4-D High-Resolution Seismic Reflection Monitoring of Miscible CO_2 Injected into a Carbonate Reservoir

Abstract

This three-phase 4-D seismic program includes up to twelve sequential 3-D surveys designed to provide a time lapse map of carbon dioxide (CO_2) movement during and containment after its injection into a carbonate reservoir. The primary objective is to improve the understanding of fluid-flow paths, reservoir architecture, reservoir properties, CO_2 movement, CO_2 containment, and post-injection CO_2 stability of a 15-acre CO_2 miscible flood in the Lansing-Kansas City Formation, central Kansas, beginning in Spring 2003 under the U.S. DOE Class Revisit Program (Project #DE-AC26-00BC15124). Sequential images obtained before, during, and after the flood will improve understanding of the flood process and potentially aid in flood management for this and other miscible floods.

Also, these data will be studied for: 1) efficient approaches to use of high-resolution, minimal deployment 4-D seismic monitoring in enhanced oil recovery programs; 2) feasibility of high-resolution imaging of a single pay zone in a succession of cyclic carbonate units; 3) effectiveness of 4-D seismic monitoring in interpreting rock properties that influence flood performance; 4) usefulness of 2-D, 2-component (2-C) shear wave seismic as a complement to 3-D P-wave imaging; 5) use of synthetic seismograms, correlated to real data, for improvement of flooding programs; 6) time-lapse seismic's potential to provide assurance of CO_2 containment; and 7) the potential to monitor long-term CO_2 stability.

4-D High-Resolution Seismic Reflection Monitoring of Miscible CO_2 Injected into a Carbonate Reservoir

This proposal contains no proprietary information.

Goals and Objectives

The objective of this research project is to acquire, process, and interpret multiple high-resolution 3-D compressional wave and 2-D, 2-C shear wave seismic data to observe changes in fluid characteristics in a oil field before, during, and after the miscible carbon dioxide (CO_2) flood that is beginning in Spring 2003 as part of the DOE-sponsored Class Revisit Project (DOE #DE-AC26-00BC15124). Unique and key to this proposed imaging activity is the high-resolution nature of the seismic data, minimal deployment design, and the temporal sampling throughout the flood. The 900 m deep test reservoir is located in central Kansas oomoldic limestones of the Lansing-Kansas City Group, deposited on a shallow marine shelf in Pennsylvanian time (Watney, 1980, 1995).

Three-dimensional seismic delineation of the movement of a miscible CO_2 floodbank through a petroleum reservoir allows identification of reservoir heterogeneity and in some situations their relationship to specific rock properties influencing sweep uniformity and the post-sweep distribution of CO_2 in the reservoir. By spatially correlating key reservoir properties, such as porosity and permeability, with unique combinations of seismic attributes, reservoir simulation models can be optimally refined and the improved understanding of the on-going flood used to improve flood management and optimize performance. Questions such as: "Where is the injected CO_2 going?" "What is the sweep efficiency?" "Are there any areas with bypassed oil?" "How can the injection and production program be improved in real time to optimize the sweep or recovery?" may be answerable while the enhanced recovery process is underway. Such questions need to be answered during the critical time between initially pressuring the reservoir with water and the eventual CO_2 "breakthrough" at producing wells. In addition, questions concerning use of hydrocarbon reservoirs for carbon dioxide sequestration can be addressed. Questions such as: "Is CO2 moving outside the pattern?" "How does the CO_2 in the reservoir change with time?" " Is CO2 migrating into overlying beds and how much is moving?" "Does seismic provide a viable monitoring tool for CO2 sequestration and containment?"

This 15-acre miscible CO_2 flood involves three production wells, two water injectors, and one CO_2 injector (Dubois et al., 2001) (Figure 1). The present reservoir simulation model for the flood area predicts slightly enhanced sweep to the #12 and #16 wells. Repeated 3-D seismic surveys may permit direct observation of the effectiveness of CO_2 containment in the flood pattern area and the geometry of the front as it moves through the reservoir. Since the flood containment is influenced and, to some degree, controlled by injection rates in the #10 and #18, and production rates in the #12, #16, and #13, observations of unplanned movement may be controlled by altering injection and production rates. This seismic program will potentially provide a unique, extremely valuable real-time assessment of CO_2 flood sweep and also an opportunity to evaluate reservoir model simulation performance at a resolution never before obtained.

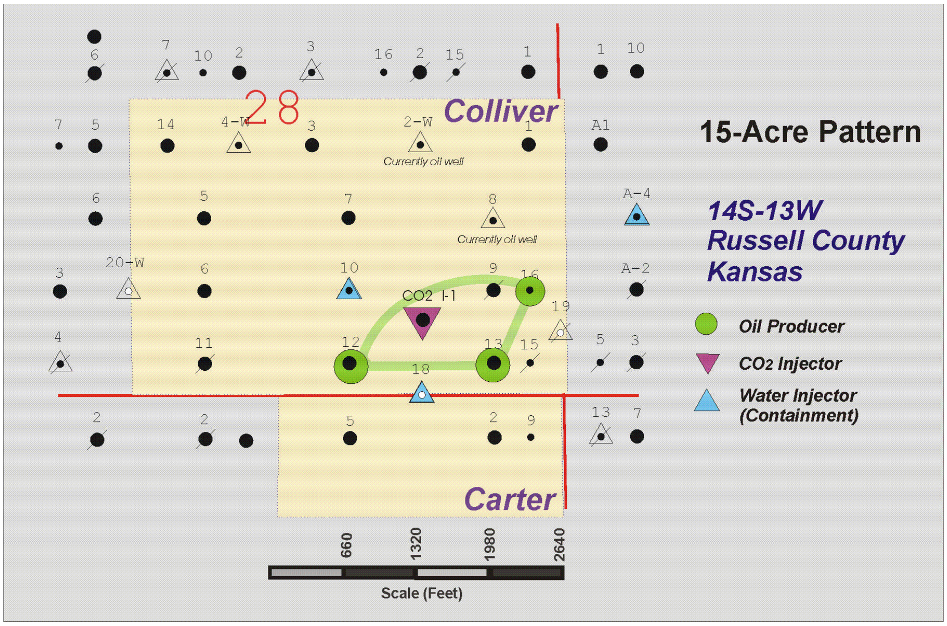


Figure 1. Map showing 15-acre flood pattern for the DOE-sponsored CO_2 miscible flood in the Hall-Gurney Field.

The seismic data will be used to directly observe and map the distribution of CO_2 saturation in the reservoir fluids and to monitor changes in saturation over the planned two to four years of CO_2 injection. These time-lapse images will allow appraisal of sweep efficiency and the identification of areas of bypassed oil with unprecedented accuracy. In contrast, conventional reservoir simulations of the saturation distribution both before and after flooding are based on reservoir properties estimated from cores, well performance, and history matching, which are limited in predictive accuracy for the properties of inter-well regions. Recent use of conventional 3-D, 3-C technologies to study CO_2 floods show great potential but lack the resolution, sampling frequency, and cost effectiveness necessary for downstream enhancement of oil recovery schemes during CO_2 injection in conventionally depleted reservoirs.

Using successive 3-D seismic surveys to monitor the progress of a flood front sweep through the reservoir will provide a detailed spatially and temporally continuous characterization (a true 4-D survey) that will permit progressive dynamic adjustments to the injection and production scheme. The 4-D survey also will provide a unique opportunity to investigate and assess dynamic flood schemes that try to compensate for non-uniform changes in fluid saturation and/or pressure. By incorporating successive seismically-based maps of lateral variation and fluid saturation and interpretations of permeability into the reservoir simulator, the injection scheme can be modified dynamically to achieve an optimal sweep of the oil reservoir. Without seismic monitoring, sweep effectiveness and reservoir heterogeneity cannot be assessed until "breakthrough," when the opportunity to perform fluid steering through modified injection and production schemes is more limited.

The viability of using seismic data to image and monitor CO_2 containment is enhanced by the phase properties of CO_2 for the conditions of this reservoir. In the flood pattern, the CO_2 is at pressures generally greater than 1,100 to 1,400 psi. At these pressures, and at the existing reservoir temperature, the CO_2 exhibits a density ranging from 0.3-0.7 g/cm^3. If CO_2 leaves the pattern area, either horizontally or vertically, it will decrease to pressures generally less than 700 psi. At these lower pressures the density of CO_2 decreases substantially to below 0.1 g/cm^3. At temperatures below 80ºF the CO_2 enters a 2-phase region and exists as both a gas and a liquid. These marked changes in density would provide enhanced impedance contrast and consequently would elevate the seismic amplitude ("bright spot") response to the presence of CO_2. In effect, CO_2 leaving the pattern either horizontally or vertically into overlying beds is markedly more visible than CO_2 in the pattern. Since production of this reservoir will be halted once the CO_2 flood is complete, reservoir pressures will decrease and therefore CO_2 densities will also decrease, enhancing the seismic signature and detectability of CO_2 increase. Time-lapse seismic imaging will be extremely sensitive to any movement of physical changes in the CO_2 remaining in the reservoir can be effectively monitored seismically to identify and characterize changes through time.

Evaluating optimal approaches of 4-D seismic as a suitable and cost-effective tool for routine monitoring of injection schemes on small, low-budget EOR projects and in lower yield, mature reservoirs is an important secondary goal of this project. Efficient sweeping of all oil from a reservoir and tracking and accounting for injected CO_2 requires high-density spatial imaging of reservoir properties. Using real-time images of fluid and contaminant movement in reservoirs, dynamic injection and recovery schemes could be designed and continuously updated using reservoir simulations based on 4-D seismic data, existing well data, and new wells optimally located during flooding that dramatically increases the cost benefit of injection programs in mature and small fields.

For 4-D seismic to be economic on small floods and where multiple 3-D surveys within the injection and production periods will be necessary, the cost of data acquisition and processing must be minimized without compromising resolution. This cost cutting requires a non-conventional approach using low-cost seismic systems that produce extremely consistent, high-resolution data in a rapid fashion. The methodology must be of sufficiently high resolution to discretely resolve CO_2 movement through very thin intervals and allow differentiation of CO_2 that has moved outside the trapping formation.

The Lansing-Kansas City reservoir at the demonstration site is only 4 m thick with the most productive interval at the top of the reservoir being about 2 m thick, requiring dominant frequencies to exceed 150 Hz to resolve the top and bottom of the 4 m thick pay zone (Gochioco 1991; Miller et al., 1995). If these frequencies can be achieved and consistently recorded, the 4-D characterization of the reservoir at the necessary spatial scale for direct detection can be achieved. As well, if the CO_2 moves outside the flood area, pressure drops and associated decreases in density will result in extreme amplitude anomalies (bright spots) that should be readily observable.

Background and Current State of Knowledge

Seismic characterization of fluids in a reservoir during production relies on changes in bulk density and bulk modulus of the rock as the native pore fluids are displaced or altered. Temporal variations in seismic attributes (such as instantaneous amplitude, instantaneous phase, instantaneous frequency, coherency, and impedance) as small as a few percent may indicate changes in pore fluid composition or fluid flow (White, 1991). Localized absence of changes in attributes between surveys may indicate underswept zones and stranded reserves (Sigit et al., 1999). Vertical and areal differences and distribution of important reservoir properties (porosity, permeability, and fluid composition) should be mappable within the horizontal limits of the survey by correlating different seismic attributes to reservoir properties. Such "attribute correlations" have proven effective in detecting changes in fluid saturation, pressures, and temperature, even using data not optimized for 4-D analysis (Johnston et al., 1998, Lumley et al., 2000; Davis et al., 2001; Anderson et al., 1998; He et al., 1998). With the relative newness of 4-D technologies, many baseline 3-D surveys used for 4-D analysis are legacy data (Johnston et al., 2000) and are not optimized for comparisons and reservoir analysis using the most effective differencing techniques.

Time-lapse 3-D (or 4-D) seismic reflection profiling has been effectively used during the last decade (Ebrom et al., 1998), to monitor conventional enhanced oil recovery (EOR) programs (Huang et al., 1998; Rogno et al., 1999; Gabriels et al., 1999; Lumley, 1995). Maintaining consistency and repeatability in acquisition and processing has been the most persistently identified problem associated with time-lapse seismic monitoring of reservoir production (Huang and Will, 2000; Druzhinin and MacBeth, 2001; Meunier and Huguet, 1998; Nivlet et al., 2001; Li et al., 2001). Distinguishing between changes in seismic characteristics that result from temporal variation in near-surface properties and changes occurring in reservoir intervals as a result of flooding remains a significant problem. Cross-equalization techniques have proven to be a most effective tool in reducing the impact of near-surface variations on amplitude, phase, arrival time (static), and spectral properties (Huang and Will, 2000; Druzhinin and MacBeth, 2001; Meunier and Huguet, 1998). The potential of multiple (>2 per EOR or CO_2 sequestration program) 3-D surveys to better differentiate changes in near-surface conditions from changes in reservoir fluids has not been evaluated.

To date, 3-D surveys monitoring changes in reservoir properties after the injection of miscible CO_2 have consisted of a baseline survey and a post- or late-production survey only (Terrell et al., 2002; Acuna and Davis, 2001; Chapman et al., 2000; Harris et al., 1996). Such sparse sampling is inadequate to support true 4-D investigations. If only two surveys have been run in the time domain, all changes observed in the reservoir must be assumed to have occurred linearly, at a constant rate through both time and space. This is assuredly an oversimplification that may result in erroneous predictions. Even if the fluid phenomena being investigated behaved linearly in time and space (an unlikely circumstance), two time-slices would not permit assessment of the uncertainty in either the rate of change with time at fixed locations or the rate of spatial change between locations. At least four 3-D surveys, separated by time, are required to achieve the minimum degrees of freedom to assess temporal changes, and additional surveys will provide more detailed information.

EOR techniques must be developed to recover oil from the large number of Class II reservoirs in the mid-continent that retain bypassed or trapped oil after water flooding. As part of a "Class II Revisit" program funded by DOE, a 15-acre CO_2 miscible flood pilot study has been designed to demonstrate the technical feasibility and economic viability of miscible EOR in a representative Lansing-Kansas City oomoldic limestone shallow-shelf carbonate reservoir. Details about this 6-year pilot project funded by the Department of Energy, Kansas Geological

Survey, Tertiary Oil Recovery Project, KU Energy Research Center, MV Energy, Murfin Drilling Company, Kinder-Morgan CO_2 Company, and the Kansas Department of Commerce & Housing are given at http://www.kgs.ukans.edu/ERC/CO2Pilot/index.html.

Monitoring CO_2 floods in carbonate reservoirs with conventional 3-D land seismic has been moderately successful within the last half decade (Harris et al., 1996; Brown et al., 2002; Duranti et al., 2000). The Reservoir Characterization Group (RCG) at Colorado School of Mines has studied and reported on two of the best known projects (Vacuum Field, New Mexico, and Weyburn Field, Saskatchewan). Anomalies in S-wave anisotropy and P-wave reflection amplitude, interpreted from time-lapse, multi-component, 3-D data and reservoir production data, correlate with fluid composition and pore pressure changes associated with CO_2 injection programs (Duranti, 2001; Herawati, 2002). In both these studies a baseline survey was acquired with a follow-up survey acquired approximately one year later still during injection or mid-injection/recovery. Those EOR projects provided key insight into the economics, efficiency, and information necessary for seismic monitoring of similar CO_2 floods.

Preferential migration of CO_2 within a producing zone, whether along fractures or associated with depositional features, appears to be mappable using seismic attributes and energy modes appropriate for the formation characteristics. Shear wave splitting and anisotropy appear sensitive to changes in stresses of fractured permeable reservoirs after CO_2 injection (Cabrera-Garzón et al., 2000). In less permeable intervals (exhibiting lower fracture density) and below parting pressures, changes in compressional wave impedance volumes seem to be sensitive to and indicative of CO_2 moving through the reservoir (Terrell et al., 2002). Lateral and vertical changes in fracture densities and orientations consistent with the local stress field were interpreted from observations of changes in shear wave anisotropy after the injection of CO_2 at Vacuum Field in New Mexico (Pranter et al., 2000). Premature breakthrough at a producing well during the Weyburn Field EOR program studied by the RCG was interpreted from impedance volumes as “fingering” of the CO_2 along more permeable channels (Brown et al., 2002). Neither field behavior was expected or predicted based on pre-flood data.

Unexpected spatial irregularities in reservoir characteristics revealed by 3-D seismic presented challenges at the CO_2 flood of the Vacuum Field in New Mexico that required the development of a new reservoir model incorporating faults and fractures in the San Andres reservoir carbonates (Roche, 2000). A 4-D seismic survey showed faulting and fracturing previously not considered significant, as major influences on compartmentalization and non-uniform production of oil from this field.

The 4-D, 3-C monitoring of the Weyburn Field CO_2 flood in the Williston Basin of Saskatchewan, Canada, revealed geologic and reservoir characteristics similar to what is expected at the Kansas Hall-Gurney Field demonstration site (Terrell et al., 2002; Herawati, 2002; Byrnes, 2000). Both fields are mature and have undergone extensive water flooding prior to CO_2 floods. Both geologic settings can be characterized as shallow carbonate shelf deposits with pay zones averaging around 4 m thick, several cyclic intervals of varying thickness within the pay zone, and decreasing permeability and porosity from top to bottom of the producing zone. The best production intervals in each field possess relatively high permeabilities (over 100 md for the Weyburn Field and just over 200 md for the Hall-Gurney Field) and high porosities (about 38% for the Weyburn Field and 28% for Hall-Gurney Field).

Neither Hall-Gurney nor Weyburn fields have a dominant fracture component that would lend itself to tracking the movement of CO_2 by observing changes in shear wave anisotropy and/or birefringence as was the case at Vacuum Field in New Mexico. Permeability in the Vacuum Field reservoir study can be characterized as predominantly fracture controlled. The Weyburn Field has some interaction between matrix porosity and fractures, but not nearly to the degree observed at Vacuum Field. There is no documentation indicating a relationship between porosity and fractures in the Hall-Gurney Field.

Contrasting these fields in this fashion and considering the seismic configuration that was most successful in tracking CO_2 floods at Weyburn and Vacuum, it is reasonable to expect changes of 20% or more in 4-D compressional wave impedance volumes as the miscible bank moves across the pattern area during the first two years of the planned CO_2 flood at Hall-Gurney (Terrell et al., 2002). However, as discovered at Vacuum Field, shear wave imaging has the potential to uncover unknown and unexpected reservoir characteristics (Davis and Benson, 2001). Findings from this seismic study of the Hall-Gurney CO_2 injection project can be contrasted and compared with CO_2 sequestration research currently active in association with the Weyburn storage and monitoring project (Pedersen et al., 2003; Khan and Rostron, 2003).

Dynamic seismic response due to reservoir production processes provides insights into the permeability structure of the reservoir (Talley et al., 1998). As seismic data track the CO_2 front in three dimensions, lag areas can be identified and physical properties refined for these areas so that the model can be updated, thereby allowing the enhancement of reservoir simulation models and potentially, temporally tailored mid-flood adjustments can be made to the water injection and fluid production program.

CO_2 sequestration in aquifers and depleted oil reservoirs, and residual CO_2 remaining as a byproduct of oil recovery programs needs to be reliably monitored during injection and while dormant during storage (Guo et al., 2002; Bachu, 2001; Nihei et al., 2001). Currently pressure build-up and fall-off in wells is the most common method of monitoring CO_2 injection (Benson, 2001). Movement of CO_2 outside geologic traps is a major concern and obstacle to the acceptance and widespread use of CO_2 sequestration (Guo et al., 2002). Time-lapse seismic is sensitive to changes in the imaged volume and could be quantified sufficiently to provide the necessary transport and fate assurances.

The inherent spatial resolution of a reflection seismic survey, even as dense a survey as the one proposed here, can be no greater than the spacing between subsurface sample points. This spacing is much larger than that required by a typical reservoir fluid-flow simulator, so the seismic data must be scaled down to match the simulator's requirements. Because the incorporation of successive surveys separated by time allows the use of prior information to refine subsequent estimates, a geostatistical procedure with Bayesian components is appropriate for decreasing the sampled volumes and thereby substantially increasing the number of sample points, an approach referred to as "*Baysian maximum entropy*" or BME estimation (Christakos, 2000).

Beyond its use for monitoring the upcoming CO_2 flood at the Hall-Gurney Field demonstration site, high-resolution time-lapse 3-D seismic techniques need to be developed that are streamlined, focused, and cost effective in tracking the progress of any size flood (Houston and Kinsland, 1998) or monitoring subsurface CO_2 sequestration sites. Conventional 3-D seismic has not proved to be a cost-effective tool for most operators trying to extend smaller fields or to capture trapped or stranded reserves on the flanks of or even within mature reservoirs. Conventional approaches to 3-D surveying will not likely meet the economic or resolution requirements of "routine" CO_2 sequestration containment assurances (Bachu, 2001, Nihei et al., 2001; Hoversten et al., 2001). Innovative approaches to and adaptation of high-resolution seismic imaging will be necessary for seismic imaging to become the cost-effective tool necessary for monitoring CO_2 floods or disposal.

Anticipated Impact and Potential for Success

Successful 4-D monitoring of a multi-year EOR program will reveal reservoir properties, fluid-flow behavior, and sweep efficiency, and identify unswept areas that contain stranded or bypassed oil as well as identify any CO_2 that has escaped containment within the flood area. On-going imaging of the flood and resulting changes to the interpreted reservoir properties will allow refinement of the reservoir simulations and the ability to test different injection and production programs to maximize recovery and compensate for flow heterogeneities. Changes in the injection scheme can optimize the material balance and retain better control of the CO_2 inventory. Production can be enhanced while a flood is in progress, modifications in well patterns made, or new production or injection wells drilled to tap previously isolated portions of a reservoir.

Analyzing the effectiveness of sweep in real time allows minor adjustments to be made to injection pressures, volumes, and recovery/injection wells. These changes may reduce the duration of the flood, increase the uniformity of the flood, and improve the design of conformance control programs such as water-alternating-gas (WAG) programs.

Efficient design and implementation of 4-D monitoring of EOR programs could significantly increase the recovery of petroleum, especially from fields with marginally economic quantities of remaining oil in place. Of the original oil in place (OOIP), approximately 30-40% is trapped by water flooding and is subsequently only recoverable using an enhanced technology, such as CO_2 miscible flooding. The remaining 60-70% of the OOIP is potentially recoverable, but in many reservoirs typically only 30% is produced even after EOR programs. The remaining 30% of potentially recoverable OOIP is either isolated from the wellbore by reservoir heterogeneity or bypassed as a result of the production program employed. These known but unrecovered reserves represent a significant potential asset (Nur, 1997).

The significant phase changes that CO_2 will undergo if it leaves the high-pressure flood pattern either horizontally (into the lower-pressure surrounding area) or vertically (into overlying intervals), will increase the acoustic (reflectivity) contrast and therefore highlight any CO_2 leaving the pattern. CO_2 becomes progressively more seismically visible as the density drops, with the pressure gradient expected at the edge of the pattern the reflectivity will dramatically increase with minimal distance from the pattern. Any CO_2 moving outside the pattern will be seismically detected as a high amplitude anomaly or bright spot. Testing and confirmation of this technology as an effective tool for monitoring CO_2 sequestration may eventually provide the verification tool necessary for this application.

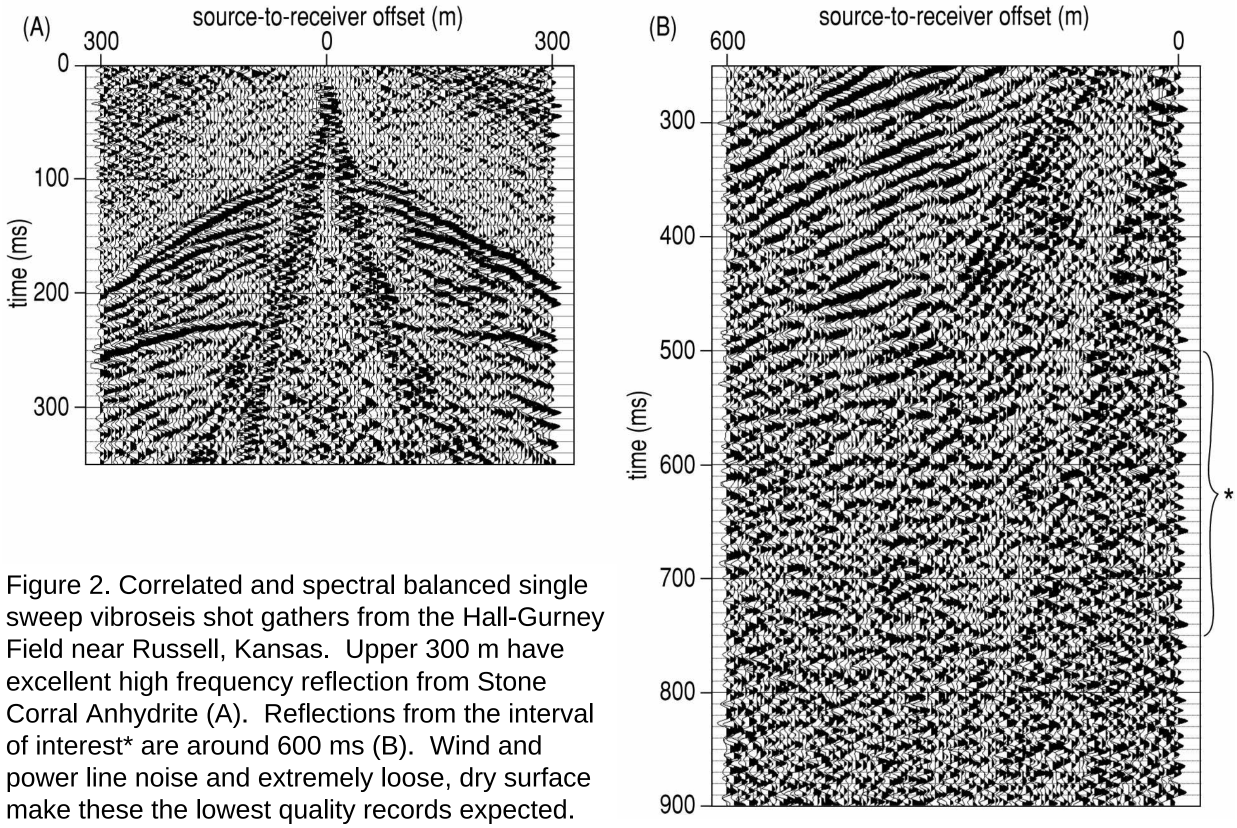


Figure 2. Correlated and spectral balanced single sweep vibroseis shot gathers from the Hall-Gurney Field near Russell, Kansas. Upper 300 m have excellent high frequency reflection from Stone Corral Anhydrite (A). Reflections from the interval of interest* are around 600 ms (B). Wind and power line noise and extremely loose, dry surface make these the lowest quality records expected.

Extending compressional wave 3-D seismic imaging to include the two shear wave components provides additional information about rock properties but often comes at an unacceptably high cost. Data acquisition equipment and procedures unique to shear wave reflection seismology can increase the cost of a geophysics program from 2 to 10 times depending on the geology. The extra costs of processing (e.g., dependence and sensitivity) and acquiring (e.g., multi-component sources and receivers, double or tripling the number of recording channels) shear wave data and other technologically advanced and expensive aspects of a well-orchestrated 3-C monitoring program may exceed the cost benefit for most smaller fields in the U.S.

EOR programs in small, mature fields can be made cost effective by avoiding full 4-D, 3-C surveys. Seismic monitoring and development of scaled-down designs incorporating optimally designed time-lapse 3-D compressional surveys with smaller well-formulated and targeted 2-D, 2-C shear wave surveys can be effectively and efficiently used for mapping flood dynamics. Amplitude differencing of compressional wave volumes should be extremely diagnostic of CO_2 escape into lower pressure units or CO_2 moving outside the pressured reservoir, foregoing the need for shear wave imaging altogether on sequestration projects (Zweigel et al., 2001; Yuh et al., 2000).

Successfully accomplishing some of the objectives/goals of this program is almost assured. Resolution potential, signal-to-noise, and penetration depths have already been estimated from walkaway tests previously conducted by the KGS at this site during the summer of 2002 (Figure 2). Test data were acquired under what is anticipated to be the worst near-surface and surface conditions that will be encountered at this site (extremely dry near-surface, all recovery wells pumping, moderate to high winds [50-60 km/hr gusts], and seismic lines parallel and beneath electric transmission lines).

Integrated with standard reservoir data these seismic results will provide field engineers snapshots of fluid movement through the reservoir along preferential flow paths. Development of more accurate and precise reservoir models will likely come from the seismic data and could be the basis for refined injection schemes. Lessons learned and techniques developed will be strong contributors to both timing and deployment approaches for future optimized seismic monitoring surveys. As well, minimal deployment 3-D for field enhancement has been needed and requested by independent oil producers for decades. Findings from these high-resolution 3-D surveys (shallow by conventional standards) will be instrumental in developing approaches to 3-D seismic surveying that extend the production of small fields by identifying areas that might contain bypassed oil.

Improving recovery methods will extend the economic life of many reservoirs. A critical component for managing reservoir performance is offered by time-lapse seismology. If the use of repeated, three-dimensional, seismic surveys can delineate changes in bulk properties over time due to reservoir processes, then a multidisciplinary reservoir management team can estimate the pressures, saturation, and fluid movements within the permeability structure of the reservoir, thereby improving recovery performance and economics.

Technical Approach / General Plan

Scope of Work

Contingent upon the successful completion of final negotiations between the partners of the CO_2 pilot study at the Hall-Gurney Field, permits and access agreements must be secured for the 810 shot points and 240 receiver stations that make up the planned 3.6 km^2 3-D deployment (Figure 3). Minor adjustments to spread and patch design will be necessary to optimize fold and azimuthal distribution for areas inaccessible or where landowner permission is not granted. Based on current reservoir simulations of the flood, the CO_2 front will form a 15-acre pie-shaped pattern with the three producing wells at the corners and the CO_2 injector well in the center. The current design provides uniform 20 to 24-fold coverage across an approximately 600 m x 450 m area centered on the flood pattern from start-up to breakthrough. Moving further away from the CO_2 injector, the two water injection wells planned for containment are all within the minimum 12-fold boundary. The 2-D, 2-C shear wave lines will intersect near the injection well and extend about 750 m away from the injector. Even if the flood strays significantly from the current expected sweep pattern this 3-D design will provide the necessary offsets, offset distribution, azimuthal control, and fold to monitor the CO_2 movement and eventual fate.

Design optimization incorporates conventional rules of thumb with high-resolution methodologies. Design simulations carefully consider key data requirements: bin size, X_{min}, X_{max}, fold, fold taper, migration aperture, squareness, azimuthal distribution, number of shotpoints per kilometer, number of live receivers per kilometer, etc. Also considered: consistency in data characteristics throughout the seasonal changes, results of a walkaway test conducted during the summer of 2002 at the site, efficiency of acquisition and processing, uniform coverage and distributions based on target depth, resolution, and aerial coverage of flood at break through.

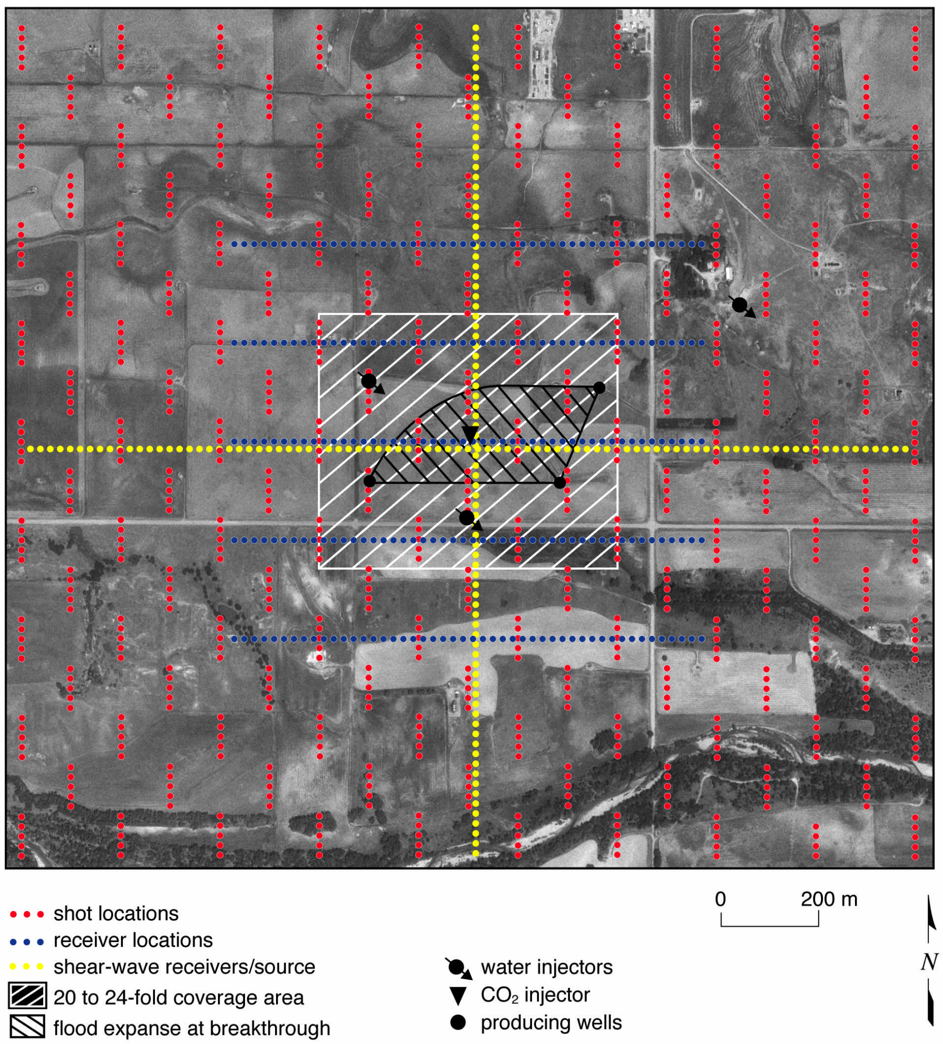


Figure 3. Orthophoto with preliminary 3-D survey design overlaying the wells involved with the CO_2 injection program. The flood extent at breakthrough (indicated by black crosshatching) is fully within the uniform 20 to 24-fold area of the survey. These 810 shot stations and 240 receiver stations will be occupied twelve times in 4_ years before, during, and after flood activities.

OMNI 3-D design software has been used to generate these preliminary designs and will be used to generate the most cost effective and signal-rich design possible for the actual site limitations.

Initial patch designs have limited bin size to a maximum 10 m _ 10 m area while maintaining uniform fold (Figure 4), offset (Figure 5), and azimuthal distributions (Figure 6 and Table 1). Shot lines are perpendicular to receiver lines and staggered to form a modified brick pattern. This pattern makes access and movement along shot lines precarious in some areas. This style patch does complicate the acquisition (source and receiver deployments), but it provides the optimum traces and trace distribution for each bin.

A 240-channel Geometrics Strataview or 240-channel Geometrics Geode distributed system networked to a StrataVisor NZ acquisition controller will record the seismic data.

Considering the offsets and power spectra of walkaway test data acquired in August 2002, a single IVI minivib with a one-of-a-kind prototype high-output Atlas rotary control valve sweeping 4 to 6 times at each source location should be optimal. Sweep frequencies for the P-wave survey will likely range from around 25 to 250 Hz with a 10 second duration. Receivers will be three digital grade 10 Hz Mark Products Ultra2w geophones wired in series with 14 cm oversized spikes. For each survey, geophones will be planted in a fresh spot but within a _ m of the station location as defined during the initial survey. The three-geophone spread will form a 1 m equilateral triangle.

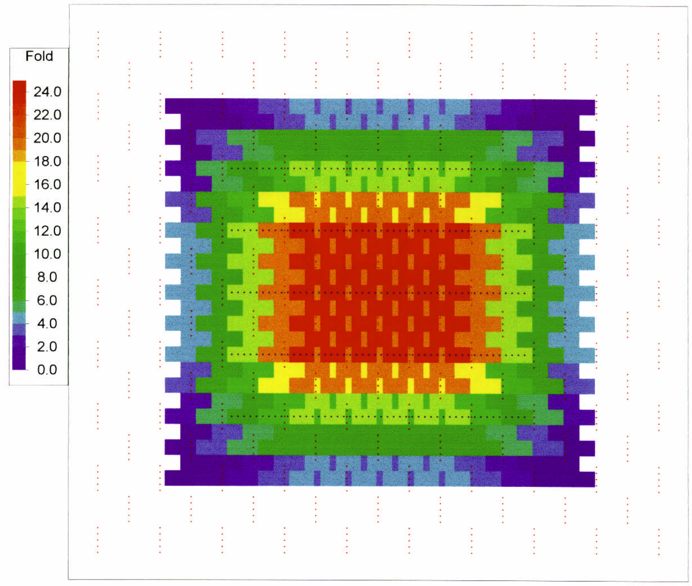


Figure 4. Foldmap with shot and receiver stations in the background. Dark green and blue areas (10 fold and less) define the migration aperture.

Shear wave data will be acquired with the same source (re-configured) and seismograph but with 14 Hz horizontal geophones and a sweep frequency ranging from around 15 to 150 Hz. Both shear wave lines (Figure 3) will be live (recorded) for all shear wave sweeps. The resulting data could be processed as 2-D or 3-D. In-field data analysis and preliminary processing in the KGS mobile processing facility will insure the highest quality data and quickest 3-D processing later at the KGS.

Accurate station surveying is essential for any 3-D seismic reflection program and critical for 4-D surveys. Integral to 4-D surveying is the demand for the utmost in accuracy and therefore repeatability of station locations. The 3.6 km^2 survey grid proposed here will be located

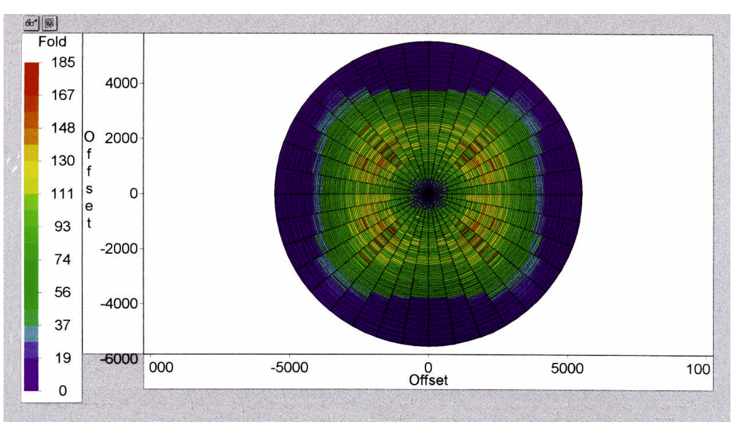


Figure 5. Rose diagram showing the fold distribution with offset and orientation to the patch center.

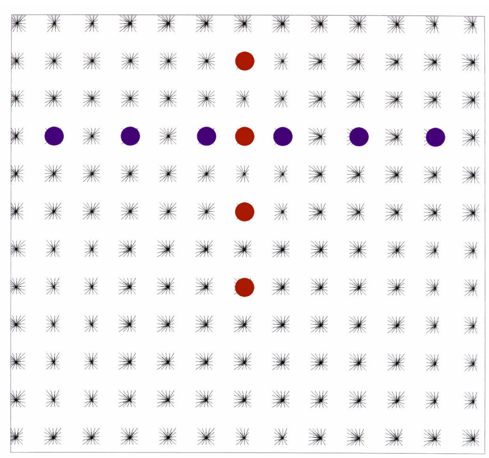


Figure 6. Spider diagram showing the uniformity of azimuthal distribution with offset for each bin.

Table 1.
3-D Survey Parameters

Target depth	910 m	
	P-wave	**S-wave**
Bin width	10 m	
Bin length	10 m	
X_{min}	694.3 m	10 m
X_{max}	1705.7 m	3.2 km
Receiver area	1.0 km^2	
Shot area	3.6 km^2	
Bin area	2.0 km^2	
Number of receivers	240	240
Number of live receivers	240	240
Number of shot stations	810	320
Receiver station interval	20 m	20 m
Shot point interval	20 m	20 m
Receiver line interval	200 m	
Shot line interval	100 m	
Number of receiver lines	5	2
Number of shot lines	19	2
Number of receiver stations/line	48	120
Number of shot stations/line	42.63	160
Total length of receiver lines	4.3 km	4.8 km
Total length of shot lines	27.6 km	

absolutely using a Trimble survey-grade DGPS system. The same digital map will be used to exactly relocate each station for each of the repeat 3-D surveys. Data for each survey will be acquired uninterrupted during 48 hours of continuous operation. If production activity permits, the pump wells will be shut down during shooting of the seismic data to improve signal-to-noise (S/N) ratio.

Generation of a 3-D stacked cube ready for interpreting a month or so after collection will require a high-throughput commercial processing package such as the 2-D/3-D ProMax (a product of Landmark) processing package currently running at the KGS on a dual processor SGI Octane workstation. High-resolution (very short wavelengths) 3-D data will be necessary to have any chance of detecting the different layers within the pay zone at around 900 m. Optimally processing these 3-D data will involve techniques and algorithms developed for petroleum applications but carefully analyzed and applied in a fashion consistent with the needs of shorter wavelength and lower signal-to-noise ratio high-resolution data. Cross-equalization techniques will be evaluated and tailored to minimize or eliminate likely changes in wavelet characteristics, velocity, or statics from survey to survey associated with seasonal changes in near-surface conditions. Conventional seismic reflection technology (2-D and 3-D) is generally considered to be in the mature stages of its development, whereas high-resolution applications, especially in the area of 3-D acquisition and processing, are still in their infancy.

Interpretation of these seismic data will primarily involve difference analysis. Volumes including instantaneous frequency, amplitude, and phase along with impedance and coherency will be generated, compared, and differenced in search of the seismic attribute or attributes most sensitive to CO_2 (fluid) movement in the reservoir. Industry experience confirms that empirical seismic attributes can be correlated with subsurface properties, and that attributes can be estimated using multivariate statistical procedures such as canonical correlation. Calculation of standard attributes and associated interpretations will be done using Kingdom Suites software. Time-to-depth conversions will be based on NMO velocity calculations and borehole sonic data. Animation of flood movement using attribute, synthetic, wiggle trace, and difference cubes will be developed and analyzed with the production of each seismic volume.

Enhancement of reservoir simulation performance will require development of 3-D volumes of geophysical properties for each cell. The first step in creating a model of the reservoir is to determine the multivariate three-dimensional semivariance, which expresses the rate-of-change with distance within the geophysical field. This is done by calculating experimental semivariograms independently for each geophysical property (e.g., impedance and amplitude) that will be mapped. From these semivariograms each cell as defined by the simulator model will be populated with the seismic properties and standard error.

The model is expanded by the introduction of time as an axis in 4-dimensional space-time with a series of cells having uniform temporal spacing. The most appropriate procedure for rescaling (or change of support, as the process is known in the geostatistical literature) involves geostatistical estimation and stochastic simulation (Christakos, 1992; Jeulin, 1994; Olea, 1999). These procedures have been applied mostly in either the time or the space dimension but can be extended to simultaneously include both time and space. The initial set of cells contain only naïve estimates because the data have only two temporal coordinates, but with the acquisition of a third and successive survey, rates-of-change with time can be estimated and used to refine the initial estimates.

Multiple qualitative and quantitative 3D models will be constructed to represent all reservoir characterization data at an appropriate range of realizations. These will both mirror and supplement the reservoir models developed as part of the demonstration project. Elements of the qualitative models will include nature of reservoir rocks, variability in reservoir quality, types, scales, and heterogeneity, reservoir architecture, definition and distribution of flow units, and nature of bedding and flow barriers. Elements of the 3D quantitative model will include grid block dimensions, porosity, effective permeabilities, compressibility, capillary pressure, and fluid properties. All data and models will be compiled in a database and visualized in 3D using one or more modeling software packages.

Reservoir simulation study at well and field levels will be carried out on the reservoir geomodels using PC-based reservoir simulator *IMEX* and using the compositional simulation module *GEM* (Computer Modeling Group Ltd., Calgary, Canada). A numerical approach that will be attempted will require correlation of seismic observations with synthetic seismograms produced from numerical reservoir simulator output, Gassmann’s equations, and simple convolution (Huang et al., 1998). Discrepancies between the simulation output and data from each new 3-D seismic image of the flood will be addressed by refining the reservoir geomodels. Each refinement of the geomodel will be tested against the existing pressure and production history for the flood to insure that the model consistently predicts the history observed. The evolution of the model will be fully documented.

Refinement of both the reservoir simulation model and the seismic interpretation will be interactive. Refinement of the reservoir simulation model will provide new distributions of properties. These in turn will be used to evaluate the seismic results and modify analysis procedures. Feedback will occur throughout the project. In addition, both the seismic and reservoir simulation predictions of saturation changes will be correlated with reported injected and produced fluid volumes to assess the error in material balance between the methods.

Evaluation of the optimum methodology and procedures for monitoring movement and eventual fate of CO_2 injected into this carbonate reservoir will be a major product.

At the conclusion of each phase a milestone is reached that represents a decision point for continuation of the project. Positive, successful findings and confidence in effectiveness of technologies will be necessary to move to the next phase. Detailed discussions and briefings with DOE representatives will represent the forum for making the decision to continue or abort the project.

Phase-by-Phase Tasks to Be Performed

PHASE ONE

Task 1—Finalize design survey
- Subtask 1.1 permits and access
- Subtask 1.2 modify shot and receiver locations based on access
- Subtask 1.3 coordinate with production schemes to minimize noise

Task 2—Acquire/process baseline 3-D P-wave & 2-D S-wave after pressuring reservoir
- Subtask 2.1 GPS survey stations,
- Subtask 2.2 standardize procedure for acquisition of 3-D volumes,
- Subtask 2.3 acquire 3-D compressional wave baseline survey
- Subtask 2.4 acquire 2-D, 2-C shear wave baseline survey
- Subtask 2.5 generate standard, high resolution 3-D volume
- Subtask 2.6 generate standard, 2-D shear cross-sections (SH & SV)
- Subtask 2.7 preliminary attribute analyses
- Subtask 2.8 compare and contrast with all geologic and reservoir information
- Subtask 2.9 evaluate data quality and potential to achieve goals and objectives

Task 3—Develop synthetic from reservoir simulations
- Subtask 3.1 run reservoir model forward in time capturing specific snap-shots
- Subtask 3.2 convert simulation output to synthetic using Gassmann's equations
- Subtask 3.3 compare and contrast baseline synthetic with real seismic volume
- Subtask 3.4 develop optimization scheme to match synthetic and real

PHASE TWO

Task 4—First time-lapse 3-D compressional survey and correlation to predicted
- Subtask 4.1 3-D P-wave survey
- Subtask 4.1.1 GPS survey stations

Subtask 4.1.2 acquire 1st 3-D P-wave survey (fixed procedure)
Subtask 4.1.3 process 1st 3-D P-wave survey
Subtask 4.1.4 refine/optimize processing flows, evaluate cross-equalization techniques
Subtask 4.1.5 reprocess both baseline and 1st time lapse using optimized flow
Subtask 4.1.6 attribute analyses
Subtask 4.1.7 evaluate data & likelihood of satisfactorily achieving goals/objectives
Subtask 4.2 Evaluate flood scheme
Subtask 4.2.1 compare differences between synthetic from simulations & real data
Subtask 4.2.2 iteratively revise flood scheme in simulations
Subtask 4.2.3 develop revised flood scheme to min. or eliminate non-linearities

PHASE THREE

Task 5—Second time-lapse 3-D compressional survey & Evaluate flood scheme
Subtask 5.1 3-D P-wave survey
Subtask 5.1.1 GPS survey stations
Subtask 5.1.2 acquire 2nd 3-D P-wave survey (fixed procedure)
Subtask 5.1.3 process 2nd 3-D P-wave survey (fixed flow based on subtask 4.1.4)
Subtask 5.1.4 attribute analysis and interpretation
Subtask 5.2 evaluate flood scheme
Subtask 5.2.1 compare differences between synthetic from simulations & real data
Subtask 5.2.2 iteratively revise flood scheme in simulations
Subtask 5.2.3 develop revised flood scheme to minimize/eliminate non-linearities

Tasks 6 & 7—repetitive cycle consistent with Tasks 4 and 5

Task 8—Fifth time lapse 3-D P-wave & evaluation of flood scheme & second 2-D, 2-C S-wave
Subtask 8.1 3-D P-wave survey
Subtask 8.1.1 GPS survey stations
Subtask 8.1.2 acquire 5th 3-D P-wave survey (fixed procedure)
Subtask 8.1.3 acquire 1st 2-D 2-C S-wave survey (fixed procedure)
Subtask 8.1.4 process 5th 3-D P-wave survey (fixed flow based on subtask 4.1.4)
Subtask 8.1.5 process 1st 2-D 2-C S-wave survey
Subtask 8.1.6 refine/optimize processing for S-wave, evaluated cross-equalization
Subtask 8.1.7 attribute analysis and interpretation
Subtask 8.1.8 evaluate data & likelihood to satisfactorily achieve goals/objectives
Subtask 8.2 Evaluate flood scheme
Subtask 8.2.1 compare differences between synthetic from simulations & real data
Subtask 8.2.2 iteratively revise flood scheme in simulations
Subtask 8.2.3 develop revised flood scheme to minimize/eliminate non-linearities

Task 9—Sixth time-lapse 3-D compressional survey & flood evaluation
Subtask 9.1.1 GPS survey stations
Subtask 9.1.2 acquire 6th 3-D P-wave survey (fixed procedure)
Subtask 9.1.3 process 6th 3-D P-wave survey (fixed flow based on subtask 4.1.4)
Subtask 9.1.4 attribute analysis and interpretation
Subtask 9.2 evaluate flood scheme
Subtask 9.2.1 compare differences between synthetic from simulations & real data
Subtask 9.2.2 iteratively revise flood scheme in simulations
Subtask 9.2.3 develop revised flood scheme to minimize/eliminate non-linearities

Tasks 10 & 11—repetitive cycle consistent with Task 9
Task 12—Evaluation of flood efficiency and detailed tracking of flood movement
- Subtask 12.1 baseline & all time-lapse seismic volumes animated
- Subtask 12.2 compare/contrast animation of simulations and seismic
- Subtask 12.3 evaluate how well seismic/simulations predict breakthrough
- Subtask 12.4 decimate seismic data to establish min. effort to monitor accurately
- Subtask 12.5 appraise cost effectiveness of 4-D seismic, oil$ > seismic$?
- Subtask 12.6 evaluate how well goals/objectives were achieved

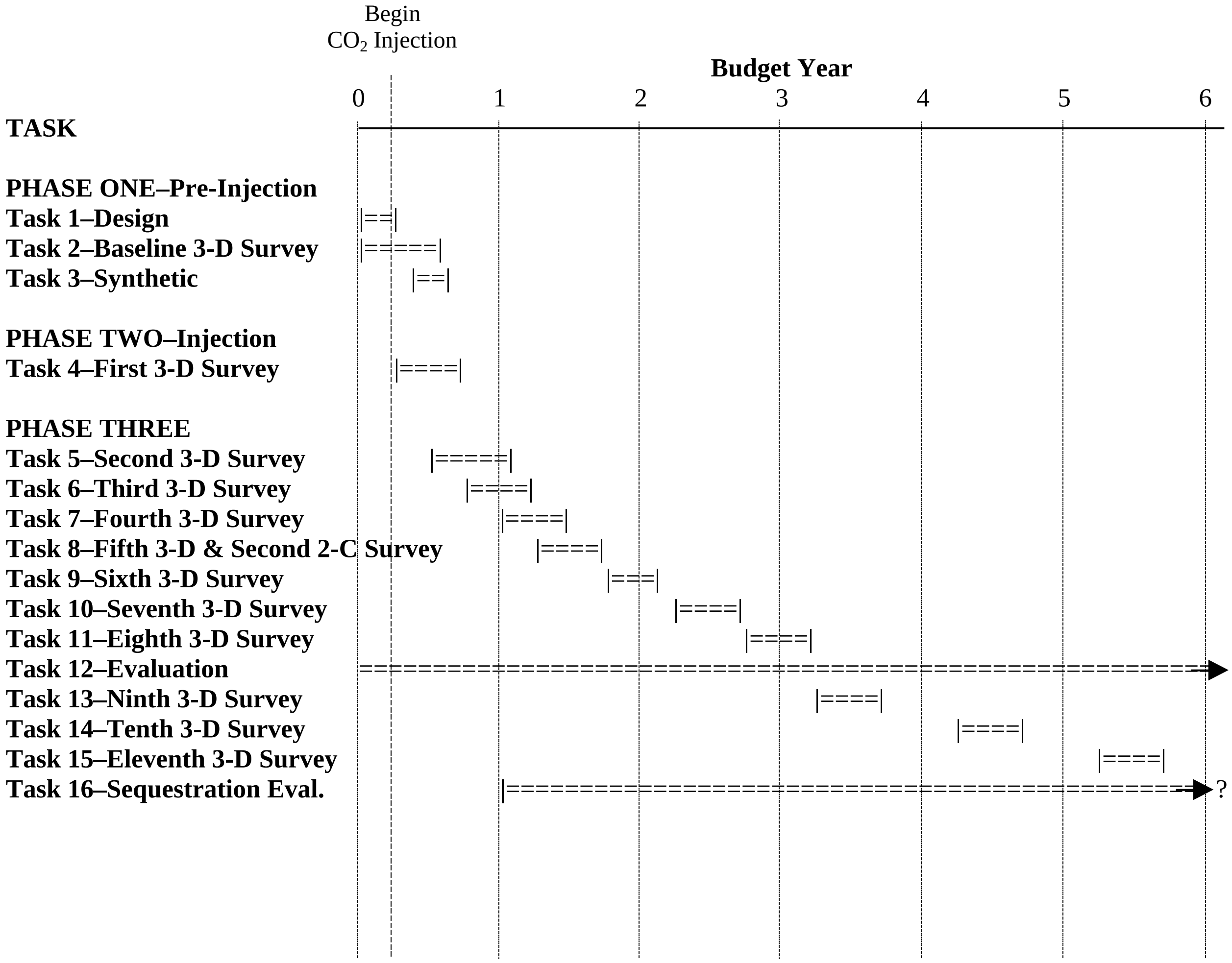
Task 13—Ninth time-lapse 3-D compressional survey & flood evaluation
- Subtask 13.1.1 GPS survey stations
- Subtask 13.1.2 acquire 7th 3-D P-wave survey (fixed procedure)
- Subtask 13.1.3 process 7th 3-D P-wave survey (fixed flow based on subtask 4.1.4)
- Subtask 13.1.4 attribute analysis and interpretation
- Subtask 13.2 evaluate flood scheme
- Subtask 13.2.1 compare differences between synthetic from simulations & real data
- Subtask 13.2.2 iteratively revise flood scheme in simulations
- Subtask 13.2.3 develop revised flood scheme to minimize/eliminate non-linearities

Task 14—Tenth time-lapse 3-D compressional survey & flood evaluation
- Subtask 14.1.1 GPS survey stations
- Subtask 14.1.2 acquire 8th 3-D P-wave survey (fixed procedure)
- Subtask 14.1.3 process 8th 3-D P-wave survey (fixed flow based on subtask 4.1.4)
- Subtask 14.1.4 attribute analysis and interpretation
- Subtask 14.2 evaluate flood scheme
- Subtask 14.2.1 compare differences between synthetic from simulations & real data
- Subtask 14.2.2 iteratively revise flood scheme in simulations
- Subtask 14.2.3 develop revised flood scheme to minimize/eliminate non-linearities

Task 15—Eleventh time-lapse 3-D compressional survey & flood evaluation
- Subtask 15.1.1 GPS survey stations
- Subtask 15.1.2 acquire 9th 3-D P-wave survey (fixed procedure)
- Subtask 15.1.3 process 9th 3-D P-wave survey (fixed flow based on subtask 4.1.4)
- Subtask 15.1.4 attribute analysis and interpretation
- Subtask 15.2 evaluate flood scheme
- Subtask 15.2.1 compare differences between synthetic from simulations & real data
- Subtask 15.2.2 iteratively revise flood scheme in simulations
- Subtask 15.2.3 develop revised flood scheme to minimize/eliminate non-linearities

Task 16—Evaluate sequestration component
- Subtask 16.1 Analyze seismic volumes for evidence of containment breach and movement
- Subtask 16.2 Develop methods and define seismic characteristics that might flag changes in CO_2 stability within reservoir
- Subtask 16.3 Map areas that might have CO_2 outside containment area—possible drill targets
- Subtask 16.4 Evaluate the effectiveness of 4-D seismic as a monitoring tool for both the injection and assurance requirements of CO_2 sequestration

TIMELINE SUMMARY



Deliverables

Throughout the project papers describing significant findings will be produced for presentation and publication at a rate of 2 to 4 per year. It is anticipated that abstracts (AAPG, GSA, AGU, etc.) and expanded abstracts (SEG & EEGS) will be prepared for presentation at national meetings with full journal articles submitted for peer review and publication. Associated with these presentations and peer reviewed journal publications will be reports and results posted on a dedicated web page. Utilizing the web as an interim reporting media has been an effective tool used by this research team to communicate results with the U.S. Army and others on previous research projects. With twelve unique data acquisition campaigns carried out on a non-uniform schedule, dynamic reporting will be done both in the field through wireless connections to the web page and at various milestones throughout the project. All reservoir simulation model refinements will be documented to provide a "history" of the changes in the model, a result of information obtained from each survey. Input files and modeling results will be available on the web. Web reporting pages will have both public and password-protected parts. Each task will have a report or segment dedicated to the associated activities. At any time there may be as many as 5 to 6 tasks with information being brought on-line simultaneously.

Approaches, techniques, or methodologies developed in association with this study will be transferred to the industry through demonstrations, publications, and seminars. The web will serve not only as the interim reporting needs, but it will also act as a data and information resource for industry. Graphics with discussion of data examples at various stages of the acquisition and processing will be available as well as any code developed for unique problems or interpretations. Availability to cooperate on field demonstrations and assist with the design of optimum surveys for similar commercial applications will be an on-going activity. All data will be made available to any industry, government, academic, and research groups requesting it.

Potential Obstacles and Mitigation Strategies

All seismic surveys have problems and setbacks. Over two decades of experience with high-resolution seismic reflection surveying provides an outstanding footing to both recognize and address obstacles that can negatively impact the usefulness of a seismic survey. Listed below are the most likely problems and tentative solutions:

access limitations—redesign 3-D survey to compensate as best possible. The only question presently relates to surface access on the southeast, other surface ownership positions have been investigated and are favorable.

acquisition equipment malfunctions—equipment is in excellent shape, the minivib manufacturer is only 2 hours away, and spare seismographs will be on-site. Redundancy exists in all hardware two or three fold (rental vib ready to be on-site within hours, only SGI workstation without a redundant system, but contract service and repair local).

weather problems—weather delays are possible, shooting will only be in best conditions for the scheduled time of year and site access issues. All-weather equipment will be used.

processing difficulties—variability between processed sections not related to CO_2 injection and cannot be compensated for using standard high-resolution processing flows. Post-stack cross-equalization and a variety of surface-consistent cross-equalization techniques will be used. At worst a delay in posting the findings will result.

hardware failures—redundant systems will be on-site for all hardware. Data will be stored on two different media and in two different places within hours of creation.

CO_2 seismically undetectable—focus will shift to secondary goals such as optimization techniques for high-resolution imaging shallow reservoirs with very small profit margins.

data resolution or signal-to-noise limitations—focus on tracking CO_2 through the entire 4 m pay zone as a single interval and look at indirect detection of the fluid changes.

non-unique reservoir simulation methods—reservoir simulations do not represent unique solutions modeling. The model(s) developed will honor all available data and variations in uncertainty.

Quality and Suitability of Facilities, Equipment, and Materials

All seismic equipment is state-of-the-art, most customized for high-resolution applications. This program boasts ownership of the most extensive, best maintained, and optimally specialized high-resolution seismic equipment in the world with expert operators possessing a wide range of field experience.

Seismic system—Geometrics 240-channel R60 StrataView w/StrataVisor NZC for 240-channel Geode

Source—IVI Buggy minivib vibrator w/3.5 psi ground pressure (15-500 Hz, 10,000 lb peak force) with Atlas high-output rotational valve (prototype)

Geophones—Triple 10 Hz U2w & Double 40 Hz L28E both by Mark Products;
GS-11D, 14 Hz horizontal, Geospace

Cables—Over 300 takeouts of seismic cable purchased within the last two years with over 2 km of pass cable

Field Processing Center—Semi truck with climate controlled processing center: Thermal printer, color plotter, three P4-class PCs, workstations for three staff, network to seismograph.

Other Supporting Software and Equipment

2-D/3-D ProMax, WinSeis 2, SIS Kingdom Suites Interpretation Package
IMEX PC Reservoir Simulator, GEM module from Computer Modeling Group Ltd.
SGI, Octane-w/dual 400 MHz processors, 40GB HD, 256 MB RAM, CD-ROM, 8mm Exabyte
25 Pentium-class PCs (over half greater than 1 Ghz)
Over 2 Terabyte portable HD space available in mobile processing center
4mm DAT, 8mm Exabyte, 9-track tape drives, CDR
36-inch high resolution color plotter

Field Support equipment—VHF radios (over a dozen handheld and vehicle mounts), Auto-line checker, Cable and geophone testing equipment, Complete set of spare parts for minivib, Generators, Surveying equipment (Trimble 4800 and 4700 differential GPS real-time sub 10 cm x,y,z), Cable adapters and jumpers, Bench grade seismograph analyzer, Tracked ATV's, three 6-wheel ATV's, portable shop with repair and maintenance capabilities, etc.

All equipment is transported to the site by KGS vehicles

1997 Freightliner with utility box and 35 ft flatbed vibrator transport trailer
2001 International with data processing center facility pulling 36 ft covered trailer

Qualification of Organization and Previous Experience

The Kansas Geological Survey is a research division of the University of Kansas and a recognized expert in high-resolution seismic reflection with demonstrated expertise in petroleum geology. Previous experience in the field includes applied research in 2-D and 3-D high-resolution imaging from the Arctic to South Texas. The objectives have been delineating subtle or small-scale geologic features at depths ranging from 2 m to 1.5 km. With applied research projects in over 30 states and 5 foreign countries focusing on difficult targets, the KGS brings an experienced high-resolution seismic imaging and reservoir geology team together capable of developing innovative techniques and formulating novel concepts. This group, as a whole, possesses decades of experience in midcontinent petroleum reservoir research.

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ATTACHMENT A

Project Timeline and Milestones

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                                             Begin
                                        CO2 injection                BUDGET YEAR
MILESTONES                                   *      *
                                   0                 0.5                1.0                1.5                2.0                2.5                3.0
TASK                               ______________________________________________________________________________________________________________________

PHASE ONE–Pre-Injection
Task 1–Design                      |====|
1.1 Permits                        |-----|
1.2 Modify pattern                    |-----|
1.3 Coord. Production scheme       |-------|
Task 2–Baseline 3-D Survey         |==========|
2.1 GPS                            |--------|
2.2 Standardize procedure             |------------|
2.3 Acquire 3-D P-wave                   |--|
2.4 Acquire 2-D, 2-C S-wave              |--|
2.5 Process 3-D P-wave                      |---|
2.6 Process 2-D, 2-C S-wave                 |---|
2.7 Attribute analysis                        |---|
2.8 Compare/contrast w/geology                 |--|
2.9 Evaluate potential                  |----------|
Task 3–Synthetic                                 |===|
3.1 Reservoir model run                          |--|
3.2 Convert to seismic synthetic                  |--|
3.3 Compare/contrast                                |--|
3.4 Optimize procedure                               |--|

PHASE TWO–Injection                          1 month after
Task 4–First 3-D Survey                     |========|
4.1 3-D P-wave survey
4.1.1 GPS                                   |-|
4.1.2 Acquire 3-D P-wave                     |-|
4.1.3 Process 3-D P-wave                     |-------|
4.1.4 Refine/optimize processing             |-----|
4.1.5 Reproc. baseline & 1st 3-D                  |--|
4.1.6 Attribute analysis                           |--|
4.1.7 Evaluate potential                          |---|
4.2 Evaluation flood
4.2.1 Compare synthetic to real                        |---|
4.2.2 Iteratively revise flood                         |---|
4.2.3 Devise new flood scheme                           |--|

PHASE THREE                                         3 months after
Task 5–Second 3-D Survey                           |=========|
5.1 3-D P-wave survey
5.1.1 GPS                                          |-|
5.1.2 Acquire 3-D P-wave                             |-|
5.1.3 Process 3-D P-wave                              |------|
5.1.4 Attributes/interpretation                            |------|
5.2 Evaluation flood
5.2.1 Compare                                                 |---|
5.2.2 Iteratively revise flood                                 |---|
5.2.3 Devise new flood scheme                   |--|
```

MILESTONES — Begin CO_2 injection * *

BUDGET YEAR: 0 | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0

TASK	
Task 6–Third 3-D Survey	6 months after |========|
6.1 3-D P-wave survey	
6.1.1 GPS	|-|
6.1.2 Acquire 3-D P-wave	|-|
6.1.3 Process 3-D P-wave	|-----|
6.1.4 Attributes/interpretation	|-----|
6.2 Evaluation flood	
6.2.1 Attributes/interpretation	|----|
6.2.2 Iteratively revise flood	|----|
6.2.3 Devise new flood scheme	|--|
Task 7–Fourth 3-D Survey	9 months after |========|
7.1 3-D P-wave survey	
7.1.1 GPS	|-|
7.1.2 Acquire 3-D P-wave	|-|
7.1.3 Process 3-D P-wave	|------|
7.1.4 Attributes/interpretation	|----|
7.2 Evaluation flood	
7.2.1 Attributes/interpretation	|----|
7.2.2 Iteratively revise flood	|----|
7.2.3 Devise new flood scheme	|----|
Task 8–Fifth 3-D & Second 2-C Survey	12 months after |========|
8.1 Surveys	
8.1.1 GPS	|-|
8.1.2 Acquire 3-D P-wave	|--|
8.1.3 Acquire 2-D, 2-C S-wave	|-|
8.1.4 Process 3-D P-wave	|----|
8.1.5 Process 2-D, 2-C S-wave	|--|
8.1.6 Refine/opt. S-wave process	|---|
8.1.7 Attributes/interpretation	|-----|
8.1.8 Evaluate data & goals	|---|
8.2 Evaluation flood	
8.2.1 Compare synthetic to real	|---|
8.2.2 Iteratively revise flood	|---|
8.2.3 Devise new flood scheme	|--|
Task 9–Sixth 3-D Survey	18 months after |=======|
9.1 Survey	
9.1.1 GPS	|-|
9.1.2 Acquire 3-D P-wave	|--|
9.1.3 Process 3-D P-wave	|----|
9.1.4 Attributes/interpretation	|-----|
9.2 Evaluation flood	
9.2.1 Compare synthetic to real	|---|
9.2.2 Iteratively revise flood	|---|
9.2.3 Devise new flood scheme	|--|

BUDGET YEAR

MILESTONES

2.0 2.5 3.0 3.5 4.0 4.5 5.0

TASK

24 months after

Task 10–Seventh 3-D Survey |=======|

10.1 Survey

10.1.1 GPS |-|

10.1.2 Acquire 3-D P-wave |--|

10.1.3 Process 3-D P-wave |----|

10.1.4 Attributes/interpretation |-----|

*10.2 Evaluation flood

10.2.1 Compare synthetic to real |---|

10.2.2 Iteratively revise flood |---|

10.2.3 Devise new flood scheme |--|

30 months after

Task 11–Eighth 3-D Survey |=======|

11.1 Survey

11.1.1 GPS |-|

11.1.2 Acquire 3-D P-wave |--|

11.1.3 Process 3-D P-wave |----|

11.1.4 Attributes/interpretation |-----|

*11.2 Evaluation flood

11.2.1 Compare synthetic to real |---|

11.2.2 Iteratively revise flood |---|

11.2.3 Devise new flood scheme |--|

Task 12–Evaluation

12.1 Baseline & all time lapse

12.2 Comp./contrast animation

12.3 Evaluate prediction

12.4 Decimate, min. effort

12.5 Appraise cost

12.6 Evaluate goals/objectives

36 months after

Task 13–Ninth 3-D Survey |=======|

13.1 Survey

13.1.1 GPS |-|

13.1.2 Acquire 3-D P-wave |--|

13.1.3 Process 3-D P-wave |----|

13.1.4 Attributes/interpretation |-----|

*13.2 Evaluation flood

13.2.1 Compare synthetic to real |---|

13.2.2 Iteratively revise flood |---|

13.2.3 Devise new flood scheme |--|

48 months after

Task 14–Tenth 3-D Survey |=======|

14.1 Survey

14.1.1 GPS |-|

14.1.2 Acquire 3-D P-wave |--|

14.1.3 Process 3-D P-wave |----|

14.1.4 Attributes/interpretation |-----|

*14.2 Evaluation flood

14.2.1 Compare synthetic to real |---|

14.2.2 Iteratively revise flood |---|

14.2.3 Devise new flood scheme |--|

TASK	BUDGET YEAR 3.0 – 3.5 – 4.0 – 4.5 – 5.0 – 5.5 – 6.0
Task 15–Eleventh 3-D Survey	60 months after |=======|
15.1 Survey	
15.1.1 GPS	|-|
15.1.2 Acquire 3-D P-wave	|--|
15.1.3 Process 3-D P-wave	|----|
15.1.4 Attributes/interpretation	|-----|
*15.2 Evaluation flood	
15.2.1 Compare synthetic to real	|---|
15.2.2 Iteratively revise flood	|---|
15.2.3 Devise new flood scheme	|--|
Task 16–Eval. Sequestration	◄====================►
16.1 Analysis for breach	◄--------------------► ?
16.2 Changes in CO_2	◄--------------------► ?
16.3 Map uncontained CO_2	◄--------------------► ?
16.4 Evaluate effectiveness	|---------------|

* New flood scheme after CO_2 injection has ceased involves production and water injection to guide remaining reserves to production wells. Simulations will not be run once the formation is shut in and no injection activities are planned.

ATTACHMENT C

Vitae of Team Members

RICHARD D. MILLER

Education

B.A., Physics (Minor, Chemistry), Benedictine College, 1980.
M.S., Physics, Emphasis Geophysics, University of Kansas, 1983.

Professional Experience

Associate Scientist, Kansas Geological Survey, University of Kansas, 1996-present.
Courtesy Associate Professor of Geology, Department of Geology, University of Kansas, 1997-present.
Chief, Exploration Services Section, Kansas Geological Survey, University of Kansas, 1987-present.
Seismic Application Research experience in thirty-three states and six foreign countries.

Pertinent Publications

Miller, R.D., A. Villella, J. Xia, and D.W. Steeples, Seismic investigation of a salt dissolution feature in Kansas: *Special Publication: Near-Surface Geophysics, Volume II,* Society of Exploration Geophysicists, in press.

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ALAN P. BYRNES

PRESENT POSITION:

Research Geologist
Kansas Geological Survey
University of Kansas
Lawrence, Kansas 66047

EDUCATION:

M.S. University of Chicago, Geophysical Sciences, 1977
B.S. University of Illinois at Chicago, Geological Sciences (honors & distinction), 1975

PERTINENT EXPERIENCE:

1997-Present	Research Geologist, Kansas Geological Survey, University of Kansas, Lawrence, KS
1995-1997	Hydrogeologist, Tetra Tech, Inc., Lenexa, KS
1983-1995	Owner/Manager, GeoCore (Special core analysis laboratory), Boulder, CO
1982-1983	Geotechnical Engineer, Xytel Corporation, Mt. Prospect, IL
1980-1982	Associate Geologist, Marathon Oil Company, Denver Research Center, Littleton, CO
1977-1980	Earth Scientist, Institute of Gas Technology, Chicago, IL
1975-1978	Research Assistant, University of Chicago, Chicago, IL

HONORS:

AAPG Roger N. Planalp Award
AAPG Jules Braunstein Award

MEMBERSHIP IN PROFESSIONAL ORGANIZATIONS:

American Association of Petroleum Geologists
Society of Petroleum Engineers
Society of Core Analysts
Society of Professional Well Log Analysts

PERTINENT PUBLICATIONS:

Byrnes, A.P., K. Sampath, and P.L. Randolph. 1979. Effect of pressure and water saturation on the permeability of western tight sandstones, Proceedings of the 5th Annual DOE Symposium Enhanced Oil and Gas Recovery, Tulsa, Oklahoma, August 22 -26, p. 247-263.

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SAIBAL BHATTACHARYA

PRESENT POSITION:

Petroleum/Reservoir Engineer
Kansas Geological Survey

EDUCATION:

M.S.	1995	University of Kansas, Lawrence, Ks., Petroleum Engineering
M.S.	1996	University of Kansas, Lawrence, Ks., Environmental Engineering
B.Tech.	1987	Indian School of Mines, Dhanbad, India, Petroleum Engineering

PERTINENT EXPERIENCE:

January, 1995-Present	Kansas Geological Survey, Petroleum Engineer
August, 1994-May, 1995	University of Kansas, Graduate Teaching Assistant in Environmental Engineering
July, 1992-July, 1994	University of Kansas, Research Assistant for the Tertiary Oil Recovery Project
1987-January, 1992	National Oil Company of India (ONGC), Reservoir Engineer

HONORS:

Recipient of the Norman Plummer Award from the Kansas Geological Survey in 1996 for outstanding engineering work.

Awarded "Certificate of Merit" by the National Oil Company of India (ONGC) for services rendered as a Reservoir Engineer in 1990.

MEMBERSHIP IN PROFESSIONAL ORGANIZATIONS:

Tau Beta Pi (engineering honor society)
Society of Petroleum Engineers
American Association of Petroleum Geologists

PERTINENT PUBLICATIONS:

Bhattacharya, S., Gerlach, P.M., and Carr, T.R., 2002, Cost-effective techniques for the independent producer to evaluate horizontal drilling candidates in mature areas; *under publication in*, Carr, T., Mason, E., Feazel, C. (eds), Horizontal wells – Focus on the Reservoir, AAPG Memoir.

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RELATED PRESENTATIONS:

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MARTIN K. DUBOIS

CURRENT POSITION:
Research Geologist
Kansas Geological Survey, University of Kansas
1930 Constant Avenue
Lawrence, Kansas 66047

FORMAL EDUCATION:

B.S. Geophysics *(cum laude)*, Kansas State University, 1974
M.S. Geology *(honors)*, University of Kansas, 1980

PROFESSIONAL EXPERIENCE:

1999-Present	Research Geologist, Petroleum Research Section, Kansas Geological Survey, University of Kansas, Lawrence, Kansas
1992-1999	Exploration Manager, John O. Farmer, Inc., Russell, Kansas
1979-1992	Consulting Petroleum Geologist, Winfield, KS
1977-1979	Graduate teaching assistant, University of Kansas, Lawrence, Kansas
1975-1977	Exploration Geologist, Cities Service Oil Company, Tulsa and Oklahoma City, Oklahoma

SELECTED HONORS:

H.A. Ireland Honor Award, graduate student award, University of Kansas, 1978.
Jules Braunstein Memorial Award for best poster at AAPG annual meeting in Denver, Colorado, 2001.
Division of Environmental Geosciences award for best poster presentation for the Division of Environmental Geosciences, AAPG annual meeting, Houston, 2002.
President's Certificate for Excellence in Presentation (Poster), Energy Minerals Division, AAPG annual meeting, Houston, 2002.

PROFESSIONAL:

American Association of Petroleum Geologists
Kansas Geological Society
Rocky Mountain Association of Geologists
AAPG Certified Petroleum Geologist #3622
Kansas Geologist License #408

ABSTRACTS AND PUBLICATIONS:

Dubois, M.K., 1980, Paleotopography's influence on porosity distribution in the Lansing-Kansas City "E" zone, Hitchcock County, Nebraska (abs.), American Association of Petroleum Geologists Bulletin, V. 64, p. 701.

Dubois, M.K., 1983, Application of cores in development of an exploration strategy for the Lansing-Kansas City "E" zone, Hitchcock County, Nebraska, Kansas Core Workshop Notes, Mid-Continent AAPG Sectional Meeting, Wichita, Kansas, pp. 147-167.

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Dubois, M.K., S.W. White and T.R. Carr, 2002, Co-generation, ethanol production and CO_2 enhanced oil recovery: a model for environmentally and economically sound linked energy systems (abs.), 2002 American Association of Petroleum Geologists Annual Convention, V. 11, p. A46. http://aapg.confex.com/aapg/hu2002/techprogram/paper_43623.htm

Dubois, M.K., S.W. White and T.R. Carr, 2002, Co-generation, ethanol production and CO_2 enhanced oil recovery: a model for environmentally and economically sound linked energy systems, KGS Open-file Report 2002-6. http://www.kgs.ukans.edu/PRS/Poster/2002/2002-6/index.html

Dubois, M.K., 2002, Economic analysis, *in* R. Reynolds, ed., Improving Oil Recovery Using Integrated Evaluation Techniques, Petroleum Technology Transfer Council seminar manual, Wichita Kansas, April 23, 2002.

Dubois, M.K., S.W. White, T.R. Carr, and A.P. Byrnes, 2002, CO_2 enhanced oil recovery, co-generation, ethanol production linked, The Class Act, DOE's Field Demonstration Best Practices Newsletter, June 2002, V. 8, No. 2. http://www.npto.doe.gov/CA/CASum2002.pdf

W. LYNN WATNEY

PRESENT POSITION:

Executive Director, The University of Kansas Energy Research Center, 1991-present.
Courtesy Professor of Geology, University of Kansas and Kansas State University, 1988-present.
Senior Scientist, Kansas Geological Survey

EDUCATION:

A.A.	1968	North Iowa Area Community College, Mason City, Iowa
B.S.	1970	"With Distinction," Iowa State University, Ames, Iowa; (Major: Geology; Minors: Chemistry, Mathematics)
M.S.	1972	Iowa State University, Ames, Iowa, Geology
Ph.D.	1985	University of Kansas, Geology

PERTINENT EXPERIENCE:

1990-1991	Special Assistant for Energy Research, Kansas Geological Survey
1987-1990	Chief, Petroleum Research Section, Kansas Geological Survey, The University of Kansas, Lawrence, Kansas
1983-1987	Chief, Geologic Investigations Section, Kansas Geological Survey, The University of Kansas, Lawrence, Kansas
1981-1983	Chief, Subsurface Geology Section
1976-1981	Research Associate, Subsurface Geology Section, Kansas Geological Survey, The University of Kansas, Lawrence, Kansas
1972-1976	Development and Exploration Geologist, Chevron U.S.A., New Orleans, Louisiana

HONORS:

Phi Kappa Phi Scholastic Honorary (Iowa State University), 1972
Erasmus Haworth Graduate Honors in Geology, (KU), 1985
Honorable Mention for Best Paper -Watney, W.L., French, J., Wong, J.C., and Black, R., 1992, Time-series analysis of natural gamma ray logs from the Midcontinent - tectonic or eustatic signal: SEPM/Society of Sedimentary Geology, Mid-year Meeting
Certificate of Merit Award, AAPG Mid-Continent Section, 1999
Candidate for President, Society of Sedimentary Geology (SEPM), 1999
Distinguished Achievement Citation from Iowa State University, 2001
Jules Braunstein Award, AAPG Annual Meeting, 2001

MEMBERSHIP IN PROFESSIONAL ORGANIZATIONS:

Member, Society for Sedimentary Geology (SEPM), American Association of Petroleum Geologists, Geological Society of America, Society of Petroleum Engineers, Kansas Geological Society
Secretary-Treasurer, Society of Sedimentary Geology (SEPM), 1996-1998
Kansas Geological Society Board of Directors, 1999-2000

PERTINENT PUBLICATIONS:

Youle, J.C., Watney, W.L., and Lambert, L.L., 1994, Stratal hierarchy and sequence stratigraphy-Middle Pennsylvanian, southwestern Kansas, U.S.A.; in Klein, G.D., ed., Pangea: Paleoclimate, Tectonics, and Sedimentation during Accretion, Zenith, and Breakup of a supercontinent: Boulder, CO, Geological Society of America, Special Paper 288, p. 267-285.

Watney, W.L., and French, J.A., 1994, Petroleum reservoir evaluation in the predictive stratigraphic analysis program, in Cecil, B.C., and Edgar, T.N., eds., Predictive stratigraphic analysis; concepts and application: U.S. Geological Survey Bulletin, p. 68-70.

Watney, W.L., French, J.A., Doveton, J.H., Youle, J.C., and Guy, W.J., 1995, Cycle hierarchy and genetic stratigraphy of Middle and Upper Pennsylvanian strata in the upper Mid-Continent, in Hyne, N., ed., Sequence Stratigraphy in the Mid-Continent, Tulsa Geological Society, Special Publication #3, p. 141-192.

Watney, W.L., French, J.A., and Guy, W.J., 1996, Modeling of Petroleum Reservoirs in Pennsylvanian Strata of the Midcontinent, USA, in, Forester, A., and Merriam, D.F., eds., Spatial Modeling of Geologic Systems, Plenum Press, p. 43-77. (3-D descriptive modeling in Victory Field and stratigraphic simulation modeling of Lansing-Kansas City)

Bohling, G.C., Doveton, J.H., and Watney, W.L., 1996, Systematic identification of sequence stratigraphic units from wireline logs: in, Pacht, J.A., Sheriff, R.E., and Perkins, B.F., Stratigraphic Analysis Utilizing Advanced Geophysical, Wireline, and Borehole Technology for Petroleum Exploration and Production: Seventeenth Annual Research Conf., Gulf Coast Section, SEPM Foundation, Houston, Tx., p. 29-37. (Lansing-Kansas City, Victory Field in Haskell County, KS.)

Watney, W.L., Kruger, Davis, J.C., Harff, J., Olea, R.A.., and Bohling, G.C., 1999, Validation of Sediment Accumulation Regions in Kansas, U.S.A.: Proceedings of Symposium, Computerized Modeling of Sedimentary Systems, Harff, ed., Computerized Basin Analysis, Springer, p. 341-360.

Watney, W.L., W.J. Guy, J.H. Doveton, S. Bhattacharya, P. M. Gerlach, G. C. Bohling, T. R. Carr, 1999, Petrofacies Analysis - A petrophysical tool for geologic/engineering reservoir characterization: Proceedings of the Fourth International Reservoir Characterization Technical Conference, American Association of Petroleum Geologists Memoir 71, p. 73-90.

Harbaugh, J. (senior editor), Watney, L. (production editor), Rankey, E., Goldstein, R., and Franseen, E., eds., 1999, Numerical Experiments in Stratigraphy, SEPM - Society of Sedimentary Geology, Special Pub. 62, 362 p.

Watney, E. and Rankey, E., 1999, "Of the Making of Earth Science Models There is No End....": in Harbaugh, J., Watney, W.L., Rankey, E., Goldstein, R., and Franseen, E., eds., Numerical Experiments in Stratigraphy, SEPM – Society of Sedimentary Geology, Special Publication 62, p. 3-21.

Bhattacharya, S., Watney, W.L., Doveton, J.H., Guy, W.J., Bohling, G., 1999, From geomodels to engineering models – Opportunities for spreadsheet computing: Gulf Coast Section Society SEPM, Advanced Reservoir Characterization for the Twenty-First Century, Nineteenth Annual Bob F. Perkins Research Conference, Gulf Coast Section, SEMP Foundation, Houston, TX. , p. 179-193.

Doveton, J.H., Watney, W.L., and Guy, W.J., 2000, Integrated analysis of reservoir petrofacies in platform carbonates of Kansas: techniques and case studies, in Johnson, K.S., ed., Platform carbonates in the southern Midcontinent, 1996 symposium: Oklahoma Geological Survey Circular 101, p. 223-225.

Watney, W.L., Guy, W.J., and Byrnes, A.P., 2001, Characterization of the Mississippian Osage Chat in South-Central Kansas: American Association of Petroleum Geologists Bulletin, v. 85, p. 85-114.

Miller, R.D., Watney, W.L., Begay, D.K., and Xia, J., 2001, High-resolution seismic reflection to delineate shallow gas in eastern Kansas, in Merriam, D.F., ed., Kansas Geological Survey Special Issue, The Compass, v. 75, p. 134-145.

Heckel, P.H., and Watney, W.L., 2002, Revision of Stratigraphic Nomenclature and Classification of the Pleasanton, Kansas City, Lansing, and Lower Part of the Douglas Groups (Lower Upper Pennsylvanian, Missourian) in Kansas: Kansas Geological Survey Bulletin 246, 68 p.

DANA ADKINS-HELJESON

Present Position:

Program Assistant
Kansas Geological Survey
1930 Constant Ave.
Lawrence, KS 66047-3726

Education:

B.S.	New Mexico Institute of Mining and Technology, Socorro, NM 87801 Basic Sciences, 1983

Pertinent Experience:

1995-Present	Kansas Geological Survey, Lawrence, KS 66047 World Wide Web site administrator Responsible for maintenance of web server, creation of web content. Largest projects include Digital Petroleum Atlas, Dakota Aquifer Program, several online versions of educational projects.
1996-Present	Kansas Geological Survey, Lawrence, KS 66047 Oracle Database programmer Created input and output screens and support software for several databases, including plugged wells, water levels, core library holdings, and electric log library. Used both PL/SQL and ColdFusion.
1992-1995	Kansas Geological Survey, Lawrence, KS 66047 Programming Created small routines using Visual Basic. Wrote and maintained contour mapping software for Macintosh.
1988-1992	Interactive Concepts Incorporated, Lawrence, KS 66044 Wrote and maintained contour mapping software for UNIX and Macintosh computers.
1983-1988	Kansas Geological Survey, Lawrence, KS 66044 Collected, reduced, and interpreted gravity and aeromagnetic data.
1978-1983	New Mexico Bureau of Mines and Mineral Resources, Socorro, NM 87801 Bibliographer

WILLIAM E. HARRISON

Deputy Director & Chief Geologist, Kansas Geological Survey [University of Kansas]

Past-President, Division of Environmental Geosciences [American Association of Petroleum Geologists]

Education

B. S. (Geology) Lamar State College of Technology
M. S. (Geology) University of Oklahoma
Ph. D. (Geochemistry) Louisiana State University

Employment History

U.S. DOE - Idaho National Engineering & Environmental Laboratory
1994-97 *Manager*, Geotechnology Department {Lockheed-Martin Idaho}
1992-94 *Manager*, Environmental, Earth, & Life Sciences {EG&G Idaho}
1989-92 *Manager*, Geoscience {EG&G Idaho}

ARCO Oil and Gas Company [Plano, Texas]
1984-89 *Research Director*, Exploration Research

Oklahoma Geological Survey/University of Oklahoma [Norman, Oklahoma]
1975-84 *Faculty/staff geologist*-First recipient, Klabzuba Chair of Geology

ARCO Oil and Gas Company [Dallas, Texas]
1973-75 *Sr. Research Geochemist*

SHELL Oil Company [Houston, Texas & New Orleans, Louisiana]
1968-71 *Exploration Geologist*

Professional Activities

Registered Geologist –WY & PA; Certified Professional Geologist (AIPG); Certified Petroleum Geologist (AAPG); DOE National Peer Review Panel; Idaho Geological Advisory Council; served in appointed and elected local, state, and national positions in various societies and associations; over 65 technical publications on petroleum and organic geochemistry, paleothermometry, heavy oil deposits, reservoir & fluid characteristics of Oklahoma oil fields, geothermal resource assessment, gas hydrates, and undiscovered oil and gas potential of Alaska; Shipboard Organic Geochemist-DSDP Leg 67-first-ever documented recovery of naturally occurring marine gas hydrates; have served as consultant to industry, academia, and state & federal agencies.

Co-Editor, AAPG Book (May 2001), *Geological Perspectives of Global Climate Change* {also co-author of Chapter 2}, 372 p.

JOHN C. DAVIS

1. Affiliation President
Davis Consultants Inc.
Box 353, Baldwin City, KS 66006-0353

2. Degrees with fields, institution, and date

M.S., Geology, University of Wyoming	1963
B.S., Geology, The University of Kansas (Lawrence, KS, USA)	1961

3. Professional experience

Junior Geologist, Pan American Petroleum Corp. (summer)	1963
Instructor, Dept. Geology, Idaho State University, Pocatello, ID	1964–66
Research Associate, Kansas Geological Survey, The University of Kansas	1966–77
President, Davis Consultants Inc	1967-2003
Associate Professor, KU Dept. Chemical & Petroleum Engineering	1970–74
Visiting Professor, WSU Dept. Geology, Wichita, KS	1969–70
Chief, Mathematical Geology Section, Kansas Geological Survey, Univ. KS	1970–2003
Visiting Senior Fellow, Dept. Geography, University of Nottingham, UK	1972–73
Courtesy Professor, KU Dept. Geography	1974–95
Professor, KU Dept. Chemical & Petroleum Engineering	1974–2003
Visiting Professor, Instituto de Geografia, UNAM, Mexico City, Mexico	1976
Senior Scientist, Kansas Geological Survey, The University of Kansas	1977–2003
Fulbright Senior Research Fellow, Austrian–American Educ. Commission	1993–94
Visiting Professor, Dept. Applied Math., Montanuniversität–Leoben, Leoben, Austria	1993–94

4. Consulting since 1995

Alps-Adria Confederation, Leoben, Austria: Umweltgeochemie in Kalkarealen/Mapping	1994-95
Amoco Exploration Co., Tulsa, OK: Assessing hydrocarbon yield for risk analysis	1995
École Nationale Supérieure du Pétrole, Paris: Risk assessment and oil prospect evaluation	1997
Chesapeake Petroleum Co., Dallas, TX: Directional steering in horizontal drilling	1998–99
Bundesministerium für wirtschaftliche Angelegenheiten, Vienna: Autocartography	1998–2003
Heinemann Oil Technology (HOT), Leoben, Austria: Risk assessment in oil exploration	2003

5. Principal publications since 1995

Total Refereed Publications since 1995: 40. A selected list of 12 publications is given below.

1. Harbaugh, J.W., J.C. Davis and J. Wendebourg, 1995, *Computing Risk for Oil Prospects: Principles and Programs*: Elsevier Science Ltd., Oxford, 452 pp., 3 diskettes.
2. Davis, J.C., 1995, Both sides of the coin—The role of probabilistic modeling in the minerals industry: *Berg- und Hüttenmännische Monatshefte*, Jahrgang 140, Heft 4, Springer-Verlag, Vienna, 190–194.
3. Pawlowsky, V., R.A. Olea and J.C. Davis, 1995, Estimation of regionalized compositions: A comparison of three methods: *Mathematical Geology*, **27**, 105–127.
4. Davis, J.C., J. Harff, W. Lemke, R.A. Olea, F. Tauber and G. Bohling, 1996, Analysis of Baltic sedimentary facies by regionalized classification: *Die Geowissenschaften*, **14**, 67–72.
5. Davis, J.C., G. Hausberger, O. Schermann and G. Bohling, 1995, Adjusting stream-sediment geochemical maps in the Austrian Bohemian Massif by analysis of variance: *Mathematical Geology*, **27**, 279–299.
6. Hausberger, G. and J.C. Davis, 1996, Methoden zur Erstellung Geochemischer Karten zur Umweltuntersuchung in der Republik Österreich: *Die Geowissenschaften*, **14**, 423–428.
7. Prohic, E., G. Hausberger and J.C. Davis, 1997, Geochemical patterns in soils of the Karst region, Croatia: *Jour. Geochemical Exploration*, **60**, 139–155.
8. Förster, H-J., J.C. Davis, G. Tischendorf, and R. Seltman, 1999, Multivariate analysis of Erzgebirge granite and rhyolite composition: Implications for classification of granites and their genetic relations: *Computers & Geosciences*, **25**, 533–546.
9. Harff, J., G.C. Bohling, R. Endler, J.C. Davis, and R. Olea, 1999, Classification and stratigraphic correlation of Holocene sediments from the Baltic Sea according to petrophysical properties (Gliederung

holozäner Ostseesedimente nach physikalischen Eigenschaften): *Petermanns Geographische Mitteilunggen*, **143**, 50–55.

10. Davis, J.C., 1998, Use of multivariate statistics for environmental mapping, *in* Tagungsband der 4. Arbeitstagung des Bereiches Umwelt, *Erdwissenschaftliche Aspekte des Umweltschutzes*: ISBN 3-95008-44-0-1, 99–104.
11. Davis, J.C., 2002, *Statistics and Data Analysis in Geology*, 3rd ed.: John Wiley & Sons, Inc., New York, 638 p. [on-line exercises at www.wiley.com/college/davis].
12. Miller, R.D., T.A. Anderson, J.C. Davis, D.W. Steeples, and M.L. Moran, 2001, 3-D characterization of seismic properties at the Smart Weapons Test Range, YPG: *Proc. Military Sensing Symposium*, Oct. 23-26, Johns Hopkins Univ., Laurel, MD, on CD-ROM, 18 p.

6. Scientific and professional societies membership

American Association of Petroleum Geologists (AAPG), Association of Earth Science Editors, International Association for Mathematical Geology (IAMG; President, 1984-1989), Kansas Geological Society, Kansas Speleological Society (Honorary Member), Phi Beta Delta Honor Society for International Scholars

7. Honors and awards

Distinguished Lecturer, International Association for Mathematical Geology	2003
University of Kansas OIP Faculty Travel Grant	2002
NSF/DAAD German Academic Exchange Grant	2001
W. Ritter v. Haidinger Medal, Geologische Bundesanstalt, Austrian Federal Government	1999
Deutsche Forschungsgemeinschaft Travel Grant	1998
German-American Academic Council Grant	1998
AAPG Hedberg Research Conference Invited Participant	1995
IAMG Best Paper Award (1983, 1995), in *Mathematical Geology*	1985, 1995
Fulbright Senior Research Fellowship, Austria	1993–94
Ledersprung Zeremonie der Montanuniversität-Leoben	1993
NAS Bilateral Exchange, US-DDR/FRG	1990, 1991, 1992
Certificate "In appreciation...[for] success of...28th International Geol. Congress" (IGC)	1989
SPE Forum Invited Participant	1988
IAMG 11th (1986) William Christian Krumbein Medal	1987
NATO Res.–Travel Grants/ASI, Nottingham, UK; Lucca, Cosenza, Italy	1973, 1975, 1983, 1986
NSF Travel Grants, 3rd ISC, Berne, 1971; 25th IGC, Sydney, 1976; 26th IGC, Paris, 1980;	27th IGC, Moscow, 1984
Industry Research Grants, Texaco; Unocal; Marathon	1983–85; 1989–92
KU Dept. Chemical & Petroleum Engineering Teaching Award	1982
UNESCO Conference Grant, COGEODATA Conference, Mexico City, Mexico	1978

8. Professional service since 1995

Member, AAPG Committee on Computer Applications to Geology	1969–97
Member, National Geologic Map Database Advisory Committee	1994–97
Member, Subcommittee on Data Quality (Geochemical), IGCP Project 360–World Map	1995–96
Member, AASG Committee on Digital Geologic Map Standards	1996–2003
Chairman, Krumbein Medal Selection Committee, IAMG	1996
Organizer/Chm., Session 2—Darss Sill Compositional Data, IAMG'97, Barcelona, Spain	1996–97
Convenor, Topics G2—Statistics, IAMG'99, Trondheim, Norway	1998–99
Member, Editorial Board, IAMG/Plenum Press, *Natural Resources Research*	1998–2003
Member, IAMG Awards Committee	1998–2002
Chairman, Organizing Committee, IAMG'2001, Cancún, Mexico	2000–2001
Reviewer for Journals/Funding Agencies	
Americal Chemical Society Petroleum Research Fund	1991–1996
Math Geology, C&G, Nat. Resources Res., AAPG Bull., AGI, NSF, DOA, *etc*.	1995–2003
Koninklijke Nederlandse Akademie van Wetenschappen	1996
Deutsche Forschungsgemeinschaft	1998

RICARDO ANTONIO OLEA

Current Position
Senior Scientist
Mathematical Geology Section
Kansas Geological Survey
1930 Constant Avenue
Lawrence, Kansas 66047

Telephone: (785) 864 2095
FAX: (785) 864 5317
Internet: olea@kgs.ukans.edu

Principal Fields of Professional Experience
Geostatistics, petroleum engineering, well log analysis, geophysics, computer science and mathematics applied to earth sciences, economic evaluation, project management, geohydrology,.

Education

1961-1966	Universidad de Chile, Santiago, Chile. Degree: Mining Engineer (6-year program)
1970-1972	University of Kansas, Lawrence, Kansas. Degree: Master of Science in Computer Science
1979-1982	University of Kansas, Lawrence, Kansas. Degree: Doctor of Engineering in Chemical and Petroleum Engineering

Recent Professional Experience

1987-1995	Associate Scientist, Mathematical Geology Section, Kansas Geological Survey, Lawrence, Kansas
1993	Visiting Research Scientist, Institut für Ostseeforschung Warnemünde, Germany (one month)
1995-Present	Senior Scientist, Mathematical Geology Section, Kansas Geological Survey, Lawrence, Kansas
1997	Visiting Research Scientist, Institut für Ostseeforschung Warnemünde, Germany (one month)

Professional Affiliations
Member, Society of Petroleum Engineers
Active Member, American Association of Petroleum Geologists
Past President, International Association for Mathematical Geology
Member, Sigma Xi

Honors Received

1966	Juan Brüggen prize to best graduating mining engineer in the country, Instituto de Ingenieros de Minas de Chile
1990	Task Committee Excellence Award, American Society of Civil Engineers
1993	Best Paper Award, Mathematical Geology, the flagship journal of the International Association for Mathematical Geology

Major Developments of Software

1985-2002	CORRELATOR, an interactive computer program for high-resolution, lithostratigraphic, well-log correlation: Kansas Geological Survey, Lawrence, Kansas

Books
1. Olea, R. A., editor, 1991, Geostatistical Glossary and Multilingual Dictionary: Oxford University Press, 177 p.
2. Olea, R. A., 1999, Geostatistics for Engineers and Earth Scientists: Kluwer Academic Publishers, Boston, 303 p.
3. Pawlowsky, V. and R. A. Olea, in press, Geostatistical Analysis of Compositional Data: Oxford University Press, 188 p.

Special Publications
1. Olea, R. A., 1972, Application of Regionalized Variable Theory to Automatic Contouring: Special Report to the American Petroleum Institute, Research Project No. 131, The University of Kansas Center for Research, Inc. in cooperation with the Kansas Geological Survey, Lawrence, Kansas, 191 p., 2 plates.
2. ____________, 1975, Optimum Mapping Techniques Using Regionalized Variable Theory: Kansas Geological Survey, Series on Spatial Analysis no. 2, Lawrence, Kansas, 137 p.

3. ____________, 1977, Measuring Spatial Dependence with Semivariograms: Kansas Geological Survey, Series on Spatial Analysis no. 3, Lawrence, Kansas, 29 p.
4. ____________, 1981, LOG II, A General Purpose Automated Well Log Evaluation System: Kansas Geological Survey, Petrophysical Series no. 1, Lawrence, Kansas, 103 p.
5. ____________, 1982, Optimization of the High Plains Aquifer Observation Network, Kansas: Kansas Geological Survey, Groundwater Series no. 7, Lawrence, Kansas, 103 p.
6. ____________, 1984, Systematic Sampling of Spatial Functions: Kansas Geological Survey, Series on Spatial Analysis no. 7, Lawrence, Kansas, 57 p.
7. ____________, 1988, CORRELATOR—An Interactive Computer System for Lithostratigraphic Correlation of Wireline Logs: Kansas Geological Survey, Petrophysical Series no. 4, Lawrence, Kansas, 85 p.
8. ____________, 2002, Lithostratigraphic Cross Section from Gove to Harper Counties, Kansas: : Kansas Geological Survey, Technical Series 16, Plate 1, Lawrence, Kansas, 1 plate.
9. ____________, 2002, Lithostratigraphic Units from Gove to Harper Counties, Kansas: : Kansas Geological Survey, Technical Series 16, Plate 2, Lawrence, Kansas, 1 plate.

Recent Peer-Reviewed Papers and Book Chapters

1. Harff, J., R. A. Olea, J. C. Davis, and G. C. Bohling, 1996, Geostatistical solution for the classification problem with an application to oil prospecting: *in* Geologic Modeling and Mapping, A. Förster and D. F. Merriam, editors, Plenum Press, New York, p. 263-279.
2. Jian, X., R. A. Olea, and Y.-S. Yu, 1996, Semivariogram modeling by weighted least squares: *Computers & Geosciences*, v. 22, no. 4, p. 387-397.
3. Olea, R. A., 1996, XVAN: a computer program for the analysis of spatial estimation errors: *Computers & Geosciences*, v. 22, no. 4, p. 445-448.
4. Olea, R. A. and V. Pawlowsky, 1996, Compensating for estimation smoothing in kriging: *Mathematical Geology*, v. 28, no. 4, p. 407-417
5. Davis, J. C., J. Harff, W. Lemke, R. A. Olea, F. Tauber, and G. C. Bohling, 1996, Analysis of Baltic sedimentary facies by regionalized classification: Die Geowissenschaften, v. 14, no. 2, p. 67-72.
6. Watney, W. L., J. C. Davis, R. A. Olea, J. Harff, and G. C. Bohling, 1997, Modeling of sediment accommodation realms by regionalized classification: *Die Geowissenschaften*, v. 15, no. 1, p. 28-33.
7. Bohling, G. C., J. C. Davis, R. A. Olea, J. Harff, 1998, Singularity and nonnormality in the classification of compositional data: *Mathematical Geology*, v. 30, no. 1, p. 5-20.
8. Harff, J., G. C. Bohling, R. Endler, J. C. Davis, and R. A. Olea, 1999, Classification and stratigraphic correlation of Holocene sediments from the Baltic Sea according to petrophysical properties (Gliederung holozäner Ostseesedimente nach physikalischen Eigenschaften): Petermanns Geographische Mitteilunggen (PGM), v. 143, p. 50-55.
9. Harff, J., W. L. Watney, G. C. Bohling, J. H. Doveton, R. A. Olea, and K. D. Newell, 2001, Three-dimensional regionalization for oil field modeling: *in* Geologic Modeling and Simulation of Sedimentary Systems, edited by D. F. Merriam and J. C. Davis, Kluwer Academic/Plenum Publishers, New York, p. 205-227.
10. Martín-Fernández, J. A., R. A. Olea-Meneses, and V. Pawlowsky-Glahn, 2001, Criteria to compare estimation methods of regionalized compositions: *Mathematical Geology*, v. 33, no. 8, p. 889-909.
11. Harff, J., G. C. Bohling, J. C. Davis, R. Endler, , H. Kunzendorf, R. A. Olea, W. Schwarzacher, and M. Voss, 2001, Physicochemical stratigraphy of Gotland Basin (the Baltic Sea) Holocene sediments: *Baltica*, v. 14, p. 58-66.

SUSAN E. NISSEN

PRESENT POSITION:
Assistant Scientist
Petroleum Research Section
Kansas Geological Survey
1930 Constant Avenue
Lawrence, Kansas 66047

EDUCATION:
B.S. Geophysics, summa cum laude, University of Delaware, Newark, Delaware, 1983
Ph.D. Marine Geophysics, Columbia University, New York, New York, 1992

PROFESSIONAL EXPERIENCE:

2000-present	Assistant Scientist, Petroleum Research Section, Kansas Geological Survey, Lawrence, Kansas
1997-1999	Team Leader, Seismic Coherence/Spectral Decomposition Team, Amoco Exploration & Production Technology Group, Tulsa, Oklahoma
1994-1999	Research Scientist/Senior Research Scientist, Seismic Coherence/Spectral Decomposition Team, Amoco Exploration & Production Technology Group, Tulsa, Oklahoma
1991-1994	Research Scientist, Integrated Facies Analysis Team, Amoco Exploration & Production Technology Group, Tulsa, Oklahoma

HONORS:
Amoco Recognition and Reward Program awards, 1996, 1998
Heezen Prize for academic and research excellence, Columbia University Department of Geological Sciences, 1986

MEMBERSHIP IN PROFESSIONAL ORGANIZATIONS:
American Association of Petroleum Geologists
American Geophysical Union
Geological Society of America
Society of Exploration Geophysicists
Kansas Geological Society
Tulsa Geological Society
Geophysical Society of Tulsa (Treasurer, 1996-1997)

SELECTED PUBLICATIONS:
Nissen, S. E., 2002, Seismic attributes for the explorationist, Kansas Geological Survey Open File Report 2002-49, <http://www.kgs.ku.edu/PRS/publication/2002/ofr49/index.html>, posted November 2002

Nissen, S. E., J. Xia, and W. L. Watney, 2002, Seismic detection of shallow natural gas beneath Hutchinson, Kansas, Kansas Geological Survey Open File Report 2002-44, <http://www.kgs.ku.edu/PRS/Poster/2002/2002-44/>, posted November 2002.

Nissen, S. E., and J. Xia, 2002, Detecting shallow natural gas beneath Hutchinson, Kansas, using high-resolution seismic reflection data, Kansas Geological Survey Open File Report 2002-37, <http://www.kgs.ukans.edu/PRS/publication/2002/ofr37/index.html>, posted August 27, 2002.

DiLeonardo, C. G., Moore, J. C., Nissen, S., and Bangs, N., 2002, Control of internal structure and fluid-migration pathways within the Barbados Ridge décollement zone by strike-slip faulting: Evidence from coherence and three-dimensional seismic amplitude imaging, Geological Society of America Bulletin, 114, 51-63.

Nissen, S. E., 2000, Interpretive aspects of seismic coherence and related multi-trace attributes, Kansas Geological Survey Open File Report 2000-84, <http://www.kgs.ukans.edu/PRS/publication/2000/ofr84/index.html>, posted February 8, 2001.

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