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

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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 in an attempt 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 30 months of seismic monitoring, one baseline and eight monitor surveys clearly detected changes that appear consistent with movement of CO_2 as modeled with fluid simulators and observed in production data.

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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.

Production of CO_2 at a well significantly outside the designed flood to the northwest was consistent with the 4-D seismic, but a complete surprise to the petroleum engineers operating the flood. Seismic data early on suggested preferential northerly movement and once the CO_2 plume moved outside the high-fold footprint of the seismic volume it could no longer be tracked. Clearly the seismic monitoring could have dramatically improved the flood efficiency if the operators would have put more confidence in and heeded the images produced during the early stages of this flood.

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.

Seismic Activities During Funding Year 3 (September 1, 2005 to August 31, 2006)

Technical Progress

Seismic data acquisition and preliminary processing on the nine 3-D reflection surveys (one baseline and eight monitor) proposed for budget periods 1, 2, and 3 has been completed or is proceeding as planned. Consistent with the proposed time line, evaluation of various interpretation approaches continues and has produced images with strong agreement to production models, volumetrics, and observations that provide the essential ground truth for this study. Data acquisition continues on schedule with the utmost care taken to insure the highest possible data quality, repeatability, and field efficiency. Preliminary data processing on eight of the nine seismic volumes is complete with secondary processing underway to enhance data resolution and interpretation potential beyond any documented studies at these depths and for beds this thin. Interpretations are still very crude and working with processed data that are still being optimized for consistency, resolution, and signal-to-noise. Several unique approaches to data equalization have allowed differencing and interpretation consistent with our previous work, enhancing confidence in the image and growth pattern suggested from preliminary processing. A variety of unexpected data and reservoir characteristics have been identified and explained, providing engineers with detailed scenarios of fluid movement unlike any reservoir study in the literature. As part of the ongoing evaluation task, unique and consistent anomalies in both amplitude and frequency data suggest the presence of CO_2 in the rock can be imaged at these depths and reservoir characteristics. In addition, as key aspects of the data are identified and enhanced with specialized processing flows, images of the CO_2 plume should become vivid. After extensive equalization of reflection data to minimize and eliminate noise and balance data signal characteristics with properties inconsistent from survey to survey and not related to fluid changes in the reservoir, time slices from the reservoir interval were differenced, resulting in interpretable patterns consistent with previous analysis. Tasks ten, eleven, and twelve were completed during budget year 3 as proposed.

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 carbonate reservoir around 900 m deep in Russell County, Kansas, was successfully monitored using high-resolution 4D/time-lapse seismic techniques. High-resolution seismic methods showed 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/4D seismic data was key to the success of this monitoring project.

Weak-anomaly enhancement of selected non-inversion, 4D-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.

Differences interpreted on consecutive time-lapse seismic horizon slices are consistent with CO_2 injection volumetrics, match physical restraints based on engineering data and model amplitude response, and honor production data. Textural characteristics in amplitude envelope images appear to correspond to non-uniform expansion of the CO_2 through the reservoir, honoring both the lineaments identified on baseline data and changes in containment pressures. Interpretations of a set of time-lapse seismic images can be correlated to a mid-flood alteration of the injection/ production scheme intended to improve containment and retard excessive northward movement of the CO_2.

Presentation and publication of results from this study have included
2005 SEG annual meeting in Houston,
2005 AAPG mid-continent section meeting in Oklahoma City,
2006 AAPG annual meeting in Houston,
2006 AAPG Rocky Mountain Section meeting in Billings, Montana,
2005 PTTC mid-continent meeting in Wichita,
2006 DOE CO_2-EOR Solicitation Pre-proposal Workshop in Houston, and
KGS Project website: www.kgs.ku.edu/Geophysics/4Dseismic.

Presentations

Miller, R.D., 2005, Progress report on time-lapse high-resolution 3-D seismic imaging to monitor a CO_2 flood in a thin carbonate reservoir in the Hall-Gurney field, Kansas: DOE Offices, Tulsa, Oklahoma, September 21.

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Presentation with Publication

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Watney, W.L., E.K. Franseen, A.P. Byrnes, R.D. Miller, A.E. Raef, S.L. Reeder, and E.C. Rankey, 2006, Characterization of Seismically-Imaged Pennsylvanian Ooid Shoal Geometries and Comparison with Modern: Annual convention of the American Association of Petroleum Geologists, April 9-12, 2006, Houston; Annual Convention Abstracts Volume, p 113.

Publication Only

Miller, R.D., A.E. Raef, A.P. Byrnes, and W.E. Harrison, 2005, 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: Kansas Geological Survey Open-file Report 2005-32.

Project Summary

- 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.
- Shortness of turnaround time of time-lapse seismic monitoring in the Hall-Gurney field provided timely support for reservoir-simulation adjustments and flood-management requirements across this very short-lived pilot study.
- 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.
- After differencing, amplitude residual data provided more pronounced anomaly contrast than previous instantaneous frequency or amplitude envelope data. Extensive and thorough equalization proved valuable in distinguishing very small percent changes between presence and absence of CO_2.
- Seismic data acquisition and preliminary processing on the nine 3-D reflection surveys (one baseline and eight monitor) has been completed within three years.
  - Preliminary data processing on the nine seismic volumes is complete with secondary processing underway to enhance data resolution and interpretation potential beyond any documented studies at these depths and for beds this thin.

  - Various interpretation approaches have produced images with strong agreement to production models, volumetrics, and observations that provide the essential ground truth for this study.
  - Interpretations are still very crude and working with processed data that is still being optimized for consistency, resolution, and signal-to-noise.
- Several unique approaches to data equalization have allowed differencing and interpretations consistent with previous approaches, enhancing confidence in the image and growth pattern suggested from preliminary processing and interpretations.
  - A variety of unexpected data and reservoir characteristics have been identified and explained, providing engineers with detailed scenarios of fluid movement unlike any reservoir study in the literature.
  - Unique and consistent anomalies in both amplitude and frequency data suggest the presence of CO_2 in the rock can be imaged at these depths and reservoir characteristics and as key aspects of the data are identified and enhanced with specialized processing flows images of the CO_2 plume should become vivid.
  - After extensive equalization of reflection data to minimize and eliminate noise and balance data signal characteristics both inconsistent from survey to survey and not related to changes in the reservoir, time slices from the reservoir interval were differenced. These differenced images provided interpretable patterns consistent with previous analysis.
  - After differencing, amplitude residual data provided more pronounced anomaly contrast than previous instantaneous frequency or amplitude envelope data. Extensive and thorough equalization proved valuable in distinguishing very small percent changes between presence and absence of CO_2.
- Time-lapse seismic monitoring of EOR-CO_2 revealed weak anomalies in these thin carbonates well below temporal resolution and were successful with moderate cross-equalization and elevated attention to consistencies in acquisition and processing. Most of all, methods applied here avoid the complications associated with inversion-based attributes and extensive cross-equalization techniques.
  - Shortness of turnaround time of time-lapse seismic monitoring in the Hall-Gurney field provided timely support for reservoir-simulation adjustments and flood-management requirements across this very short-lived pilot study.
  - 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.
- Distribution and geometries associated with similarity seismic facies and seismic-lineament patterns are suggestive of a complex ooid shoal depositional motif, an interpretation consistent with an oolitic lithofacies reservoir type. Oolitic facies are imaged on these seismic data at a resolution significantly greater than previously documented.

Current Status

The injection of CO_2 was halted and water injection began as part of WAG in July of 2005. At that time seven 3-D surveys had been completed (six monitor and one baseline) within approximately 18 months. The first monitor survey after water injection was completed in January 2006 (monitor survey number seven), with the second after water injection began completed in August

2006 (monitor survey number eight). Based on flood simulations, water injection should severely alter the pressure and fluid distribution across the entire field within six months. Results from the seventh and eighth monitor surveys images of the reservoir consistent with movement of CO_2 out of the pattern to the north.

During fall of 2006, production data from oil wells north and outside the CO_2 confinement area showed a steady increase in oil production. Production levels increased several times normal production for these 50+-year-old wells. These measured oil production data are suggestive that the seismic images successfully tracked the northward movement of the CO_2 long before engineering simulations or production data either detected or even considered this possibility. Continued monitoring of the CO_2 plume and enhancement to processing and interpretation work flows will not take place due to project termination by sponsor. Several publications previously submitted to reviewed but unrefereed journals will be refined and submitted to upper-tier refereed outlets under no-cost extensions of this project.

	Budget Period I	Budget Period II	Budget Period III	Budget Period IV	Budget Period V	Budget Period VI
Task	Year 1 2003-2004	Year 2 2004-2005	Year 3 2005-2006	Year 4 2006-2007	Year 5 2007-2008	Year 6 2008-2009
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		■	■	■	■	■