Funding opportunity number: ***DE-PS26-05NT42472-07***
Opportunity Title: **Support of Advanced Coal Research at U.S. Colleges and Universities**
Area of Interest: ***07- Advancements in Assessment of Geological Reservoirs for*** CO_2 ***Sequestration***

Core Program: ***Joint University/Industry Application***

Business Officer: ***Shaki Commissariat***

Principal Investigator: ***Fred Hilterman, Research Professor***
504 Science and Research Bldg 1
Department of Geosciences
University of Houston
Houston, TX 77204-5006
Tel.: 713-743-5802, Fax: 713-748-7906, E-mail: fhilterman@uh.edu

Co-PI:
Charlotte Sullivan, Research Assistant Professor, Visiting Assistant Professor
504 Science and Research Bldg 1
Department of Geosciences
University of Houston
Houston, TX 77204-5006
Tel.: 713-743-3415, Fax: 713-748-7906, E-mail:esulliva@mail.uh.edu

Title of Project: ***Application of cutting-edge 3-D seismic attribute technology to the assessment of geological reservoirs for*** CO_2 ***sequestration***

Date of Application: ***July 7, 2005***

Total Project Cost: ***$533,333***
DOE share: ***$400,000***
Applicant share: ***$133,333***

PROJECT NARRATIVE - TABLE OF CONTENTS

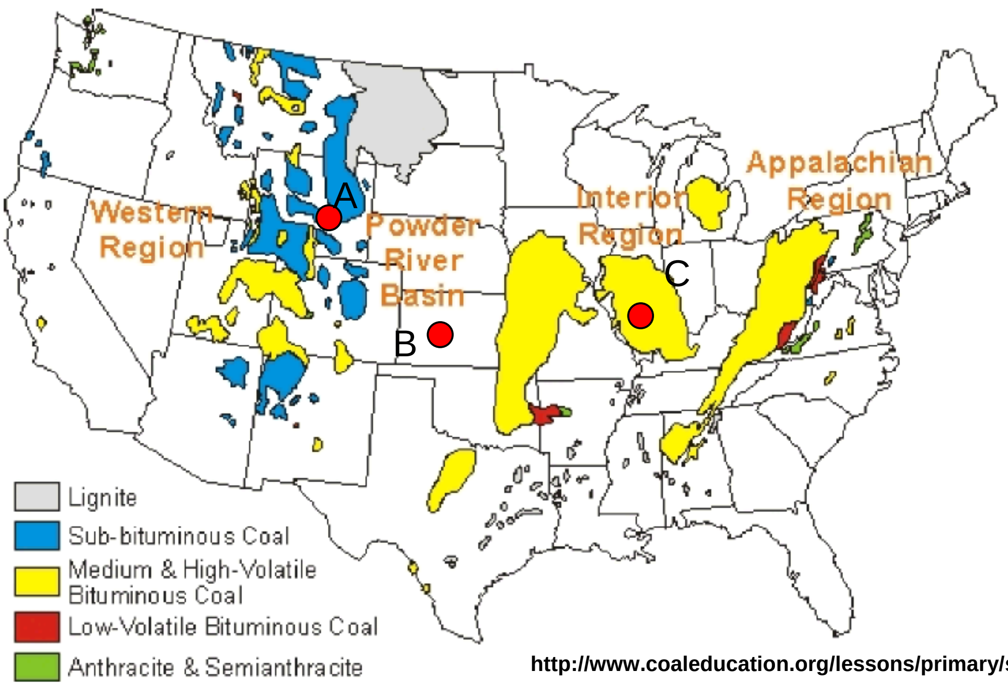
1.0 SCIENTIFIC OBJECTIVES

1.1 Project Objectives

Our ***aim*** is to develop innovative seismic technology and workflows that can be used to improve assessment of structural integrity and reservoir heterogeneity of geological reservoirs for CO_2 sequestration associated with coal-industry activities. Our selected seismic surveys emphasize onshore reservoirs in coal-producing or emission-producing regions (Wyoming, Kansas, Illinois, and Ohio) and represent a diversity of terrains, geology, lithologies, and porosity/permeability systems. Our ***specific objectives*** are to: 1) calibrate and test new frequency- and angle-dependent seismic attributes and novel target-oriented processing for the quantification of reservoir porosity, permeability, and saturations, 2) integrate new spectral decomposition and multi-trace seismic attributes to address special problems in imaging small scale structural and stratigraphic features in 3-D seismic from a range of geologic areas that form likely candidates for gigaton-scale CO_2 sequestration, and 3) validate attribute and processing results with field-based petrophysical and engineering data. Dickman Field, Ness County, Kansas will serve as a test bed for the evaluation of our attribute-based seismic technology. At this field, we will simulate a reservoir/aquifersystem to highlight the added value this study brings to the selection of candidates for CO_2 sequestration.

The new technologies and workflows that will result from this project have the potential to significantly reduce uncertainty in selecting reservoirs for large-scale geological carbon storage experiments, and to significantly expand the base of knowledge for evaluating geological reservoirs for CO_2 sequestration.

Coal Production in the USA -



http://www.coaleducation.org/lessons/primary/summary/coalpro.pdf

Figure 1. Location of 3-D seismic data available for this study. 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 within major saline aquifers. These data sets are: A) Teapot Dome, Wyoming, a major CO_2 study site for the DOE; B) Dickman Field, Kansas, within the multi-state, mid-continent saline aquifer; and C) Patoka Field, Illinois, in the Illinois Basin.

1.2 Merit Review Criteria Discussion: Core Program Joint University/Industry Application

1.2.1 Overall Merit of Proposed Project

Geological reservoirs and saline aquifers provide one of the most viable means of storage for thousands of gigatons of carbon in the form of CO_2 (Carr et al., 2003; Friedmann, 2003). The Western Interior Plains (WIP) aquifer system in Kansas alone has the potential to sequester hundreds of millions of metric tons of CO_2 (Nissen et al., 2004; Carr and Merriam, *in press*). Depleted oil and gas reservoirs have long been used to store natural gas (Dallbauman, 2004), and seismic technology and reservoir simulation are standard components for assessment of associated seals, reservoir heterogeneity and compartmentalization, and to quantify reservoir storage, saturations, deliverability, product loss, and the movement of fluids through time (Cole et al., 2002; Calvert, 2005). Compared with the storage of natural gas, the sequestration of very large quantities of CO_2 in reservoirs must additionally address differences in the behavior and trapping mechanisms of CO_2 in underground formations. These requirements demand more rigorous, seismic-scale quantification of seals, heterogeneity such as fractures, and matrix porosity, permeability and saturations, as well as the development of technology for more *quantitative* 4-D seismic monitoring of fluid movement and product loss (Hawkins, 2004; Gasperikova et al., 2004). In order to meet the goal of near zero coal-associated CO_2 emissions by 2015, there is an immediate need to improve seismic technology for application to large-scale CO_2 field experiments (Friedmann, 2003). This is most expeditiously achieved by the *adaptation of cutting edge, petroleum seismic technology to the specific needs of* CO_2 *sequestration.* There is broad recognition of the critical role seismic technology will have in the geologic storage of CO_2 (Calvert, 2004, 2004; Keach and McBride, 2004; Drahovzal and Harris, 2004), and numerical forward modeling of seismic data indicates that changes in seismic amplitude following CO_2 injection are different for supercritical and liquid phases and should be seismically detectable, given an adequate signal to noise ratio (Yuh and Gibson, 2001). Field applications of geophysical methods to CO_2 sequestration include experimental application of borehole geophysical methods, field-scale passive microseismicity, and *qualitative* seismic monitoring of fluid movement (Terrell et al., 2002; Raef et. al., 2004; Vasco, 2004). However, none of the current geophysical technologies addresses the proper scale of seismic *imaging* and seismic–guided *quantitative* geological assessment needed to sufficiently reduce uncertainties. ***Our proposed research addresses this problem.***

At the Center for Applied Geosciences and Energy (CAGE, which incorporates the Allied Geophysical, Reservoir Quantification, and Rock Properties Labs) at the University of Houston, we are, together with our colleagues at the Kansas Geological Survey (KGS) and elsewhere, developing *innovative breakthrough technology* for imaging of small scale reservoir architecture (Marfurt, 2005; Nissen et al., 2004; and Sullivan et al., 2005), and for *quantification* of saturations, porosity and permeability in hydrocarbon reservoirs (Hilterman and Liang, 2003; Hilterman and Van Schuyver, 2003; Goloshubin et al., 2005; and Zhou et al., 2005). For this proposed ***Core Program Joint University/Industry*** project, we have assembled a multi-disciplinary team of globally recognized reflection seismologists and industry-experienced petroleum geologists, and reservoir engineer, and augmented by talented graduate students who are uniquely qualified to transform state-of-the-art petroleum seismic technology into CO_2 sequestration technology. Our proposed research work has the potential to greatly accelerate the feasibility of large-scale CO_2 storage experiments by providing technology and workflows for reducing uncertainty and for improving confidence in the predictive models for gigaton-scale geological carbon sequestration.

Depleted reservoirs, salt domes, and saline formations are not the only candidates for benign, permanent carbon storage. There is also acute interest in the injection of CO_2 into coal beds that are not mineable, either as CO_2 sinks (Stricker, 2004) or in order to produce trapped methane (Figure 2). Two current projects at the University of Kansas involve experimentally studying the reservoir mechanisms and feasibility of subsurface processing of landfill gas (~ 45% CO_2 and 50% CH_4) and emissions from cement kilns (~ 50% CO_2 and 50% N_2) using coal seams to produce additional methane and, in exchange, sequester CO_2. Our seismic curvature technology is applicable to imaging of stratigraphic occurrences of mixed coal and sand as well as to imaging production-controlling, field-scale fracture systems of shale gas reservoirs (Hakami et al., 2004; Sullivan et al., 2004). Such black shale gas reservoirs may be capable of sequestering millions of tons of carbon per square kilometer in the Appalachian Basin (Nuttall, 2004; Nuttall et al., 2004), and in other foreland basins in the United States.

1.2.1.1 Scope of Work

In this section we cover the general scope of our proposed work, the state of the art for 3-D seismic attributes related to amplitudes, frequency and angle, and to multi-trace volumetric attributes. We then describe the relation of this seismic technology to assessing geologic reservoirs for CO_2 storage and to our approach to validate the attribute analysis through reservoir simulation.

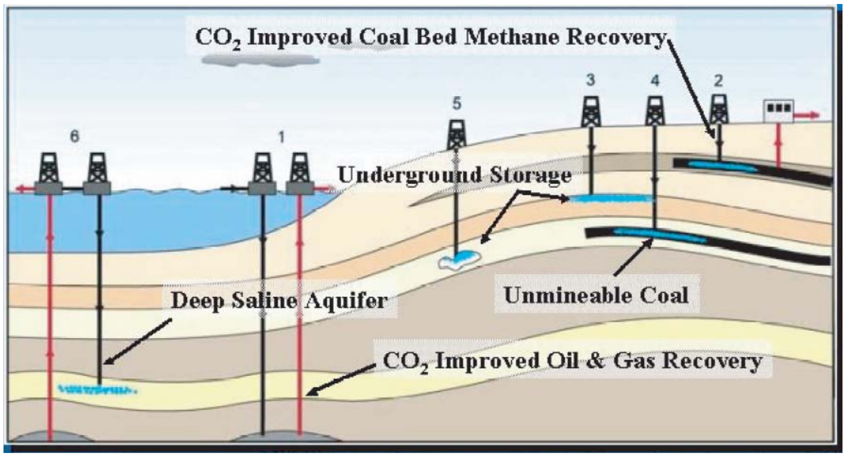


Figure 2. Geologic options for CO_2 sequestration. Our proposed technologies are applicable to all of these situations, but will target the largest groups of beneficiaries where point sources of CO_2 emissions are located proximal to oil and gas field activities. (From Riley et al., 2003, after http:/www.spacedaily.com.news/greenhouse-00j.html)

1.2.1.1.1General Scope

We will apply cutting-edge, seismic technologies discussed below to assess geological reservoirs for large scale CO_2 sequestration, and will calibrate our attribute models with geological and engineering data. We will then validate these technologies history matching production/pressure performance of a severely-depleted oil reservoir and its active aquifer, using industry standard simulators. Model discrepancies will be resolved by fine-tuning attribute analyses techniques. Reservoir-associated aquifers are a particularly attractive target for CO_2 sequestration (Carr et al., 2003), and the uniqueness of this project is that it offers a perfect opportunity to fine tune and validate the applicability of new 3D attribute analysis techniques to characterize a reservoir-aquifer system. The reservoir-aquifer model will be simulated in a compositional simulator to evaluate its potential for use as a CO2 sequestration site. Finally, we will summarize the knowledge gained from this study to develop practical workflows that can be applied to quantitatively assess candidates for large-scale CO_2 storage reservoirs.

1.2.1.1.2 State of the Art and Relation to Proposed Work

Recently acquired data from seismic field experiments and physical modeling exhibit amplitude losses that are dependent on the incident angle and frequency. The observed amplitude loss is explained by recent wave-propagation theory (Pride et al., 2003), which indicates that new frequency and angle dependent attributes are promising tools for more quantitatively imaging reservoir structure and estimating reservoir porosity and permeability. Physical, numerical, and field tests are being undertaken at the University of Houston to quantify these attributes. In addition to this cutting-edge research on frequency- and angle- dependent attributes, geophysical researchers at the University of Houston and the Kansas Geological Survey have recently developed, calibrated, and validated multi-trace geometric and other seismic attributes that greatly enhance detection and resolution of small features, previously considered to be subseismic. ***In this project, we propose to apply these innovative petroleum industry technologies to the geologic sequestration of CO_2, and to validate this approach through simulation of a severely depleted water-drive oil reservoir, and separately simulating the potential for CO_2 injection into the reservoir/ aquifer system, using simulation parameters generated by our new seismic attributes.***

1.2.1.1.3 Frequency and Angle-Dependent Attributes

Numerous laboratory and field examples show superior reservoir imaging capabilities with **low-frequency seismic components** that are normally filtered out in conventional data processing. Physical modeling experiments (Goloshubin et al., 2002), using three different portions of a sandstone layer saturated with different fluids verify this phenomenon, as shown in Figure 3. The oil-saturated part is more visible at very low (~5 kHz) frequencies, whereas water- and air-saturated parts are well detected at 15 kHz and 50 kHz, respectively. These observations cannot be explained by tuning effects.

The experiments of Goloshubin et al. (2002) have been verified by multiple field tests, where hydrocarbon zones were undetected with conventional seismic but were identified using analysis of low frequency data (Figure 4). The low value of the quality factor *Q* for the low frequency waves is a characteristic feature of the permeable fluid-bearing layers (Korneev et al., 2004).

Korneev et al. (2004) and Goloshubin et al. (2001) analyzed VSP data recorded at a natural gas storage field in Indiana. Due to gas injection in the summer and withdrawal in the winter, the reservoir fluid changed seasonally (Daley et al., 2000). At low frequencies, a water-saturation signature was distinguished from the gas-saturation signature (Figure 5a). *These observations have important implications for monitoring fluid movement in CO_2 storage reservoirs*.

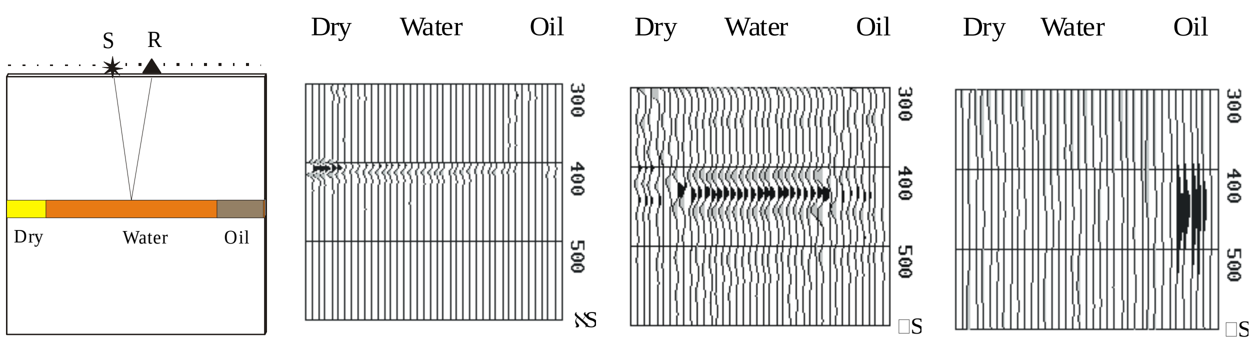
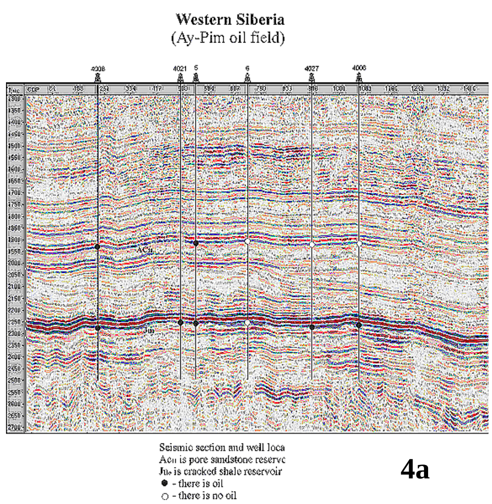


Figure 3. Physical modeling experimental setup (left panel) for porous layer with different fluid content (air, water, oil) and common offset gather images of reflection from the layer at different frequencies (from Goloshubin et al., 2002). The reflection for liquid-saturated layer dominates at low frequencies with an increasing phase delay.

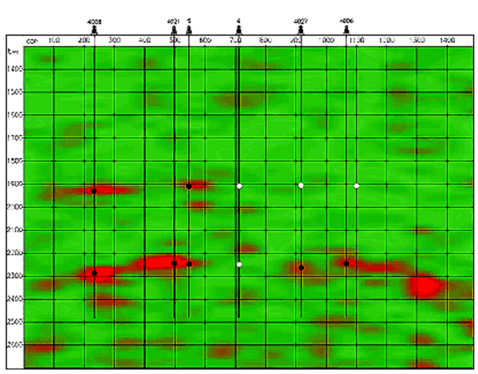
The fact that reflection, transmission, and attenuation in fluid-saturated solids are frequency-dependent has been discussed in the literature (Geertsma and Smith, 1961; Dutta and Ode, 1983; Santos et al., 1992; Denneman et al., 2002; Pride et al., 2003). Castagna et al. (2003) report “low-frequency shadows” associated with hydrocarbons. We admit that this can be an artifact of the numerical data processing, but we note that such late arrivals of the low-frequency reflected signal are consistent with the results shown in Figure 3. In addition, *low-frequency signal can be introduced by the heterogeneity of the reservoir and thus can be assessed as a means of measuring the integrity of geological reservoirs for CO_2 sequestration*

A summary of our findings on frequency dependent attributes is as follows:

1. The reflection coefficient from a plane interface between dry and fluid-saturated rocks is both frequency- and angle- dependent.
2. At low frequencies, the reflection coefficient has an explicit expression of frequency. In particular, this means that the reservoir fluid flow properties can be evaluated based on analysis of the reflection signal. The most productive reservoir zones can be accurately mapped with the new method proposed here.



4a



4b

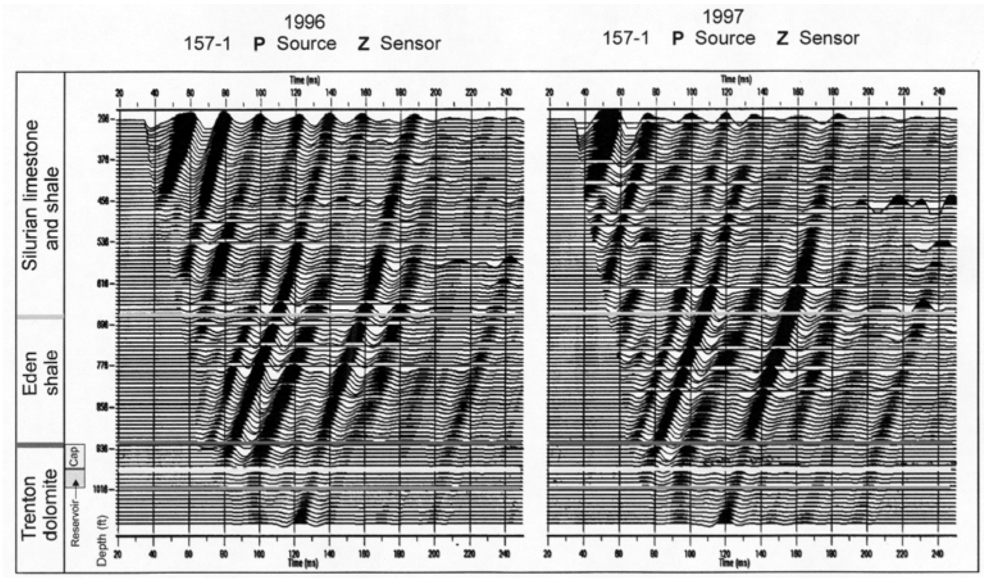
Figure 4. A seismic line from Ay-Pim Western Siberia oil field was used to image two different types of oil-saturated reservoirs. The well data indicate that the upper reservoir AC11 consist of an 11-15 m thick sandstone with varying fluid content. The lower reservoir Ju0 is represented by 15-20 m thick fractured shale. There is no evident correlation between well content and high frequency standard seismic imaging (a). In contrast, the oil-saturated domains of both the sandstone reservoir AC11 and fractured shale reservoir Ju0 create high amplitude low-frequency (<15 Hz) reflections (b). The data for processing and analysis are courtesy of Surgutneftegas

3. The proposed theory explains the results obtained in the frequency-dependent analysis of field and laboratory data (Goloshubin *et. al.*, 1996, 2002; Goloshubin and Bakulin, 1998; Goloshubin and Korneev, 2000; Korneev *et. al.*, 2004).
4. The relaxation time is closely related to the tortuosity factor. The values of tortuosity reported in the literature range from one to infinity (Molotkov, 1999). A rock/fluid classification by the respective characteristic values of the relaxation times and tortuosity can enhance the high-quality delineation of saturations and fluid movement. Recent advances in the modeling of fluid flow at a microscopic scale (Silin, et al., 2003) show how to estimate the tortuosity factor for different types of rocks *and* different depositional processes.
5. The proposed new imaging technology can be used for tracking propagation of injected fluid and for investigation of cap rock integrity in CO_2 geologic sequestration projects.

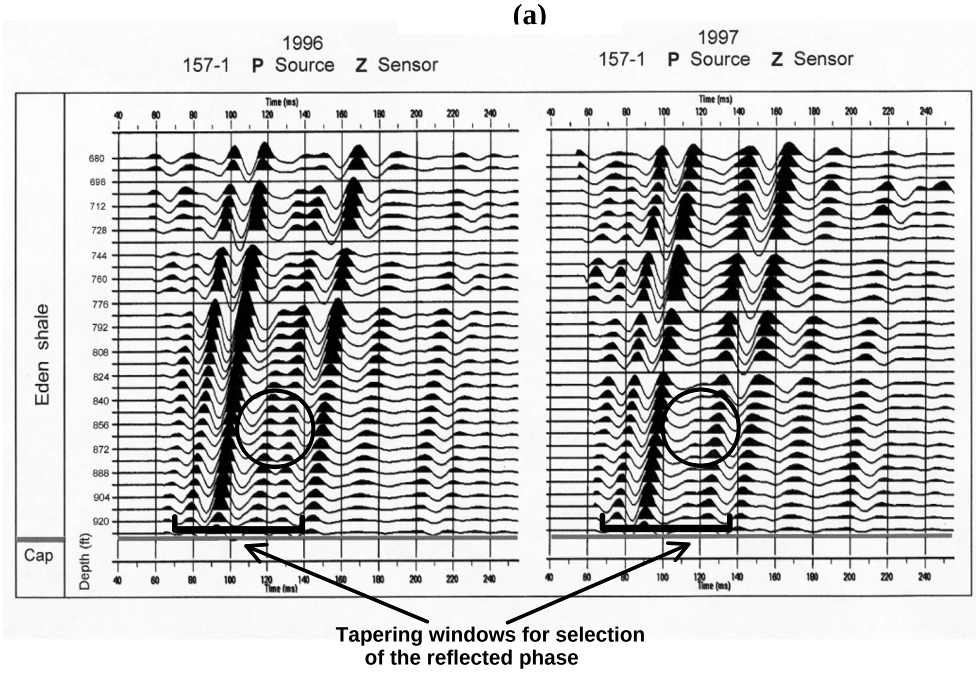
Target-Oriented Processing for Frequency- and Angle Dependent Attributes

The calibration of seismic frequency-dependent reflectivity measurements to reservoir properties is based on the assumption that robust amplitudes are obtained for individual frequency components of the propagating wavelet. However, the frequency content of the seismic wavelet is distorted by conventional data processing with normal move out (NMO) providing the most significant distortion. With the introduction of anisotropic NMO processing, the wavelet frequency content on the very far-offset trace can be almost one-half that of the normal-incident wavelet. This is not an acceptable condition when calibrating loss mechanisms to reservoir properties as a function of frequency. Hilterman and Van Schuyver (2003) developed a processing technique that does migration without NMO corrections, followed by a target-oriented NMO correction. The common depth point (CDP) gather on the right side of Figure 6 illustrates the retention of wavelet frequency when target-oriented processing is applied.

In addition to preservation of frequency, the quality of the seismic image is improved significantly with target-oriented processing. Our studies show that that NMO stretch needs to be addressed for quantitative analyses of amplitudes as a function of frequency.



(a)



(b)

Figure 5. Upgoing wave fields (a) for 1996 (left) and (b) 1997 (right) reveal the low-frequency changes in reflections from the Trenton dolomite at a gas storage facility in Indiana. The zoomed section (b) shows the reflections from the reservoir. Changes are clearly visible in the circled area.

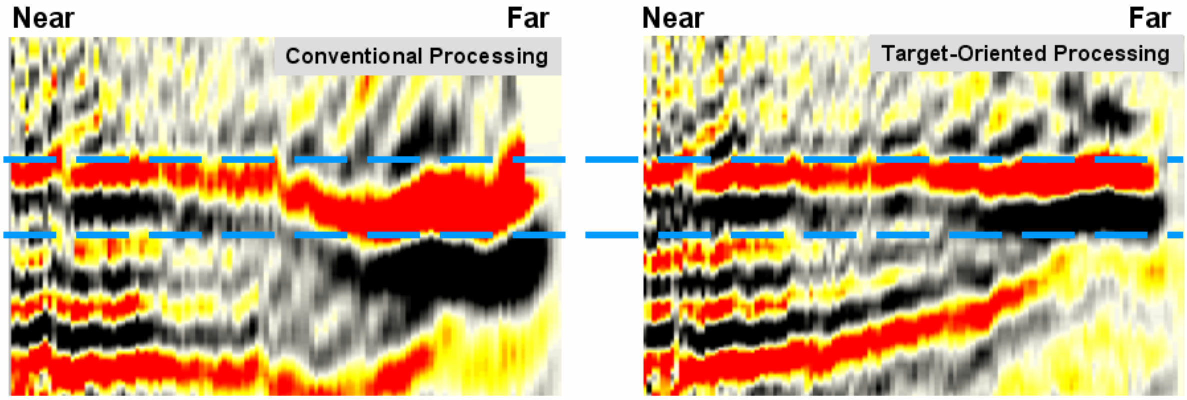


Figure 6. CMP gathers illustrating target-oriented processing (right side) versus conventional processing. In contrast to the results of conventional processing, the frequency content of the propagating wavelet within the dashed target interval is not distorted by target-oriented processing.

1.2.1.1.4 Multi-trace Geometric Attributes and Spectral Decomposition

In contrast to conventional amplitude extractions, geometric (also called **multi-trace**) attributes are a direct measure of *changes in seismic texture*. Modern multi-trace geometric attributes facilitate the recognition of irregular geologic features by avoiding the need to pre-interpret horizons and by enhancing subseismic lateral variations in reflectivity. Geometric attributes include the well-established coherence measures, coupled with recent developments in spectrally limited estimates of volumetric curvature and coherent energy gradients. Coherence measures the lateral changes in waveform, and as such is often sensitive to small faults and differential pressure and to lateral changes in stratigraphy, such as channels and sinkholes. Components of reflector curvature, including the most negative, most positive, Gaussian curvature and related shape indices, are complimentary to coherence measures.

A mathematically independent measure of tuning is through **spectral decomposition**, originally presented by Partyka et al. (1999). As with the recently introduced SPICE algorithm (Liner et al., 2004), spectral decomposition is sensitive to lateral changes in reflectivity, but is designed to enhance *vertical* changes in reflectivity. Geometric attributes and spectral decomposition are powerful tools that can accelerate the interpretation of very large seismic volumes as well as greatly aid imaging and interpretation of small-scale or subtle reservoir features.

Recent AGL volumetric attribute work in black shales and carbonates of the Fort Worth Basin has made significant breakthroughs in imaging small scale features including: the importance of azimuthally limiting seismic volumes to improve lateral resolution (Jyosyula et al, 2003; Jyosyula, 2004); the sensitivity of newly developed volumetric curvature attributes to delineate cracks and flexures that fall below traditional understanding of seismic resolution (al-Dossary et al., 2004); as well as improvements in signal-to-noise ratios through enhanced structure oriented filtering of seismic data (Marfurt, 2005) and crack-preserving smoothing of dip/azimuth volumes (al-Dossary and Marfurt, 2003). In studies of reservoirs on the Central Basin Platform of West Texas, Blumentritt et al. (2003) and Serrano et al. (2003) demonstrated the relation between models explaining stresses associated with polyphase deformation and the lineaments in curvature volumes. Other recent applications of multi- trace geometric attributes to image and map previously subseismic features include prediction of azimuth of greatest probability of open fractures (Figure 9) and non sealing faults (Nissen et al., 2004), and the discrimination between karst and tectonic collapse features (Sullivan et al., 2005).

Although reflector curvature calculated from outcrop and from discrete interpreted seismic horizons is well correlated to fracture intensity (Lisle, 1994; Hart, et al., 2002; Roberts, 2001; Stewart and Wynn, 2002, and Bergbauer et al., 2003), the AGL researchers appear to be the first to publish and calibrate curvature for 3-D data volumes. This methodology provides, for the first time, a method of imaging curvature of irregular seismic events and avoiding errors associated with manual picking of low amplitude, discontinuous reflectors. *These attributes have the potential to image features related to fractures and non-sealing faults that may compromise seal integrity of CO_2 storage reservoirs, but which cannot be detected with other methods.* In addition, volume-based estimates are of particular value for interpreting reservoir heterogeneity that has low signal-to-noise ratios. This type of heterogeneity occurs in the mixed coal-sand lithologies of many areas that are candidates for geologic sequestration of CO_2.

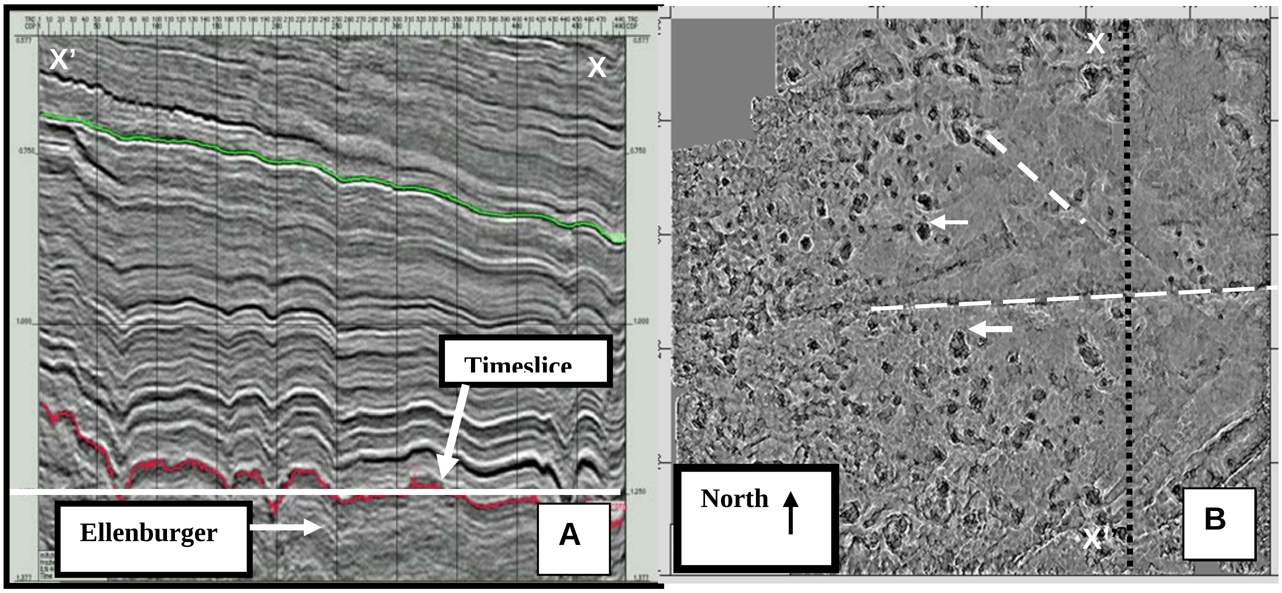
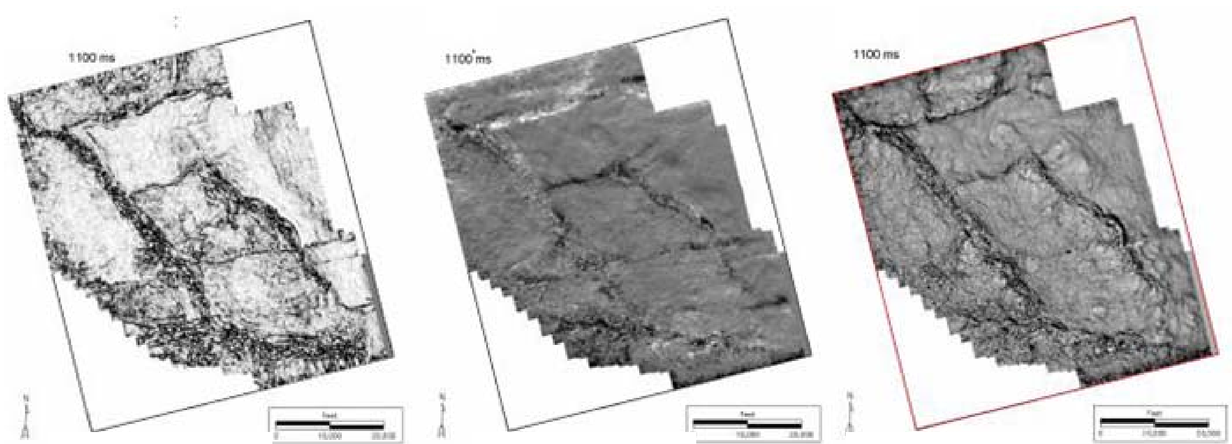


Figure 7. Conventional vertical section (A) and time slice through multi-trace mean curvature attribute volume (B) from the Fort Worth Basin. Note the chaotic nature of the reflectors in the conventional section. In contrast, in the curvature image, the well-organized dark circular areas (white arrows in B) are sinkhole-like karst features in the Ordovician Ellenburger. Well-imaged lineaments associated with faults and fractures (dashed white lines) that cut both the Ellenburger and the overlying shale gas reservoir are also visible in the attribute time slice. Vertical seismic section is along dashed line X-X' in Figure 7B. Field of view is approximately 23 km in both images. After Sullivan, et al., 2003.



8A **8B** **8A**

Figure 8. Comparison of three different attribute volumes from a single 3-D survey. 8A is the Principal Component Coherency with Edge Preserving smoothing; 8B is an inline dip derived attribute, and 8C is the Most Negative Curvature. These attributes are independent of each other but are coupled through the geology. Each attribute shows subtle features that may not be obvious in other volumes. East-west field of view is about 14 km. Data courtesy of Oxy Permian.

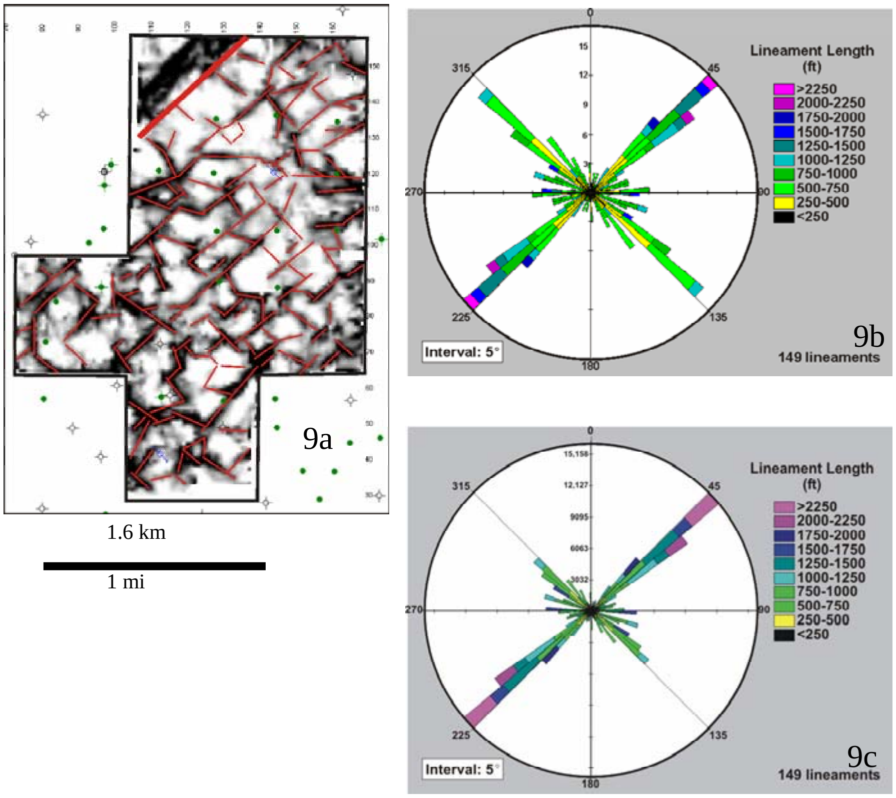


Figure 9. Interpretation of seismic lineaments in the Most Negative curvature volume along the base of the Dickman Kansas Mississippian aquifer, which is a regional potential CO_2 sequestration reservoir. Rose diagrams show (b) frequency (number of lineaments) vs. azimuth and (c) length of all lineaments vs. azimuth. Correlations between fluid production and distance to lineaments with the two major trends (northeast and northwest) show that the northeast-trending lineaments represent barriers to fluid flow and that the northwest-trending lineaments represent open faults and joints. (After Nissen et al., 2004).

1.2.1.1.5 Approach

Our approach to adapting high resolution 3-D seismic attribute technology to the assessment of CO_2 reservoirs *involves academic researchers, teaching professors, graduate students, and industry advisors.* We will conduct attribute analysis of seismic volumes *from three selected sites* across the continental United States. These sites represent unique data sets for addressing discrete issues.

Teapot Dome, north of Casper, Wyoming, is operated by **DOE as the Naval Petroleum Reserve #3 and the Rocky Mountain Oilfield Testing Center (RMOTC)**. The field has a recent (2000) vintage 3-D survey and contains over 1600 wells, with a large volume of supporting rock, log and engineering data. The field has multiple hydrocarbon bearing zones and multiple aquifers, steeply dipping beds, complicated fault systems, and over 100 years of production data, including production from steam and water floods (Freidmann, 2003). The data from this field will be especially valuable in calibrating seismic attributes.

Patoka Field, in the Illinois Basin, contains about 8 square miles of 3-D seismic and contains both depleted reservoirs and the Mt Simon saline aquifer, which is a potential regional target for CO_2 sequestration. There are abundant well and engineering data from this field, and our industrial partner, **Continental Resources of Illinois, Inc.,** will closely work with us on evaluating and calibrating seismic attributes in this field.

Dickman Field, Ness County, Kansas will serve as a test bed for the evaluation of our attribute-based seismic technology. At the height of its production, the field consisted of 11 producing wells. Detailed oil and water production records have been maintained providing adequate information for reservoir simulation. DST (drill stem test) data extending from early 1960s to date clearly show that the reservoir has produced under an active water drive with average reservoir pressure hovering above 1200 psi. Preliminary multi-trace attribute work on the field confirms the utility of volumetric curvature to map lineaments that, when correlated to production, separate azimuths of sealing faults from water conduits (Nissen et al., 2004). We will build a static reservoir model (geomodel) for all four study areas, but at Dickman field, we will also build and populate a dynamic reservoir model and will carry our work through to reservoir simulation. This will allow us to evaluate the ability of our attributes to accurately predict reservoir parameters to evaluate candidate reservoirs particularly severely depleted oil fields that produce under active water drives, for sequestering CO_2.

1.2.1.1.6 Relation of Improved Seismic Attribute Analysis to Modeling Reservoir-Aquifer Systems

Important petrophysical properties that affect fluid flow in the reservoir include porosity, permeability, thickness, and heterogeneities such as fractures. Fracture properties such as orientation, permeability, and distribution are critical to determining fluid flow. However, fracture characterization is frequently based on analog outcrops, or on reservoirs where *in situ* stress measurements are absent, and core data is limited. Porosity and permeability maps may be available for the reservoir, but are less reliable in the aquifer. Because aquifers are seldom drilled intentionally, there is generally limited logs/cores data available with which to model the aquifer with any degree of precision. To evaluate the potential of aquifers to sequester, one needs to have a good understanding of aquifer petrophysical properties, and this is where the application of advanced 3D attribute analysis is expected to deliver dividends.

Without having to drill any additional expensive deep wells into the aquifer, 3-D seismic data provides a spatial distribution of rock properties over its area of coverage. Application of newly developed attributes is expected not only to characterize fractures better in a reservoir-aquifer system but also better estimate the distribution of porosity and permeability in both the reservoir and the underlying aquifer.

This project offers a perfect opportunity to fine tune and validate the applicability of new 3-D attribute analysis techniques to the assessment of a regional reservoir-aquifer system. We will apply attribute analysis to map porosity, permeability, thickness, and fracture properties in the reservoir interval, and will compare these data to reservoir properties from logs and cores. We will validate the hydrocarbon reservoir model, including fracture characterization, developed from attribute analysis, by simulating the production/pressure histories of the producing wells. Discrepanies between simulation results and pressure/production histories will be addressed by fine-tuning the techniques for attribute analyses to build a consistent geo-model for the reservoir-aquifer system. Finally, this model will be simulated to study the effectiveness of CO2 sequestration.

1.2.3 Qualifications of Principle Investigators and Key Personnel

Dr. Fred Hilterman, **project PI** is a professor at the Department of Geosciences at University of Houston, is Director of the RQL geophysical consortium, and teaches a variety of graduate geophysics courses. Fred has over 40 years experience in seismic R&D and management, and is internationally acclaimed for his role in using seismic technology to better quantify reservoir properties.

Charlotte Sullivan, project Co-PI, **and project manager**, is a research assistant professor and visiting assistant professor, with over 25 years international and domestic industry experience in hydrocarbon exploration and development, including planning and implementing waterfloods and CO_2 floods . She teaches three geology courses and conducts research in stratigraphy and calibration of seismic attributes.

Kurt Marfurt, professor, and Director of the U of H Allied Geophysical Labs, has 20 years petroleum industry experience and 10 years academic experience. He is co-inventor of coherency, spectral decomposition, and is the first geophysicist to publish multi-trace geometric seismic attributes. He is currently expanding his attribute technology to prestack data volumes with the goal of better delineating fractures and illuminating subtle changes in lithology in the common azimuth and common offset domains.

Susan Nissen, who will **manage the KGS project team**, is a geophysicist with 14 years of petroleum-related research experience. She led a seismic attributes development team while a research scientist at Amoco and has been involved in 2-D and 3-D seismic interpretation and attribute analysis in Kansas for the past five years, since joining the Energy Research Section at the KGS. She is currently the PI of DOE project DE-FC26-04NT15504, which tests seismic attributes for the improvement of reservoir characterization of fractured and karst-modified reservoirs.

Saibal Bhattacharya is a Petroleum Engineer with 11 years of reservoir engineering experience that includes field operations and integrated field studies. He is currently the PI of DOE's PUMP (Preferred Upstream Management Practices) project DE-PS26-00BC15304.

Timothy R. Carr is Co-Director of the University of the Kansas Energy Research Center, Chief of Energy Research at the Kansas Geologic Survey, and adjunct teaching Professor of Geology at the University of Kansas. He is a contributor to Interstate Oil and Gas Compact Commissions report on regulatory aspects of carbon capture and storage, and is the Principal Investigator for developing a distributed NATional CARBon Sequestration Database and Geographic Information System (NATCARB) (http://www.natcarb.org). He is also the author of numerous papers on CO_2 sequestration.

1.3 Relevance and Outcomes/Impacts

Our teams at the University of Houston and at the University of Kansas have the expertise and resources to develop and calibrate the proposed new technologies, to test them through reservoir characterization workflows and reservoir simulation, and to generate a standard toolbox of technologies for the rigorous assessment of CO_2 reservoir architecture and petrophysical parameters. The seismic tools and methodologies to be developed and calibrated in this project are based on conventional P-wave data; and are designed to be appropriate for large and small companies, and consultants.

An important component of our project is to perform advanced technology reservoir simulations of CO_2 injection in the Dickman field, in Kansas. This field is one of many depleted oil reservoirs in the mid continent, and is also associated with the Mississippian saline aquifer unit of the Western Interior Plains aquifer system, one of the largest regional-scale saline aquifer systems in North America (Jorgensen et al., 1993; Carr and Merriam, *in press*). The hydrocarbon reservoir simulations we undertake will include history matching of the reservoir, as well as predicted response to CO_2 injection into the reservoir and separately, into the underlying aquifer. Many carbonate aquifers, including the Mississippian saline unit, are karsted. In preliminary work on Dickman field, Nissen et al. (2004) showed the utility of multi-trace curvature attributes in seismically mapping karst-enhanced fractures, and presented methods for distinguishing probable fluid conduits from fluid barriers. The proposed simulations of this specific reservoir and the underlying aquifer in regard to geologic architecture, hydrologic conditions and processes will provide additional insight into assessing the WIP aquifer system for CO_2 sequestration potential.

This work is directly relevant to the objectives of the DOE/ NETL University Coal Research Program. In addition to highlighting concerns of the coal industry to environmental issues, and to providing graduate students opportunities to be more involved in the coal industry, the application of our new attribute technology to the imaging and assessment of CO_2 sequestration in oil reservoirs has the potential to overcome previous barriers in technology development that to date have hindered large-scale CO_2 sequestration experiments. Our toolbox of technologies and workflows will accelerate the identification of solutions for coal-related energy and environmental problems, and will target a large community of beneficiaries, particularly in geographical areas where producers of hydrocarbons and coal-fired electricity are in close proximity. In those areas, such as the Illinois and Appalachian Basins, coal and hydrocarbon producers may both benefit from the attribute-based evaluation of a single, shared cost, 3-D survey. For the hydrocarbon producer, these benefits may include identifying reservoir compartmentalization with by-passed pay, or constructing a seismic based reservoir model that forms the basis for an energy efficient CO_2 flood. The coal producer or large-scale coal consumer may benefit from use of the same survey for assessment of saline aquifers and depleted reservoirs for CO_2 sequestration. Because enormous volumes of CO_2 are estimated to be sequestered in depleted oil reservoirs, and especially in black shales (Nuttall, 2004) and in saline formations (Car, et al., 2004), we feel the results of our proposed research will play a critical role towards achieving nearly total carbon closure by the year 2015. The 4-D monitoring of large CO_2 reservoirs is becoming increasingly economic, with the development of in-place sources and receivers (Meuneir et al., 2000), and we feel that our proposed research can play a crucial role in this future direction.

1.4 Project Timetable

In support of this proposed DOE /NETL project we have designed a **plan of work that assures a high probability of achieving our objectives by 1) having clear objectives that address a well defined problem, 2) combining an expert team with appropriate data, 3) having realistic tasks and timetables, and by 4) building on scientifically sound, current technology.** Our project timetable is organized around the completion of eight major tasks as listed below and shown in Figure 10.

- **Task 1.0 Assemble and QC data**
- **Task 2.0 Generate seismic attributes**
  - **Task 2.1 Generate single-trace and multi-trace seismic attributes**
  - **Task 2.2 Perform target oriented migration of pre-stack seismic data**
  - **Task 2.3 Generate frequency dependent and offset-dependent attributes**
- **Task 3.0 Conduct structural/stratigraphic interpretation of seismic volumes**
- **Task 4.0 Calibrate seismic attributes with geological and engineering data**
- **Task 5.0 Validate seismic attribute analysis results**
  - **Task 5.1 Construct integrated geomodel of Dickman Field, Kansas.**
  - **Task 5.2 Simulate Dickman Field. History-match production/pressure**
  - **Task 5.3 Refine seismic attribute analysis techniques**
- **Task 6.0 Evaluate CO2 sequestration in reservoir-aquifer systems**
  - **Task 6.1 Refinet integrated geomodel of reservoir-aquifer system in Dickman Field**
  - **Task 6.2 Simulate effectiveness of CO2 sequestration in Dickman Field**
- **Task 7.0 Develop workflows to evaluate depleted oil reservoirs for CO2 sequestration**
- **Task 8.0 DOE reporting and technology transfer**

In the first year we address **Tasks 1.0- 5.1**, as well as **Task 8.0.** We start our project by assembling and loading into workstations, the data sets for each study area. These data sets include 3-D seismic volumes, production, petrophysical, and engineering data. Currently we have, in-house, 3-D post-stack seismic for all study areas, as well as pre-stack data from Teapot Dome, Wyoming, and from Patoka, Illinois. We will generate seismic attributes **(Task 2.0)**, including single-trace and multi-trace attributes (**Task 2.1**). We will perform Target-Oriented Migration (TOM) on pre-stack data (**Task 2.2**), and will then generate frequency-dependent and offset- dependent attributes (**Task 2.3**). We will experimentally generate multi-trace attributes on a Target-Oriented Migration volume. We will start **Task 3.0** (attribute-guided interpretation of structural and stratigraphic features) for each data set. During the last quarter of 2006, we will begin calibration of our attributes (**Task 4.0**) with geological and engineering data, and initiate the task of validating our attributes (**Task 5.0**) through the construction of an integrated geomodel of the severely depleted hydrocarbon reservoir at Dickman Field, Kansas (**Task 5.1**). In addition, we will compile and submit a midyear and end-of-year progress report to the DOE **(Task 8.0),** and will begin technology transfer with technical presentations of our findings.

In year 2, we focus on the calibration of seismic attributes (**Task 4.0**) with a wide variety of geologic and engineering and on the validation of the results of our seismic attribute analyses (**Task 5**). We will construct a seismic-based static reservoir framework (geomodel) for each study site as a continuation of our structural and stratigraphic interpretation (**Task 3.0**), and will populate the geomodels with reservoir parameters derived from multi-trace attributes, frequency-and angle- dependent attributes, petrophysical log, core, electrical image log, tracer, pressure, microseismic and other available data**.** This is expected to occupy two graduate students for most of the year. We will address the Kansas Dickman survey first, and will upscale various petrophysical parameters (thickness, porosity, permeability, and saturation distributions) of the static geomodel to build an integrated and consistent geomodel (**Task 5.1**). In the fourth quarter of year 2, we will simulate of the hydrocarbon reservoir at Dickman field, matching available production and pressure histories (**Task 5.2**). Discrepancies between the results of the attribute analysis, log/core analysis, and reservoir simulation results will be resolved by refining the attribute analysis techniques (**Task 5.3**). We will correlate details of our reservoir simulation with results of our attribute analyses to evaluate CO_2 sequestration in the active aquifer that forms the free water level below the producing reservoir (**Task 6.0**). Water-charged depleted reservoirs are important prospective sinks to sequester CO_2. However, current techniques in characterization and modeling reservoir-aquifer systems using wireline logs and core data may not always capture *in situ* heterogeneity due to presence of fracture networks. The use of aquifers associated with hydrocarbon reservoirs for CO_2 sequestration is fraught

APPLICATION OF CUTTING-EDGE 3-D SEISMIC ATTRIBUTE TECHNOLOGY
TO THE ASSESSMENT OF GEOLOGICAL RESERVOIRS FOR CO2 SEQUESTRATION

Project Schedule

Task Description	FY06				FY07				FY08			
	Jan 06	Apr 06	Jul 06	Oct 06	Jan 07	Apr 07	Jul 07	Oct 07	Jan 08	Apr 08	Jul 08	Oct 08
Task 1.0 Assemble and QC data												
Task 2.0 Generate seismic attributes												
Task 2.1 Generate single-trace and multi-trace seismic attributes												
Task 2.2 Perform target oriented migration of pre-stack seismic data												
Task 2.3 Generate frequency-dependent and offset-dependent attributes												
Task 3.0 Conduct structural/stratigraphic interpretation of seismic volumes												
Task 4.0 Calibrate seismic attributes with geological and engineering data												
Task 5.0 Validate seismic attribute analysis results												
Task 5.1 Construct integrated geomodel of Dickman Field, KS												
Task 5.2 Simulate Dickman field - history match production/pressure												
Task 5.3 Refine seismic attribute analysis techniques												
Task 6.0 Evaluate CO2 sequestration in reservoir-aquifer systems												
Task 6.1 Construct integrated geomodel of reservoir-aquifer system in Dickman field												
Task 6.2 Simulate effectiveness of CO2 sequestration in Dickman field												
Task 7.0 Develop seismic-based workflows for CO2 reservoir assesment												
Task 8.0 DOE reporting and technology transfer												

Figure 10. Project timetable, showing scheduled tasks and subtasks in relation to the life of the project. There is no field component to this project and all listed tasks will be complete by the end of Fiscal Year Three. Technology transfer and reporting continue throughout the life of the project, and we anticipate that we will continue to publish results and implications of this work after the end of the third year.

with risks, particularly in settings where the *in situ* fracture system is left out of the model because of inherent limitations of conventional modeling. This part of the project will help confirm the role of advanced attribute analysis to confirm the presence or absence of fracture systems in any sequestration candidate. Such confirmation will go a long way in reducing risks associated with CO_2 sequestration projects in oil reservoirs. After validating the attribute analysis techniques by modeling the hydrocarbon reservoir, the same techniques will be employed to model the reservoir-aquifer system (**Task 6.1**). Such a model will, for the first time, indicate the presence or absence of fractures in the aquifer and also provide a spatial distribution of porosity and permeability that will increase the accuracy of fluid flow modeling. In addition, we will compile and submit a second year midyear and end of year progress report to the DOE, and will continue to present the results of our work to a variety of audiences (**Task 8.0**)

In year 3, we will finish tasks that are related to refining and validating our reservoir models (**Tasks 3-5**) and perform reservoir simulation on the active saline aquifer associated with the Dickman oil reservoir (**Task 6.0**). We will finish development of an integrated geomodel of the reservoir-aquifer system (**Task 6.1)** and will then simulate injection of CO_2 into the reservoir-aquifer system to evaluate the effectiveness of CO_2 sequestration in water-driven depleted oil fields (**Task 6.2**). CMG's compositional simulation GEM will be used to evaluate CO_2 sequestration potential. Important questions that will be addressed in **Task 6.2** include:

a) How much CO_2 can be sequestered in the aquifer given that some of the injected gas will dissolve in the aquifer water and some will displace the water around the well to irreducible water saturation (Swi)? The colume available to sequester CO_2 in the aquifer is (1-Swi). Also, some CO_2 is expected to be dissolved in the water at the given reservoir pressure, temperature, salinity, and oil composition.

b) How much CO_2 can be sequestered in the reservoir given that some of the injected gas will dissolve in the remaining oil saturation thus swelling the oil, and some will displace the surrounding water saturation to limits of irreducible saturations? The volume available to sequester CO_2in the reservoir is (1-Swi-Sorw) times the pore volume, where Sorw is residual oil saturation. Thus per unit pore volume, the amount of CO_2 that can be sequestered in the reservoir is less than that in the aquifer. On the other hand, CO_2 solubility in residual oil in the reservoir is far greater than aquifer water providing additional storage capacity. However, oil saturated with

CO_2 swells in volume and this effectively increases Sorw, and thus reduces the storage volume multiplier, i.e., (1-Swi-Sorw). It is only through this combination of sensitivity analyses and simulation studies that the effectiveness of using abandoned aquifer-driven reservoirs to sequester CO_2 can be evaluated in totality.

c) Can CO_2 capture in the reservoir-aquifer system be improved by using a horizontal well located down dip as the injector well?

d) At what pressures should CO_2 be injected to optimize time and volume of sequestration?

Based on the results of **Tasks 2-6**, researchers at the University of Houston and the University of Kansas will collaborate to determine the most effective attribute technologies for imaging and quantifying reservoir heterogeneity (**Task 7**), and will develop the most effective workflows for seismic attribute identification of reservoir features and improved quantification of lithology, porosity and permeability at the appropriate scale for evaluating candidate oil reservoirs for CO2 sequestration. In addition, we will compile and submit the third year midyear and final progress reports to the DOE (**Task 8**); will present our work at various venues; and will prepare manuscripts for publication.

1.5 Evaluation Phase

Deliverables from this project include Best Practice Workflows for (1) multi-trace attribute identification and imaging of reservoir heterogeneity, (2) statistical prediction of porosity and lithology through calibration of impedance inversion and wave-shape classification attributes, and (3) statistical prediction of permeability through calibration of our new frequency-and angle-dependent attributes and our fracture-sensitive geometric attributes.

Measures of success will be:

- High correlation of new multi-trace attributes and frequency- and angle- dependent attributes to geologic, production, or engineering data.

- Sharp seismic images of geologic features that are usually considered to be subseismic
- Good history matches of Dickman field reservoir performances to details of the reservoir simulation of the associated active saline aquifer, upon application of seismic attributes to generate reservoir parameters for simulation.

1.6 Roles of Participants

Permanent university staff on this project will include three researchers from the University of Kansas **(Nissen, Bahattacharya, Carr)** and three researchers **(Hilterman, Marfurt, and Sullivan)** from the University of Houston. In addition there will be one graduate student at the University of Houston, who will be employed for nine months each year, and one graduate student at the University of Kansas, employed twelve months each year. Our industrial partner is **Continental Resources of Illinois, Inc.,** and we have **three unpaid expert resource individuals,** listed below.

The University of Houston will provide overall project administration for technical and budgeting tasks. **Fred Hilterman** is the PI for the proposed project; **Charlotte Sullivan** is the Co-PI and will be the Project manager. Fred will lead the research in developing and calibrating the frequency-dependent and incident angle-dependent attributes, as well as leading the application of his new target oriented migration to CO_2 sequestration. Charlotte will be the point person for required DOE reporting. She will also conduct geological studies, calibrate multi-trace attributes with engineering and wellbore data, and advise graduate students involved with the project. **Kurt Marfurt** will customize algorithms for the AGL multi-trace seismic attributes to meet new geologic challenges and will monitor calibration of AGL seismic attributes. Graduate students, along with the professors, will generate and interpret all pre- and post-stack attributes. Students will also participate in running state-of-the-art commercial impedance inversion, performing 3-D visualizations, and calibrating multi-trace attributes.

Susan Nissen, who will be project manager for the **KGS project team**, will also conduct seismic interpretation, attribute analysis and calibration, and data integration for geomodel construction. **Saibal**

Bhattacharya will conduct engineering, modeling, and simulation studies. **Tim Carr** will provide interpretations of geological and engineering data for calibration with seismic attributes. He will also work on the construction of geostatistical 3-D reservoir models.

Our industrial partner, **Continental Resources of Illinois** will provide an in-kind contribution, staff time for assembling, interpreting, and integrating geological, seismic and engineering data of reservoirs and aquifers in the Patoka field, which is located in a major coal-producing area of the Illinois Basin. **Continental** will also work closely with our researchers and graduate students in the calibration and validation of attributes, technologies and workflows. Two other non-partner companies or organizations, **Rocky Mountain Oilfield Testing Center (RMOTC), and Grand Mesa Operating Company,** have provided 3-D seismic data, as well as well bore and engineering data.

We are fortunate to have the support of three unpaid expert resource individuals: CO_2 sequestration scientist **Julio Friedman**, Head of the Carbon Management Program, Energy & Environment Directorate at Lawrence Livermore National Laboratory; **Gennady Goloshubin**, Research Professor, Department of Geosciences, and pioneer researcher in frequency- and angle- dependent seismic attributes; and **Doug Tunison**, Technical Services Manager, **RMOTC**. These technical experts will provide insight into various issues during the project.

2.0 FACILITIES AND EQUIPMENT

All facilities and equipment necessary for the project are available at the University of Houston and/or the University of Kansas.

2.1 University of Houston – All staff and students involved in this project are part of the Center for Applied Geosciences and Energy (CAGE, which incorporates the Allied Geophysical, Reservoir Quantification, and Rock Properties Labs) at the University of Houston, CAGE has state-of-the-art commercial software products in seismic interpretation, processing, imaging, inversion, modeling, visualization, reservoir calibration, and reservoir simulation. Our computational network includes a 48-node Xenon Beowulf cluster, and 5 Tbytes of Raid-5 disk linked to a Sun V-880 server and 25 Sparc workstations. Kurt Marfurt, director of CAGE, is a co-PI in the Sun Microsystems Center of Excellence in Geosciences which provides access to a 98-node Sun Starfire supercomputer.

2.2 University of Kansas - All University of Kansas staff and students involved in this project are part of the Kansas Geological Survey (KGS). The KGS is equipped with a state-of the-art distributed computer system with the latest workstations, storage devices, routers, and software that presently supports a large publicly accessible well database, as well as websites and databases for several DOE-sponsored projects, including the MIDCARB and NATCARB CO_2 sequestration projects, the GEMINI petroleum reservoir analysis project, and the Digital Petroleum Atlas. In-house log analysis and reservoir characterization software *PfEFFER*, *Kipling*, and *GEMINI*, as well as state-of-the art commercial seismic interpretation, well log analysis, reservoir characterization and modeling, and reservoir simulation software is also available.

3.0 REFERENCES

Al Dossary, S., Y. Simon, and K.J. Marfurt, 2004, Inter azimuth coherence attribute for fracture detection: 74th Annual International Meeting Society of Exploration Geophysicists, Expanded Abstracts, 183-186.

Al-Dossary, S., and K. J. Marfurt, 2003, Fracture-preserving smoothing: 73rd Annual International Meeting Society of Exploration Geophysicists, Expanded Abstracts, 378-381.

Al-Dossary, S., and K. J. Marfurt, 2003, Improved 3-D seismic edge-detection filter applied to Vinton Dome, Louisiana: 73rd Annual International Meeting Society of Exploration Geophysicists, Expanded Abstracts, 2370-2372.

Al-Dossary, S., and K. J. Marfurt, 2005, 3-D volumetric multispectral estimates of reflector curvature and rotation: *submitted* to Geophysics.

Bergbauer, S., T. Mukerji, and P. Hennings, 2003, Improving curvature analyses of deformed horizons using scale-dependent filtering techniques: AAPG Bulletin, **87**, 1255-1272

Blumentritt, C. H., E. C. Sullivan, K. J. Marfurt, and M. Murphy, 2003, 3D seismic attribute illumination of Paleozoic tectonics, Central Basin Platform, west Texas: 73rd Annual International Meeting Society of Exploration Geophysicists, Expanded Abstracts, 1711-1714.

Calvert, R., 2005, Insights and methods for 4D reservoir monitoring and characterization: Society of Exploration Geophysicists and European Association of Geoscientists and Engineers, 2005 Distinguished Instructor Short Course, Distinguished Instructor Series **8,** 219p**.**

Carr T. R., and Merriam, D. F., 2005 *In press*, Use of Relational Databases to Evaluate Regional Petroleum Accumulation, Groundwater Flow, and CO_2 Sequestration in Kansas: American Association of Petroleum Geologists Bulletin. Accepted for publication and revised.

Carr, T. R., L. H. Wickstrom, C, P. Korose , R. S. Fisher, W. Solano-Acosta, and N. Eaton, 2003, Online tools to evaluate saline aquifers for CO_2 sequestration: Kansas Geological Survey Open-file Report 2003-33.

Castagna, J. P., S. Sun, and R. W. Siegfried, 2003, Instantaneous spectral analysis: Detection of low-frequency shadows associated with hydrocarbons: The Leading Edge, **22,** 120-127.

Chopra, S., V. Sudhakar, G. Larsen, and H. Leong, 2000, Azimuth-based coherence for detecting faults and fractures: World Oil, 57-62.

Cole, S., D. Lumley, M. Meadows, and A. Tura, 2002, Pressure and saturation inversion of 4D seismic data by rock physics forward modeling: 72rd Annual International Meeting Society of Exploration Geophysicists, Expanded Abstracts, 2475-2478.

Daley, T., E. Majer, and R. Gritto, 2000, Progress and issues in single well seismic imaging, 70th Annual International Meeting of the Society of Exploration Geophysicists, Expanded Abstracts, 1552-1555.

Dallbauman, L., 2004, GTI research on reservoir sequestration: Gas Tips, Spring. http://www.gastechnology.org/webroot/downloads/en/4ReportsPubs/4_7GasTips/Spring04/GTIRschOnCO2Sequest.pdf.

Drahovzal, J.A., and D. C. Harris, 2004, potential reservoirs for geologic sequestration in the East Continental Rift basin: MIDCARB Open File Report http://www.midcarb.org/reports.shtml.

Dutta, N. C. and H. Ode, 1983, Seismic reflections from a gas-water contact, Geophysics **48**, 2, 148–162.

Friedmann, S. J, D. Nummedal, and V. Stamp, 2004, Science and Technology Goals of the Teapot Dome Field Experimental Facility, 3rd Annual Conference on Carbon Sequestration (paper), NETL, Alexandria, VA.

Friedmann, S. J., 2003, Thinking big: science and technology needs for large-scale geological carbon storage experiments: International Journal of Energy Research.

Gasperikova, E., G. M. Hoversten, and F. Cassassuce, 2004, A feasibility study of geophysical methods for monitoring geologic CO_2 sequestration: 74th Annual International Meeting, Society of Exploration Geophysicists, 1567-1570.

Geertsma, J., and D.C. Smith, 1961, Some aspects of elastic wave propagation in fluid saturated

Goloshubin, G. and Korneev, V., 2000, Seismic low-frequency effects from fluid-saturated reservoir, 70th Annual International Meeting Society of Exploration Geophysicists, Expanded Abstracts, 1671-1674.

Goloshubin, G. M. and A. V. Bakulin, 1998, Seismic reflectivity of a thin porous fluid-saturated layer versus frequency, 68th Annual International Meeting Society of Exploration Geophysicists, Expanded Abstracts, 976-979.

Goloshubin, G. M., A. M. Verkhovsky, and V. V. Kaurov, 1996, Laboratory experiments of seismic monitoring, 58th Mtg.: Eur. Assn. Geosci. Eng., Session:P074.

Goloshubin, G., 2005, Using frequency-dependent seismic attributes in imaging a fractured reservoir zone, to be presented at the 75th Annual International Meeting, Society of Exploration Geophysicists.

Goloshubin, G., Daley, T. and Korneev, V., 2001, Seismic low-frequency effects in gas reservoir monitoring VSP data, 71st Annual International Meeting Society of Exploration Geophysicists, Expanded Abstracts, 1693-1696.

Goloshubin, G., Korneev, V. and Vingalov, V., 2002, Seismic low-frequency effects from oil-saturated reservoir zones: 72nd Annual International Meeting Society of Exploration Geophysicists, Expanded Abstracts, 1813-1816.

Gough, D. J. and J. S. Bell, 1982, Stress orientations from oil well fractures in Alberta and Texas, Canadian Journal of Earth Sciences, **18**, 1358-1370.

Gough, D.J. and Bell, J.S., 1982, Stress orientations from oil well fractures in Alberta and Texas, Canadian Journal of Earth Science, **18**, 1358-1370.

Hakami, A., K. J. Marfurt, and S. Al-Dossary, 2004, Curvature attribute and seismic interpretation: Case study from Fort Worth Basin, Texas, U.S., 74th Annual International Meeting, Society of Exploration Geophysicists, Expanded Abstracts, 544-547.

Hart, B.S., R. A. Pearson, and G. C. Rawling, 2002, 3-D Seismic horizon-based approaches to fracture swarm sweet spot definition in tight-gas reservoirs: The Leading Edge, **21**, 28-35.

Hawkins, D. G., 2003, Passing gas, policy implications of leakage from geologic carbon storage sites: in Gale, J., and Kaya, J., (editors), Proceedigns of the 6th International Conference on Greenhouse Gas Control techniques, Kyoto, Japan, October, 2002, Amsterdam, 2003: Elsevier.

Hilterman, F. and C. van Schuyver, 2003, Seismic wide-angle processing to avoid NMO stretch, 73rd Annual International Meeting Society of Exploration Geophysicists, Expanded Abstracts, 215-218.

Hilterman, F.J. and L. Liang, 2003, Linking rock-property trends and AVO equations to GOM deep-water reservoirs, 73rd Annual International Meeting Society of Exploration Geophysicists, Expanded Abstracts, 211-214.

Jorgensen, D. G., J. O. Helgesen, and J. L. Imes, 1993, Regional aquifers in Kansas, Nebraska, and parts of Arkansas, Colorado, Missouri, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming – Geohydrologic framework, USGS Professional Paper 1414-B, 72 p.

Jyosyula, S., 2004, Azimuthally dependent Seismic attribute analysis: unpublished M. S. Thesis, University of Houston.

Jyosyula, S., K. J. Marfurt, and E. C. Sullivan, 2003, Karst related vertical collapse structure and related lineament detection by seismic attributes on Fort Worth basin seismic data volume, 73rd Annual International Meeting Society of Exploration Geophysicists, Expanded Abstracts, 1715-1718.

Keach, R. W., and McBride, W., 2004, Preliminary results from a structural analysis of a 3D reflection volume over the eastern edge of the Coridlleran Thrust Belt, Wyoming, USA, [Abstract]: GSA Annual Meeting, November.

Korneev, V. A., G. M. Goloshubin, T. M. Daley, and D. B. Silin, 2004, Seismic low-frequency effects in monitoring fluid-saturated reservoirs: Geophysics, **69,** 522-532.

Liner, C., C.F. Li, A. Gersztenkorn, and J. Smythe, 2004, SPICE: a new general seismic attribute: 74th Annual International Meeting Society of Exploration Geophysicists, Expanded Abstracts, 433-436.

Lisle, R. J., 1994, Detection of zones of abnormal strains in structures using Gaussian curvature analysis: AAPG Bulletin, **78**, 1811-1819.

Marfurt, K. J., 2005, Robust estimates of 3-D reflector dip: *Submitted to* Geophysics.

Maxwell, S.C., D.J. White, H. Fabriol, Passive seismic imaging of CO_2 sequestration at Weyburn, 2004 [Expanded Abstract]: 74th Annual International Meeting Society of Exploration Geophysicists.

Meuneir, J., F. Huguet, and P. Meynier, 2000, Reservoir monitoring using permanent sources and certical receiver antennae: 70th Annual International Meeting Society of Exploration Geophysicists, Expanded Abstracts, 1619-1622.

Molotkov, L. A., 1999, On the coefficients of pore tortuosity in the effective Biot model: Journal of Mathematical Sciences, **108**, 752-757.

Nissen, S. E., K. J. Marfurt, and T. J. Carr, 2004, Identifying subtle fracture trends in the Mississippian Saline Aquifer Unit using new 3-D seismic attributes: Kansas Geological Survey Open File 2004-56, <http://www.kgs.ku.edu/PRS/publication/2004/2004-56/>.

Nuttall, B. C., C. F. Eble, R. M. Bustin, and J.A. Drahovzal, 2004, Analysis of the Devonian shale in Kentucky for potential CO_2 sequestration and enhanced natural gas production: 3rd Annual conference on CO_2sequestration (NETL), Alexandria, VA, 22p.

Nuttall, B.C., 2004, GIS methods for reservoir assessment and estimating CO_2 sequestration capabilities [Abstract]: GSA Annual Meeting, November.

Partyka, G., J. Gridley, and J. A. Lopez, 1999, Interpretational applications of spectral decomposition in reservoir characterization: The Leading Edge, **18**, 353-360.

Pride, S.R., J.M. Harris, D.L. Johnson, L. Mateeva, K.T. Nihei, R.L. Nowack, J.W. Rector, H. Spetzler, R. Wu, T. Yamomoto, J.G. Berryman, M. Fehler, 2003, Permeability dependence of seismic amplitudes: The Leading Edge, **22**, 518-525.

Raef, A. E., Miller, R. D., Byrnes, A. P., and Harrison, W. E., 2004, 4-D seismic monitoring of the miscible CO_2 flood of Hall-Gurney Field, Kansas, U.S.: The Leading Edge, **23**, 1171-1176.

Riley, R.A., J.J. Wells, J. McDonald, L.H.Wickstrom, 2003, Assessment of CO2 sequestration for enhanced recovery in Ohio: MIDCARB website: http://www.midcarb.org/Documents/AAPG-Eastern-2003/1-Assesmnt_CO2_Seq_Ohio.pdf

Roberts, A., 2001, Curvature attributes and application to 3D interpreted horizons: First Break, **19**, 85-99.

Ryder, R. T., 1998, Appalachian Basin Province (067), in Donald L. Gautier, D.L., Gordon L.D., Attanasi, E.D. (*eds.):* National Oil and Gas Assessment and Onshore Federal Lands U. S. Geological Survey Open-File Report 95-75-N

Santos, J. E., J.M. Corbero, C.L. Ravazzoli, and J.L. Hensley, 1992, Reflection and transmission coefficients in fluid-saturated porous media. Journal of Acoustical Society of America, **91**, 1911-1923.

Serrano, I. C., C. H. Blumentritt, E. C. Sullivan, K. J. Marfurt, and M. Murphy, 2003, Seismic attribute delineation of lineaments and reservoir compartmentalization: An example from the Devonian Dollarhide Field, Central Basin Platform, west Texas: 73rd Annual International Meeting Society of Exploration Geophysicists, Expanded Abstracts, 1744-1747.

Silin, D.B., V. A. Korneev, and G. M. Goloshubin, 2003, Pressure diffusion waves in porous media: 73rd Annual International Meeting Society of Exploration Geophysicists, Expanded Abstracts, 2323-2326.

Stewart, S. A., and T. J. Wynn, 2000, Mapping spatial variation in rock properties in relationship to scale dependent structure using spectral curvature: Geology, **28**, 691-694.

Stewart, S.A., and Wynn, T.J., 2000, Mapping spatial variation in rock properties in relationship to scale dependent structure using spectral curvature: Geology, v. 28, 691-694.

Stricker, G.D., 2004, Assessment of carbon dioxide sequestration in Fort Union coal beds in the northern Rocky Mountains and Great Plains coal basins: Geological Society of America *Abstracts with Programs,* **36**, 5, 541.

Sullivan, E. C., K. J. Marfurt, and C. Blumentritt, 2004, Application of volumetric seismic attributes to fractured reservoirs: A potentially important technology for the Appalachian Basin, GSA Combined NE and SE Sections, March Meeting.

Sullivan, E. C., K. J. Marfurt, and M. Ammerman, 2003, Bottoms up karst: New 3D seismic attributes shed light on the Ellenburger (Ordovician) carbonates in the Fort Worth Basin (north Texas, USA), 73rd Annual International Meeting Society of Exploration Geophysicists, Expanded Abstracts, 482-485.

Terrell, M. J., T. L. Davis, L.T. , Brown, and R.F. Fuck, 2002, Seismic monitoring of a CO_2 flood at Weyburn field, Saskatchewan: 72nd Annual International Meeting of the Society of Exploration Geophysicists, 1673-1676.

Vasco, D. W., 2004, Seismic imaging of reservoir flow properties: Time lapse pressure changes: Geophysics **69,** 511-521.

Yuh, S.H., and R.L. Gibson, 2001, Time –lapse seismic monitoring of CO2 sequestration in hydrocarbon reservoirs: 71nd Annual International Meeting of the Society of Exploration Geophysicists, Expanded Abstracts, 1627-1630.

Zhou, Z., F.J. Hilterman, and H. Ren, 2005, Water-saturation estimation from seismic and rock-property trends: *to be presented at the* 75th Annual International Meeting of the Society of Exploration Geophysicists.

4.0. STATEMENT OF PROJECT OBJECTIVES

Application of cutting-edge 3-D seismic attribute technology to the assessment of geological reservoirs for CO_2 sequestration

4.1 OBJECTIVES

Our ***aim*** is to develop innovative seismic technology and workflows that can be used to improve assessment of structural integrity and reservoir heterogeneity of geological reservoirs for CO_2 sequestration. We have selected four study areas representative of the range of most-likely candidates for gigaton-scale CO_2 sequestration associated with the coal industry. Our ***specific objectives*** are to: 1)*test and calibrate* new frequency- and angle-dependent seismic attributes for the quantification of reservoir porosity, permeability, and saturations, 2) *apply* new spectral decomposition and multi-trace seismic attributes to address special problems in imaging small scale structural and stratigraphic features, 3) *validate* attribute and processing results with novel reservoir simulation of CO2 injection into a saline aquifer associated with a severely depleted hydrocarbon reservoir. *This work has the potential to reduce uncertainty and significantly expand knowledge of the assessment of CO2 storage reservoirs.*

4.2 SCOPE OF WORK

We will apply innovative petroleum-industry based seismic-attribute technologies developed at the University of Houston to the assessment of geological reservoirs for large scale CO_2 sequestration. The Dickman field in Kansas will serve as a test bed for this study. The simulation of CO2 injection into a depleted reservoir/active aquifer system will be based on seismic attribute derived parameters. This simulation will also allow us to estimate CO_2 storage capacity of a typical depleted mid continent reservoir. We will combine our results to develop practical workflows for the application of this technology to CO_2 storage for the coal industry.

4.3. TASKS TO BE PERFORMED

Task 1.0 Assemble and QC data

Task 2.0 Generate seismic attributes

Task 2.1 Generate single-trace and multi-trace seismic attributes

Task 2.2 Perform target oriented migration of pre-stack seismic data

Task 2.3 Generate frequency dependent and offset-dependent attributes

Task 3.0 Conduct structural/stratigraphic interpretation of seismic volumes

Task 4.0 Calibrate seismic attributes with geological and engineering data

Task 5.0 Validate seismic attribute analysis results

Task 5.1 Construct integrated geomodel of Dickman Field, Kansas.

Task 5.2 Simulate Dickman Field. History-match production/pressure

Task 5.3 Refine seismic attribute analysis techniques

Task 6.0 Evaluate CO2 sequestration in reservoir-aquifer systems

Task 6.1 Construct integrated geomodel of reservoir-aquifer system in Dickman Field

Task 6.2 Simulate effectiveness of CO2 sequestration in Dickman Field

Task 7.0 Develop seismic-based workflows for CO2 reservoir assessment

Task 8.0 DOE reporting and technology transfer

4.4. DELIVERABLES

Deliverables, other than those identified on the "Federal Assistance Reporting Checklist" will include: workflows and best practices for attribute-based assessment of geological reservoirs for CO_2sequestration; case histories of the generation of attribute-guided geomodels; and results of attribute-based reservoir simulation of injection of CO_2 into an important regional deep saline aquifer.

4.5. BRIEFINGS/TECHNICAL PRESENTATIONS

Principal investigators will participate in the Annual Contractors Meeting in June of 2006, and a peer review of the project in 2008, We will accomplish technology transfer through presentations at national, regional and local professional meetings, through publications in professional journals, short courses and classroom teaching. Various aspects of the project will be posted on the University web sites, in open file reports on the University of Kansas MIDCARB website, and on the website for Teapot Dome.