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 seals, 2) to develop a reservoir model and 3) 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: Using the Hampson-Russell program STRATA, we have begun the process of generating both elastic impedance and acoustic impedance volumes by inversion of 0-10 degree and 20-30 degree angle gathers and 0-45 degree full-stack angle gathers. By generating an acoustic impedance volume from full-stack data and elastic impedance volumes from near- and far-angle gathers, we hope to improve the 3-D predictability of the porosity, saturation and permeability trends in the Mississippian reservoir. After incorporating additional well log impedance values in the inversions of the variable angle, pre-stack time migrated seismic data, we plan to use the Hampson-Russell program EMERGE to correlate seismic impedance values with the distribution of lithologic units, porosity and permeability.

Concurrently, we are evaluating the application of spectral decomposition to map the basal Pennsylvanian sandstone channel system that locally overlies the Mississippian and the distribution of saturation and permeability in the Mississippian dolomites. From an initial review, we have found that the areal energy distribution of the low frequency spectra is different from that of the high frequency spectra. The same review also strongly suggests that volumetric attribute maps of the distribution of low frequency energy might correlate with reservoir properties that relate to production. If we are encouraged by further analysis, we would plan to integrate this work with the attribute studies of impedance inversions of the pre-stack time migrated seismic volumes

We have developed a partial-area fracture model for the reservoir and plan to extend the model over the entire survey area and delineate those important fracture trends that compartmentalize the reservoir and influence fluid mobility. To carry out this work, we plan to extract and analyze curvature attribute maps of the porous Mississippian interval from the impedance volumes extracted from the pre-stack seismic data. *The results of this work and the impedance inversion and spectral decomposition analyses will provide the framework for the reservoir model and production simulation studies of the field.*

Teapot Dome Field: We completed pre-stack and post-stack Kirchhoff time migrations and depth migrations of the 3-D seismic data at Teapot Dome, during the third calendar quarter of 2007. The aim of that work was to generate a pre-stack 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.

Due to the graduation of the student working with the Teapot Dome data and the delay in the DOE disposition of incremental funding, we have not yet been able to staff the project and follow-up the completion of the depth migration work with further analyses. We are currently seeking a suitable candidate to carry out this work and complete the project.

The work required to complete the Teapot Dome study is the following:

1. *Carry out impedance inversion of the new seismic volumes.*

2. *Extract attributes from the inverted volumes and complete the structural analysis of faults and fractures in the Tensleep to basement section.*

3. *Calibrate seismic data with well data to map porosity, permeability and the oil saturation of the Tensleep reservoir.*

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 pre-stack 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. Ground roll noise is a typical problem with on land, 3D seismic surveys in areas of near surface, glacial till deposits such as the Mid-continent.

The CO2 sequestration target Mt. Simon Formation overlies granite basement, which occurs in the depth range of about 1.1 to 1.2 seconds at Patoka. Reflections from the Mt. Simon are only distinguishable at far offsets on shot gathers. The noise in the Patoka seismic data limits our capability to carry out high quality structural and stratigraphic analyses of the Mt. Simon Sandstone and the shallower CO2 sequestration targets.

If reprocessing efforts are not successful in the near future, we will continue our reservoir analyses with inversion volumes of the post-stack time migrated seismic data originally provided by Continental Resources, Inc. The process itself of inversion of post-stack data has some potential to reduce the noise in the inverted volumes. *Our expectation is that we will successfully solve the ground roll problem and generate a pre-stack time migrated data volume with adequate resolution to evaluate the potential of the CO2 sequestration target reservoirs 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**

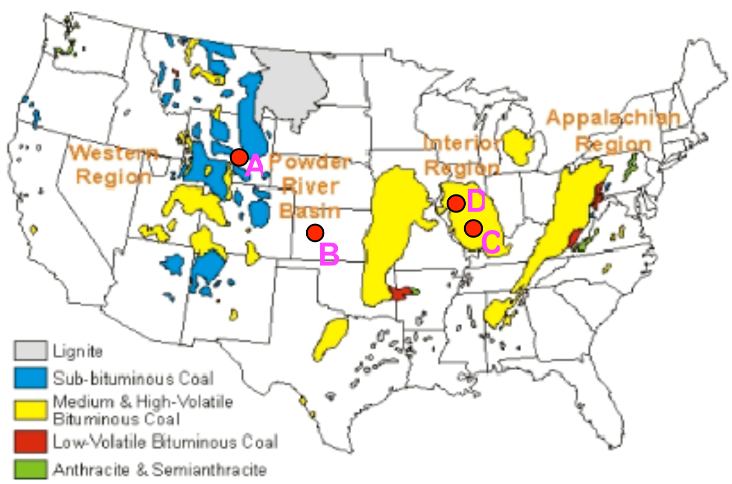

Figure 1. 3-D seismic data sets available for this study are located at: A) **Teapot Dome**, Powder River Basin, Wyoming, a major CO_2 study site for the DOE; B) **Dickman Field,** Kansas, within the Mid-Continent area underlain by the Mississippian Western Interior Plains saline aquifer; and C) **Patoka and** D) **Sciota Fields**, Illinois Basin, underlain by the Cambrian Mt. Simon Formation, a regional saline aquifer. We selected these data sets 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 Pre-stack Seismic Data

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 pre-stack 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 2). Ground roll noise is a typical problem with on land, 3D seismic surveys in areas of near surface, glacial till deposits such as the Mid-continent.

The CO2 sequestration target Mt. Simon Formation overlies granite basement, which occurs in the depth range of about 1.1 to 1.2 seconds at Patoka. Reflections from the Mt. Simon are only distinguishable at far offsets on shot gathers (Figure 2). The noise in the Patoka seismic data limits our capability to carry out structural and stratigraphic analyses of the Mt. Simon Sandstone and shallower CO2 sequestration targets.

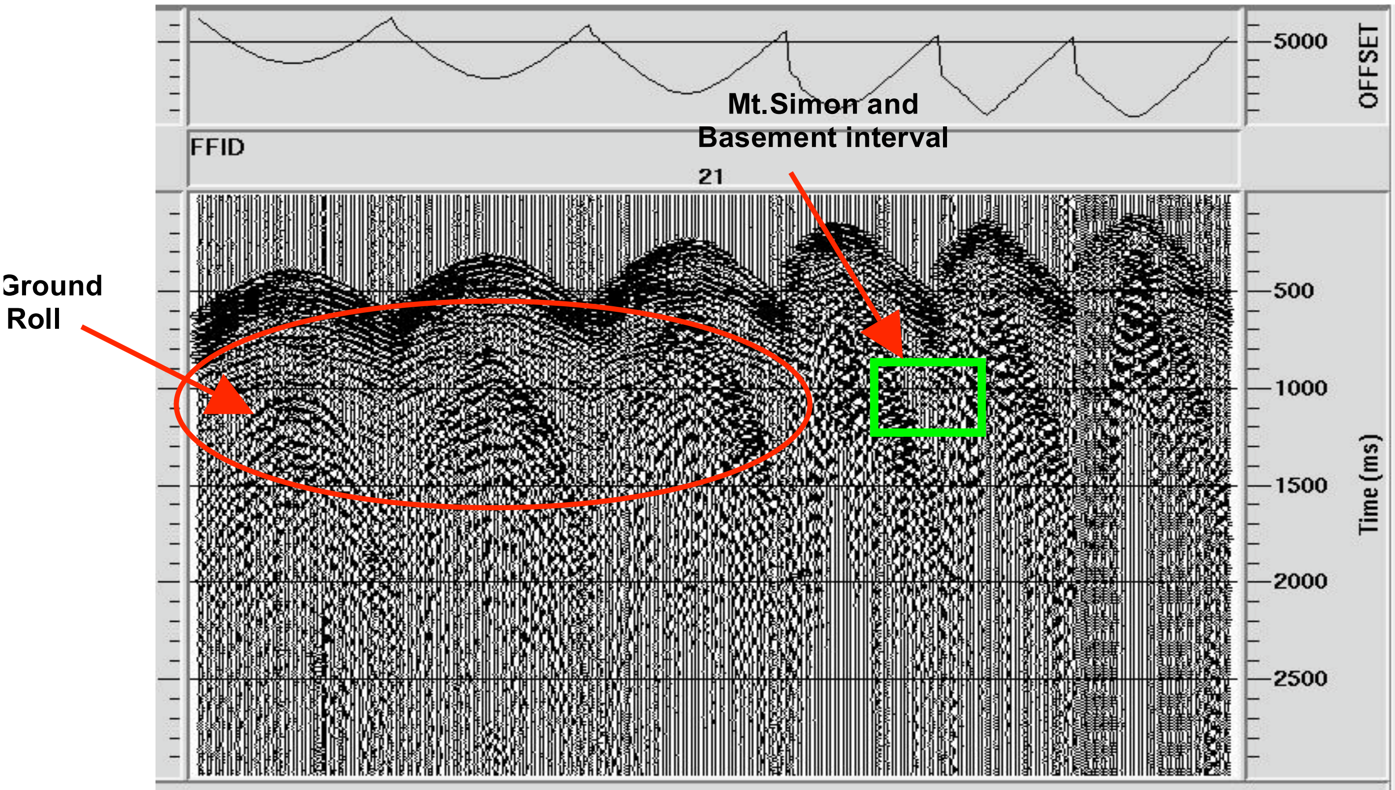

Figure 2. Original shot gathers with severe ground roll (Rayleigh waves) below 0.5 seconds, which severely degrade the resolution in the Mt. Simon interval.

We have described our efforts to remove the ground roll from the Patoka pre-stack data in previous reports. Those efforts have included the application of a low-cut filter (8-10-200-240) and the selective application of time-variant filtering. Geophysical Development Corporation (GDC) recently carried out a model-based noise analysis of the data, which encountered the same problems that were not resolved by our earlier attempts to improve the resolution of the data.

Paradigm Geophysical has agreed to review the data and, if possible, suggest a plan to deal with the noise problem. We have also begun to evaluate the application of a Radon transform methodology to reduce the ground roll noise in the data and plan to carry out variable offset angle time migrations, which might help to resolve the noise problem. Continental Resources, our industry partner, plans to assess the merits of using an outside contractor to reprocess the seismic data.

If reprocessing efforts are not successful in the near future, we will continue our reservoir analyses with inversion volumes of the post-stack time migrated seismic data originally provided by Continental Resources. The process itself of inversion of post-stack data has some potential to reduce the noise in the inverted volumes. Our expectation is that we will successfully solve the ground roll problem and generate a pre-stack time migrated data volume with adequate resolution to evaluate the potential of the Mt. Simon sandstone and the shallower CO_2 sequestration target reservoirs in the Illinois Basin.

Teapot Dome field: We completed pre-stack and post-stack Kirchhoff time migrations and depth migrations of the 3-D seismic data at Teapot Dome, during the third calendar quarter of 2007. The aim of that work was to generate a pre-stack 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.

Due to the graduation of the student working with the Teapot Dome data and the temporary lack of funding for a replacement, we have not yet followed up completion of the depth migration work with further analyses. We are currently seeking a suitable candidate to carry out this work and complete the project.

The work required to complete the Teapot Dome study is the following:

1. Carry out impedance inversion of the new seismic volumes
2. Extract attributes from the inverted volumes and complete the structural analysis of faults and fractures in the Tensleep to basement section.
3. Calibrate seismic data with well data to map porosity, permeability and the oil saturation of the Tensleep in 3D.

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. 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 successor reservoir simulation studies.

Dickman Field: We successfully carried out 0-10 degree, 10-20 degree and 20-30 degree offset angle pre-stack time migrations and a whole-stack (0-45 degree) pre-stack time migration of the Dickman 3-D seismic data over the entire survey area, during the last reporting period. Refer to **Task 3** below for the status of work on the inversion of the pre-stack migration volumes.

Subtask 2.3 Generate Frequency Dependent and Offset-Dependent Attributes

We have begun to evaluate the application of spectral decomposition to map the distribution of reservoir lithologies and oil saturation in the Dickman Field sandstone and carbonate reservoir. We have found that the areal energy distribution of the low frequency spectra in the interval containing basal Pennsylvanian sandstones is different from that of the high frequency spectra. This work also strongly suggests that volumetric attribute maps of the distribution of low frequency energy might correlate with reservoir properties that relate to production. If we are encouraged by further analysis, we would plan to integrate this work with the attribute studies of impedance inversions of the pre-stack time migrated seismic volumes (See **Task 3.0** below, Dickman Field).

Task 3.0- Conduct Structural/Stratigraphic Interpretations of Seismic Volumes.
Dickman field: A time structure map on the top of the Mississippian (the top of the oil-productive dolomite reservoir) shows the limits of the field and the locations of the Schaben 4 and Sidebottom 6 wells. These are the only wells in the area that penetrate the entire Mississippian porous dolomite (Figure 3). Not shown on the map, because it is unknown, is the distribution of overlying basal Pennsylvanian siliciclastic channel sandstones that are locally oil productive and appear to share a common oil-water-contact with the Mississippian dolomites.

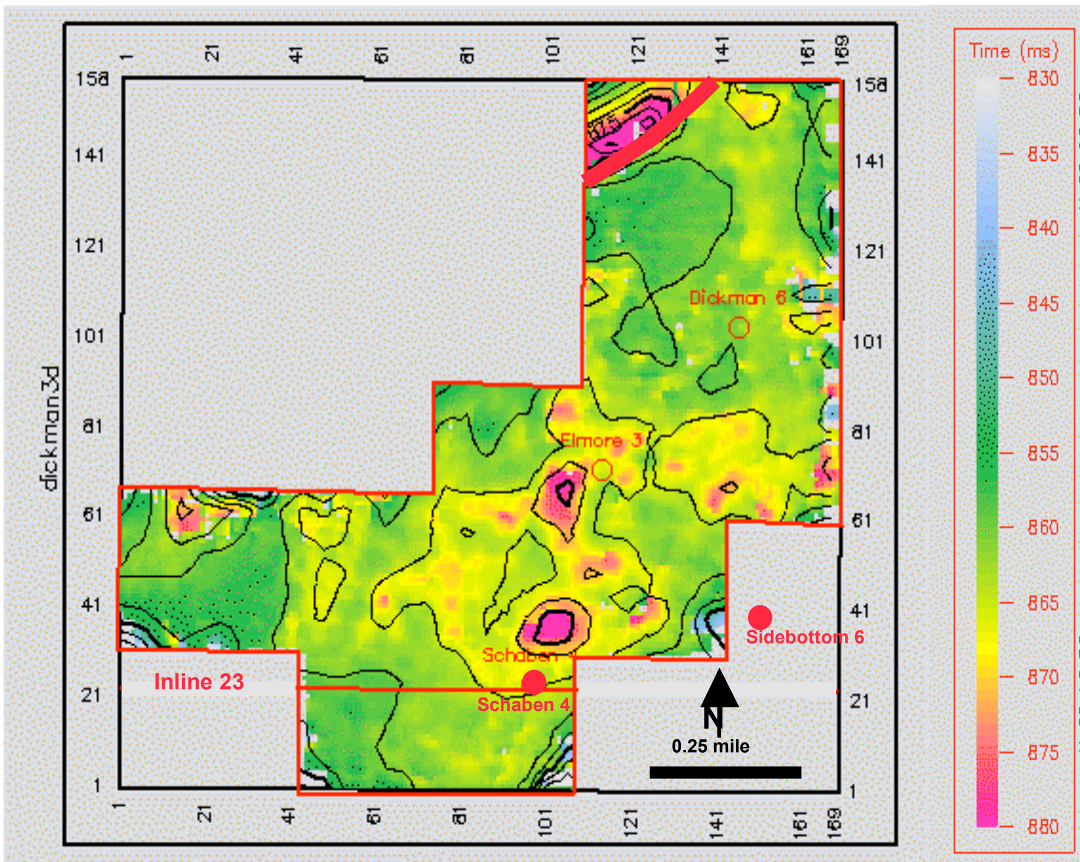

Figure 3. Top Mississippian time structure map (pre-STM) at Dickman Field. Schaben 4 and Sidebottom 6 are the only wells in the area that penetrate the entire Mississippian porous dolomite interval. The dark green areas are above the oil-water-contact at approximately -1981 feet subsea (~860 ms TWT). See Figure 6 for Inline 23 profile extracted from acoustic impedance volume.

Using the Hampson-Russell program STRATA, we have begun the process of generating both elastic impedance and acoustic impedance volumes by inversion of 0-10 degree and 20-30 degree angle gathers and 0-45 degree full-stack data (Figure 4). By generating an acoustic impedance volume from full-stack data and elastic impedance volumes from near- and far-angle gathers, we hope to improve the 3-D predictability of the porosity, saturation and permeability trends in the Mississippian reservoir.

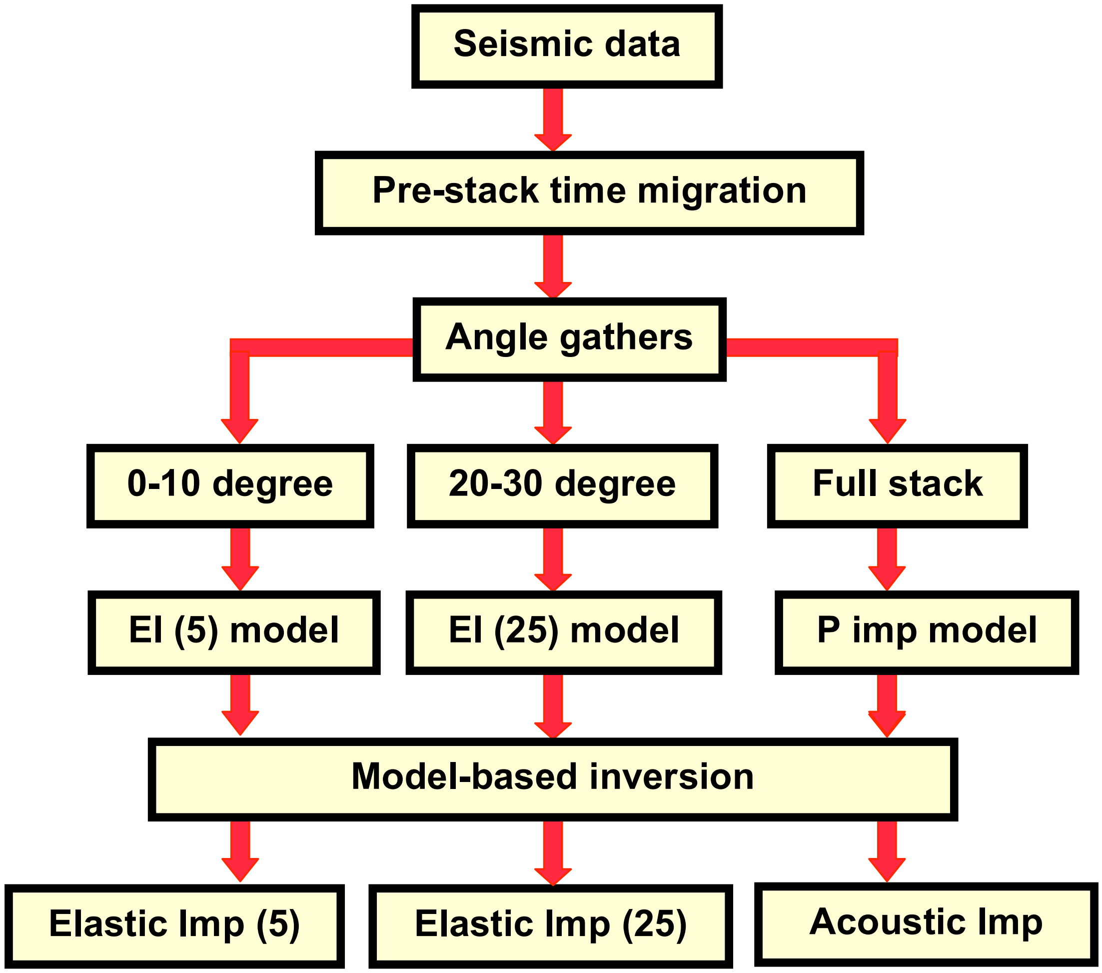

Figure 4. Workflow for extraction of elastic impedance (EI) volumes and acoustic impedance volume from pre-stack time migrations of the Dickman seismic data. Integration of well data with the seismic data will require multiple iterations of the workflow to obtain an optimized result.

Our initial inversions integrate log data from only one well, the Schaben 4, which is the only well within the survey area that penetrates the entire porous Mississippian interval (the depleted oil reservoir and the underlying Western Interior Plains saline aquifer system) (Figure 5). The logs run in Schaben 4 are the density, gamma ray and resistivity (Guard log). We generated a pseudo-sonic log from the resistivity log (P-wave_corr 5 in Figure 5) to carry out our initial impedance inversions. In subsequent inversions, we plan to add control from sonic logs in a few wells that only penetrated the upper, oil-bearing part of the porous Mississippian.

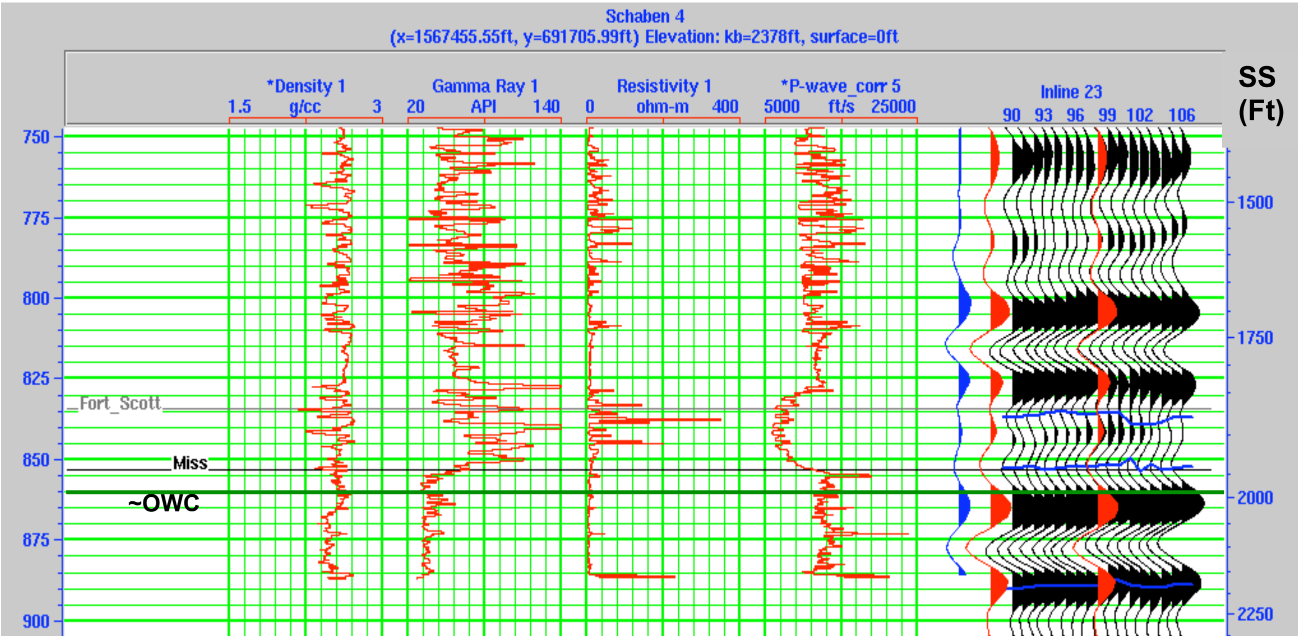

Figure 5. Well log correlation for Schaben 4. The blue trace is a synthetic trace and the red trace is the average seismic trace. The well penetrates the entire Mississippian porous dolomite interval.

An inline profile across the location of the deep Schaben 4 well from the acoustic impedance volume illustrates the impedance variations within the porous dolomites of the upper Mississippian interval and within the thin, overlying interval correlative with the basal Pennsylvanian channel sand system (Figure 6). Intriguingly, high impedance values (red impedance values) in the interval immediately above the top Mississippian might prove to correlate with the basal channel sandstones.

After incorporating additional well log impedance values in the inversions of the variable angle, pre-stack time migrated seismic volumes, we plan to use the Hampson-Russell program EMERGE to correlate seismic impedance values with the distribution of lithologic units, porosity and permeability.

Concurrently, we are evaluating the application of spectral decomposition to map the basal Pennsylvanian sandstone channel system that locally overlies the Mississippian and the distribution of saturation and permeability in the Mississippian dolomites.

We have developed a partial-area fracture model for the reservoir, but we need to extend the model over the entire survey area and to delineate those important fracture trends that compartmentalize the reservoir and influence fluid mobility. To carry out this work, we plan to extract and analyze curvature attribute maps of the porous Mississippian interval from the impedance volumes extracted from the pre-stack seismic data. The results of this work and the impedance inversion and spectral decomposition analyses will provide the framework for the reservoir model and production simulation studies of the field.

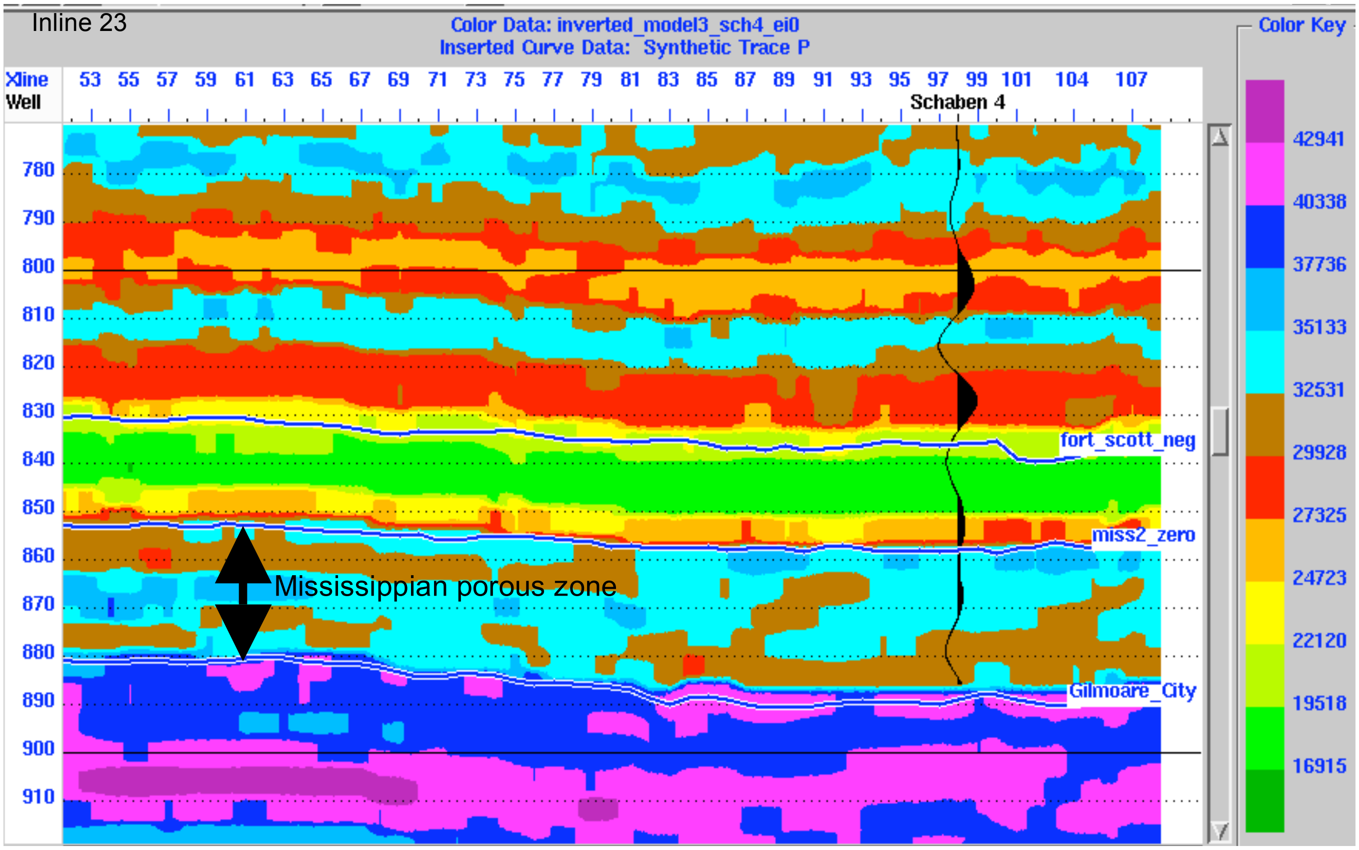

Figure 6. Dickman Field. Acoustic impedance inversion of full angle, pre-stack time migrated seismic volume correlated with a synthetic seismogram generated from a Schaben pseudo-sonic log (Faust transform of resistivity log). See Figure 3 for the location of profile in the survey.

Teapot Dome Field: Because of the graduations of student research assistants and a late disbursement of DOE funding for Fiscal Year 2, we suspended work to analyze further the relationships between attribute lineations, FMI and core-derived fracture interpretations and Tensleep productivity during this report period. We expect to continue this work during the next period.

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 phase of the study is to develop a well-constrained, dual-permeability reservoir model that will be suitable for fluid-flow simulation studies of the Tensleep and will demonstrate a seismic-based modeling process with wide applicability in a range of geologic settings. The actual reservoir simulation of production data is beyond the scope of this project.

Illinois Basin-Patoka and Sciota Fields: Work on Sciota and Patoka fields has been deferred pending completion of the migration of the pre-stack data at Patoka field. We plan to carry out impedance inversions of the data from both fields to determine if we can develop 3-D models of the porosity distribution of the Mt. Simon sandstone from the analysis of seismic attributes extracted from the inverted data volumes. Refer to **Task 2.2** above for the status of the reprocessing work on the pre-stack seismic data.

Task 4.0- Calibrate Seismic Attributes with Geological and Engineering Data

Dickman Field: We have deferred work on the integration of seismic and well data pending inversion of the pre-stack migrated data volume, which has just begun (Refer to **Task 3** above for the status of the inversion work).

Task 5.0-Validate Seismic Attribute Analyses Results

We have completed the reprocessing of the pre-stack seismic data for Dickman field (See **Subtask 2.2** above). Our sub-recipient, the Kansas Geological Survey, will carry out the major subtasks, which are to complete the construction of an integrated geomodel at Dickman field and to carry out a reservoir simulation of the field production history.

Subtask 5.1 Construct Integrated Geomodel of Dickman Field, Kansas

Our goal is to validate the results of seismic attribute analyses with a reservoir simulation of the pressure and production history of the field. A necessary requirement to achieve this goal is the construction of an integrated geomodel. The following summarizes our state-of-the-knowledge geomodel for Dickman field.

1. A small structural closure has localized an oil accumulation in the porous Mississippian dolomites, which has an OWC at about -1980 feet subsea and an oil column of about 35 feet.

2. The porous Mississippian saline aquifer underlying the oil accumulation ranges from 200 to 300 feet thick and is a CO2 sequestration target in the Mid-Continent area.

3. The contact between the porous Mississippian and the overlying seal (Pennsylvanian shale and conglomerates of the Cherokee Group) is a karst surface and a slight angular unconformity, which dips to the west.

4. Fractures in the porous Mississippian are aligned N45E and N45W, and the two fracture trends formed at different times. Geologic and production data suggest that the northeast-trending fractures are clay and silt-filled and closed while the northwest-trending fractures are open and form conduits for water to move from the underlying aquifer into the oil zone.

5. Basal Pennsylvanian conglomerates were deposited in the topographically low areas on the Mississippian unconformity. The distribution of the thickest conglomerates may correlate with the distribution of closed fractures.

Important missing pieces of the geomodel are the 3-D distributions of porosity and fractures in the porous Mississippian carbonates. To obtain the porosity distribution, we plan to correlate porosities derived from well logs with the seismic impedance data generated from the reprocessed seismic data. We plan to further assess our field fracture model with attribute maps extracted from the impedance volume of the entire survey area.

CONCLUSIONS

Dickman Field:

We have found that the areal energy distribution of low frequency spectra is different from that of the high frequency spectra. This work also strongly suggests that volumetric attribute maps of the distribution of low frequency energy might correlate with reservoir properties related to production.

COST STATUS

Baseline Costs Compared to Actual Incurred Costs

Oct 1- Dec 31	Plan	Costs	
Federal	$34,134	$11,814	$22,320
Non-Federal	$13,249	$0	$13,249
Total	$47,382	$11,814	$35,568

Table 1. Forecasted Cash Needs vs. Actual Incurred Costs

Analysis of Variance

The University of Houston received the delayed second increment of funding from the DOE during this reporting period. Because of the late receipt of the funding, UH was not able to add new staff to replace those lost to graduation, resulting in a net positive balance for federal costs. The KU Research Center, a cost share partner, has not submitted a cost share amount for the period, because of the resignation of their P.I. and a shortage of staff to work on the project. Continental Resources, our industry cost share partner, has replaced the staff lost during the past two years and should now be able to participant in the project in the future. We have scheduled a meeting in Oklahoma City on January 31, 2008 with Continental Resources, Inc. executives to identify areas for collaboration on this project.

MILESTONE PLAN AND STATUS

Critical Sub-Milestones for 2008

1. Complete pre-stack time migration of Patoka field seismic data by **April 30, 2008** (*Subtask 2.2)*.

2. Use Dickman field well log and core data to develop the reservoir property dataset (Sw and porosities) for calibration and validation of seismic attributes by **April 30, 2008,** (*Task 4.0*).

3. Calibrate seismic attributes with well data at Dickman field by **June 30, 2008** (*Task 4.0*).

Actual Progress Compared to Milestones

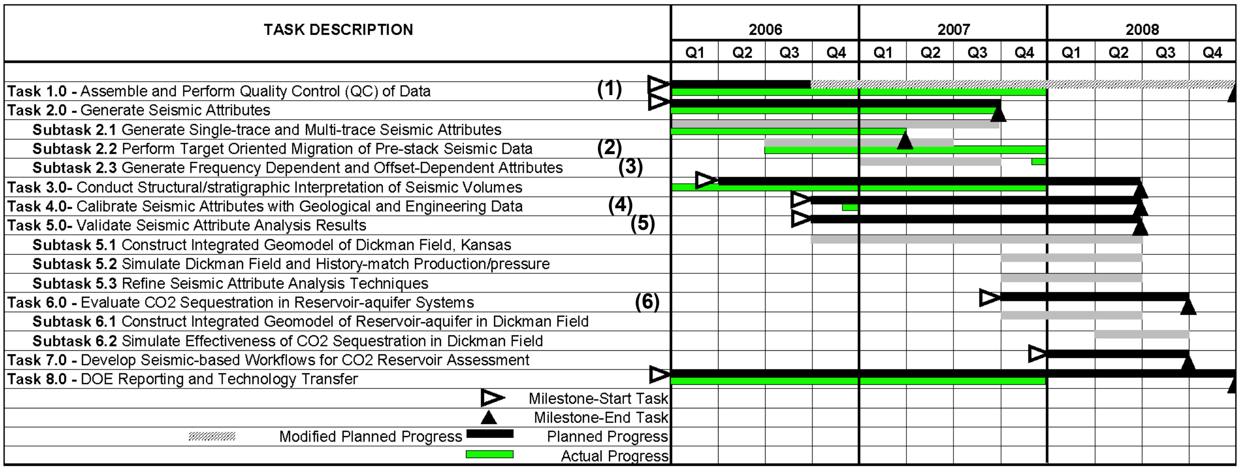

Table 2. Gantt chart

(1) QC of data will continue throughout project.
(2) Patoka migration delayed by noise problem
(3) Deferred pending evaluation of
(4) Further work deferred until next period.
(5) Deferred until next period.
(6) Deferred until next period.

SUMMARY OF SIGNIFICANT ACCOMPLISHMENTS

1. Using spectral decomposition at Dickman Field, we have found that the areal energy distribution of the low frequency spectra is different from that of the high frequency spectra. This work strongly suggests that volumetric attribute maps of the distribution of low frequency energy might correlate with reservoir properties that relate to production.

2. Using the Hampson-Russell program STRATA, we have generated both elastic impedance and acoustic impedance volumes from 0-10 degree and 20-30 degree offset angle stack gathers and a 0-45 degree full-stack gather at Dickman Field. By generating an acoustic impedance volume from full-stack data and elastic impedance volumes from near- and far-angle gathers, we hope to improve the 3-D predictability of the porosity, saturation and permeability trends in the Mississippian reservoir and aquifer.

ACTUAL OR ANTICIPATED PROBLEMS AND SIGNIFICANT EVENTS

1. The delay in receiving the second year DOE funding increment has adversely affected our ability to replace students who have graduated in a timely manner. During the next period, we will review the need to adjust project milestones to reflect the temporary cutback in research efforts due to lack of funding and staff.

2. We plan to meet with executives from Continental Resources, Inc., our industry partner, in Oklahoma City on January 31, 2008 to discuss collaboration on the

project. We are very hopeful that this meeting will lead to specific actions that will resolve the current shortfall in their cost share contributions.

3. Dr. Fred Hilterman has elected to step down as the Director of the Reservoir Quantification Laboratories at UH to become a Distinguished Research Professor at UH and Chief Scientist at GDC, a geophysical company. He will remain involved in the project work. Dr. Chris Liner will join the Geophysics faculty on January 15, 2008. He will become the new Director of the Reservoir Quantification Laboratories and Consortia. Dr Liner was a professor for fifteen years at the University of Tulsa before joining Saudi Aramco, where he has worked for the last three years.

4. Dr. Jianjun Zeng has joined the Department of Geosciences at UH as a Research Scientist to provide full time geologic and geophysical support for this project. Her previous position was Senior Geologist Consultant with CNOOC. Funding for this position will come from UH general funds.

TECHNOLOGY TRANSFER ACTIVITIES

We will make the results of the research available on the KU CO2 sequestration studies website and the CAGE website at UH. Several researchers plan to present the results of their work at professional meetings early in 2008.

CONTRIBUTORS

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