baseline in November 2003 (a), first monitor survey in January 2004 (b), second monitor survey in March 2004 (c), and third monitor survey in June 2004 (d).

It is unlikely the area of the reservoir involved in the flood has uniform rock properties considering the geology as interpreted from seismic and well data. Based on ooid shoal geometries, it is not unreasonable to postulate that the seismically interpreted boundaries represent shoal boundaries and a possible tidal channel on the east and therefore, potentially, restrictions to CO_2 flow. Within the flood area vertical and horizontal changes in reservoir porosity and permeability within and between bedsets would be expected to result in non-uniform migration both horizontally and vertically. The interpreted bounding anomalies could be expected to influence areal pressure distribution and CO_2 flow. Differences in permeability within bedsets could be anticipated to result in vertical differences in permeability, as observed in CO2I#1, and CO_2 movement along thin higher-permeability intervals for the distance that the high-permeability bedset extends.

Monitor surveys were acquired at gradually increasing time intervals following the pre-CO_2 injection or baseline survey, acquired in November 2003, with injection of CO_2 starting December 2003. Seismic monitoring of CO_2 movement began with the first monitor survey 6 weeks after starting injection (M1), followed by the second monitor survey about 12 weeks after start of CO_2 injection (M2), then a third monitor survey at 26 weeks (M3), and fourth monitor 42 weeks after start of CO_2 injection (M4; Figure 9).

Movement of CO_2 is a function of injected CO_2 volume and pressure in CO2I#1, injected water volumes and pressures in wells 10 and 18, the production rates and bottom hole pressures in wells 12 and 13, and the distribution of reservoir properties in the flood area. Expansion of the CO_2 plume appears to be predominantly in a northeast/southwest direction (Figure 9). Some CO_2 flooding to the north of CO2I#1 was modeled in reservoir

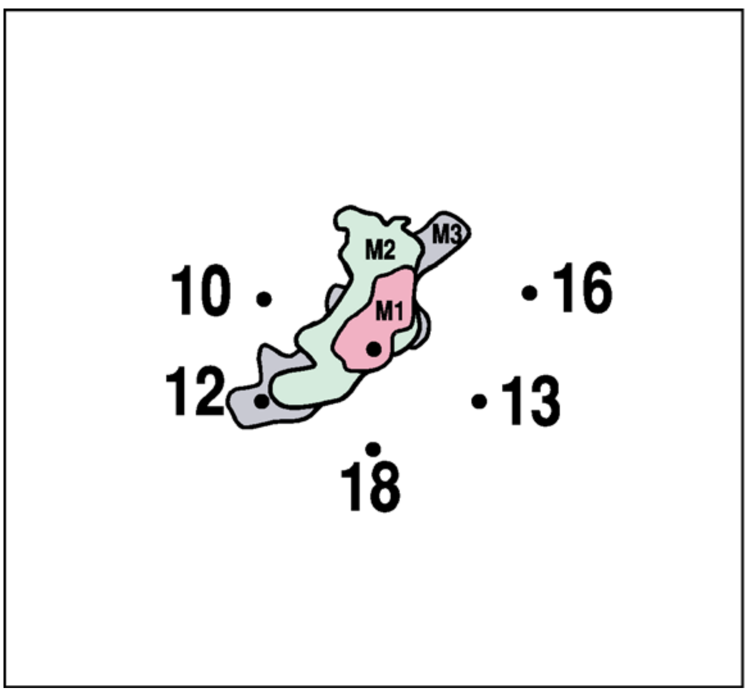


Figure 9. Interpreted boundary of the CO_2 plume based on the first three monitor surveys (January, March, June 2004). Note CO_2 movement toward well #13 only began to occur between the March and June surveys in response to increased water injection in well 7. Also note the northwest appendage evident on the March 2004 survey has receded in response to the increased water injection in well 10.

simulations prior to initiation of the flood. However, the northward extent of the CO_2 area defined by seismic response is greater than reservoir simulations predicted. This may reflect more focused CO_2 movement than modeled due to several factors including: 1) restriction of movement to the east in response to the observed barrier; 2) decreased pressure drop to the southeast toward well 13 due to the presence of the barrier; 3) possible enhanced permeability to the north, as indicated by good reservoir properties in wells 8 and 1; 4) under-production early in the flood resulting in movement of CO_2 away from producing wells; and 5) under-injection in well 10 for the actual reservoir properties compared with those modeled resulting in less containment to the north than modeled.

As expected, changes in injection and production rates impacted the movement of the CO_2. An apparent recession of the CO_2 plume between monitor surveys M2 and M3 in the northwest is consistent with the response expected from an increase in water injection rate in well 10 initiated during that time interval (Figure 9).

Seismically, trends in lithologic relationships may be observable on a lineament attribute map of the horizon interpreted as the L-KC “C” (Figures 10 and 11). A strong northeast/southwest series of lineaments are evident across the entire area. The most pronounced of these lineaments lies between CO2I#1 and well 13 and extends across the entire survey area. Another notable northeast/southwest-trending lineament bounds the western edge of the pilot area. Also evident is a secondary trend of much smaller and more

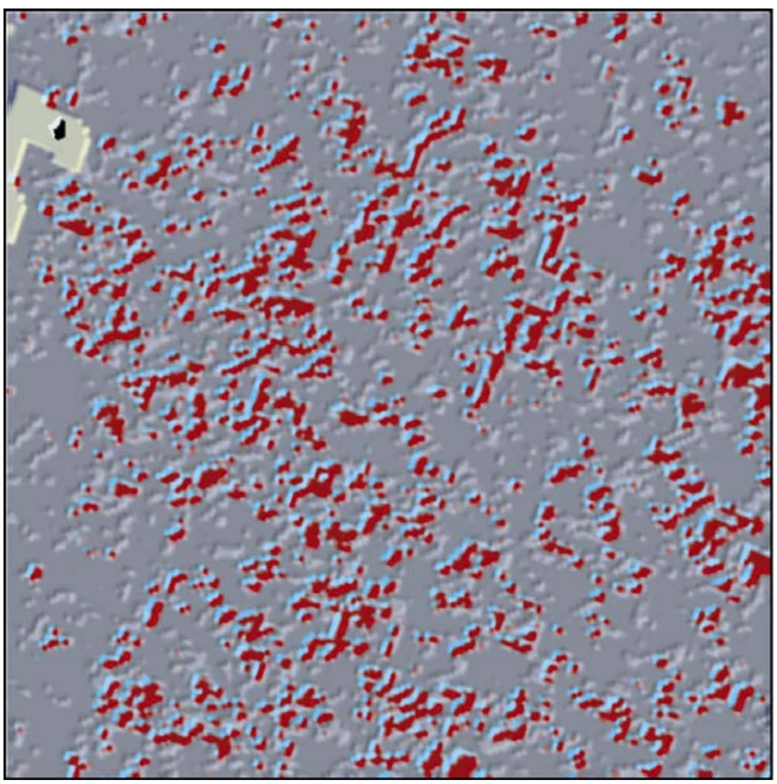


Figure 10. Lineament attribute map. The principal trend is northeast/southwest with secondary trends oblique to the principal trend with an orientation around west-northwest by east-southeast. The principal trends can be traced across the survey area, while the secondary trends are much more discontinuous.

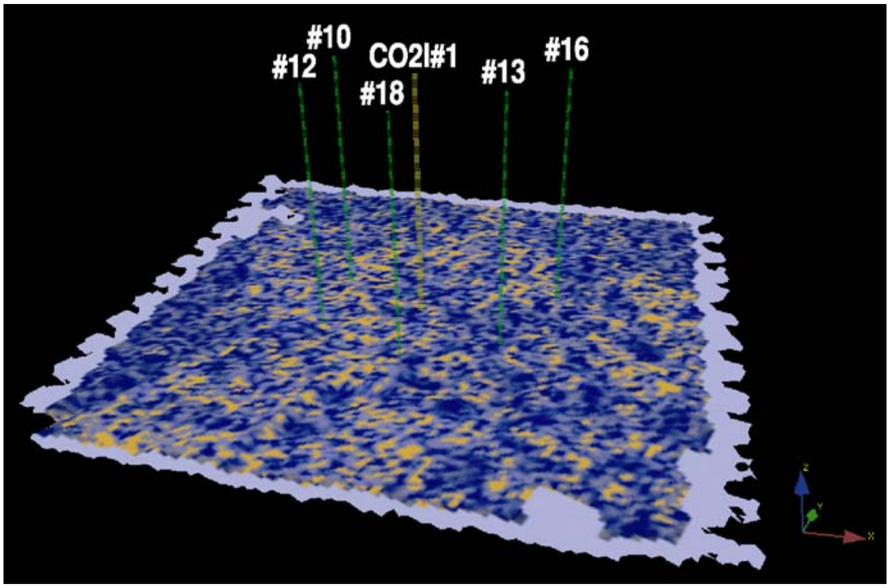


Figure 11. Seismic lineament maps rotated and annotated with well locations. The main trend of lineaments, shown in gold, is NNE-SSW.

discontinuous lineaments with a more east northeast/west-southwest trend. These are especially pronounced in the northern half of the survey area. The possibility was investigated that these lineaments are a processing artifact representing a byproduct of the receiver and shot lines orientation that after grid rotation during the binning process would have a bearing consistent with that rotation. The orientation of the primary and secondary seismic lineaments is not consistent with the 22° grid rotation. Therefore, these lineaments are interpreted to not represent artifacts of processing or acquisition.

A strong correlation exists between the preferential movement of the CO_2 through this reservoir and features evident on the lineament attribute map. Overlaying the lineament attribute map with the amplitude envelope attribute image provides added support for the suggestion that orientation of rock properties might be influencing fluid movement through this reservoir (Figure 12).

Of particular interest are the two lineaments that appear to be influencing the expansion of the CO_2 plume at the time of the second 3-D survey (Figure 12b). A generally west-to-east lineament running immediately south of well 12, in conjunction with water injection in well 18, can be interpreted to be diverting the southernmost "tail" of the CO_2 plume from northeast to southwest to move westerly. Under the pressures and fluid present along the southern edge of the CO_2 plume at the time of this survey, this lineament might represent a change in permeability and therefore is effectively channeling the CO_2 in more of a southwesterly direction. A second dominant lineament runs approximately northeast to southwest between CO2I#1 and well 13 and was previously identified on the lineament-only attribute map. At the time of the second survey, the CO_2 plume had only just contacted this lineament southeast of CO2I#1.

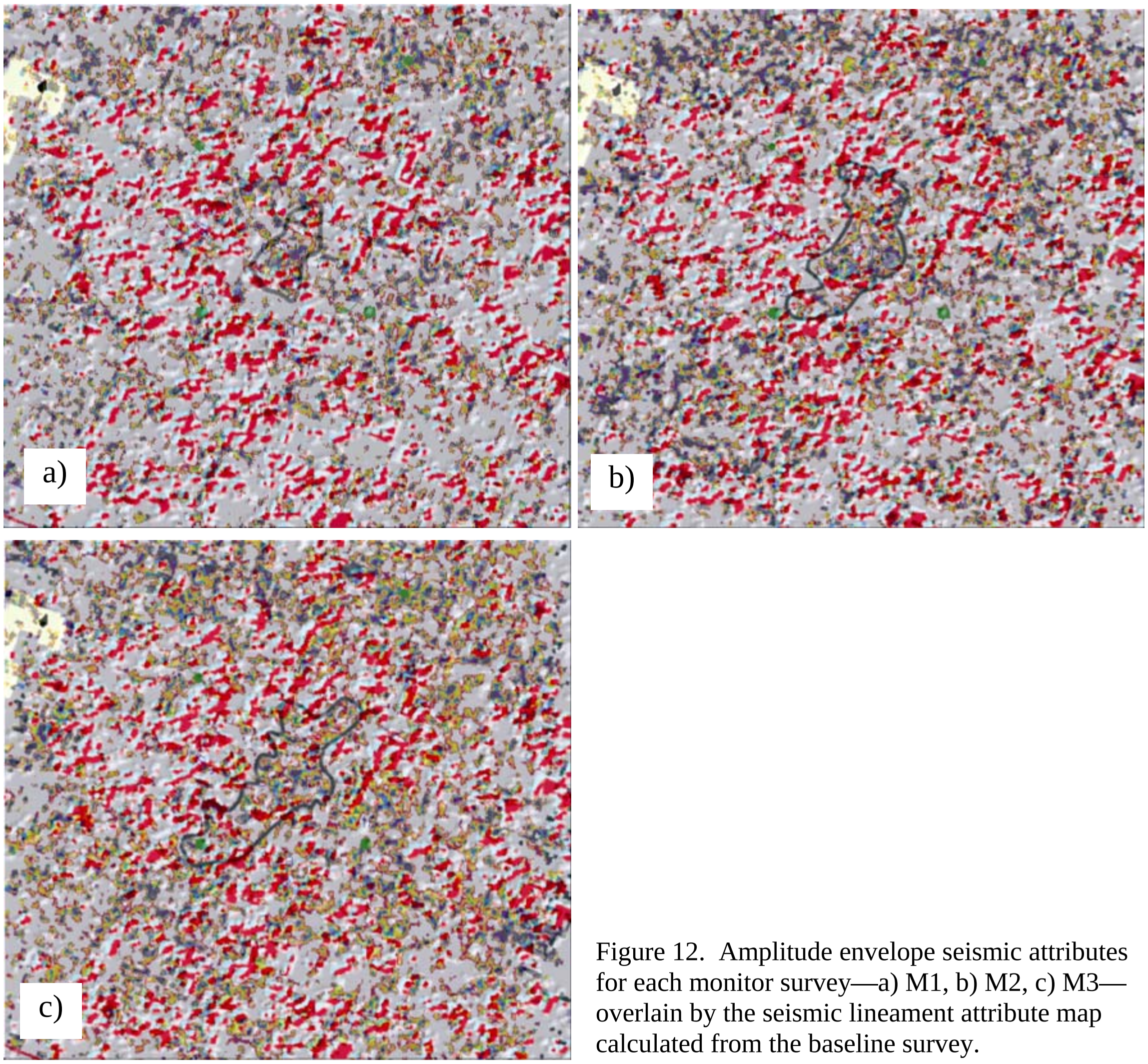


Figure 12. Amplitude envelope seismic attributes for each monitor survey—a) M1, b) M2, c) M3—overlain by the seismic lineament attribute map calculated from the baseline survey.

Clearly development of the CO_2 plume is strongly influenced by features enhanced on the seismic lineament attribute maps (Figure 13). Comparing each interpreted amplitude envelope map for the three monitor surveys overlain by the lineament map it seems that growth of the CO_2 plume is consistently influenced by several key lineaments it encounters through time and lateral expansion. The two dominant lineaments are easy to identify, but of particular importance are the apparent breaches in the "barrier" as defined by the northeast/southwest lineament. These offsets could represent pathways through this northeast/southwest barrier and would provide CO_2 access to well 13.

The similarity facies attribute map overlain by the L-KC horizon structure map provides a deeper look into possible lithologic explanations for the rate and path of the CO_2 (Figure 14). From the facies map the northeast/southwest directionality of the lithology is evident. Detailed examination shows that the area near well 13 appears both topographically and lithologically different compared to the areas around wells 12 and CO2I#1. This difference may account for the delayed response of well 13.

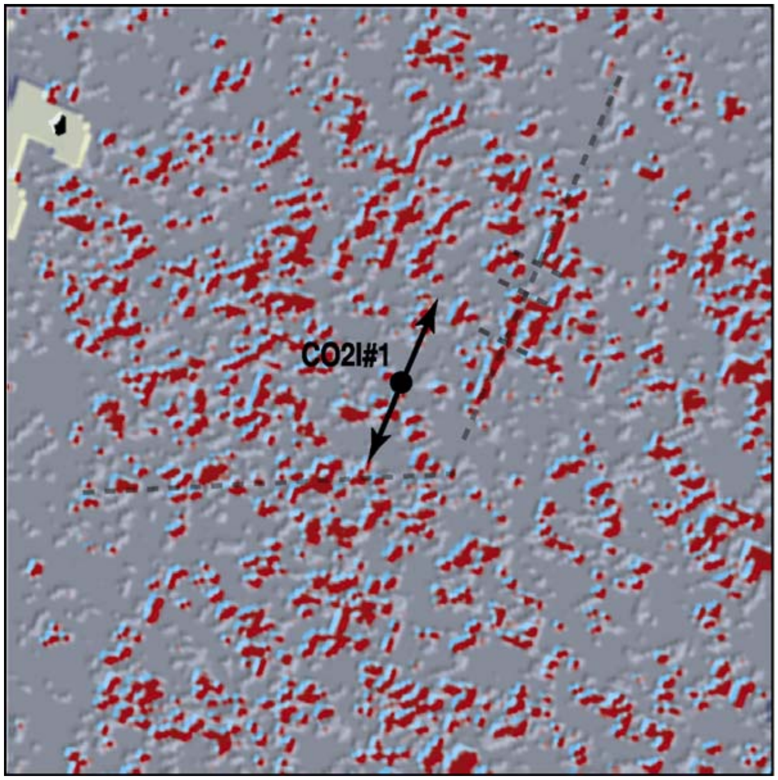


Figure 13. Major lineaments that appear to be influencing fluid movement away from CO2I#1.

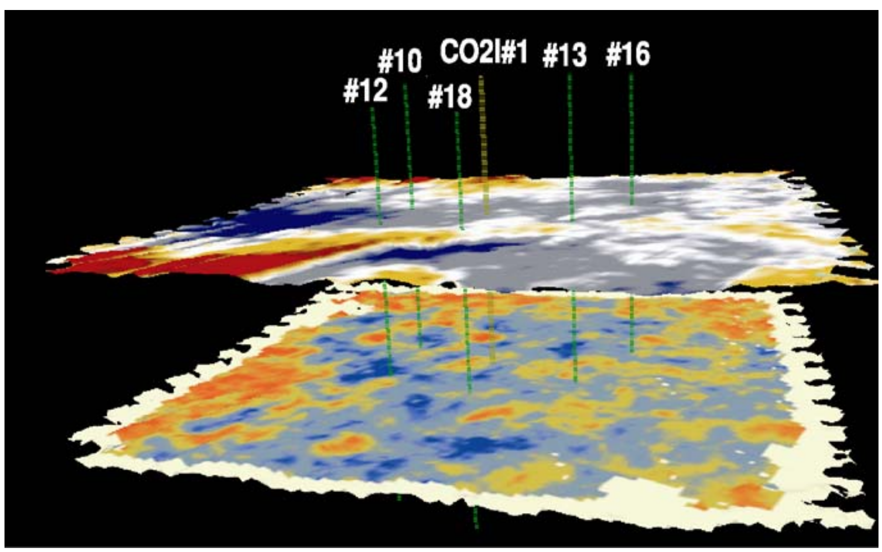


Figure 14. Similarity "seismic facies" map on bottom of diagram. Highest similarity is shown in blue and lowest similarity shown in red. The better reservoir properties occur in blue areas as demonstrated by preferred (faster) EOR-fluid movement in those areas and generally in a SW-NE trend. Well 13 has had delayed response as a result of being separated from a CO_2 injection well (yellow) by lower (golden-red) quality reservoir properties. The distribution and geometries associated with similarity seismic facies patterns are suggestive of a complex ooid shoal depositional motif, which is supported by oolitic litho-facies being the known reservoir in this interval (image ~ 0.75 mi. square). Upper map in diagram is a time structural map showing highest areas in red and lowest areas in blue.

Update on Fourth (October 2004) Monitor 3-D Seismic Survey

Over 790 shot stations were recorded during the October 2004 monitor survey. Data quality overall was good with a slight increase in signal-to-noise ratio that was attributed to a decrease in the average wind speeds over the recording period and increased soil moisture conditions as a result of a wetter than normal fall. Average daily production was around 150 shot stations.

Figure 15. David Thiel operating the IVI minivib2 with GPS tracking and guidance system. A two to four times increase in power was obtained after installation of an Atlas rotary style servo valve in comparison to the factory Moog valve.

Equipment and parameters used during the October 2004 survey were as nearly identical to those used during the previous four surveys (baseline and three monitor surveys) as possible. The IVI minivib2, outfitted with a GPS tracking system, occupied the designed source stations with the exception of three on sandbars (too wet and represented an elevated equipment risk), six in a milo field ready for harvest, and one due to construction of a new pond (Figure 15). All shots were recorded with a Geometrics StrataVisor NZC controller operating ten 24-channel Geodes deployed along five 48-channel survey lines (Figure 16). An eleventh Geode was used to record the pilot, which was sent via radio to the recording vehicle from the vibrator. Three 10-Hz Mark Products Ultra geophones were planted in a triangle measuring about a half-meter on a side centered on the GPS-located station.

Figure 16. Sunset during October 2004 survey. Some data were collected at night to avoid wind noise that increased during the afternoons.

Figure 17. Weather was very pleasant most days with highs in the 70s to 80s and lows around 40. The seismic recording vehicle housed the Geometrics NZC controller and one Geode used to record the vibrator ground force. All data were transmitted to the recording vehicle from the other ten Geodes via ruggedized Ethernet cables. Graduate student Theresa Rademacker of Lincoln, Nebraska, recorded data and performed initial data quality control monitoring of the 240-channel uncorrelated vibroseis data and ground force pilot trace.

With no moisture and daytime temperatures in the 70s to 80s, data acquisition progressed rapidly (Figure 17). The one-square-mile survey area was covered in just over six days. More than 60 Gigabytes of data were recorded during this acquisition period. Data were transferred each day from the hard drive on the controller to the computers located in the mobile processing vehicle via Ethernet. Once the data were transferred to truck-mounted computers, the data were checked for quality and analyzed to determine if the overall data set would benefit from the reoccupation of any shot stations. In general about 15% of all stations were reoccupied in an attempt to improve the signal-to-noise ratio (S/N).

Reduction in wind noise was routinely possible during night acquisition in comparison to during the average day at this site. Clear nights with light and variable winds were the rule, allowing large time windows without interruptions and stoppages due to weather noise. During night shooting, the increased safety and productivity actualized by using the DGPS route and tracking system was dramatic. Even with the very rough and sometimes treacherous terrain around the Smoky Hill River on dark nights (no moon luminance or cloudy), production rates exceeding 15 shot stations per hour were easily maintained. Once the vibrator operator became accustomed to using the computer/DGPS route and tracking system, the only reason to look outside the cab was to make sure obstacles such as tree limbs or ditches dug, appearing since last survey, were not in the vibrator's path.

Surface conditions, especially the vegetation, changed noticeably throughout the first year (Figure 18). Soil moisture conditions changed as evident in slight changes in weathering velocity calculated from first arrivals. Only during the January 2004 survey was the ground frozen. Little change in data quality was observed that could be directly related to that particular ground condition. The normal crop cycle for dryland wheat grown in this part of the Midwest is two years long and includes a growing year and a fallow year. During the fallow year, volunteer vegetation (grasses and weeds) grow rapidly.

Figure 18. November 2003 survey (upper left), January 2004 survey (upper right), March 2004 survey (middle left), June 2004 survey (middle right), and October 2004 survey (lower left).

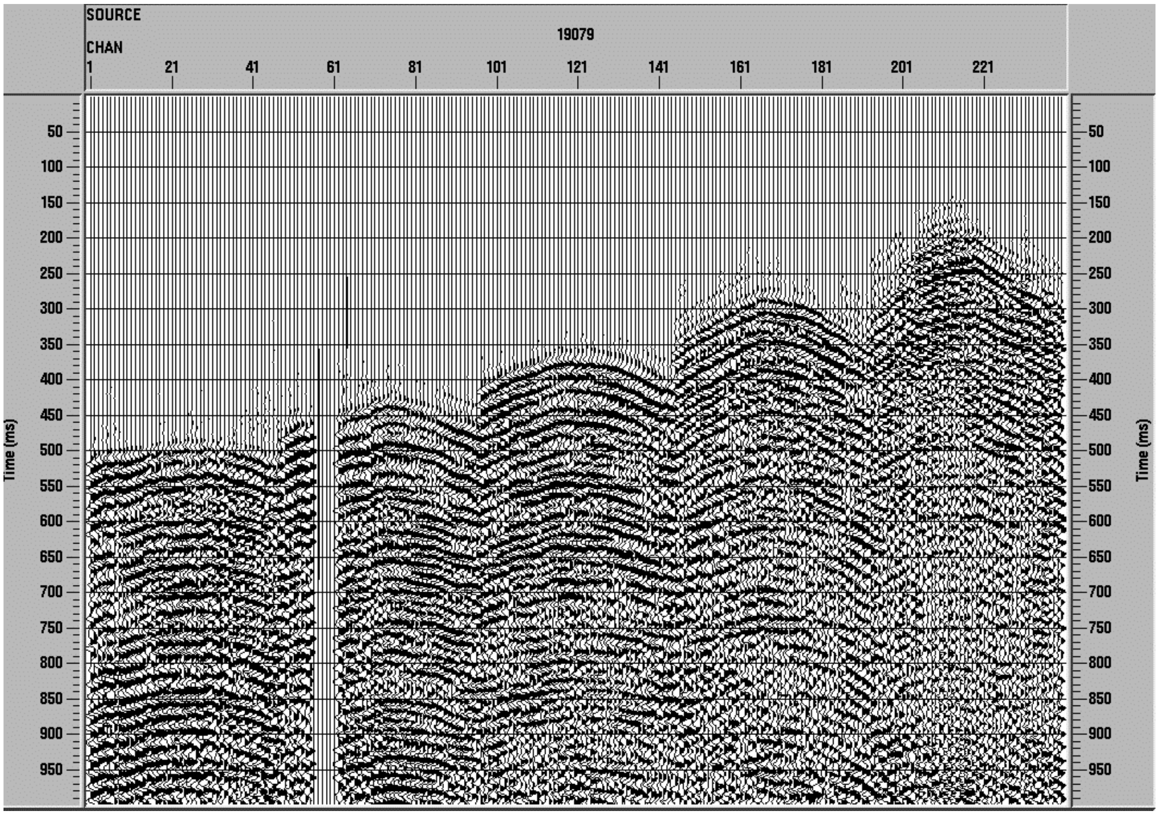


Figure 19. A 240-channel shot gather from station 19079. Reflection events dominate the four-shot vertically stacked shot gather. Coherency of events is excellent and the dominant frequency of this un-filtered shot record is around 80 Hz. After spectral balancing the dominant frequency easily exceeds 100 Hz.

An increase in the S/N was observed on data from the October 2004 survey (Figure 19). As previously noted, this increase in signal is likely related to increased soil moisture and reduced average wind speed during the recording of these 790+ shot stations. Reflection events are very coherent and possess a reasonably broad bandwidth. Reflections arriving at 850 msec and deeper at source offsets in excess of 1 km have excellent signal strength and sufficient coherency to estimate velocity.

Progress Report on Preliminary Processing and Interpretation of the Fourth Monitor Survey (October 2004)

Preliminary interpretation of the October 2004 3-D survey suggests increased "fingering" in the CO_2 migration (Figure 20). Considering the lateral resolution of these data, small objects (sub-wavelength) will be smeared to appear much larger. Therefore a narrow higher permeability zone may possess a seismic signature several times larger than the actual affected area. With that in mind, the fingers from the main CO_2 body may be representative of regions that are several times smaller than they appear on the amplitude attribute data. These fingerlike features have all the necessary characteristics to suggest that this seismic response is based on changes in fluid composition.

One obvious consideration is the volumetrics of a feature this large and the apparent growth since the June 2004 survey. Basic volumetric balance with injected CO_2 and the CO_2 area shown by seismic requires that the defined area of CO_2 represent movement of CO_2 in a thin interval and not through the entire C-zone pay section. Volumetrics would also support the interpretation that the fingers may be narrower than they appear on the seismic data.

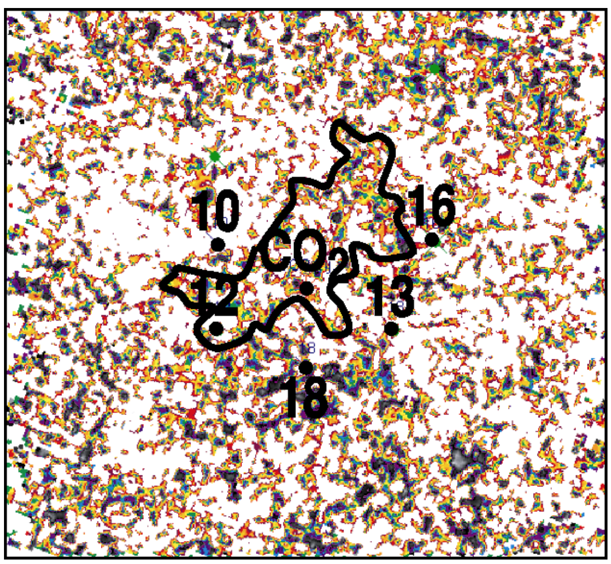


Figure 20. Amplitude envelope attribute for a very preliminary processed October 2004 survey. Fingering is becoming much more pronounced with the general trend of those accelerated migration paths consistent with the secondary lineament orientations previously identified.

Overlaying the four monitor surveys is preliminary due to how early the October 2004 data are in the processing phase (Figure 21).

Interpretation of the areal pattern change can be interpreted to show that growth toward well 13 appears to be accelerating between June 2004 and October 2004, but the path of the CO_2 is not direct. If this interpretation is correct and movement toward well 13 is following narrow, directed pathways, then gradual breakthrough might be anticipated as exhibited by field production.

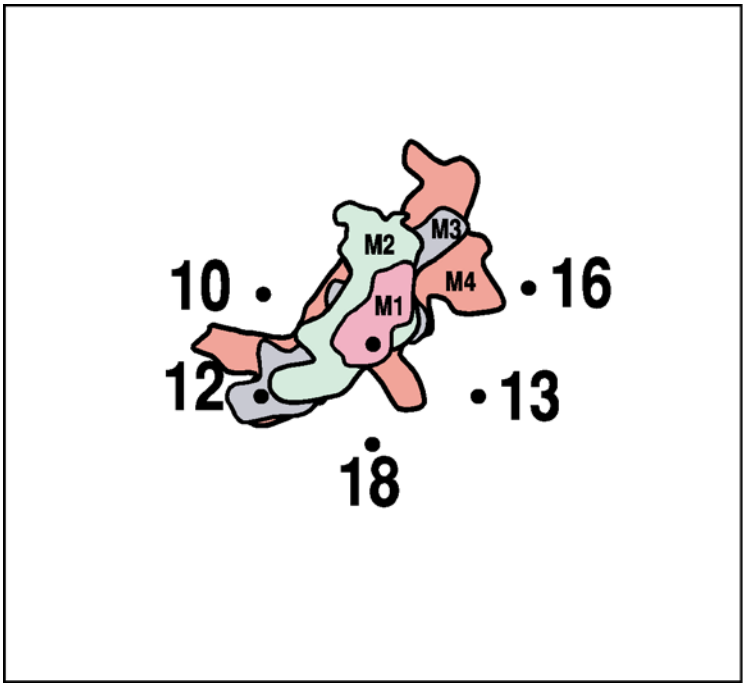


Figure 21. Overlay of monitor survey 1 (M1), monitor survey 2 (M2), monitor survey 3 (M3), and monitor survey 4 (M4). Apparent fingering along the secondary lineament orientations is quite pronounced.

Small concentrations of CO_2 began to appear in well 13 at very low levels (0.49 %) in August 2004, but may have represented pre-flood natural CO_2 in reservoir water. By October 2004, CO_2 concentration had increased (3.09% of total gas) but was still below levels suggesting breakthrough. In December 2004, CO_2 concentrations increased to 6.44%, suggesting limited breakthrough had occurred. With low production and delay in oil or gas arrival at well 13, the field operations team decided that well stimulation should be performed. A process known as Huff-n-Puff (injection of CO_2 directly into well 13 to modify the relative permeability around the well) was initiated. Following this treatment, concentrations of CO_2 are no longer reliable measures of the progression of the main CO_2 body.

This gradual increase in concentration of CO_2 in well 13 is consistent with a possible fingering scenario. The seismically mapped progression of CO_2 between CO2I#1 and well 12 exhibited a more uniform flood front, consistent with the observed increase in CO_2 concentrations in well 12. The different response in well 13 suggests either a different migration pattern and/or migration mechanism at work between CO2I#1 and well 13.

Comparing the interpretation of the preliminary processed October 2004 survey with the seismic lineament attribute map, the general trends of the fingering and main body are still consistent with the interpreted “barriers” associated with the major lineaments (Figure 22). One of the more interesting observations is the location where the CO_2 appears to have moved east through this northeast/southwest “barrier.” Looking at the lineament attribute map only (Figure 23), this location exhibits anomalous seismic response along an otherwise relatively continuous expanse of this feature. Considering the pressure field

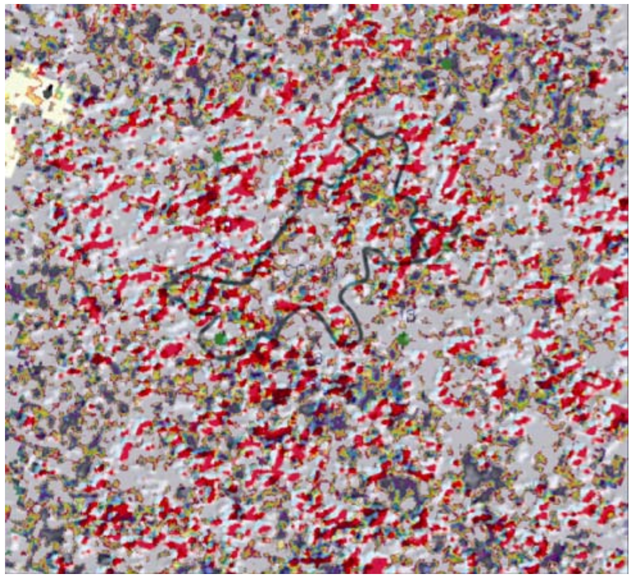


Figure 22. October 2004 survey amplitude envelope attribute map with interpretations of the CO_2 “front” overlain by the lineament attribute map.

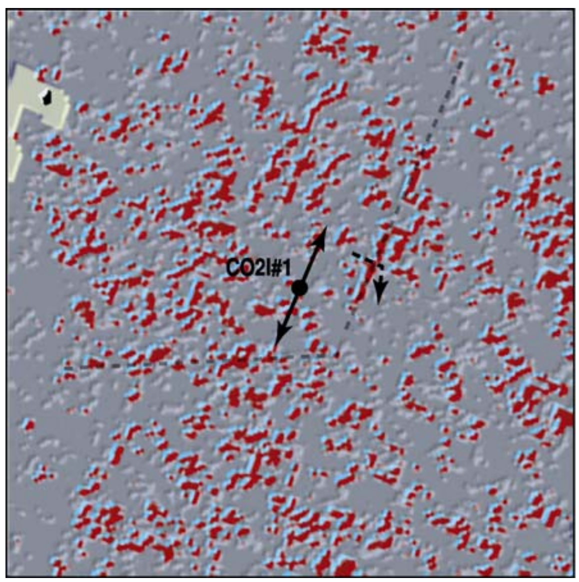


Figure 23. Major lineaments that appear to be influencing fluid movement away from CO2I#1, including the possible route the CO_2 took to breach the barrier associated with the northeast/ southwest lineament.

established around well 13, once the CO_2 has moved through this “barrier” it should move more quickly toward well 13. If this interpretation is correct, the volume of CO_2 moving to well 13 may be controlled by the nature of the “break” in the possible barrier.

This preliminary interpretation of the October 2004 (Figure 20) data will be further examined with processing and interpretation. Throughout the pilot study it has been known that well 13 response to injection in CO2I#1 was complex and potentially indicative of some form of restriction between wells CO2I#1 and 13. The present interpretation of the 4-D seismic data supports this conclusion.

July 2005 Site Visit—Sixth Monitor Survey

The first five monitor surveys were acquired during the first 16 months of this project while CO_2 was being injected. The next and seismically more challenging component started on June 21, 2005, with initiation of water injection (Figure 24). The sixth 3-D survey was acquired during the first two weeks of July 2005.

Figure 24. Sun setting over the site with well 7 pumping in the background.

Processed data from all five monitor surveys give good indications that CO_2 was imaged, reservoir heterogeneities are relatively consistent from one survey to the next, and images from each monitor survey show consistent expansion of the CO_2 plume.

Data from the sixth monitor survey represent the last data acquired that might not be affected by the injection of water designed to chase the CO_2 and, depending on how the water affects signal response, may be the last survey that provides a clear image of the complete CO_2 plume. As water injection pressures change in the field, the saturations of the various components change. Less than two weeks of water injection separates the end of CO_2 injection on June 20, 2005, and the acquisition of the sixth monitor survey in July 2005. Given the size of the horizontal sampling window at the reservoir depth and the volume of water injected, and the corresponding radius of water invasion, the influence of the injected water on seismic imaging of the CO_2 plume at the time of the survey is considered negligible and limited to the single imaged pixel containing the CO2I#1 well.

Production Overview

Over the 18 months between start of CO_2 injection on December 4, 2003, and the end of continuous CO_2 injection and initiation of the first water injection on June 21, 2005, CO_2 was generally injected at a rate of 2.5-3.0 gallons/minute (~20 tons/day) at bottom-hole pressures of 1,800-1,900 psi. By June 21, 2005, approximately 8,500 tons of CO_2 were injected into CO2I#1. The rate of oil production from wells 12 and 13 has averaged between 2.0 and 5.0 barrels/day since the beginning of 2005.

Site Conditions

With higher-than-average rainfall during the early part of the summer, the seismic acquisition characteristics, such as source and receiver coupling, near-surface attenuation, and unconfined water table depth, are much more conducive to the propagation of high-frequency seismic body waves than is normally observed during July. As is normally the case in this part of Kansas, the midday and afternoon/evening winds are challenging for high-quality, high signal-to-noise recording of the low-amplitude high-frequency signals necessary for high-resolution surveying. Unlike previous 3-D surveys over the past 18 months at this site, no attempt was made to record during the middle portion of the day or during afternoons. All data were recorded between 6:00 pm and 9:00 am. As has been clearly shown on previous surveys, the improvement in data quality is significant and justifies the additional acquisition expense.

More rainfall also resulted in an increase in night-flying insects, which presented a problem for operating the seismograph at night. To avoid enclosing the seismograph operator and equipment, which would have involved climate control (air conditioner and generator) and increased noise, mosquito netting was draped over the seismograph vehicle (Figure 25). This kept the air temperature equivalent to the outside air, allowed a breeze at the operator station and across the equipment, and kept insects away.

Data Acquisition

Data were acquired at over 790 shot stations with a location accuracy of better than 0.5 m (Figure 26). All receiver stations were deployed within 0.2 m of previous locations using DGPS. To avoid environmental noise, the data were acquired between 6:00 pm and 9:00 am over a 7-day window between July 7 and 13. For this survey, as with the March 2005 survey, the operator of the field was not in a position to shut down the peripheral pumping units during the seismic data acquisition and therefore noise from those pumps resulted in notable deterioration in signal-to-noise ratios on raw data.

Figure 25. Mosquito netting was draped over the seismograph vehicle to keep the air temperature equivalent to outside air, allow a breeze at the operator station and across the equipment, and keep insects away.

Figure 26. Data were acquired at over 790 shot stations with a location accuracy better than 0.5 m. All receiver stations were deployed within 0.2 m of previous locations using DGPS.

Overall data quality was consistent with the five previous surveys. Ultra-near-surface conditions have changed with crop rotation and farming practices. These changes are noticeable on shot gathers from some areas. However, they are predominantly evident in subtle reductions in the amplitude of the higher portions of the reflection bandwidth. Balancing these frequencies reduces the spectral differences and to a limited extent reduces the signal-to-noise ratio. Fortunately, less than 20% of the survey area has seasonal crop rotation issues.

Data acquisition in most areas around the site has been consistent throughout the almost two years of recording (Figure 27). For the most part, the water table in the river valley areas of the site has been consistent, and stations with the highest data quality in seasonally consistent areas (not affected by farming practices) have routinely provided the highest quality data. It is likely these better-than-average data locations have stiffer soils, higher water tables, shallower bedrock, etc., relative to the other lower-quality areas around this site.

Figure 27. Data acquisition in most areas around the site has been consistent throughout the almost two years of recording.

Data Processing Update—August 2005

Based on the results of the first year of seismic monitoring of the CO_2 injection process, results suggest that seismic reflection methods have been effective at providing data that can be used to image the movement of CO_2 across this 3000-ft-deep, 15-ft-thick reservoir interval. Based on present processing and interpretation methods, CO_2 movement is best imaged by extremely low amplitude changes in the amplitude envelope attribute and subtle variations in instantaneous frequency.

To extract as much information as possible from the data, stacked sections must be produced that fully capture and enhance the relevant information content of the data. The focus of this enhancement activity is on coherency, signal-to-noise ratio, and resolution. Stacked sections produced to date have been preliminary and intended to satisfy the need for quick turnaround at the expense of identifying the best processing and interpretation methods. The rapid development of interpreted seismic sections was necessary to provide seismic imaging of the flood for the on-going CO_2 flood management. Dynamic adjustment to injection and withdrawal management and flood design is likely to be a future application of the method as an EOR monitoring/evaluation tool.

To enhance the image quality for interpretation and image resolution, several aspects of data processing must be addressed. Enhancement of coherency can be achieved by improving uniformity of source wavelet properties and statics. In addition, optimized velocity corrections can improve wavelet consistency from trace to trace. Signal-to-noise ratio is always an important characteristic when dealing with high-resolution seismic reflection data. Improvements in signal-to-noise ratio require optimizing the frequency bandwidth, ensuring consistency in phase, elimination of as much noise through muting and filtering as possible, and pre-stack statics. Finally, to extract the highest resolution interpretations possible, the upper corner reflection frequency must be identified and the focus of spectral shaping (keeping in mind the need for a broad bandwidth) must be determined, as well as resolving statics issues and balancing amplitude characteristics.

Enhancement processing began midway through the second year of the program. All data will undergo the optimized enhancement flow in a consistent fashion. Initial analysis suggests phase correction pre-correlation and pre-vertical stacking results in a better than 20% increase in bandwidth and in data coherency (Figure 28). Spiking deconvolution improved the reflection bandwidth and provides improved wavelet characteristics, but decreases the apparent signal-to-noise ratio. This is a tradeoff that is necessary and turns out to be all positive based on downstream processing.

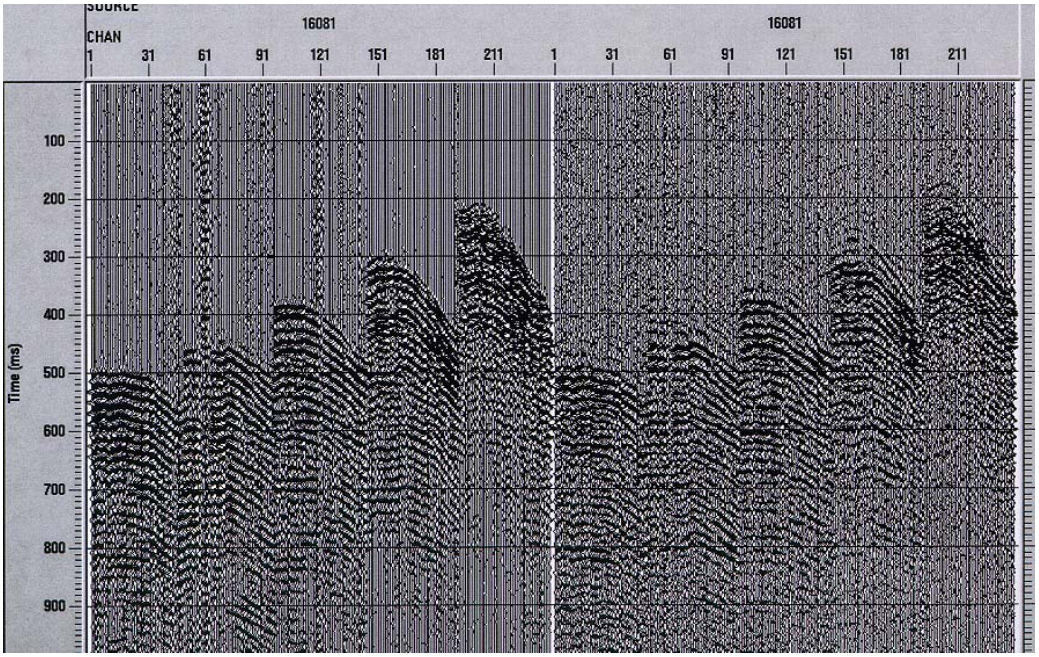


Figure 28. Raw correlated shot gather (right) compared to the same shot gather after phase filtering and spiking deconvolution shot gather (left).

Amplitude attributes provide important information about where CO_2 is present within the pattern. Based on the acquisition design, the amplitude distribution within the grid has natural artifacts associated with the pattern (Figure 29). Correction to this non-uniform distribution in amplitudes will eliminate the shadows evident on the amplitude envelope attribute consistent with the receiver grid. After amplitude distribution corrections only minor linear artifacts remain, predominantly inline and crossline to the imaged space (Figure 30).

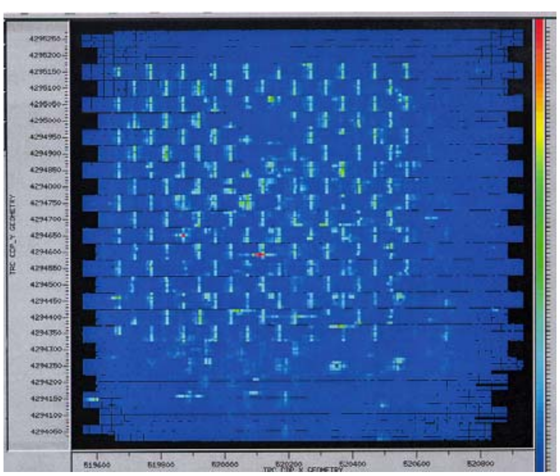


Figure 29.

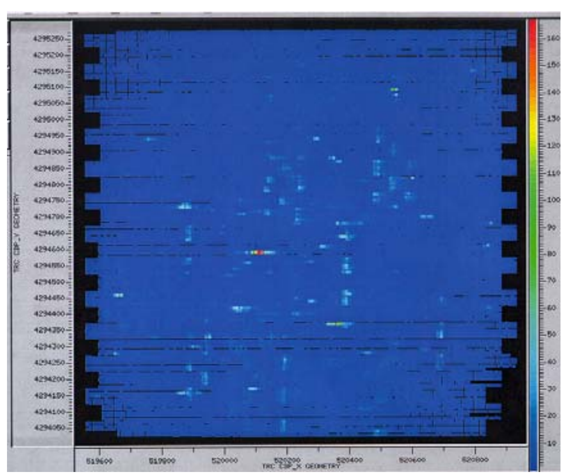


Figure 30.

During preliminary processing, source and receiver statics were corrected for using surface-consistent correlation statics routines (Figure 31). These corrections were adequate for general stacked sections, but lack the station-specific accuracy necessary for high quality image construction. After the application of residual statics focusing on a 500-msec window surrounding the target reflection, a significant improvement can be noted in the coherency of the unstacked, moved-out shot gather (Figure 32).

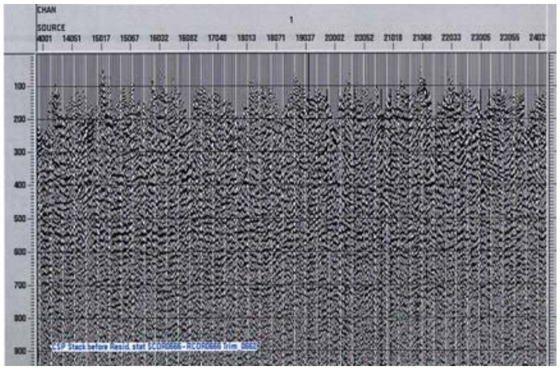


Figure 31.

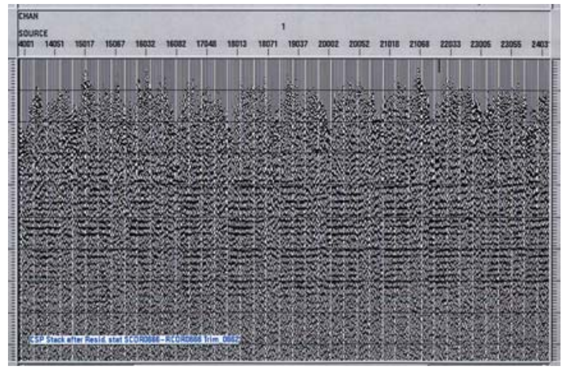


Figure 32.

After gathering the data into common receiver bins, and applying residual statics in a fashion consistent with application of the same statics routine on common shot gathers, reflection coherency improves dramatically and the spectral (therefore resolution) also makes a marked improvement. Common receiver stacks possess good signal-to-noise ratios but lack the sitewide coherence and consistency in arrivals indicative of a section with all near-surface effects removed (Figure 33). In the middle of the seismic volume, the data are higher amplitude and seem to possess better shallow continuity in comparison to the lower-fold data near the ends of the spread. This is consistent with the CMP stacked volumes interpreted during the preliminary stages of processing. After a residual statics operation was applied to the receiver gathers, problems associated with coherency, bandwidth, and amplitude all seem to dramatically reduce (Figure 34). The pre-residual statics data are the same data that were used to produce the stacked volumes that were interpreted and suggestive of differences related to the presence of CO_2.

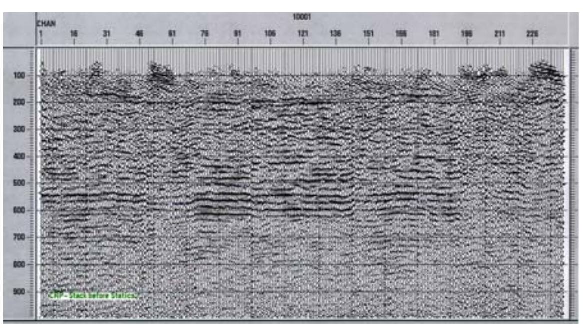


Figure 33.

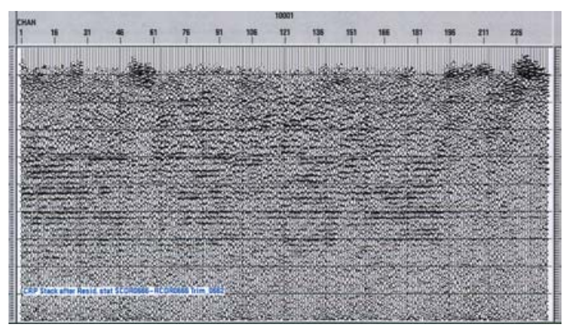


Figure 34.

Funding Year 3 Planned Activities

1) Renegotiate permits and access agreements with six tenant farmers (Figure 35).
2) Acquire, process, and interpret two more high-resolution 3-D compressional wave seismic data sets to continue imaging and documenting changes in fluid characteristics.
3) Continue to reprocess and refine interpretation of baseline and six monitor 3-D surveys collected during funding years 1 and 2.
4) Continue refinement of flood simulations incorporating time-lapse seismic images acquired during year 1 and year 2.
5) Continue geostatistical analysis and non-linear extrapolations between seismic mid-points at sub-bin scale for each 3-D data set started during funding year 2 and infill temporal estimation of CO_2 growth to provide sub-day sampling of plume development.
6) Improve integration of synthetic models of flow-simulated fluid distribution and seismic attributes and site seismic response.

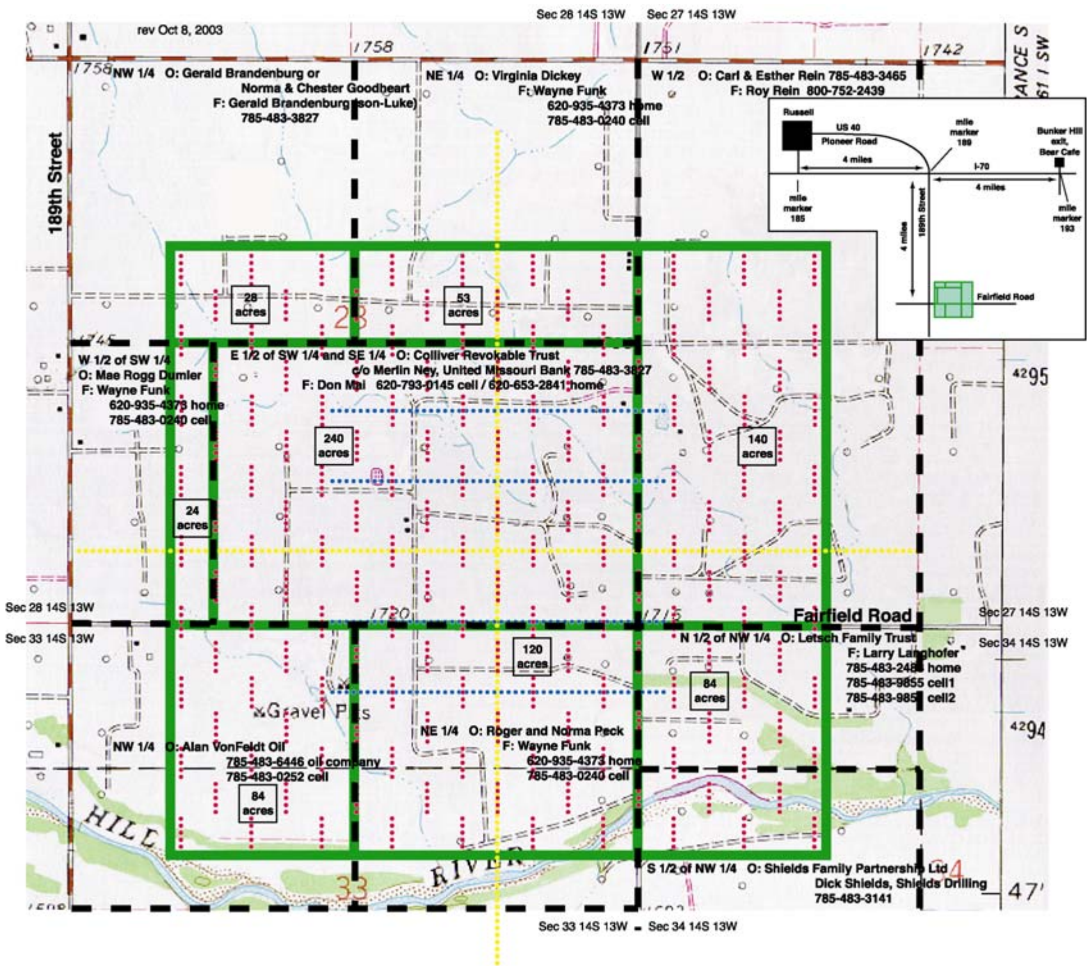


Figure 35. Site map with landowners and tenant farmers.

The same 240-channel Geometrics Geode distributed system networked to a StrataVisor NZ acquisition controller will record seismic data throughout year 3. The source and source parameters will continue to be a single IVI minivib2 with a prototype high-output Atlas rotary control valve sweeping five times at each source location. Sweep frequencies for the P-wave survey will span from 25 to 250 Hz over a 10-second duration. Receivers will be three digital grade 10-Hz Mark Products Ultra2w geophones wired in series with 14-cm oversized spikes. Geophones will be planted in a fresh spot but within 0.5 m of the station location as defined during the baseline and previous six monitor surveys. The three-geophone spread will form a 0.5-m equilateral triangle.

Absolute source and receiver location over the 3.6 km^2 survey grid will be maintained using a Trimble survey-grade DGPS system. The original digital map developed during the baseline survey will be used to exactly relocate each station for each of the repeat 3-D surveys.

As with previous data, a 3-D stacked cube ready for interpreting will be generated using the 2-D/3-D ProMax (a product of Landmark) processing package currently running at the KGS on a dual processor SGI Octane workstation. Refinements to processing flows and reprocessing of previous data sets will be continuous throughout year 3. Optimal processing of these 3-D data have involved techniques and algorithms developed for petroleum applications but carefully analyzed and applied in a fashion consistent with the needs of the shorter wavelength and lower signal-to-noise ratio of high-resolution data. Cross-equalization techniques have not been necessary with the consistency in data acquisition, but will continue to be appraised with each new data set.

Interpretation of seismic data will continue to increase through year 3. Volumes including instantaneous frequency, amplitude, and phase, along with impedance and coherency will continue to be generated, compared, and differenced in search for the seismic attribute(s) most sensitive to CO_2 movement in the reservoir. Success with instantaneous frequency will be built on and resulting images improved and fine-tuned over those developed in year 2. Landmark's interpretation software Kingdom Suites has proven extremely adaptable to the high-resolution nature of these data and will continue to be the primary interpretation software used during year 3.

Our first attempts at correlating empirical seismic attributes with subsurface properties, and estimates made of attributes using multivariate statistical procedures such as canonical correlation, began during the latter part of year 2 and will continue with increased vigor during year 3. Improved accuracy of flood-movement animations using attribute, synthetic, wiggle trace, and difference cubes will continue with assistance from geostatistical analysis of each seismic volume.

Enhancement of reservoir simulation performance requires development of 3-D volumes of geophysical properties for each cell using geostatistical approaches. We will begin enhancing the crude models developed during year 2 and attempt to determine the multivariate three-dimensional semivariance, which expresses the rate-of-change with distance within the geophysical field. From these semi-variograms each cell, as defined by the simulator model, can be populated with the seismic properties and standard error.

Started during year 2 and fully developed during year 3, this model will be expanded through the introduction of time as an axis in four-dimensional space-time with a series of cells having uniform temporal spacing. The most appropriate procedure for rescaling includes geostatistical estimation and stochastic simulation. These procedures have been applied mostly in either the time or space dimension but will be extended to simultaneously include both time and space. The initial set of cells contains only estimates because the data have only two temporal coordinates, but with the acquisition of a third and successive surveys, rates-of-change with time can be estimated and used to refine the initial estimates.

During funding years 3 and 4, multiple qualitative and quantitative 3-D models will be constructed to represent reservoir characterization data at appropriate realizations. These will both mirror and supplement the reservoir flow-simulation models. Elements of the qualitative models will include the nature of reservoir rocks; variability in reservoir quality, types, scales, and heterogeneity; properties architecture; and nature of bedding and flow barriers. Elements of the 3-D quantitative model will include grid block dimensions, porosity, effective permeability, compressibility, capillary pressure, and fluid properties. Data and models will be compiled and visualized in 3-D using one or more modeling software packages.

Year 3 will continue the process of refining through iteration both the reservoir simulation model and the seismic interpretation. Refinement of the reservoir simulation model will provide new distributions of properties. These, in turn, will be used to evaluate the seismic results and modify analysis procedures. In addition, both the seismic and reservoir simulation predictions of saturation changes will be correlated with reported injected and produced fluid volumes to assess the error in material balance between the methods. Reservoir simulation, presently using the Computer Modeling Group, Inc. PC-based reservoir simulator *IMEX*, will be further refined and will incorporate use of the *GEM* compositional simulation module. Further integration will correlate seismic observations with synthetic seismograms produced from the numerical reservoir simulator output, Gassmann's equations, and simple convolution.

Budget Period III. Seventh and Eighth Monitor Surveys

(all listed dates should be adjusted three months forward [e.g., July 2005 as defined as a start date for task ten should be adjusted to October 2005 to compensate for the delay in starting CO_2 injection])

Task Ten – Seventh Time-Lapse 3-D Survey and Evaluate Flood Scheme:
(July 2005 – November 2005)

Subtask 10.1 3-D P-wave survey
Subtask 10.1.1 GPS survey stations
Subtask 10.1.2 acquire 7th 3-D P-wave survey (fixed procedure)
Subtask 10.1.3 process 7th 3-D P-wave survey (fixed flow based on subtask 4.1.4)
Subtask 10.1.4 attribute analysis and interpretation
Subtask 10.2 evaluate flood scheme
Subtask 10.2.1 compare differences between synthetic from simulations & real data
Subtask 10.2.2 iteratively revise flood scheme in simulations
Subtask 10.2.3 develop revised flood scheme to minimize/eliminate non-linearities

Task Eleven – Eighth Time-Lapse 3-D Survey and Evaluate Flood Scheme:
(October 2005 – February 2006)

Subtask 11.1 3-D P-wave survey
Subtask 11.1.1 GPS survey stations
Subtask 11.1.2 acquire 8th 3-D P-wave survey (fixed procedure)
Subtask 11.1.3 process 8th 3-D P-wave survey (fixed flow based on subtask 4.1.4)
Subtask 11.1.4 attribute analysis and interpretation
Subtask 11.2 evaluate flood scheme
Subtask 11.2.1 compare differences between synthetic from simulations & real data
Subtask 11.2.2 iteratively revise flood scheme in simulations
Subtask 11.2.3 develop revised flood scheme to minimize/eliminate non-linearities

Task Twelve – Evaluation of flood efficiency and detailed tracking of flood movement
(February 2006 – June 2006)

Subtask 12.1 animate baseline and all time-lapse seismic volumes
Subtask 12.2 compare/contrast animation of simulations and seismic
Subtask 12.3 evaluate how well seismic/simulations predict breakthrough
Subtask 12.4 decimate seismic data to establish min. effort to monitor accurately
Subtask 12.5 appraise cost effectiveness of 4-D seismic, oil$ > seismic$?
Subtask 12.6 evaluate how well goals/objectives were achieved

REFERENCES (Copies included on CD as the Appendix to this report)

1. Byrnes, A.P., R.D. Miller, and A.E. Raef, 2005, Evolution of reservoir models incorporating different recovery mechanisms and 4-D seismic—Implications for CO_2 sequestration assurances [Abs.]: Poster presented at the annual conference of the American Association of Petroleum Geologists, June 19-22, Calgary, Alberta, Canada.
2. Miller, R.D., A.E. Raef, A.P. Byrnes, and W.E. Harrison, 2004, Progress Report Year 1: 4-D high-resolution seismic reflection monitoring of miscible CO_2 injected into a carbonate reservoir: Kansas Geological Survey, Open-file Report 2004-45.
3. Miller, R.D., A.E. Raef, A.P. Byrnes, and W.E. Harrison, 2004, Project Facts: 4-D high-resolution seismic reflection monitoring of miscible CO_2 injection into a carbonate reservoir; *in* DOE Fact Sheet CO_2 EOR Technology—Technologies for Tomorrow's E&P Paradigms: U.S. Dept. of Energy, Office of Fossil Energy, National Energy Technology Laboratory, Strategic Ctr. for Natural Gas and Oil, 2 p.
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5. Miller, R.D., A.E. Raef, A.P. Byrnes, J.L. Lambrecht, and W.E. Harrison, 2004, 4-D high-resolution seismic reflection monitoring of miscible CO_2 injected into a carbonate reservoir in the Hall-Gurney field, Russell County, Kansas [Exp. Abs.]: Society of Exploration Geophysicists, p. 2259-2262.
6. Raef, A.E., R.D. Miller, A.P. Byrnes, and W.E. Harrison, 2004, 4-D seismic monitoring of the miscible CO_2 flood of Hall-Gurney field, Kansas: *Leading Edge*, v. 23, no. 11, p. 1171-1176.
7. Raef, A.E., R.D. Miller, A.P. Byrnes, W.E. Harrison, and E.K. Franseen, 2005, Time-lapse seismic monitoring of enhanced oil recovery CO_2-flood in a thin carbonate reservoir, Hall-Gurney field, Kansas, U.S.A.: Poster presented at the annual meeting of the American Association of Petroleum Geologists, Calgary, Alberta, Canada, June 22; Kansas Geological Survey, Open-file Report 2005-24.
8. Raef, A.E., R.D. Miller, E.K. Franseen, A.P. Byrnes, W.L. Watney, and W.E. Harrison, 2005, 4-D seismic to image a thin carbonate reservoir during a miscible CO_2 flood—Hall-Gurney field, Kansas, USA: *Leading Edge*, v. 24, no. 5, p. 521-526.

Appendix

The Appendix consists of PDF conversions of Year 2 publication and presentation files. Full citations of these documents are listed in the “References” section, p. 41.