Application of Cutting-Edge 3-D Seismic Attribute Technology to the Assessment of Geological Reservoirs for CO2 Sequestration

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EXECUTIVE SUMMARY

The *goals* of this three-year project are to develop innovative 3D seismic attribute technologies and workflows to assess the structural integrity and heterogeneity of subsurface reservoirs with potential for CO_2 sequestration. Our *specific objectives* are: 1) to apply advanced seismic attributes to quantify the thickness, porosity, permeability and lateral continuity of CO2 sequestration target reservoirs and the integrity of the seal and to develop a reservoir model and 2) to validate the reservoir model with reservoir simulation studies.

The *primary study areas* are **Dickman field**, Kansas; **Teapot Dome field**, Powder River Basin, Wyoming; and **Patoka and Sciota fields**, Illinois Basin. These areas represent a range of geologic settings associated with major coal producing and emission generating regions of the United States.

Dickman Field: We have successfully carried out 0-10 degree, 10-20 degree and 20-30 degree offset angle prestack time migrations and a whole-stack (0-45 degree) prestack time migration of the Dickman 3-D seismic data over the entire survey area. We processed the expanded 3-D survey on a grid of 82.5 feet by 82.5 feet to match the grid size used in earlier studies of a partial seismic dataset. We plan to generate an acoustic impedance volume from the reprocessed seismic data to aid in mapping the reservoir properties of the objective porous Mississippian interval.

Teapot Dome Field: We have completed prestack and post-stack Kirchhoff time migrations and depth migrations of the 3-D seismic data at Teapot Dome. The aim of this work was to generate a prestack depth migrated seismic volume to better resolve the structural features of Teapot Dome field and the seismically-derived reservoir properties of the CO2 sequestration target Tensleep Formation and to determine the structural integrity of the seal rock. We have not yet completed a quantitative assessment of the results of the reprocessing, but preliminary observations indicate the following.

1. The prestack reprocessing by UH has improved the seismic definition of the apparent south-dipping basement fault and other basement features and appears to enhance reflectors between the high amplitude events in the sedimentary section.

2. The sharpness of delineation and the lateral continuity of structural features and attribute anomalies on time slices from the reprocessed data volumes are as good as or better than similar images extracted from the commercially processed seismic data.

3. The depth of the basement top in the deepest well in Teapot Dome correlates exactly with the basement horizon pick in the depth migrated seismic volume.

Very few studies of prestack depth migrated land 3-D seismic surveys have been published in the United States, and we are not aware any studies of advanced seismic attribute volumes extracted from prestack depth migrations of 3-D land data that have been published. Successful inversion of the reprocessed seismic volumes and integration with well data should provide a unique dataset to develop a structurally and stratigraphically integrated geomodel of the Teapot Dome Tensleep reservoir for reservoir simulation tests in the future.

Patoka Field: The development of an effective method to remove ground roll (Rayleigh waves) continues to be a major challenge in the reprocessing of the prestack 3-D seismic data at Patoka field. High amplitude-low frequency ground roll events severely degrade the seismic data in the depth range of the CO2 sequestration target Mt. Simon Sandstone.

To remove the ground roll but retain low frequency reflections from zones of interest, we applied a processing sequence that uses time-variant filtering. Our initial application of this process did not significantly improve the resolution of the zone of interest. We plan to continue to evaluate time-variant filtering and to investigate the use a coherence algorithm to remove the ground roll. The successful removal of ground roll should allow us to generate a prestack time migrated data volume with adequate resolution to evaluate the potential of the Mt. Simon Sandstone as a deep CO2 sequestration reservoir in the Illinois Basin.

APPROACH

The *aim of this project* is to develop innovative seismic attribute technology and workflows and to apply this methodology to improve the assessment of the structural integrity of seals and reservoir heterogeneity of geological reservoirs for CO_2 sequestration. The specific objectives are to: 1) apply advanced seismic attributes to quantify the thickness, porosity, permeability and lateral continuity of CO_2 sequestration target reservoirs and develop a reservoir model and 2) validate the reservoir model with reservoir simulation studies of CO_2 injection into a saline aquifer associated with a depleted hydrocarbon reservoir.

We have selected four study areas that represent a range of most-likely candidates for gigaton-scale CO_2 sequestration associated with the coal industry (Figure 1). **Dickman field** in Kansas will serve as a pilot area to test the viability of using attribute-based reservoir parameters in computer simulation models of the reservoir. Geophysical logs and production data from wells in the study objective Mississippian-aged carbonate oil reservoir and 3-D seismic data are available to use in the computer model studies. Pre-project work suggests that seismic attributes can successfully delineate reservoir characteristics that affect fluid flow. This study will test the capability to use attribute-derived parameters to predict fluid flow in a depleted oil reservoir under water drive. If successful, the results of the study will provide a basis to estimate the capacity of similar Mid-Continent reservoirs to store CO_2. The **Teapot Dome field** in Wyoming has 3-D seismic data and over 1600 wells with a large amount of supporting rock, log and engineering data from multiple producing zones. We will use core data, geophysical logs from 35 wells, including five wells with borehole image logs, and production data from the complexly fractured and faulted study objective Pennsylvanian-aged Tensleep depleted oil reservoir to calibrate seismic attributes with the rock data. The **Patoka and**

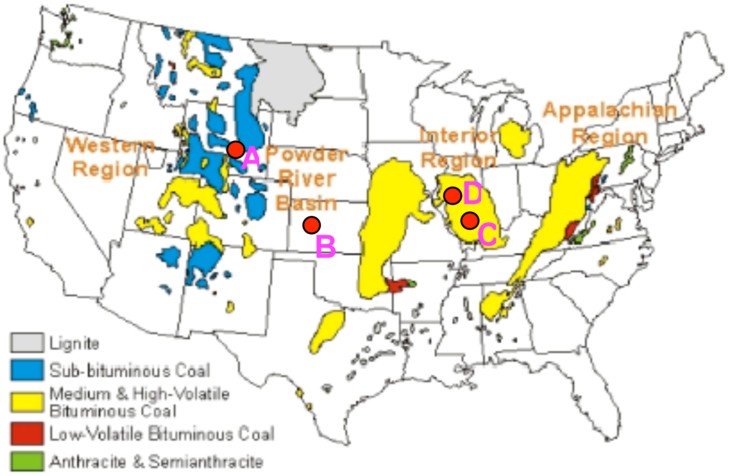


Figure 1. 3-D seismic data sets available for this study are located at: A) **Teapot Dome**, Powder River Basin, Wyoming, a major CO_2 study site for the DOE; B) **Dickman Field,** Kansas, within the Mid-Continent area underlain by the Mississippian Western Interior Plains saline aquifer; and C) **Patoka and** D) **Sciota Fields**, Illinois Basin, underlain by the Cambrian Mt. Simon Formation, a regional saline aquifer. These data sets were selected for either their proximity to major coal producing or emission generating regions of the United States or for their location near major saline aquifers.

Sciota fields in Illinois have well and 3-D seismic data for evaluating the seal integrity and the storage potential of the Cambrian-aged Mt. Simon Formation saline aquifer, a potential regional target for CO_2 sequestration.

We will integrate the results of the field studies to assess CO_2 sequestration possibilities for the coal industry. The work has the potential to significantly reduce uncertainties and to expand our technical awareness of how to effectively and safely store CO_2 in depleted oil reservoirs and saline aquifers.

RESULTS AND DISCUSSION

Task 1.0 - Assemble and Perform Quality Control of Data

We had expected to complete this task in 2006, and we have made substantial progress toward meeting this milestone. However, we now recognize that this work will continue intermittently throughout the project because of the large sizes of the field data sets and the continual acquisition of additional data. We have modified the Gantt chart accordingly.

Task 2.0 - Generate Seismic Attributes

Subtask 2.1 Generate Single-trace and Multi-trace Seismic Attributes

We have generated a range of seismic attributes from available commercial seismic datasets for each field area to evaluate the quality of the data and to train graduate students involved in the project.

Subtask 2.2 Perform Target Oriented Migration of Prestack Seismic Data

Teapot Dome field: We have completed prestack and post-stack Kirchhoff time migrations and depth migrations of the 3-D seismic data at Teapot Dome. The aim of this work was to generate a prestack depth migrated seismic volume to better resolve the structural features of Teapot Dome field and the seismically-derived reservoir properties of the CO2 sequestration target Tensleep Formation and to determine the structural integrity of the seal rock. For an initial comparison of the commercially processed RMOTC prestack seismic data with the UH processed prestack seismic data, we extracted line 120 from the RMOTC and UH prestack time migrated data volumes and the UH prestack depth migrated data volume (Figure 2). We have not yet completed a quantitative assessment of the results of the reprocessing, but a visual comparison of the three different versions of line 120 suggests the following.

1. The prestack reprocessing by UH has improved the seismic definition of the apparent south-dipping basement fault and other basement features and appears to enhance reflectors between the high amplitude events in the sedimentary section.
2. The depth profile may contain less high frequency data than the time migrated profiles.

3. The depth of the basement top in the 74-CMX-16 well projected to line 120 in Figure 2C correlates exactly with the depth of the migrated top basement horizon.

A better evaluation of the quality of the reprocessing will be possible after a more comprehensive analysis of the relationships between geologic features on the depth migrated volume and well data constraints. Refer to the Teapot Dome Field discussion in the Section 3 below for comparisons of attribute maps from UH and RMOTC processed seismic volumes.

Very few studies of prestack depth migrated land 3-D seismic surveys have been published in the United States, and we are not aware any studies of advanced seismic attribute volumes extracted from prestack depth migration of 3-D land data that have been published. Successful inversion of the reprocessed seismic volumes and integration with well data will provide a unique dataset to develop a structurally and stratigraphically integrated geomodel of the Teapot Dome Tensleep reservoir for reservoir simulation tests in the future.

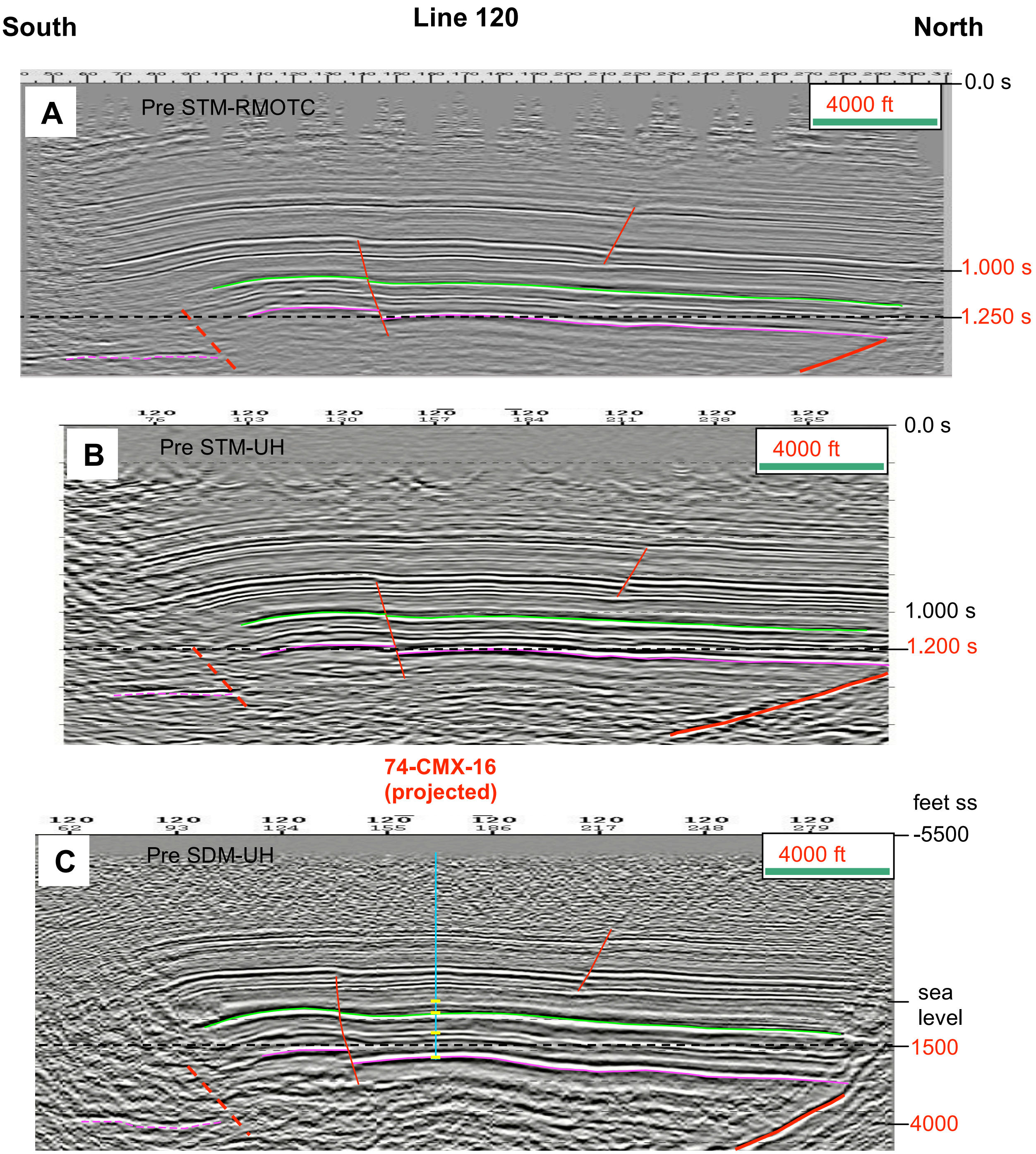


Figure 2. Teapot Dome field line 120 extracted from three different 3D seismic volumes. **A.** Prestack time migrated volume from RMOTC. **B.** Prestack time migrated volume processed by UH. **C.** Prestack depth migrated volume processed by UH. *Horizons*: Tensleep (green), granite basement (pink). *Formation tops:* (yellow bars) Goose Egg, Tensleep, Madison, granite-from shallow to deep in 74-CMX-16. *Faults:* red. No vertical exaggeration in depth profile. See Figure 12 for location of line. Because of different seismic processing datums, TWT values are not exactly correlative between UH and RMOTC volumes. Red values along time axes indicate the locations of slices shown in Teapot Dome Field part of Section 3.0 below.

Patoka Field: The development of an effective method to remove ground roll (Rayleigh waves) continues to be a major challenge in the reprocessing of the prestack 3-D seismic data at Patoka field. High amplitude-low frequency ground roll events severely degrade the seismic data from depths of about 0.6 seconds and deeper (Figure 3). The CO2 sequestration target Mt. Simon Formation overlies granite basement, which occurs in the depth range of 1.1 to 1.2 seconds. Reflections from the Mt. Simon are only distinguishable at far offsets.

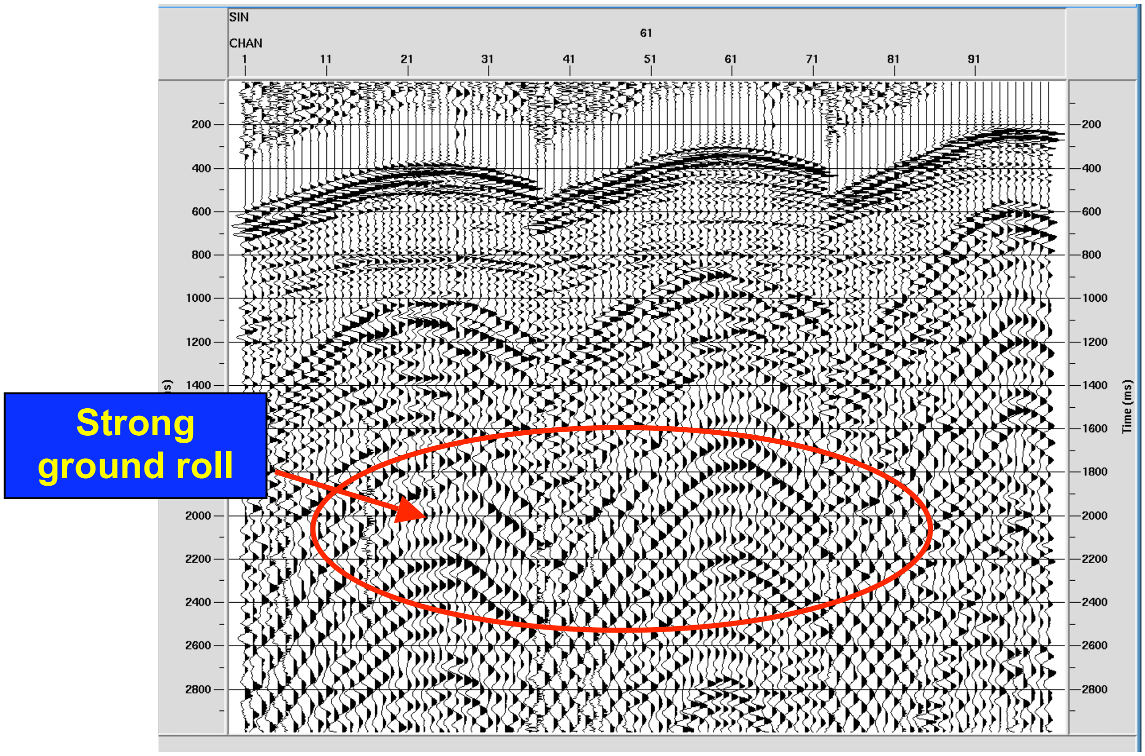


Figure 3. Patoka field original shot gathers after linear moveout correction. Seismic data extends to 3.0 seconds and includes low velocity ground roll noise (Rayleigh waves).

To remove the ground roll, we have applied a processing sequence that uses time-variant filtering (Figure 4). The objective of this method is to remove ground roll but to retain low frequency reflections from zones of interest. In our first attempt to apply this process, a moveout correction of 4000 feet per second linear shifted the low velocity Rayleigh waves and other seismic data to below 2.0 seconds (Figure 5). We then removed the Rayleigh waves with a time-variant filter and applied an inverse linear moveout correction to restore the remaining data to pre-moveout time locations (Figures 6 and 7). Our initial application of this process removed ground roll in the basement section below about 1.6 seconds, but did not remove the ground roll in the shallower intervals (Figure 7) and is not significantly different visually from the results of low cut filtering (Figure 8). A spectral analysis shows that the selective application of time-variant filtering retains desirable low frequency energy that is lost by the application of a low cut filter on the entire seismic data set (Figure 9).

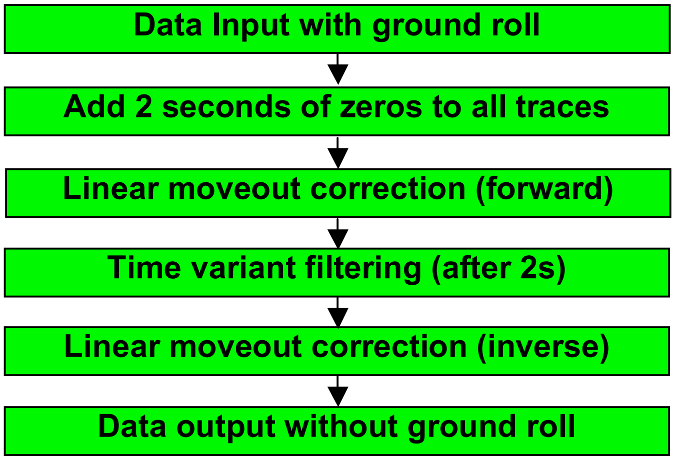


Figure 4. Processing flow to remove ground roll (Rayleigh waves) from Patoka field prestack 3-D seismic data.

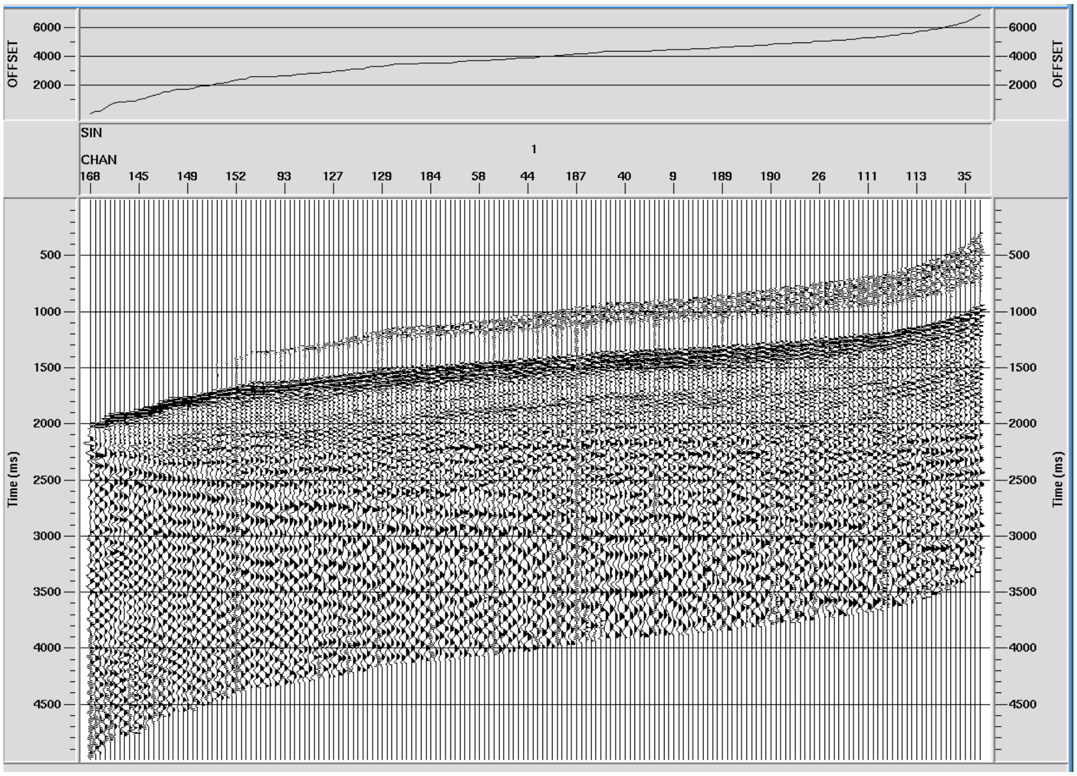
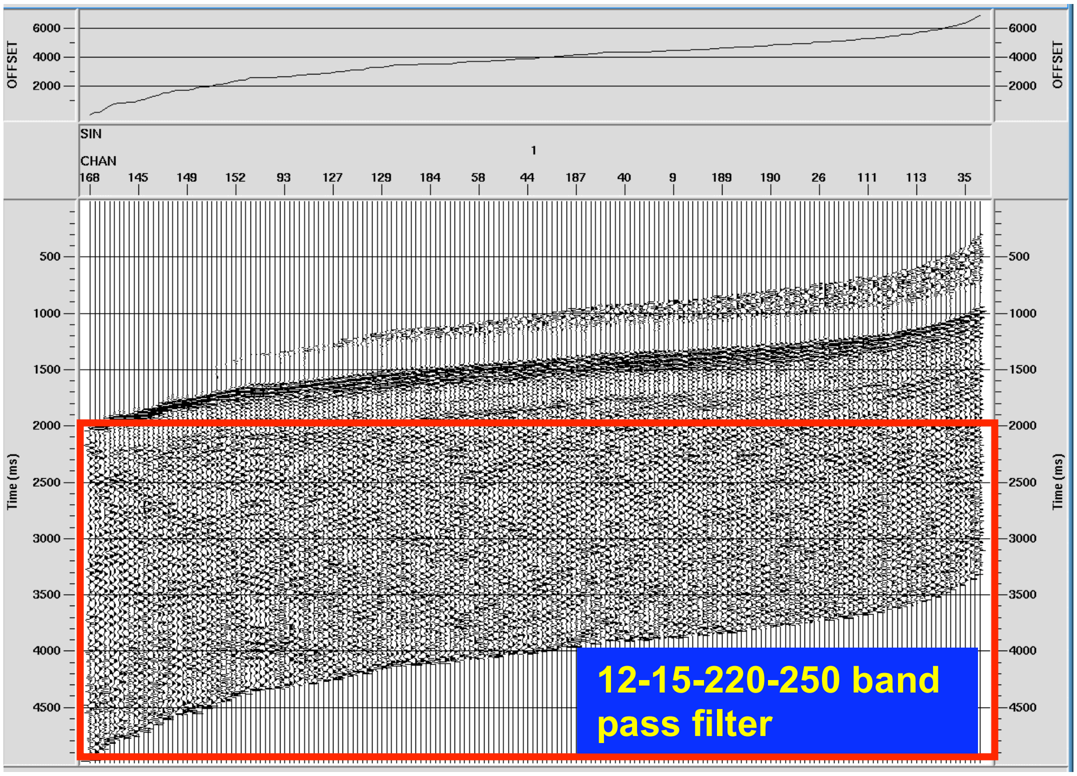
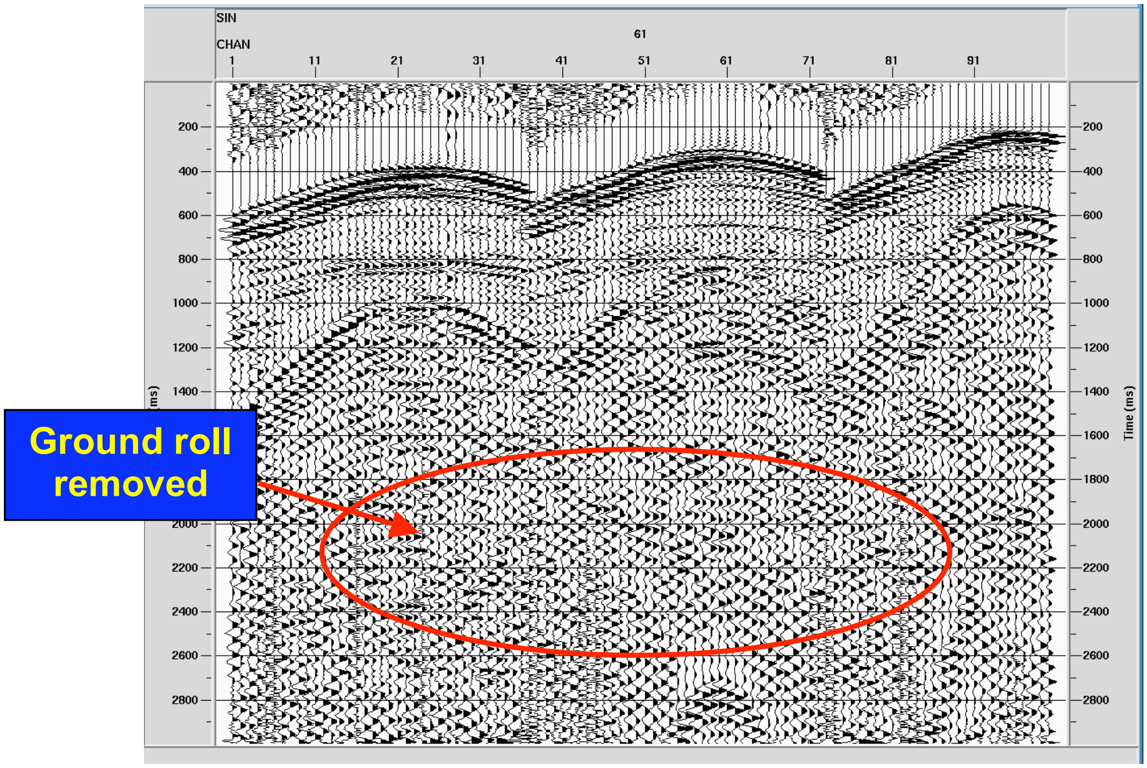


Figure 5. Patoka field original shot data sorted by offset after linear moveout correction. Prior to LMO, we added zeros to all traces from 3.0 to 5.0 seconds to extend the time axis of the input data to 5.0 seconds. The LMO correction moved the ground roll and other seismic data to below 2.0 seconds.



12-15-220-250 band pass filter

Figure 6. Patoka field original shot data sorted by offset after linear moveout correction and removal of ground roll by time variant filtering.



Ground roll removed

Figure 7. Patoka field shot gather after removal of ground roll by time variant filtering and inverse LMO correction to restore data to original locations on 0.0 to 3.0 sec time axis.

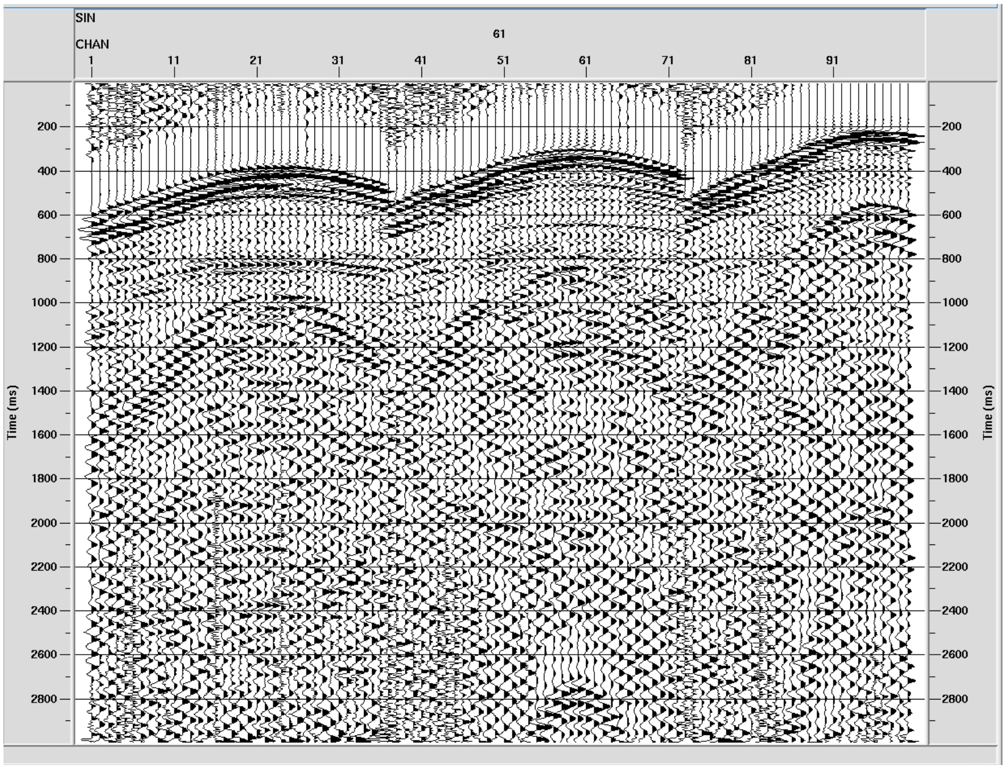


Figure 8. Patoka field shot gather after removal of ground roll by low cut filtering of the original data from 0.0 to 3.0 seconds.

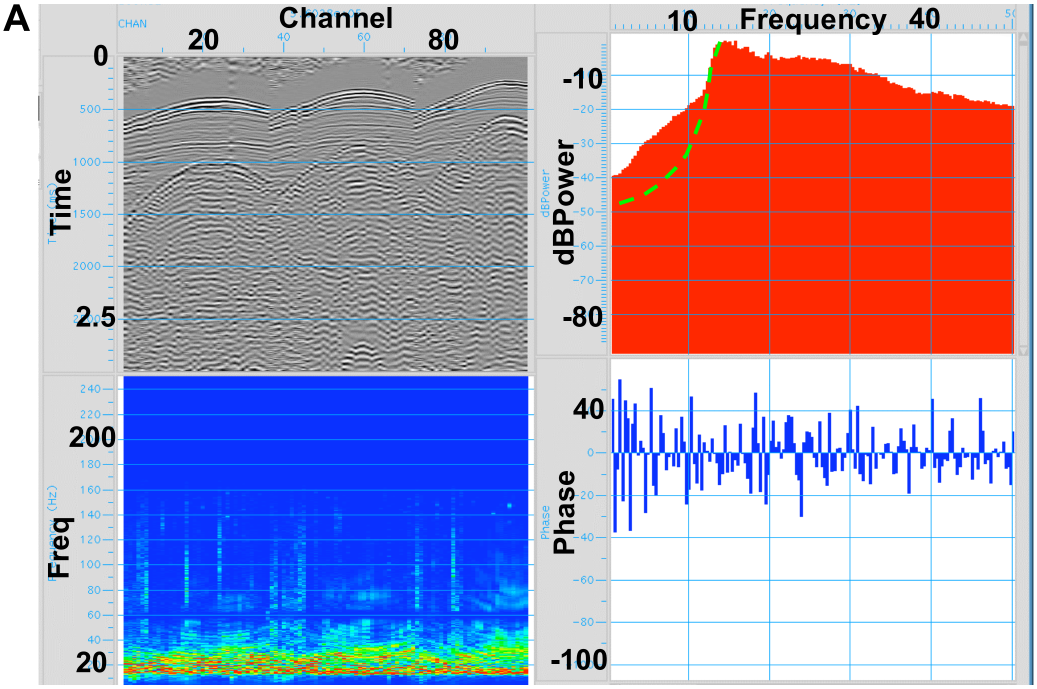


Figure 9. See caption below.

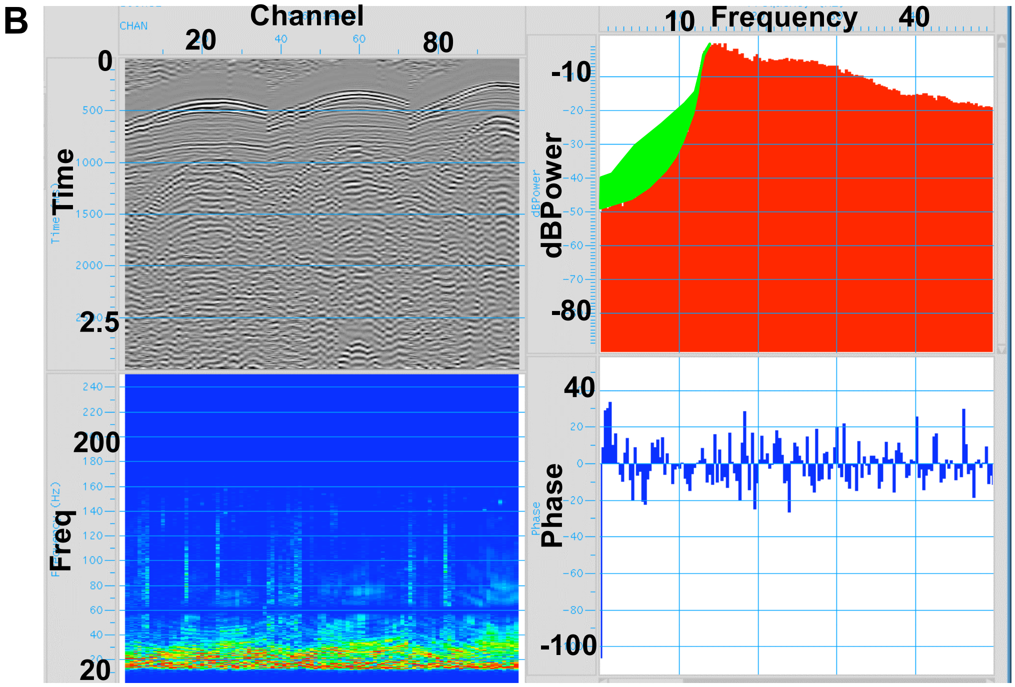


Figure 9. Simple spectral analysis of Patoka field seismic data after filtering to remove ground roll. **A.** Time variant filtering. **B.** Low cut filtering. The solid green area in Figure 9B represents low frequency energy lost with low cut filtering but preserved with time variant filtering above dashed-green line in Figure 9A.

Although we have not yet improved the seismic resolution of the Mt. Simon sandstone and overlying intervals with the time-variant filtering process, we plan to continue to evaluate the method. We will also investigate an alternative method that uses a coherence algorithm to remove ground roll. We hope that the successful removal of ground roll will lead to a prestack time migrated data volume with adequate resolution to evaluate the potential of the Mt. Simon sandstone as a deep CO2 sequestration target reservoir.

Dickman Field: We have successfully carried out 0-10 degree, 10-20 degree and 20-30 degree offset angle prestack time migrations and a whole-stack (0-45 degree) prestack time migration of the Dickman 3-D seismic data over the entire survey area (Figures 10 and 11). We processed the expanded 3-D survey on a grid of 82.5 feet by 82.5 feet to match the grid size used in earlier studies of a partial poststack seismic dataset. We plan to generate an acoustic impedance volume from the reprocessed seismic data to aid in mapping the reservoir properties of the objective porous Mississippian interval.

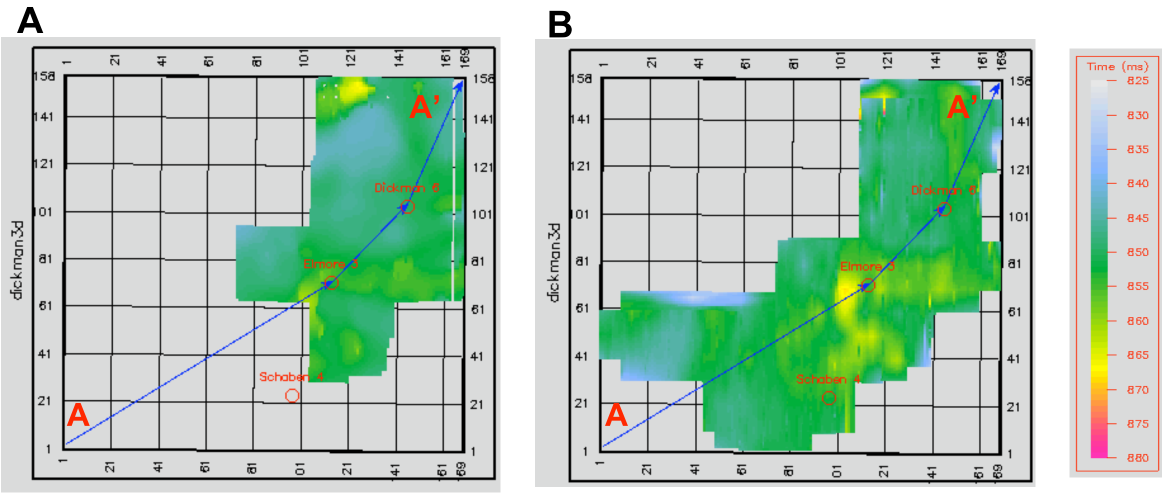


Figure 10. Dickman Field TWT structure maps on top Mississippian and location of seismic section A-A' (Figure 11). Schaben 4 is the only well in the survey area with a modern porosity log (GR-FDC) through the entire Mississippian porous interval. **A.** Commercially processed poststack time migration of partial dataset of the 3-D seismic survey. Pre-project work was limited to this coverage. **B.** UH processed prestack time migration of the complete 3-D seismic survey area.

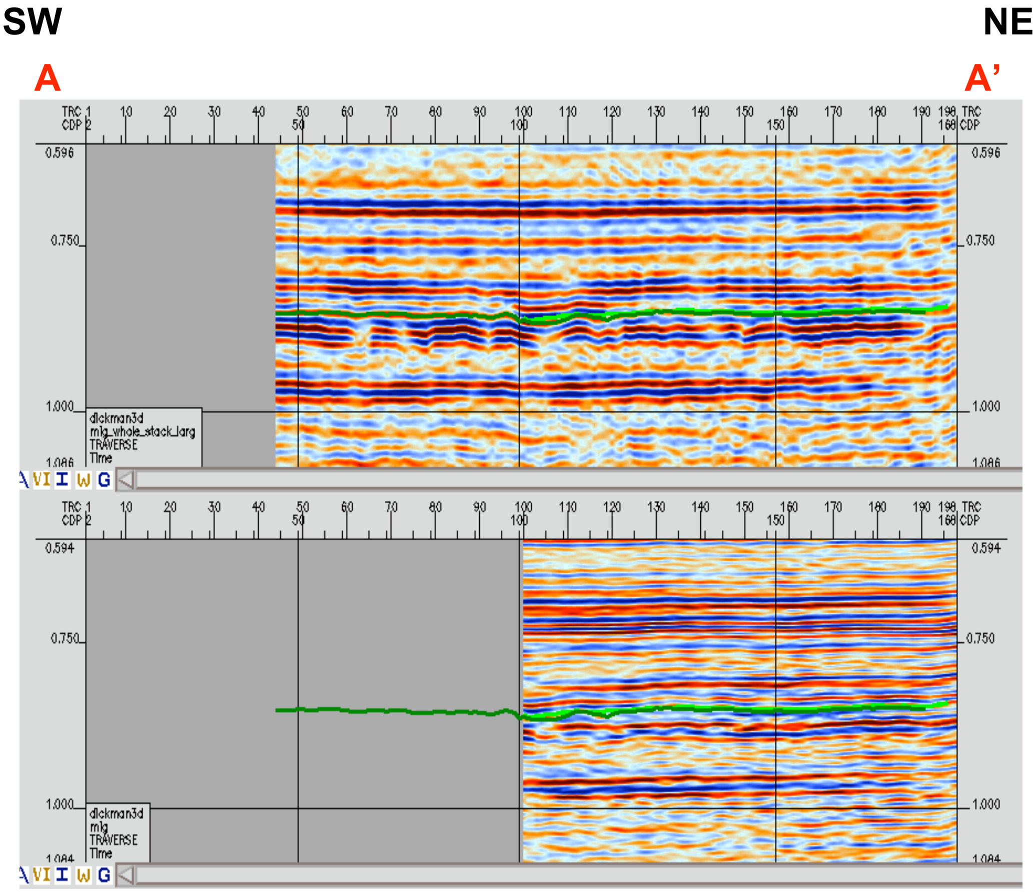


Figure 11. Dickman Field seismic section A-A'. **A.** UH processed prestack time migration of the complete 3-D seismic survey area. **B.** Commercially processed poststack time migration of partial dataset of the 3-D seismic survey. Green horizon is top of the objective Mississippian porous zone.

Subtask 2.3 Generate Frequency Dependent and Offset-Dependent Attributes

Work on this task has been deferred pending further evaluation of prestack azimuthal binning and a review for the need of carrying out frequency and offset dependent attribute studies. This work may be integrated with attribute studies of impedance inversions of the prestack migrated seismic volumes.

Task 3.0- Conduct Structural/Stratigraphic Interpretations of Seismic Volumes.

Teapot Dome Field: Graduations of student research assistants and a late disbursement of DOE funding has set back our plans to analyze further the relationships between attribute lineations, FMI and core-derived fracture interpretations and Tensleep productivity during this report period.

We have extracted time slices near the basement from prestack 3-D seismic data reprocessed by UH and visually compared the results with time slices from the previously available commercially processed data volume (Figures 12, 13 and 14). In general, the resolution of the extractions from the UH volumes is as good as or better than extractions from the commercially processed volume with respect to the sharpness of delineation and the lateral continuity of the structural features and attribute anomalies. We cannot make a definitive assessment of the value of the UH reprocessing with the available extractions, because TWT values tie to different datums and have not yet been exactly correlated between the UH and commercially processed volumes. We plan to recalculate attribute volumes using the prestack depth migrated seismic volume, which will facilitate the exact positioning of seismic data with log depths and should result in a better evaluation of the potential for developing a reservoir model with a deterministic fracture system component.

In the longer term, matching a Tensleep reservoir model with well production data will be the best test of the viability of the reservoir model. Our goal in this study is to develop a well-constrained, dual-permeability reservoir model for fluid-flow simulation studies of the Tensleep and to demonstrate a seismic-based modeling process with wide applicability in a range of geologic settings.