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 to: 1) 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) 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 continued to process the expanded 3.5 square-mile 3-D seismic survey of the field, which we acquired from the operator late last year. In order to effectively compare our earlier analyses with analyses of the expanded survey area and to correct for previously unrecognized processing problems introduced by incorrect header data, we are reprocessing the expanded 3-D survey. This work requires re-sampling the velocity model on a common grid spacing and re-migrating the prestack data volume. We will carry out a 0-45 degree offset angle prestack time migration and 0-10 degree, 10-20 degree and whole-stack prestack time migrations of the regridded seismic data.

We plan to extend the seismic horizons mapped in the area of the partial seismic dataset into the expanded area and to extract an acoustic impedance volume of the entire dataset. We will use the results to predict the 3-D distribution of porosity and saturation in the porous Mississippian oil reservoir of Dickman field and in the saline aquifer underlying Dickman field with the aim of developing a robust geologic model of the field.

Teapot Dome Field: In our last report, we suggested that lineaments on attribute maps that do not correlate with the known larger faults on the Teapot Dome structure might indicate fractures or small displacement faults, which could compartmentalize reservoirs. To evaluate this idea, we have begun an analysis of the lineaments on most negative curvature attribute maps of key horizons. We have applied a program developed by a UH graduate student, which automatically generates rose diagrams of curvature lineation azimuths, to map the entire survey area. Clear similarities between rose diagram and attribute map lineations suggest that the this new methodology can produce accurate analyses of very complicated lineament maps in a fraction of the time required to carry out a similar analysis using manual methods.

We also have compared the seismic attribute-derived rose diagrams with manually generated FMI log-derived rose diagrams from a fracture study of five wells at Teapot Dome by West Virginia University. The results of this comparison are equivocal. The rose diagrams from both sets of data are similar for two wells and dissimilar for three wells, and a strong NE lineation direction that is apparent on many of the attribute-derived rose diagrams is not seen on the FMI log-derived rose diagrams. We plan to compare the results of manually and auto-generated rose diagrams in local areas to evaluate further the methodology and the significance of the similarities and differences.

If this methology proves to be useful for characterizing reservoir properties, we would focus on the Goose Egg Formation (reservoir seal rock), the Tensleep "A" and "B" sands, the Tensleep "B" Dolostone and and an interval at the top of granite basement. We also might expand the scope of the study to include the Crow Mountain Formation, a saline reservoir with possible potential for CO2 sequestration in the region In the longer term, matching a Tensleep reservoir model, which incorporates a deterministic fracture system, with well production data would be the best test of the viability of a reservoir model. *Our aim 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.*

We have completed pre-stack and post-stack Kirchhoff time migrations of the 3-D seismic data at Teapot Dome. An analysis of the fold of the seismic data versus source-receiver offset distance indicates that a significant loss of fold at far-offsets severely limits the capability to image features on the flanks of Teapot Dome and below a depth of the about 9000 feet. The results of applying NMO, DMO, refraction statics and spherical divergence corrections and deconvolution have resulted in improved reflector continuity and vertical resolution. A better evaluation of the quality of the reprocessing will be possible when depth migrated seismic volumes are available, and we can determine if the spatial relationships of geologic features are compatible with well data constraints.

Patoka and Sciota Fields: A review of previous processing work on the Patoka Field seismic data revealed that we had not optimized the binning parameters for the survey by auto-binning. To correct this problem, we have manually re-binned the survey data to optimize the number of CDP clusters in single bins and reprocessed the re-binned data through the deconvolution step. Although some effects of ground roll noise remain, the reprocessing has improved the continuity of reflectors. A possible structure in the basement is now evident that we had not recognized on the earlier processed data. The velocity analysis prior to migration is in progress.

Mattoon and Tuscola in Illinois are on the shortlist of four cities in competition to provide a site for the world's first near-zero-emissions coal power plant, a DOE **FutureGen** project. The DOE and a worldwide consortium of 10 energy companies will announce the winning site in 2007. *The results of our work on the Patoka field in Illinois could directly affect the evaluation of the storage capacity of the Illinois Basin Mt. Simon sandstone, which is the reservoir targeted for disposal of CO2 to be produced at either of the proposed Illinois power plant sites.*

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 severely 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 severely 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**

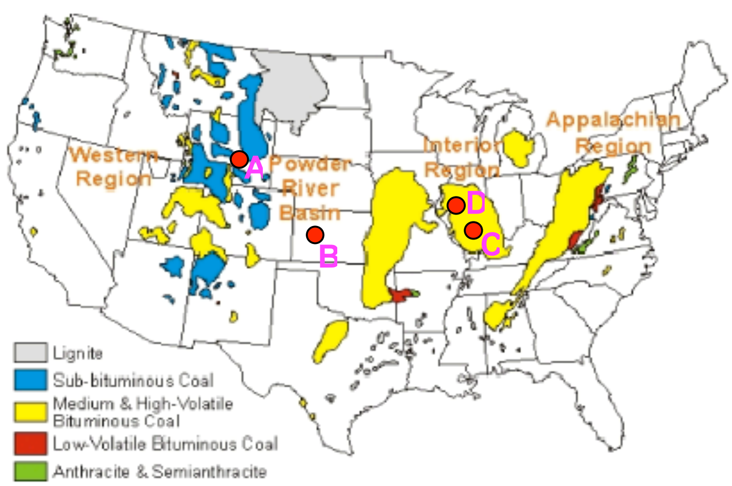


Figure 1. 3-D seismic data sets available for this study are located at: A) **Teapot Dome**, Powder River Basin, Wyoming, a major CO_2 study site for the DOE; B) **Dickman Field,** Kansas, within the Mid-Continent area underlain by the Mississippian Western Interior Plains saline aquifer; and C) **Patoka and** D) **Sciota Fields**, Illinois Basin, a candidate area for the DOE **FutureGen** project. 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 understanding of how to effectively and safely store CO_2 in depleted oil reservoirs and saline aquifers.

Mattoon and Tuscola in Illinois are on the shortlist of four cities selected to provide a site for the world's first near-zero-emissions coal power plant, a **DOE FutureGen project**, which is part of a 10 year, $2 billion government commitment for clean coal technology research. The DOE and a worldwide consortium of 10 energy companies will announce the winning site in 2007. *The results of our work on the Patoka and Sciota fields in Illinois could directly affect the evaluation of the storage capacity of the Illinois Basin Mt. Simon sandstone, which is the reservoir targeted for disposal of CO2 to be produced at either proposed Illinois power plant.*

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. We plan to carry out advanced seismic attribute studies on reprocessed pre-stack seismic data volumes from **Dickman**, **Teapot Dome** and **Patoka fields.** Reprocessing of these data volumes is in progress.

Subtask 2.2 Perform Target Oriented Migration of Pre-stack Seismic Data

Teapot Dome field: We have completed pre-stack and post-stack Kirchhoff time migrations and nearly completed depth migrations of the 3-D seismic data at Teapot Dome (Figure 2). The aim of this work is to improve signal/noise ratio and to generate an optimized 3-D velocity model for depth migration. We carried out the processing using the applications Focus and Geodepth, which Paradigm Geophysical provided to the University of Houston. An analysis of the fold of the seismic data versus source-receiver offset distance illustrates the effects of acquisition footprint on fold in localized areas and the significant reduction of fold with depth and distance from the center of the structure (Figure 3). The maximum total fold is 57. For near-offset CMPs (0-1000 ft), the fold ranges up to 20; for mid-offset CMPs (5000-10000 ft) up to 36; for far-offset CMPs (10000-18000 ft) up to 12. The significant loss of fold at far-offsets severely limits the capability to image features on the flanks of Teapot Dome and below a depth of the about 9000 feet. The results of applying NMO, DMO, refraction statics and spherical divergence corrections and deconvolution followed by time variant scaling and residual statics has resulted in a gradual improvement of the resolution of the raw seismic data (Figure 4).

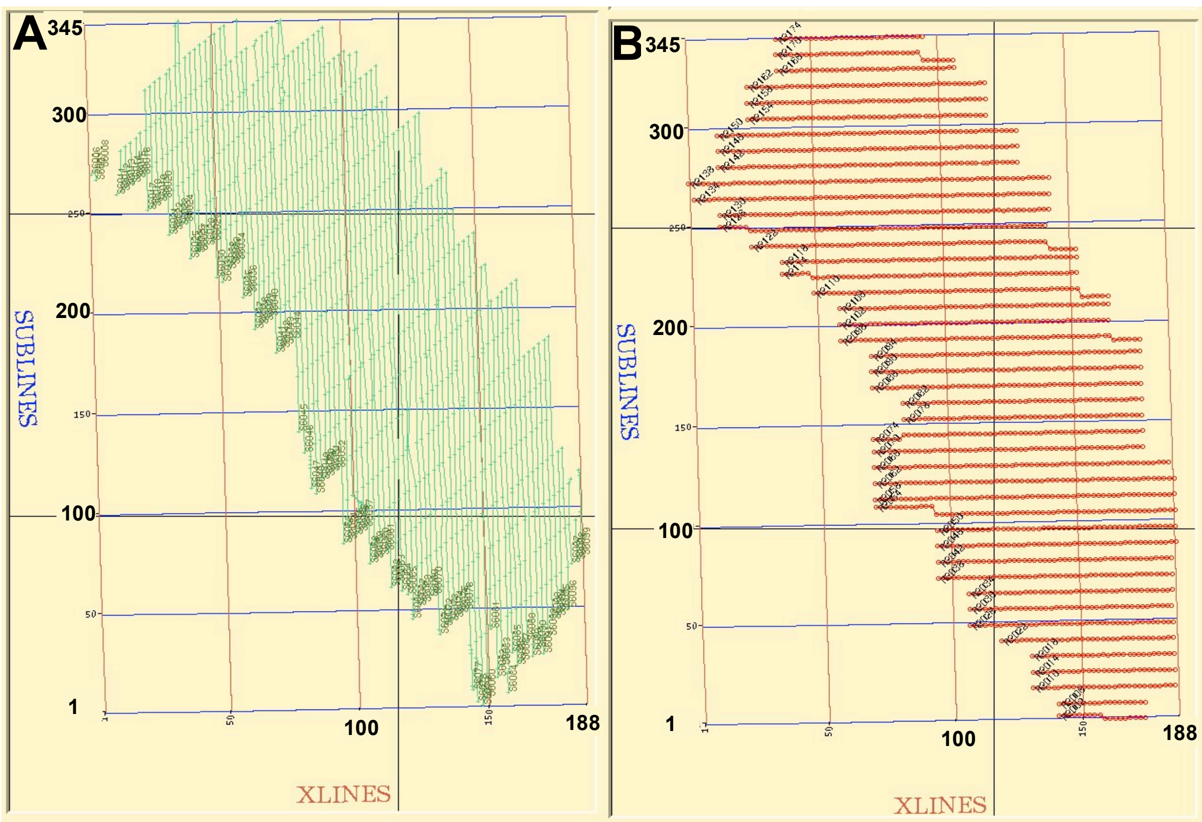


Figure 2. Seismic coverage of Teapot Dome field. **A.** Shot locations (green dots). **B.** Receiver locations (red dots). The line spacing is 110 feet by 110 feet.

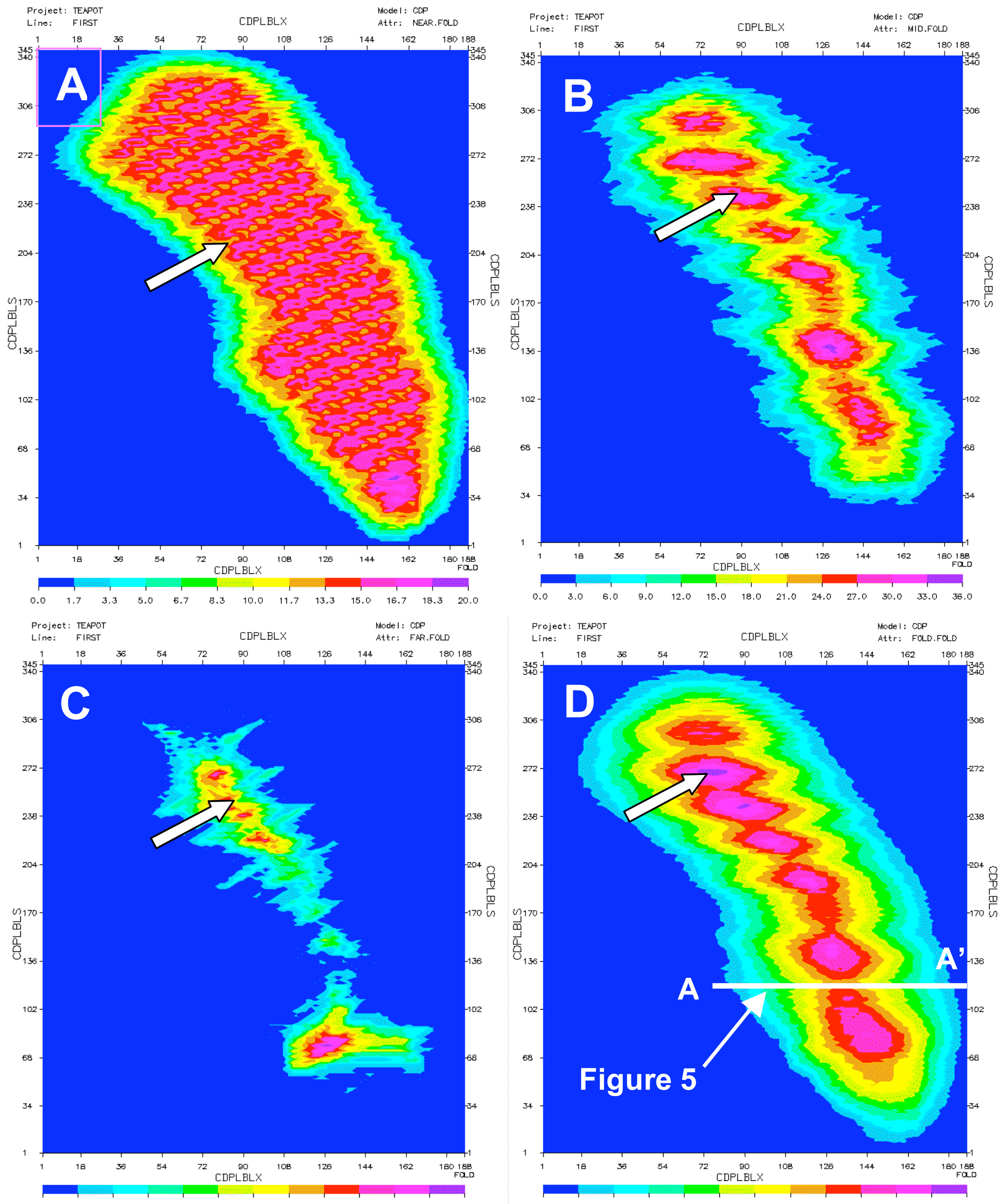


Figure 3. Fold analysis of Teapot Dome seismic data. **A.** Near-offset (0-5000 ft.) fold, **B.** Mid-offset (5000-10000 ft.) fold, **C.** Far-offset (10000-18000 ft.) fold, and **D.** Total fold. Maximum fold is 57. Blue color in background is area of zero fold (no data). White arrows point to acquisition footprints that trend EW and N59E and that relate to source and receiver alignments. See Figure 5 for seismic section A-A’.

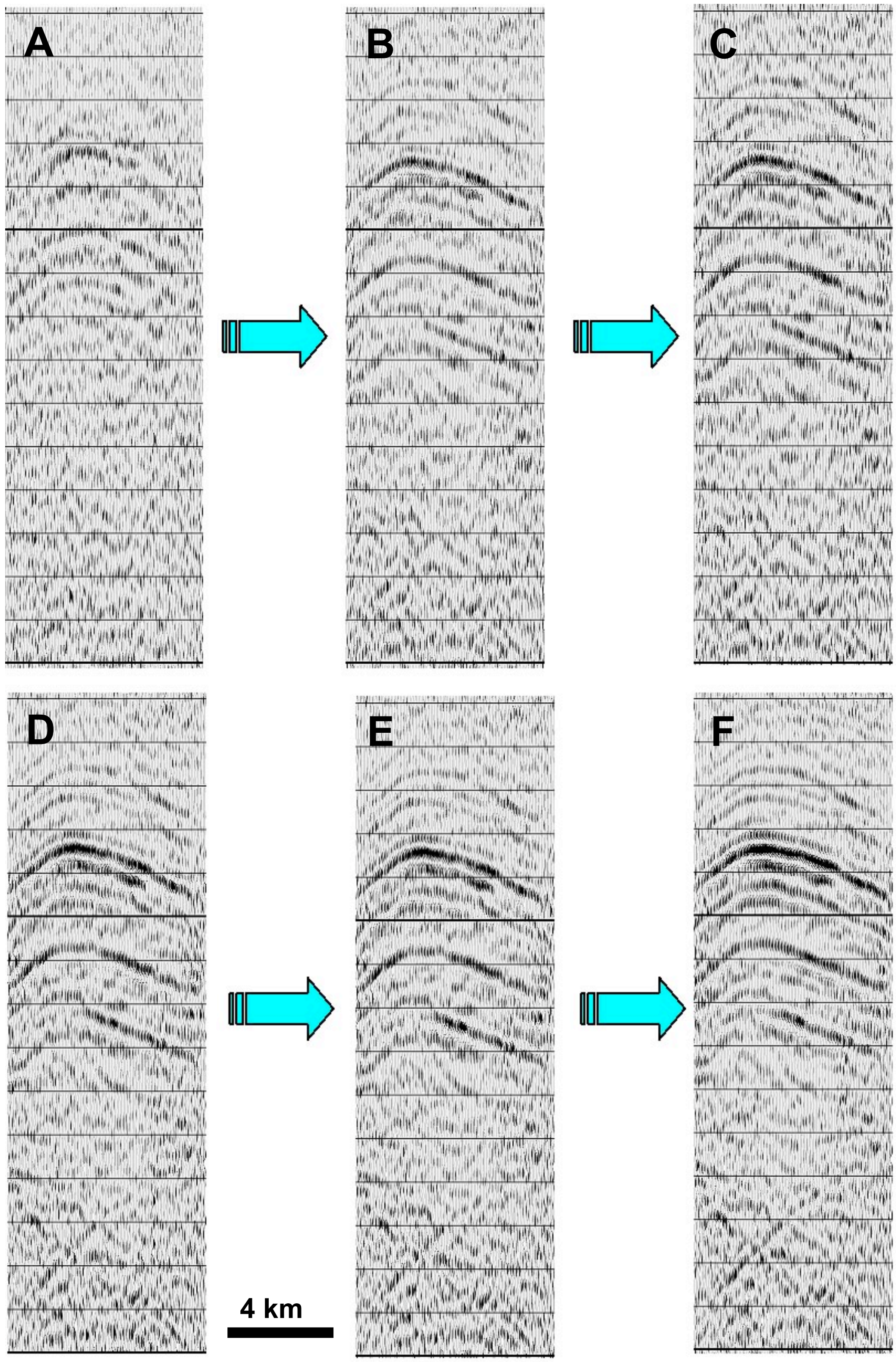


Figure 4. Summary of the processing flow on horizontally compressed images prior to migration of subline 120. **A.** Application of NMO and DMO corrections and stack of raw data, **B.** Application of refraction statics to Figure 4A, **C.** Application of spherical divergence correction to Figure 4B, **D.** Deconvolution of Figure 4C, **E.** Application of time variant scaling to Figure 4D and **F.** Application of residual statics to Figure 4E. These snapshots of the processing flow illustrate a stepwise increase in S/N ratio and improvement in reflector continuity.

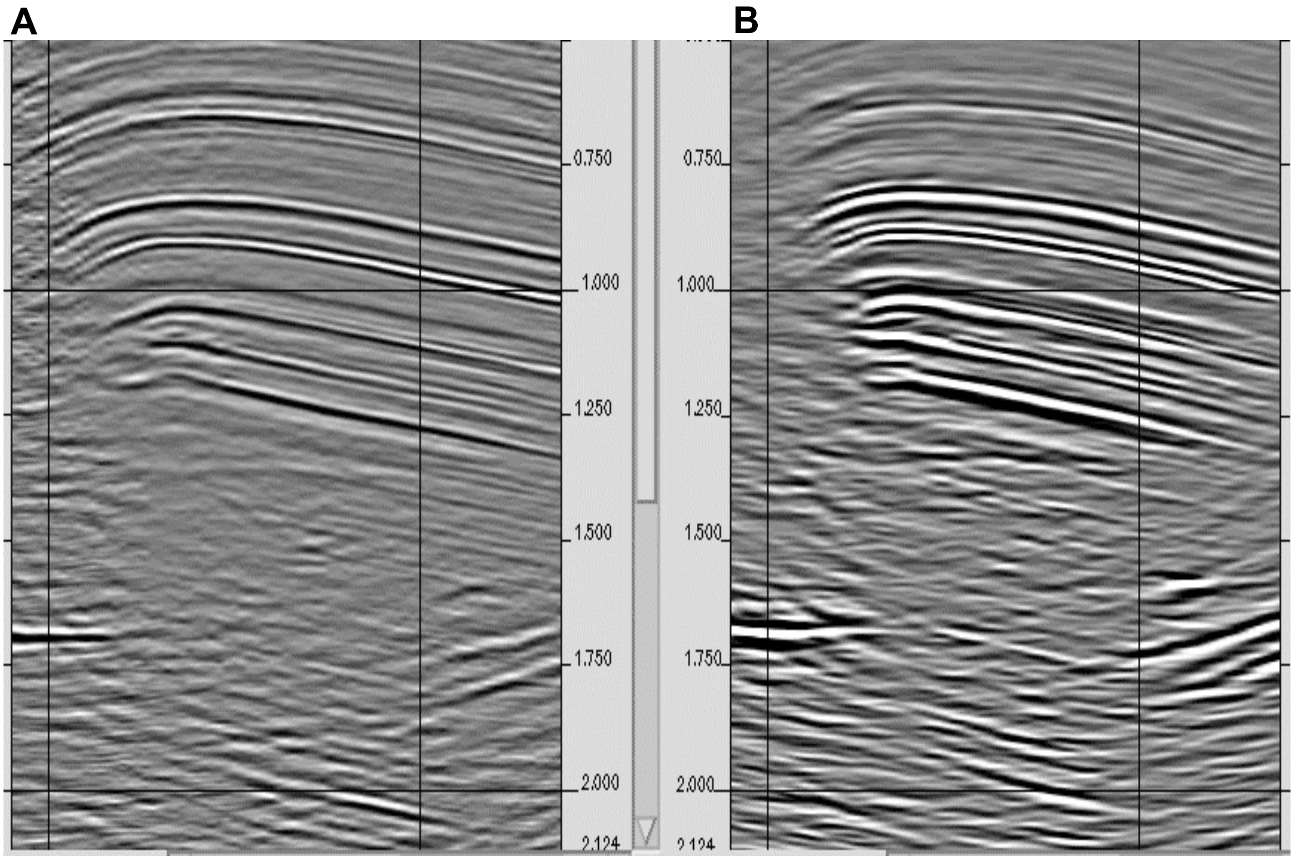


Figure 5. Comparison of pre-stack time migrated subline 120 at Teapot Dome (Section A-A' on Figure 3). **A.** Profile from RMOTC processed pre-stack time migrated seismic data volume. **B.** Profile from UH processed pre-stack time migrated seismic data volume.

To compare the commercially processed RMOTC data with the UH processed data, we have extracted subline 120 from both pre-stack time migrated data volumes (Figure 5). Our first impression is that the reprocessing by UH has improved reflector continuity and the vertical resolution of horizons. A better evaluation of the quality of the reprocessing will be possible when depth migrations of the migrated seismic volumes are available, and we can determine if the known spatial relationships of geologic features are compatible with well data constraints.

This work is the first phase of the seismic data processing sequence that will enable us to generate high-resolution attribute maps of pre-stack depth migrated land seismic data, which we expect will provide improved images of the anisotropic features of the Tensleep reservoir. If we can satisfactorily carry out and validate the depth migrations, which are almost complete, then the continuing uncertainties regarding time-depth curves and well log-seismic correlations at Teapot Dome should be resolvable. Very few studies of pre-stack 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 pre-stack depth migration of 3-D land data that have been published. The results of this work should provide a framework for developing a structurally and stratigraphically integrated geomodel of the Teapot Dome Tensleep reservoir for further reservoir simulation tests.

Patoka Field: A review of the processing results of the last period, which we generated on a SeisUP seismic processing system, revealed that we had not optimized the binning parameters for the survey through the application of the SeisUP auto-binning option. The auto-binning option randomly separated cell-sized clusters of CDPs into two or more bins instead of assigning the maximum possible number of traces in a cluster to a single bin, which would have been the preferred result. The less than optimum binning resulted in lack of reflector continuity on the brute stacks and difficulties in the determination of stacking velocities. Because of these problems and the availability of a graduate student with experience on the ProMAX seismic processing system, we have manually re-binned the survey data to optimize the number of CDP clusters in single bins. In this process, we re-defined the survey origin, adjusted the grid size and slightly rotated the grid. We have reprocessed the re-binned data through the deconvolution step (Figure 6).

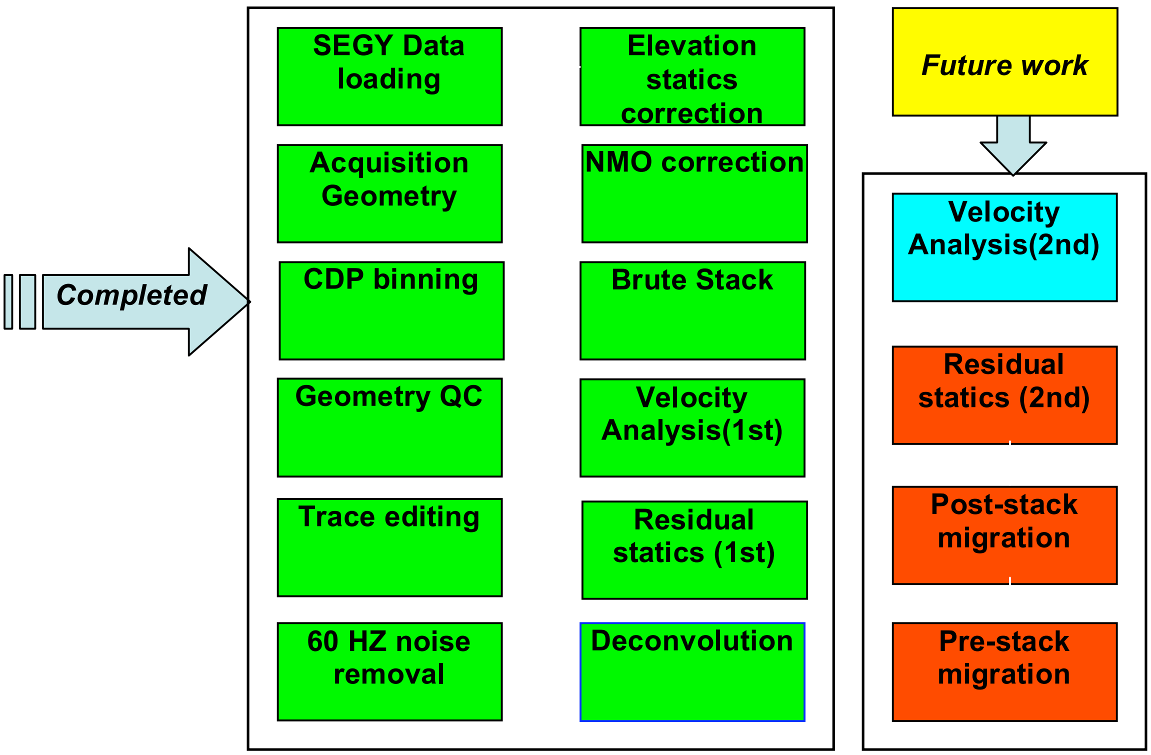


Figure 6. Processing workflow for prestack migration of Patoka 3-D seismic survey. Work has been completed through the deconvolution step (green boxes). Velocity analysis is in progress (blue box). Application of residual static corrections and the migration of the data are the final steps to be done (red boxes).

The emphasis of the reprocessing has been to improve the S/N ratio by removing 60HZ noise and ground roll in the original data. To remove the bands of 60HZ noise produced by power transmission lines and electrical equipment at the surface, we applied a 60HZ, notch filter, which effectively removed the noise (Figures 7 and 8). Low frequency and high amplitude Rayleigh waves (ground roll) in the Patoka survey severely degraded the resolution capabilities of the original seismic data by partially masking reflections from essentially all intervals of interest. Spectral analysis indicates that the dominant frequency of Rayleigh waves is less than 12HZ. We applied an Ormrsby low-cut filter

(8-10-200-240) prior to velocity analysis to remove the ground roll effects and improve resolution, but we did not apply filtering to the original data set. Although some effects of ground roll remain, the filtering improved the continuity of reflectors (Figures 7 and 9). To evaluate the effects of filtering, we plan to migrate both the original data and the filtered data and compare the results. After a residual statics correction and predictive deconvolution, a possible structure in the basement is evident on inline 70 that was not as apparent prior to deconvolution (Figure 10). The velocity analysis prior to migration is in progress (Figure 6).

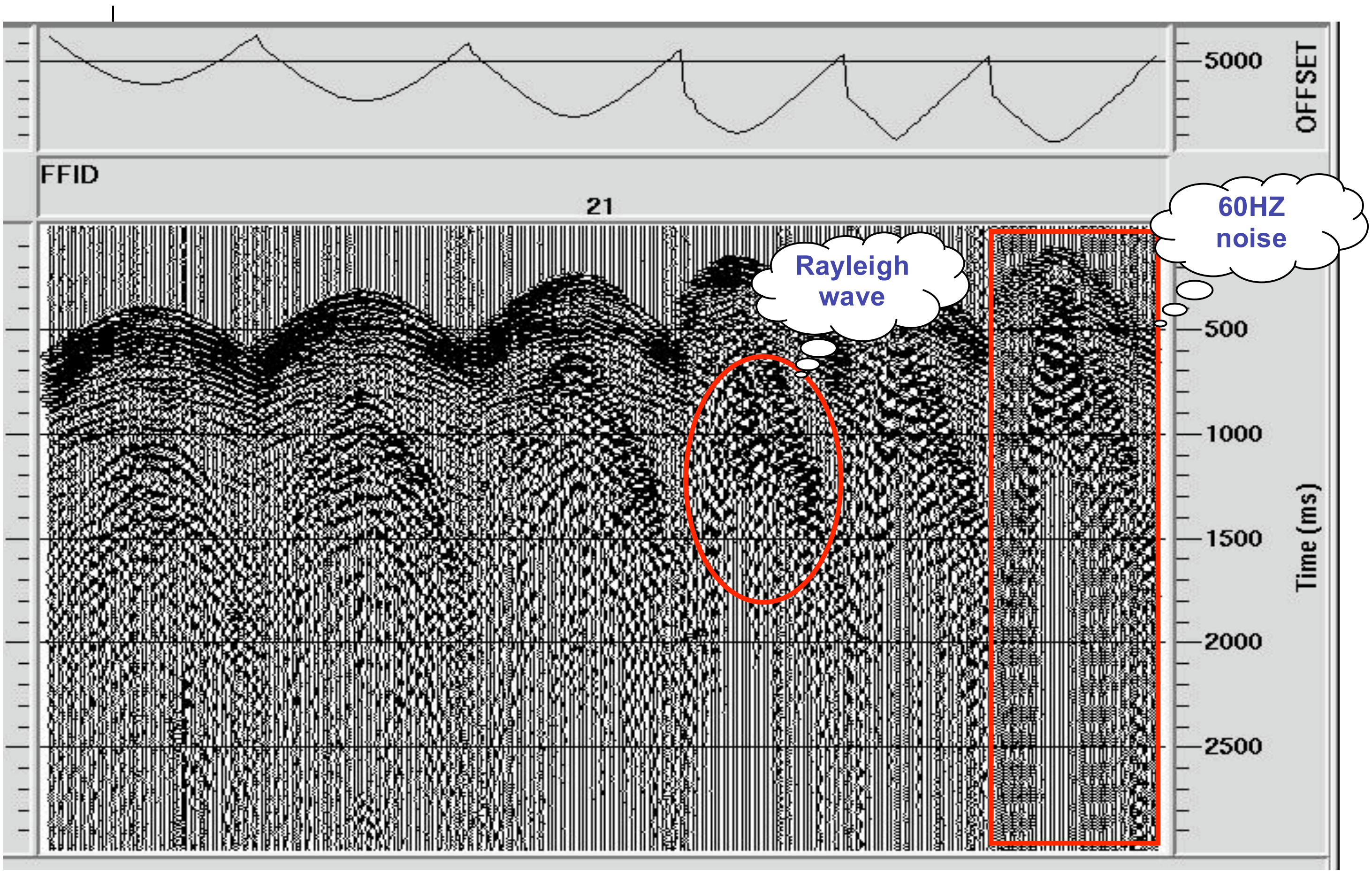


Figure 7. Six shot gathers from the Patoka seismic survey (TWT vs offset distance). Rayleigh waves or ground roll and 60HZ noise are evident throughout the survey.

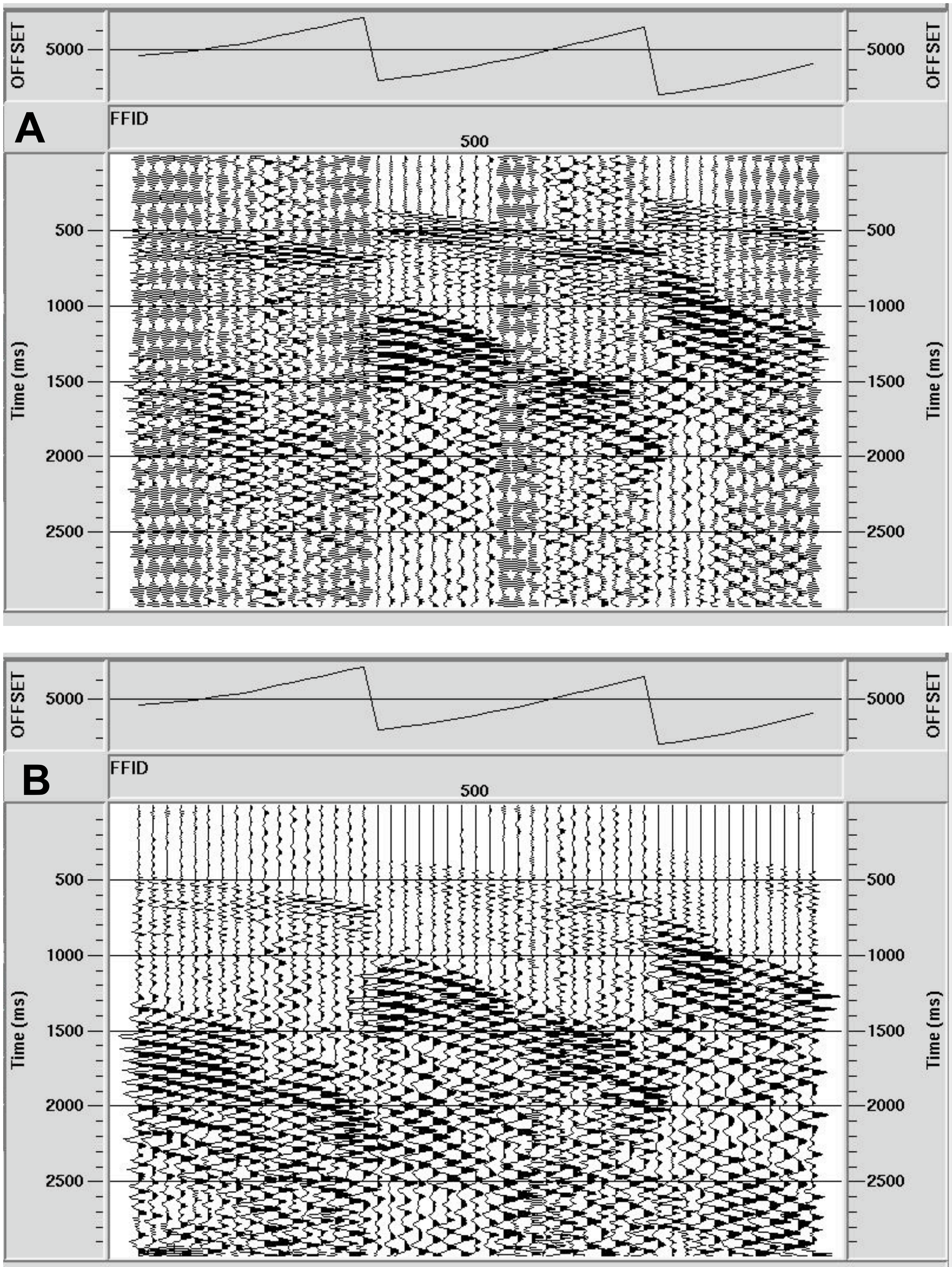


Figure 8. Three shot gathers from the Patoka survey (TWT vs offset distance) showing results of filtering to remove 60HZ noise. Each gather contains all of the traces from a single shot. **A.** Original data with 60HZ noise (compare with Figure 7). **B.** Data after removal of 60HZ noise with a 60HZ notch filter showing improved reflector continuity.

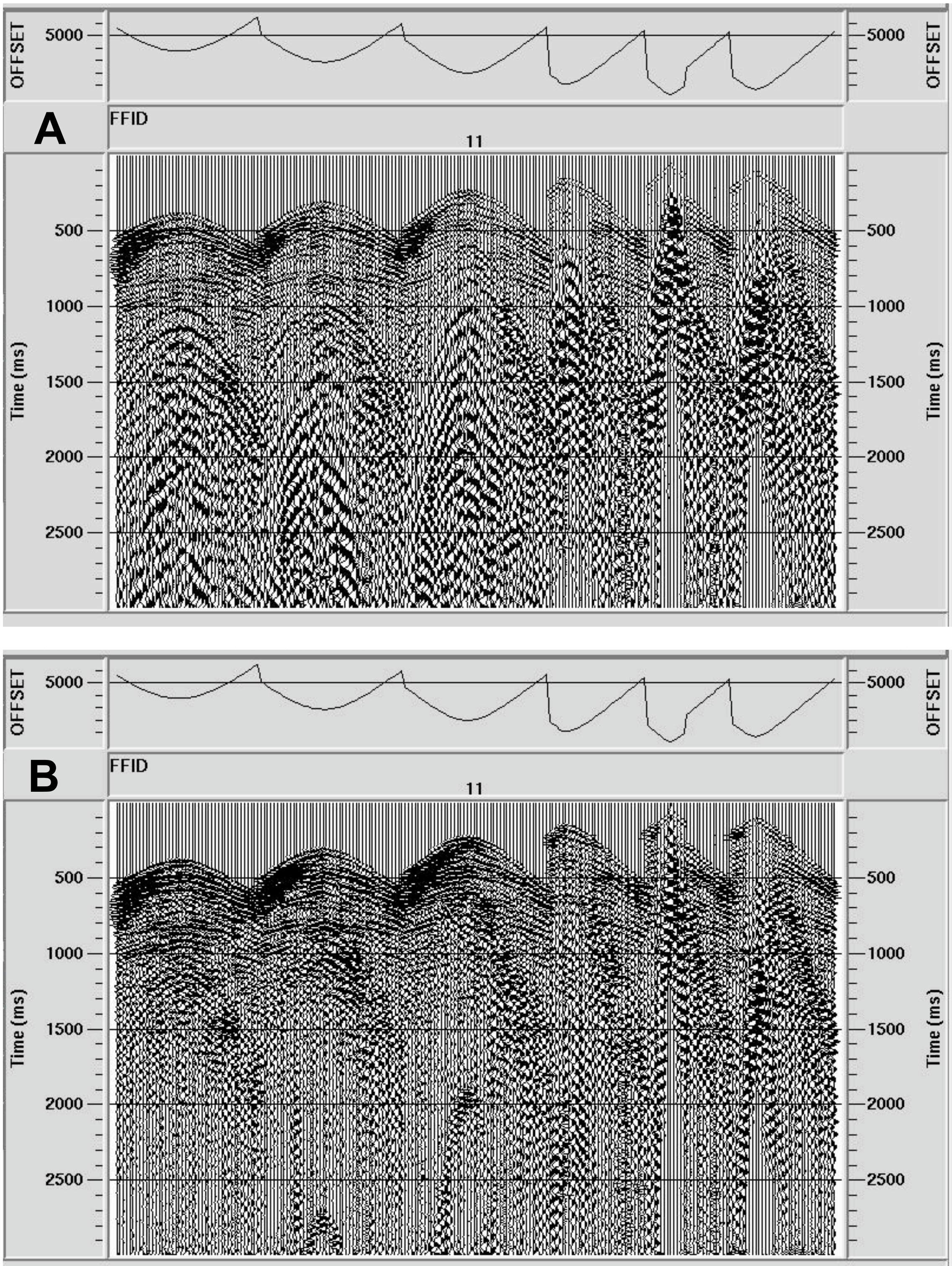
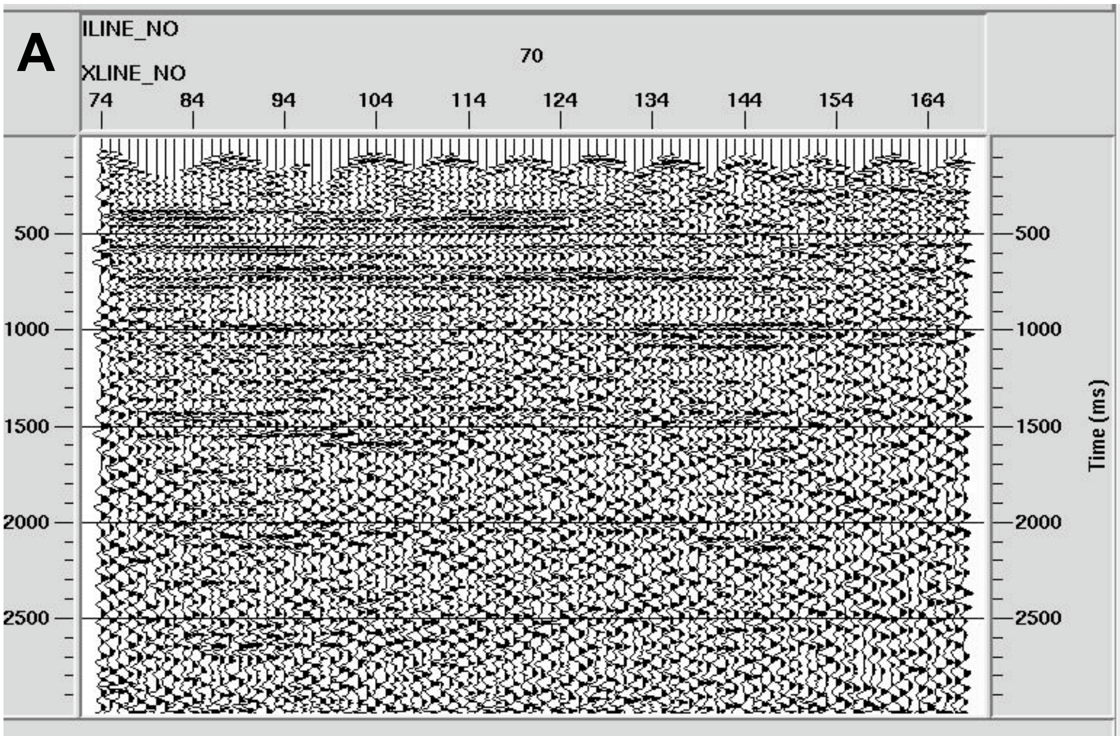


Figure 9. 228-channel shot gather from the Patoka survey showing results of filtering to remove ground roll. **A.** Original data with ground roll (compare with Figure 7). **B.** Figure 4A after removal of ground roll with an Ormrsby low-cut filter (8-10-200-240)



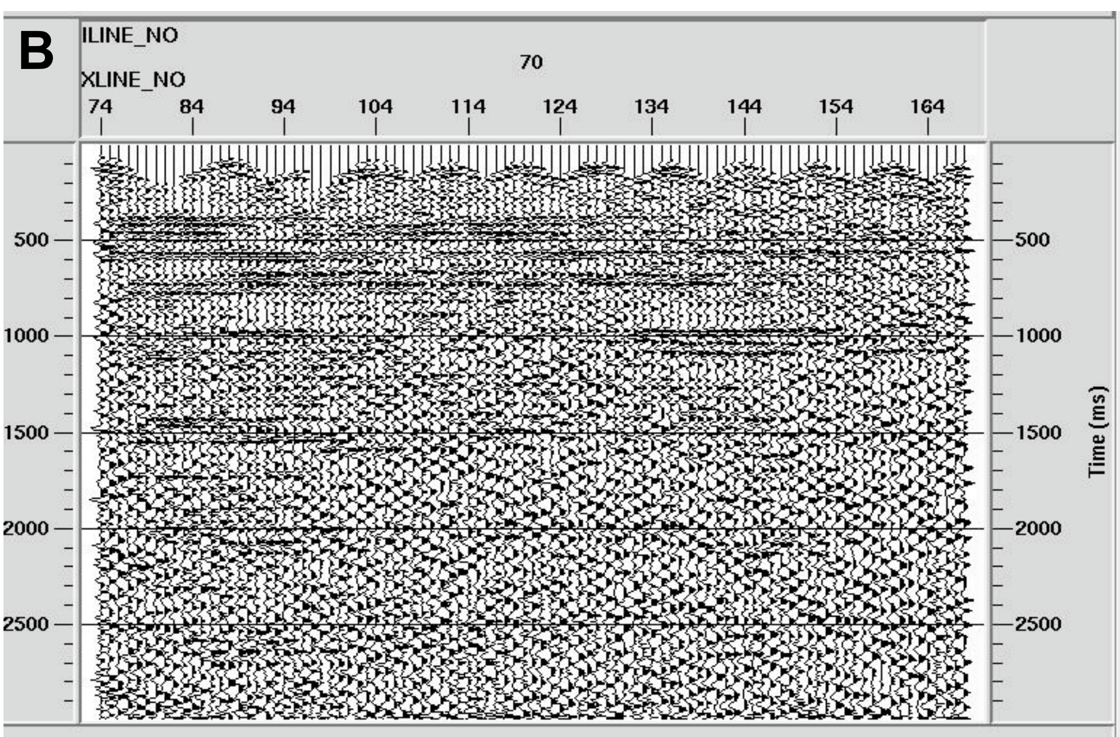


Figure 10. Comparison of inline 70 before and after deconvolution. **A.** Stack after residual statics correction. **B.** Stack after residual statics and predictive deconvolution. A possible basement structure is evident between lines 104-164 at the TWT interval of 2.0-2.5 sec.

Dickman Field: During the last report period, we had generated pre-stack time migrated data volumes for the expanded 3.5 square-mile 3-D survey of Dickman field using conventional azimuthal binning and a modified azimuth-limited migration algorithm. We carried out this work to evaluate the relative resolution of an attribute lineation as a function of the mean azimuth direction of azimuthal-limited migrated volumes (Perez and Marfurt, 2006 and Perez and Marfurt, 2006, *in review*). The line spacing of the expanded survey was 82.5 feet by 110 feet.

The line spacing of the partial seismic dataset, which we used for earlier analyses of fracture directions in the porous Mississippian objective, is 82.5 feet by 82.5 feet. In order to effectively compare our earlier analyses with analyses of the expanded survey area and to correct for previously unrecognized processing problems introduced by incorrect header data, we are reprocessing the expanded 3-D survey on a grid of 82.5 feet by 82.5 feet. This work requires re-sampling the velocity model and re-migrating the prestack data volume. We are preparing to carry out a 0-45 degree offset angle prestack time migration and 0-10 degree, 10-20 degree and whole-stack prestack time migrations of the regridded seismic data.

We plan to extend the seismic horizons mapped in the area of the partial seismic dataset into the expanded area and to extract an acoustic impedance volume of the entire dataset. We will use the results to predict the 3-D distribution of porosity and saturation in the porous Mississippian oil reservoir of Dickman field and in the saline aquifer underlying Dickman field with the aim of developing a robust geologic model of Dickman field for reservoir simulation studies.

Subtask 2.3 Generate Frequency Dependent and Offset-Dependent Attributes

Work on this task has been deferred pending further evaluation of pre-stack azimuthal binning and a review for the need of carrying out frequency and offset dependent attribute studies.

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

Teapot Dome Field: During the last period, we utilized attribute maps of the RMOTC-processed seismic data for an initial evaluation of fault continuity in the Paleozoic and basement section on the southern closure of Teapot Dome. We have now extended this work to evaluate the possibility of using lineaments derived from curvature attribute maps to characterize fracture distributions in the Tensleep reservoir. For this initial test of the methodology, we extracted maximum negative curvature maps from a curvature attribute volume for a strata slice near the Tensleep "B" sand and a horizon map near the top of the basement (Figure 11). We used a 10 ms window centered on the horizon of interest to calculate the attribute values, which means that the values represent a statistical analysis of approximately 80 feet of section. We have shown the spatial relationships between the 10 ms windows and the stratigraphic zones of interest on Figures 11A and 11B (See red arrow-brackets). For comparison purposes, we also show