FINAL TECHNICAL REPORT

March 1, 2005, through August 31, 2006

SEISMIC MONITORING OF METHANE PRODUCTION FROM COAL SEAMS IN ILLINOIS

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Supported by the Illinois Clean Coal Institute
Project Number: 04-1/5.1A-1
Project Manager: Dr. Ronald Carty, ICCI

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ABSTRACT

Gas Technology Institute, with support from the Illinois Clean Coal Institute and cooperation of the Illinois State Geological Survey, designed and implemented a comprehensive research project to determine the viability of seismic techniques for site selection and development of coalbed methane production from Illinois coals. The focus of the studies was on viability of seismic techniques for delineation of thin coal seams and tracking of the desorbed gas front by time-lapse (4-D) seismic surveys. Results from these studies would be equally applicable to monitoring of the CO_2 front in geologic CO_2 sequestration operations as in both cases the physical process involves the presence of a gas phase (CO_2 or methane) into initially water saturated coal seams.

The issue of seismic resolution relative to thin coal seams was investigated in a series of seismic surveys that included surface seismic, vertical seismic profiling, and crosswell seismic imaging. Results were positive and encouraging. The data proved that thin coal seams can be reliably mapped by properly designed seismic surveys. The first leg of the 4-D seismic survey was completed and the second leg awaits the onset of gas production at the ISGS site in White County, IL; expected to occur in late 2006 or early 2007. GTI will fund this survey at its own cost estimated at about $29,000.00. Results from the 4-D survey will be submitted to ICCI as an addendum to the present report.

In the course of the project, the scope of work was expanded to include the study of hydraulic fracturing (a well completion technique used for enhancing gas production from coal seams and tight sands reservoirs) in south and south-central Illinois. The industry partner for these efforts was BPI-Energy. Hydraulic fracturing research involved forward modeling, fracture design, and fracture diagnostics. The work was performed with support and participation of BPI-Energy engaged in a coalbed methane production project in Shelby County, Illinois. The work was completed in July, 2006. Results from fracture modeling showed that fracture containment at this site would be very low and nearly all vertical fractures would grow out of zone. Fracture diagnostic survey proved that hydraulically created fractures were complex and except for the shallow seams where fractures were horizontal, all fractures had one vertical component and at least one horizontal component.

Appendix A contains proprietary information

EXECUTIVE SUMMARY

Gas Technology Institute (GTI), with support from the Illinois Clean Coal Institute (ICCI), cooperation of the Illinois State Geological Survey (ISGS), and participation of two Illinois producing companies (BP-I Energy and Royal Drilling Corporation) carried out a series of field and laboratory research aimed at the development of efficient methods and techniques for production of natural gas from coal seams in Illinois. In general, development of any coalbed methane project requires accurate mapping of the host seams, delineation of the preferred flow path; i.e., high permeability trend, and application of an appropriate production enhancement technique. With these requirements in mind, the present project was focused on the following three areas.

1- Determination of viability of seismic techniques for accurate imaging of thin coal seams in Illinois.

   Advanced seismic techniques have proven successful in providing detailed subsurface images of conventional oil and gas reservoir rocks and thicker coal seams. However, Illinois coal seams are shallow and thin with the thickness rarely exceeding 10 feet and as such, they could be transparent to seismic waves. The issue of seismic resolution relative to thin coal seams was investigated in a series of seismic surveys that included surface seismic, vertical seismic profiling, and crosswell seismic imaging. Results were positive and proved that the thin Illinois coal seams can be seismically mapped through properly designed surveys. A simple guideline for these surveys was developed. This phase of work was initiated under a CO_2 sequestration project and continued in the present project.

2- Investigation of time-lapse seismic (4-D) for mapping the position of the desorbed methane and delineation of high permeability trends.

   In the absence of any direct far-field permeability measurement technique, high permeability trends can be delineated by progressive mapping of the gas front. Although 4-D seismic (two or more surveys repeated over time) has proven successful in monitoring of gas movements in conventional oil and gas reservoirs, because of low velocity and high compressibility of coal seams, it is not known if the technique would be viable for mapping the gas front in thinner coals. This issue was investigated through a number of laboratory measurements and a planned 4-D survey.

   Laboratory measurements showed that velocity changes resulting from the addition of a gas phase into water saturated coal samples are large enough to render the 4-D seismic imaging a viable technique for monitoring the gas front and delineation of high permeability trends. The first leg of the field survey was completed at the ISGS pilot sit in White County, Illinois. The second leg will be surveyed upon the establishment of sustained gas production expected to occur in late 2006 or early 2007. In the event that no sustained gas flow would occur at ISGS site, a crosswell survey in a gas producing well at BP-I site will be performed. Results from the second survey will be submitted as an addendum to the present report.

3- Development of knowledge and understanding of hydraulic fracturing as a production enhancement technique for Illinois coal seams.

   Work relative to hydraulic fracturing research involved forward modeling, fracture design, and fracture diagnostics. The work was performed with support and participation of BPI-Energy engaged in a coalbed methane production project in Shelby County, Illinois. The work was completed in July, 2006. Results from fracture modeling showed that fracture containment at this site would be very low and nearly all vertical fractures would grow out of zone. Fracture diagnostic survey proved that hydraulically created fractures were complex and except for the shallow seams where fractures were horizontal, all fractures had one vertical component and at least one major horizontal component.

A brief summary of research activities and results is presented in the remainder of this section. The original task structure proposed in the proposal will be followed.

Task 1. Laboratory Experiments and Analyses

Laboratory experiments included measurement of acoustic velocity of coal samples with water and gas saturation. The data proved that addition of a gas phase into water saturated coal causes substantial velocity reductions. Figure 1 exhibits sonic travel time for gas saturated portion of a core sample (the top trace) and water saturated portion of the same sample (other four traces). The corresponding velocities for gas and water saturated sections are 1859 and 2555 meters per second.

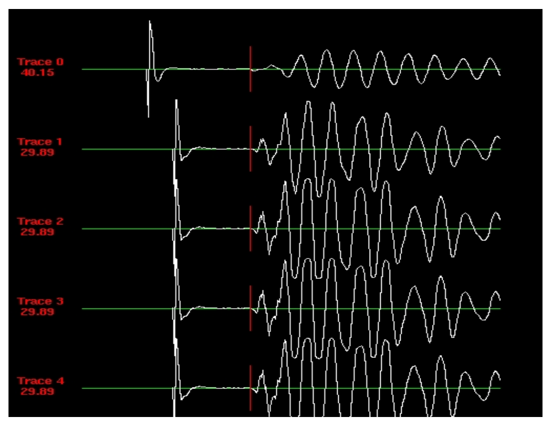


Figure 1. Travel time for a gas and water saturated coal sample

Task 2. Data analysis and Modeling

Data analysis and modeling included seismic and hydraulic fracture modeling. Forward seismic modeling showed that: 1) It is indeed possible to seismically detect the thin coal seams at the ISGS site, and 2) Hydraulic fractures created in coal seams at both ISGS and BPI sites would be mostly horizontal with the vertical section breaking out of the intended seams.

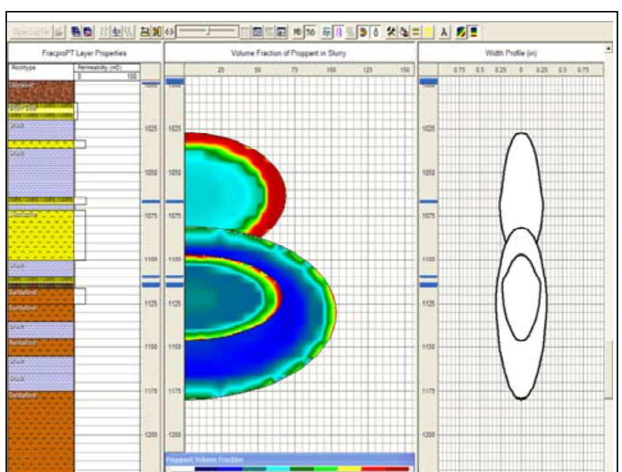


Figure 2. Modeling results showing possible overlapping fractures at Hon#9

Figure 2 exhibits results from fracture modeling for simultaneous fracturing of three seams at the ISGS site. Note that all three fractures grow out of their corresponding target seams (shown as thin blue bands) and extend to considerable distances above and below the seams. Modeling also showed that concurrent fracturing of other seams would result in the overlap of fractures.

Task 3. Field Data Acquisition

Field data acquisition included seismic survey at ISGS site and fracture diagnostic survey at BP-I site. Figure 3 is an overlay of core and log data on the crosswell seismic section obtained in well Hon #9 in White County, Illinois exhibiting the accuracy of crosswell seismic imaging. As mentioned earlier, this survey will be repeated in late 2006 or early 2007 and results will be presented in an addendum to the present report.

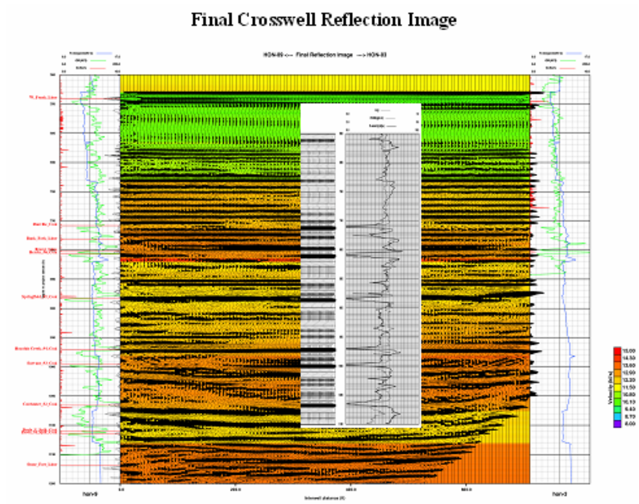


Figure 3. Corsswell seismic section at well Hon #9 site, White County, Illinois

Fracture diagnostic data acquisition included the deployment of 16 super sensitive tiltmeters capable of continuous measurement of surface deformations resulting from hydraulic fracturing. The data and subsequent data analysis showed that all shallower fractures were horizontal and the deeper fractures had a minor vertical component and a major horizontal component. Results from fracture diagnostic surveys depict the nature of fracturing and provide valuable information for design of the optimal field development pattern.

Task 4. Integration, Report, and Technology Transfer

Compilation of data and preparation of reports continued throughout the project and will continue albeit at a lesser extent. Although no new funding is presently available for continuation of efforts, we believe pursuing the development of coalbed methane production has the promising of turning a portion of the 14 trillion cubic feet of gas resource in Illinois to a substantial producible reserve.

Our technology transfer efforts included presentations at the Pittsburgh Coal Conference, the annual meeting of the American Association of Petroleum Geologists, and publication in two issues of GasTips, a GTI-DOE publication featuring the major results from the ongoing research and development.

Conclusions and Recommendations

Despite the sizeable coalbed methane resources of Illinois, production from this statewide source of natural gas has lagged behind and it has been only recently that some producing companies have begun considering serious coalbed methane exploration and production efforts. The parameters contributing to this lag are the shallow depth causing the gas content to be relatively small and difficulties in completion of shallow seams. However, with the prevailing high gas prices, investments in the development of this resource are beginning to become economically justifiable. The key to success in coalbed methane production in Illinois is modification of technologies that have been proven in the San Juan basin and elsewhere and their tailoring to the Illinois coal environment. Specific recommendations from the work performed are summarized below:

A - Seismic Delineation of Coal Seams

Combining the results from the actual surveys, spectral decomposition, and forward modeling, the following conclusions can be drawn:

1- At 10-50 Hz bandwidth the resolution is very low and results from surface seismic surveys are not reliable.
2- At 10 -200 H z bandwidth, high resolution imaging is possible and surface seismic data would be reliable for mapping of the "coal seam packages" as a whole.
3- The use of impulsive sources for surface seismic surveys is strongly recommended.
4- VSP surveys (10-300 Hz bandwidth) noticeably enhance the resolution.
5- Under geologic conditions similar to those at the ISGS pilot site, position of the injected or evolved gas can only be imaged at higher frequencies through cross-well seismic applications.

B - Hydraulic Fracturing

Extensive fracture modeling and fracture diagnostic survey resulted in a clear understanding of the process and proved that:

1- Shallower hydraulic fractures at depths to about 750 feet grow horizontally and deeper fractures have a minor vertical component and a major horizontal component. These parameters should be taken into account for design of field development patterns and determination of drainage zone for each well.
2- Vertical fractures grow out of zone and therefore, simultaneous fracturing of seams at close proximity of each other has the same results as those achieved through staged fracturing.
3- Under conditions similar to the BPI site, it is safe to assume a circular drainage pattern for coalbed methane wells.

Appendix A to this report contains proprietary information and is not available for public distribution except to the sponsors of this project.

OBJECTIVES

The principal objective of this research and development project was development of understanding and techniques for efficient production of natural gas from Illinois coal deposits. Factors influencing the success of coal-bed methane (CBM) production can be categorized as *uncontrollable* such as gas content and permeability and *controllable* such as well location and well completion techniques. The key to the success of CBM projects is accurate delineation and characterization of the uncontrollable elements and tailoring of the controllable parameters to take advantage of the natural settings.

Relative to accurate delineation of Illinois coal deposits, the project objective was to investigate the viability seismic techniques for accurate imaging of thin coal seams in Illinois and to determine if it would be possible to map the position of the desorbed gas front using advanced time-lapse (4-D) seismic techniques. The first question relates to selection of a field for CBM development and the second addresses the need for determination of the dominant flow path; i.e., the high permeability trend, for design of the optimal field development well pattern.

In addition, Illinois coal deposits are generally in the form of thin, low permeability, multiple seams separated by thin layers of sedimentary deposits. The coal seams are usually water saturated and occur at depths less than 1200 feet below the surface. Under these conditions, proper dewatering of the seams and the subsequent gas production would be at very low rates hindering the economics of such projects. The same is equally true for CO_2 injection where large volume of gas would have to be injected at high rates and over a long period of time. In reality, any CBM production or CO_2 sequestration project to be technically and economically successful, hydraulic fracturing of the target seams is an imperative. Characterization of hydraulic fracturing of Illinois coal seams and determination of fracturing mode(s) under the local conditions constituted the project's objective relative to well completion techniques.

In summary, the project was focused on the following three areas:

1- Determination of viability of seismic techniques for accurate imaging of thin Illinois coal seams.

   Research on seismic resolution relative to thin coal seams was initiated under a previous project and continued in the present project. The work included forward modeling and implementation of a series of seismic data acquisition surveys that included surface seismic, vertical seismic profiling, and crosswell seismic imaging. Results were positive and proved that the thin Illinois coal seams can be seismically mapped through properly designed surveys. A simple guideline for these surveys was developed.

2- Investigation of time-lapse seismic (4-D) for mapping the position of the desorbed methane and delineation of high permeability trends.

This issue was investigated through a number of laboratory measurements and a planned 4-D survey. Laboratory measurements showed that velocity changes resulting from the addition of a gas phase into water saturated coal samples are large enough to render the 4-D seismic a viable technique for monitoring the gas front leading to delineation of high permeability trends. The first leg of the field survey was completed at the Illinois State Geological Survey (ISGS) pilot site in White County, Illinois. The second leg will be surveyed upon the establishment of sustained gas production expected to occur in 2006 or early 2007. Results from the second survey will be submitted as an addendum to the present report.

3- Development of knowledge and understanding of hydraulic fracturing as a production enhancement technique for Illinois coal seams.

Work relative to hydraulic fracturing research involved forward modeling, fracture design, and fracture diagnostics. The work was performed with support and participation of BPI-Energy engaged in a coalbed methane production project in Shelby County, Illinois. The work was completed in July, 2006. Results from fracture modeling showed that fracture containment at this site would be very low and nearly all vertical fractures would grow out of zone. Fracture diagnostic survey proved that hydraulically created fractures were complex and except for the shallow seams where fractures were horizontal, all fractures had one vertical component and at least one major horizontal component.

The work on achieving the project objectives was performed under the following four tasks:

Task 1: Laboratory experiments and analyses
Task 1 focused on measurement of changes in bulk elastic properties of coal due to introduction of a gas phase into water saturated coal samples. These lab experiments were performed on two sets of Illinois coal samples. The first set of samples were obtained from a surface mine in close proximity to the Illinois State Geologic Survey (ISGS) coalbed methane pilot project site in White County, Illinois and the second set was obtained from an underground mine in central Illinois, near Springfield.

Task 2: Data analysis and modeling
Task 2 included design and implementation of a comprehensive advanced field seismic survey including densely populated surface lines, vertical seismic profiling (VSP), and crosswell seismic survey. Field surveys were designed and implemented at the ISGS site. The data assembled through Task 1 was used for development of synthetic seismograms for prediction of seismic response at the ISGS site and fracture modeling for prediction of fracture dimensions at ISGS and BPI-Energy sites.

Task 3: Field Data Acquisition
The first leg of the 4-D seismic survey was completed through a previous project and the second leg will be completed in the near future. The second survey at ISGS site awaits the establishment of sustained gas production at this site which is expected to occur in

late 2006 or early2007. Field data acquisition performed under the present project also included detailed fracture diagnostic survey at BPI-Energy site.

Task 4: Integration, Report, and Technology Transfer

Task 4 included integration of data from various phases of the project, preparation of reports, and preparation of papers at the Pittsburgh Coal Conference and at the annual conference of the American Association of Petroleum Geologists (AAPG). Two technical papers were also published in the DOE/GTI periodical (GasTips) that highlights the recent technological achievements in the DOE sponsored research programs.

INTRODUCTION AND BACKGROUND

Remaining coal resources in the Illinois Basin are about 284 billion tons 211.4 billion tons of which are in Illinois. Computations based on coal resource and coal gas content yield 21-25 trillion cubic feet (Tcf) (Lombardi, 2001) of coalbed methane (CBM) resource for the Illinois Basin at least 14 Tcf of which is in Illinois. Nonetheless, there is currently no substantial CBM production in Illinois. The primary reason for this lag is the nature of the coal seams as being relatively thin with low permeability and as such, the well completion technologies developed in the Rocky Mountain region are not directly applicable to the Illinois coals. Specifically, CBM production in Illinois requires efficient production stimulations through effective hydraulic fracturing which is difficult to achieve in thin and shallow coal seams.

Site selection for CBM production from thin coal seams is a non-trivial task. Production is primarily from desorbed gas that occurs after substantial depressurization through dewatering. For depressurization to be effective, the target seams must be contained between impermeable overlying and underlying beds, structurally closed and undisturbed, laterally continuous, and free of small-scale discontinuities. One of the challenges associated with CBM production from Illinois coal seams is thus accurate and reliable mapping of the target coal seam(s). This challenge stems from the fact that it has been suspected that since the conventional seismic waves have wavelengths that are much larger than the thickness of the coal bed; the seams may be transparent to conventional seismic frequencies.

The second and equality important class of issues for CBM production is design of the optimal field development pattern such that the wells are sited along high permeability trends. In the absence of any direct far-field permeability measurement technology, these trends can be determined only in an after-the-fact manner by seismic imaging of the evolved gas fronts. Time-lapse seismic imagery (4-D seismic) has been used quite successfully for more than a decade to monitor the gas movements in conventional oil and gas reservoirs. The principle behind the technique is reduction in seismic velocity, bulk density, and bulk modulus resulting from the presence of a gas phase in liquid saturated porous rocks. The challenge associated with using this technique in coal beds is that coal in itself is quite compressible relative to conventional sedimentary rocks and has relatively low acoustic velocity. As such, the goal was to determine whether seismic velocity changes caused by addition of a gas phase into the coal cleat system would be large enough to be resolved by seismic imaging. The laboratory work performed in this project was designed to test this issue.

A second issue regarding CBM production in Illinois stems from the fact that Illinois coal deposits is generally in the form of thin, low permeability, multiple seams separated by thin layers of sedimentary deposits. The coal seams are usually water saturated and occur at shallow depths below the surface. Under these conditions, proper dewatering of the seams and the subsequent gas production would be at very low rates hindering the economics of such projects. The same is equally true for CO_2 injection where large volume of gas would be injected at high rates and over a long period of time. In reality, for either of the two cases to be technically and economically successful, hydraulic fracturing of the target seams is an imperative.

Because of the shallow depths of coal deposits in Illinois, hydraulically created fracture planes in Illinois coals could be vertical and confined to coal seams, vertical but including the inter-bedded sediments, horizontal and confined, horizontal and vertically connected, or several combinations of these cases. It is obvious that each of these scenarios has its own flow regime ranging from very efficient to counterproductive. The work performed in this regard included augmentation of information on mechanical properties of coal seams with those of inter-bedding sediments and forward modeling for prediction of fracture geometries for a range of fracturing parameters. The FRACPRO PT 3-D was used for fracture modeling.

EXPERIMENTAL PROCEDURES

Laboratory measurements and field data acquisition carried out under this project were aimed at determining: (1) if time-lapse seismic techniques can provide data and information on the preferred flow path of coalbed methane, (2) whether thin coal seams of Illinois can be reliably mapped seismically, and (3) development of data on mechanical rock properties for use in hydraulic fracturing and fracture modeling.

Rationale for Laboratory Studies

For dewatering and producing wells to be effective, they must be placed along high permeability trends. However, no reliable geophysical techniques for determining permeability of subsurface sediments are presently available and in the absence of any direct measurement tool, effects of lateral permeability variations can be determined in an after-the-fact manner through time-lapse seismic surveys. In these surveys, the progress of the gas front is mapped after pre-set time periods the duration of which is determined from reservoir engineering studies. Integrating the seismic information with reservoir data within the local geologic framework would provide a dependable tool for predicting the flow direction, which can then used to select locations for production wells.

Laboratory Measurements

Our laboratory studies focused on measuring changes in acoustic velocity resulting from addition of a gas phase into water saturated coal samples. Blocks of coal were collected from two coal mines, one in Southern Illinois near the ISGS site and one in Central Illinois near Springfield (Figure 5). Multiple 70 by 342 millimeter cores (2.75 by 13.5

inch) were cut from these blocks in the lab for acoustic measurements. In cases where high friability of the coal sample prevented us from cutting sufficient cores to the desired length for all of the tests, the test apparatus was reconfigured to accommodate shorter (five-inch) cores. In the reconfigured setup, two additional pairs of transducers were added for simultaneous measurements in two orthogonal directions without extraction and reinsertion of the core. Figure 6 shows the setup of the core sleeves and transducers.

Measurements were made under four confining pressures - 0, 1, 2, and 3 Mega Pascal (14, 145, 290, 435 psi respectively). In these measurements, the cores are inserted into an instrumented sleeve housing an array of six ultrasonic source transducers and six receivers (Figure 7). The sleeve is connected to a cap with signal input/output connectors and flow ports allowing flow from either end of the sleeve. The assembly is then placed inside a high pressure reaction cell, and the reaction cell is placed inside a constant temperature chamber. Gas injection into the space between the instrumented sleeve and the inner wall of the cell provides the confining pressure that can be externally regulated and maintained at the desired level. Using the external and internal manifolds, gas or liquid can be injected into the core while recording continues.

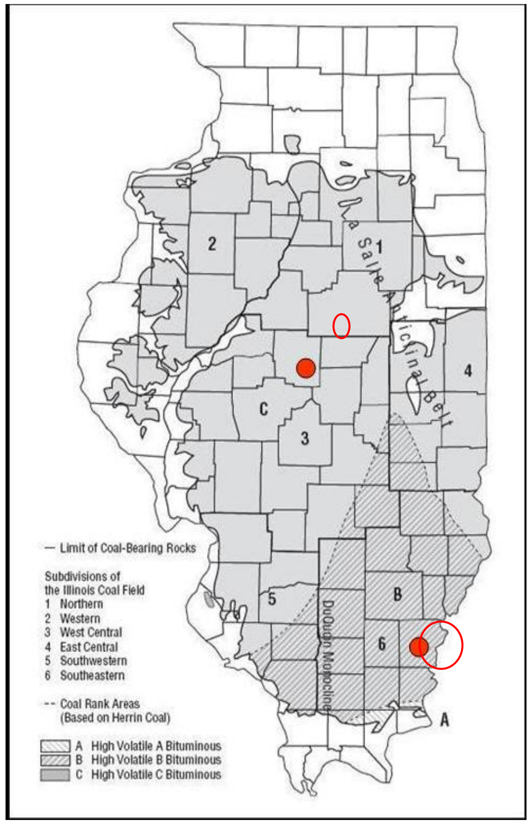


Figure 5, Location map for sampling sites (Red dots), ISGS pilot site (Open circle), and BPI-Energy site (Small open ellipse)

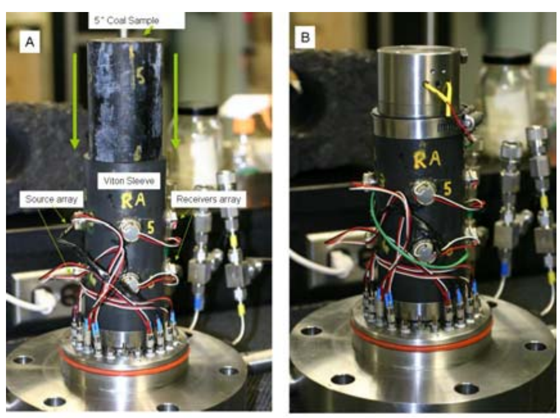


Figure 6. Transversely Instrumented Sleeve

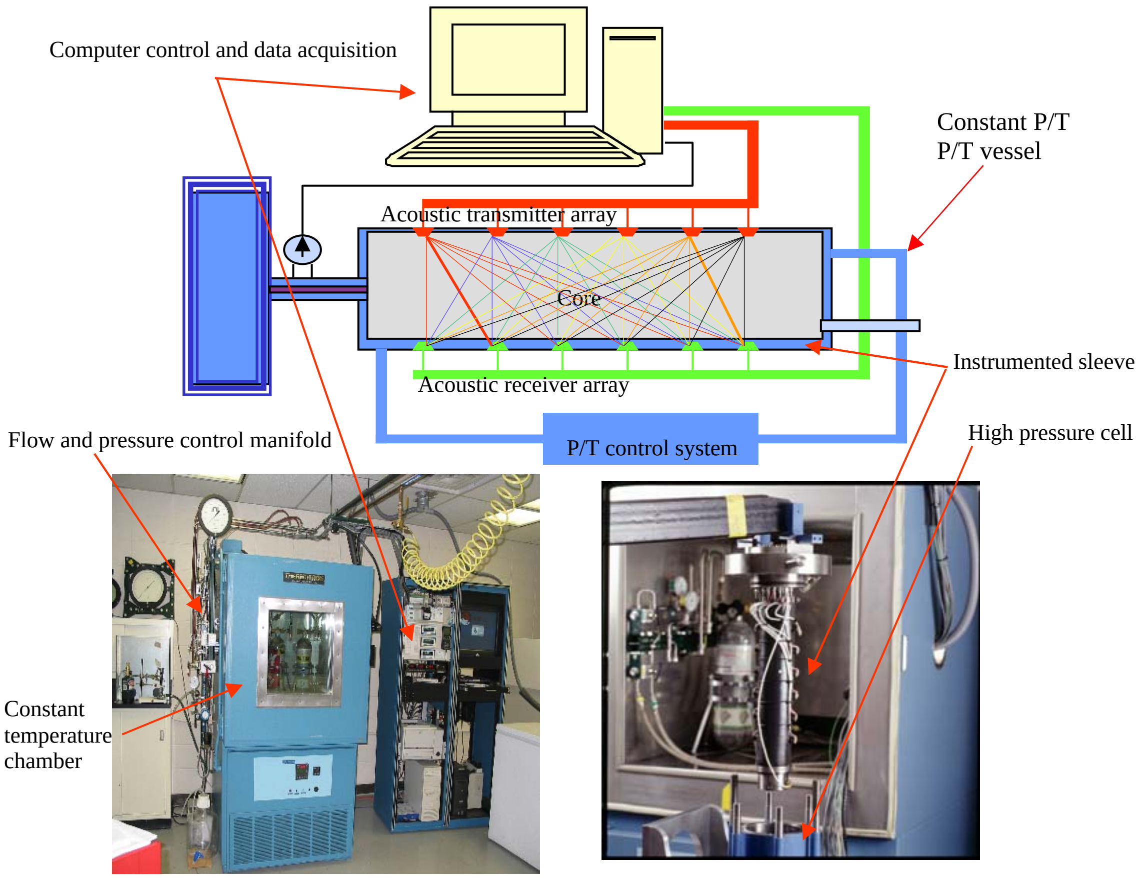


Figure 7. Ultrasonic Petrophysics Laboratory

A total of 40 data points were acquired in this project augmenting 140 data points acquired during the previous work. Figure 8 provides an example of changes in compressional (P) wave velocity resulting from introduction of a gas phase into the water saturated coal. This figure is a screen dump from the data acquisition system and shows the recorded travel times. The image is from a point in time when the injected gas had reached the space between the first transducer pair causing travel time to increase from 29.89 microseconds for water saturated samples (Traces 1 through 4) to 40.15 microseconds for the gas saturated sample (Trace 0), translating to a 34% decrease in P wave velocity.

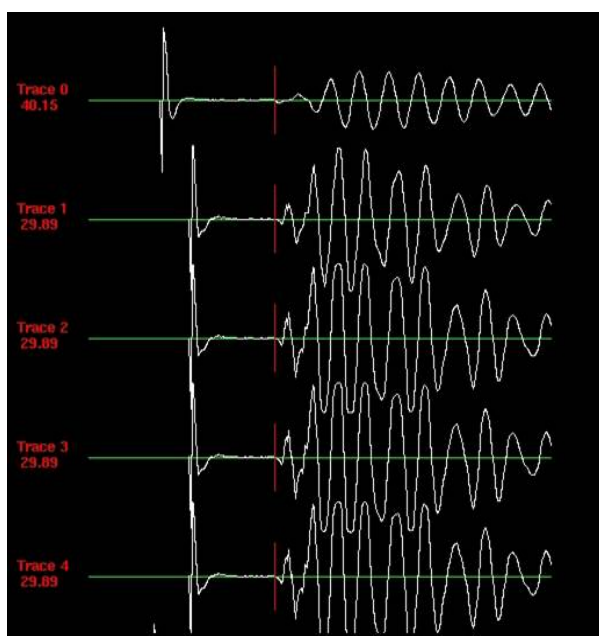


Figure 8. Travel time for gas and water saturated coal sample

Rationale for Field Experiments

Although the resolution of seismic techniques for conventional sedimentary rocks is rarely better than 5m (~16.4 f), Van Reil (1986) and has shown that coal beds as thin as 0.75 m (2.46 f) can be resolved by reflection seismic methods. The higher resolving power of seismic techniques for coal seams is due to the very high reflection coefficient at the interface between the coal and contiguous sand or shale beds. It has been well established that for a normal incident wave the amplitude of incident and reflected waves follow the following relationship (Telford, 1978):

$$A_2/A_1 = (\rho_2 V_2 - \rho_1 V_1)/(\rho_2 V_2 + \rho_1 V_1)$$

where A_1 and A_2 are the amplitudes of incident and reflected waves, ρ_2 and ρ_1 densities of the interfacing beds and $V_2$and V_1 are the corresponding seismic velocities. In the case of coal seams, the impedance contrast between the coal seam and the interfacing beds is exceptionally high because both the density and velocity values for coal are much smaller than those for the interfacing shale or sand beds. For example, when a coal seam with 1.2 grams per cubic centimeter density and 1200 meters per second seismic velocity interfaces with a sand bed with 2500 meters per second velocity and 2.2 g/cc density, the reflection coefficient will be 0.585, meaning that nearly 58% of the energy will be reflected from the interface.

Widess (Widess et. al., 1986) showed that the amplitude of a seismic wave reflected from a thin bed or seam can be calculated by $4\pi\alpha\beta/\lambda$, where α is the reflection coefficient for the bed (assuming a thick bed), β the bed thickness, and λ the wavelength. Seismic resolution is thus proportional to the reflection amplitude, bed thickness, and wavelength. Widess concluded that the thickness of a bed must be at least 1/8 of the dominant seismic wavelength to be resolvable. Thus, a key question to be addressed was whether advanced seismic techniques could identify individual coal seams within a coal 'package' or whether the overall low frequency signal from the 'package' would mask the individual high frequency event(s).

Field Experimental Design

A - Seismic Data Acquisition

To answer the seismic resolution question, we carried out a series of seismic data acquisitions in the White County, Illinois at the ISGS pilot site (Figure 9). These were four densely populated surface lines plus one vertical seismic profile (VSP) and one crosswell survey. The location of the seismic lines, crosswell, and VSP surveys are shown on this figure. This multiple survey approach allowed us to use a wide seismic frequency range to evaluate the merits and limitations of seismic technique at all possible resolutions.

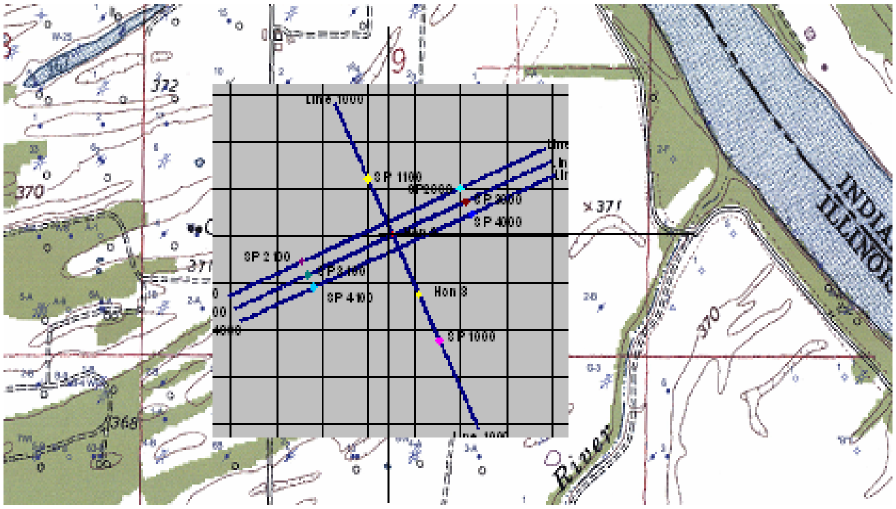


Figure 9. Location of seismic lines and survey wells at the ISGS pilot site

It is well established that the earth materials between the seismic source and receiver act as a high-cut filter eliminating the higher frequency content of the seismic events. In vertical seismic profiling, where the receivers are lowered inside the wellbore and the source is on the surface, this filtering layer is eliminated at the receiver end while the shot receiver distance is almost halved, thereby more of the high frequency content would be preserved. In cross-well systems, where both the seismic source and the receiver are placed inside the well bore, the highest frequencies are maintained leading to the highest possible resolution.

ISGS drilled and cored a well (Hon # 9) in the center of the pilot site and made this well available for VSP and cross-well surveys. Nine coal seams, each 1.5 to 4 feet in thickness were cored at this site (Table 1). Information from this well was used in our survey design to assure that the field efforts would lead to useful data and knowledge. These seams were thinner than we had anticipated and created a challenge to seismic resolution.

Table 1. Coal seams encountered in well Hon # 9

Coal	*Top (ft)*	*Base (ft)*	*Log Thickness (ft)*	*Core Coal Thickness (ft)*
Danville	758.0	762.0	4.0	3.6
Herrin #6	806.0	810.0	4.0	5.0
Springfield #5	882.0	886.0	4.0	4.0
Houchin Creek #4	971.0	972.0	1.0	1.5
Survant #3	996.0	1000.0	4.0	4.1
Colchester #2	1066.0	1068.0	2.0	1.6
Davis - upper split	1110.0	1111.5	1.5	1.4
Davis - middle split	1114.0			2.1
Davis - lower split		1118.0	4.0	1.2

The goal of the field study was to determine which acquisition geometry (or combination of geometries) was best suited for imaging the coal seam continuity. Cross-well data (frequencies of more than 500 Hz) was expected to have the highest resolution, but required the presence of two wells spaced less than 700 feet apart for deployment of sources and receivers and only provided a 2-D slice of the inter-well region. VSP was expected to have an intermediate resolution between cross-well and surface seismic. 3-D images can be obtained from vertical seismic profiling (VSP) data, but the coverage is limited to a ring approximately 1/2 of the target depth (in this case, about 500 ft from the receiver well). Surface seismic provides the largest area coverage but has the lowest resolution.

The design was completed and implemented in December, 2003. To optimize the resolution of the surface seismic and VSP, a high frequency IVI-2 MiniVibe capable of sweeping up to 500 Hz was used in this study. To optimize resolution, 40 Hz geophones were used to record the surface seismic data. Ninety-six surface receivers were spaced at 18 ft intervals to ensure that high frequency data would not be spatially aliased. Figure 10 provides pictures of Well Hon 9 being drilled, a surface seismic line, control panel of the cross-well seismic gear, and the MiniVibe rig used in the surveys.


Figure 10.1. Well Hon 9


Figure 10.2. Seismic Line 1000

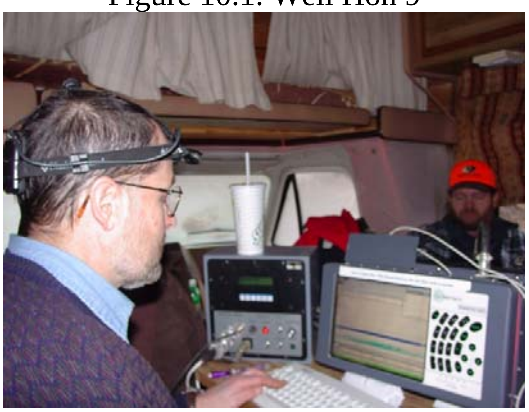


Figure 10.3. Cross-well Data Acquisition Control


Figure 10.4. MiniVibe used in the Survey

Line 1000 shown in Figure 10.2 is the line running across the two wells used for the cross-well survey and is the Northwest to Southeast line shown in Figure 9. Lines 2000, 3000, and 4000 were run perpendicular to Line 1000 for understanding the out-of-plane heterogeneity in Line 1000 and in the cross-well data. For each line the receivers were fixed and the vibration points were located every 36 ft from the end of the receiver ‘spread’ in each direction for 1500 ft. This survey geometry resulted in a ‘full fold’ extent of approximately 0.3 miles per line. For each source point four 7-second linear sweeps (20-400 Hz, 1 second listen) were correlated and stacked. The data were recorded using the Distributed Geometrics Geode system. The data were digitally sampled at 0.5 ms intervals using a 24-bit sigma-delta converter and written to SEG-D format.

In December 2003, Z-Seis acquired one cross-well seismic survey between wells Hon 9 and Hon 3. During the initial cross-well logging, it was discovered that the Hon 3 well had a loggable depth of only 830 feet rather than 1018 feet due to the plug slipping up-hole during cementing. The survey was logged with this depth restriction. Externally generated surface noise during logging required re-logging of the site. Hon 3 was deepened to 985 feet and the survey reacquired by Z-Seis as their in-kind contribution to the ICCI/GTI project.

B - Fracture Diagnostic Survey

Hydraulic fracturing involves injection of a high viscosity proppant carrying fracturing fluid at selected intervals in a wellbore. The injection pressure is high enough to overcome the sum of the local minimum principal stress and the rocks resistance to fracturing. Down to an approximate depth of about 750 feet, these fractures are usually horizontal and pancake shape. Hydraulic fractures in deeper wells are almost vertical and extend along the direction of the intermediate in situ principal stress. Because hydraulic fractures provide a high permeability conduit for gas flow, the drainage area of a hydraulically fractured well is elliptical in contrast with the circular drainage area of non-fractured wells. The knowledge of the fracturing mode (horizontal or vertical) and fracture azimuth in case of vertical fractures is thus critical for selection of production wells to minimize well interference and to avoid leaving portions of the reservoirs un-drained.

Creation of extensive hydraulic fractures in the subsurface causes minute yet detectable transient surface deformations that can be recorded and used for determination of the fracturing mode and fracture azimuth. In these measurements a number of high precision devices (tiltmeters) that measure changes in the local vertical to a few nanoradians are deployed on predetermined arrays around the wellbore and record the surface deformations during hydraulic fracturing operations.

Actual ground deformation resulting from a vertical fracture is normally an elongated surface depression and two parallel uplifts, albeit in nanometers. The surface expression of a horizontal fracture resembles a simple hill centered at the wellbore. Figure 11 (After Pinnacle Technologies Inc.) is an exaggerated graphic representation of surface deformation resulting from vertical, horizontal, and dipping fractures.

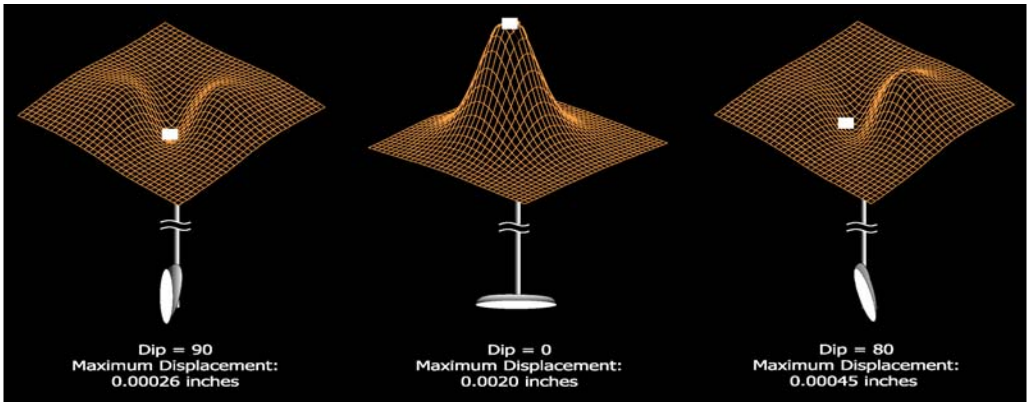


Figure 11. Surface deformation resulting from vertical, horizontal, and dipping fractures

Tiltmeter survey at BPI-Energy site in Shelby County, Illinois was performed by Pinnacle Technologies as a subcontractor to the project. In this survey a 16-tiltmeter array was deployed around the wellbore and ground deformation was continuously monitored during the fracturing operations. Figure 12 exhibits the instrument position and theoretical and actual surface tilt resulting from fracturing at a depth less than 750 feet below the surface. On this figure, the + symbols are the tiltmeter locations, the red vectors are theoretical tilts for a horizontal fracture at this depth, and the black vectors are the actual measured tilt values. Allowing for small variations resulting from local soil conditions and background noise, theoretical and observed values are excellent agreement. Figure 13 shows the actual ground deformation caused by this fracture. Note that the shape of ground deformation indicates creation of a horizontal fracture.

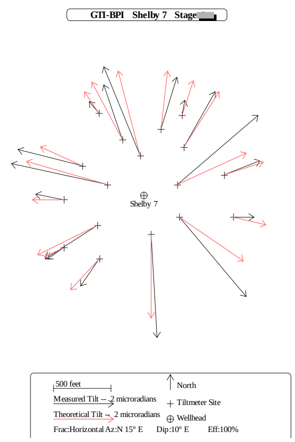


Figure 12. Tiltmeter array at BPI Shelby # 7 site

Fracturing at this site took place in five stages. The fracture mode and orientation was accurately determined for all five stages. To protect the data confidentiality, detailed results from all surveys are presented in a confidential Appendix to this report. However, the general information that can be publicly disclosed for use by other producers is summarized in the forthcoming sections of this report.

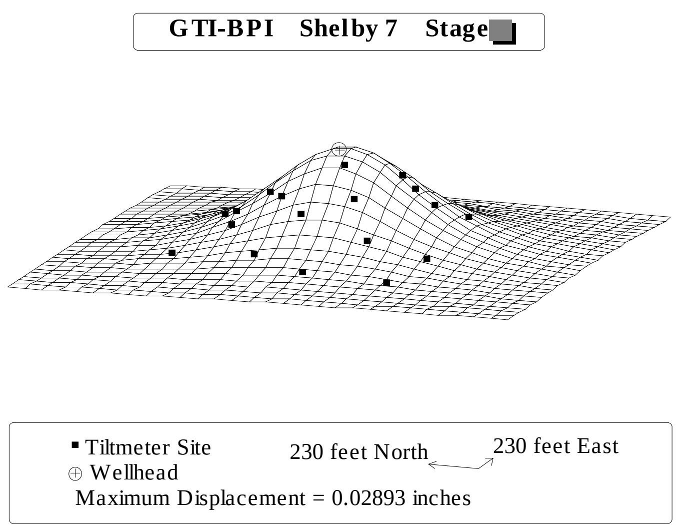


Figure 13. Ground deformation during one of fracturing stages at Shelby #7

RESULTS AND DISCUSSIONS

Task 1. Laboratory Experiments and Analyses

Laboratory measurements of coal physical properties are difficult and time consuming. This is primarily due to high friability of coal, its low matrix permeability, and pressure dependency of compressional wave velocity. The dilemma is that while “good” samples for laboratory measurements have to be solid and free of fractures, such specimens are not necessarily representative of large bodies of coal. To overcome these difficulties, experiments must be repeated multiple times on multiple samples to arrive at some meaningful average values. We developed in excess of 140 data points for coal samples from two Illinois coal mines. A summary of results for the best 20 samples is shown on Table 2.

Table 2. Compressional Wave Velocity under Gas and Water Saturation

Sample Number	Confining Pressure (MPa)	P-w Travel Time, (Gas/Dry)	P-w Travel Time (Water)	Vp @ Gas Saturation	Vp @ Water Saturation
1	3.9	39.45	30.79	2,756	2,151
2	1.9	31.14	29.95	2,175	2,092
3	2.9	42.19	30.50	2,947	2,130
4	2.9	34.83		2,433	
5	2.9	38.85		2,714	
6	2.9	42.35	32.13	2,958	2,244
7	2.9	47.14	32.25	3,293	2,253
8	3.9	39.38	38.44	2,751	2,685
9	3.9	38.90	38.56	2,717	2,693
10	3.9	46.10	41.46	3,220	2,896
11	3.9	45.16	40.72	3,154	2,844
12	2.9	39.33	32.49	2,747	2,269
13	2.9	44.87	32.40	3,134	2,263
14	2.9	42.08	37.56	2,939	2,624
15	2.9	41.87	37.88	2,925	2,646
16	2.9	53.43	34.02	3,732	2,376
17	2.9	53.93		3,767	
18	2.9	36.19	32.02	2,528	2,237
19	2.9	37.94	32.52	2,650	2,272
20	1.9	40.97	32.52	2,862	2,272
Average	3.05	41.81	34.48	2920	2409

These laboratory measurements allowed us to determine acoustic velocity changes that resulted from injection of a gas phase into water-saturated coal samples and thus evaluate the feasibility of time-lapse seismic surveys for monitoring the position of the desorbed gas front (or CO_2 in sequestration project) in coal. Note that in all cases compressional wave velocity for water saturated samples is higher than that for the same sample with gas saturation. Figure 14 is a graphic representation of the data.

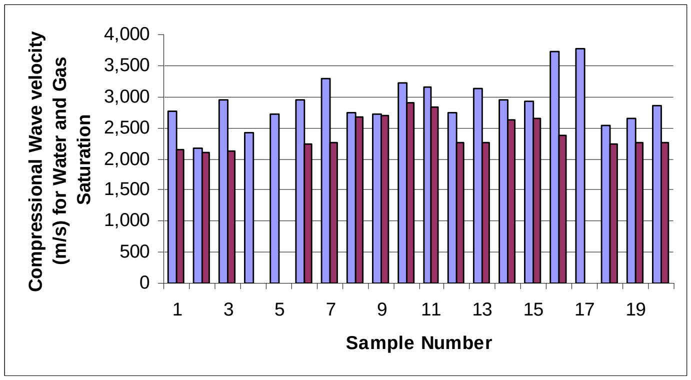


Figure 14. Graphic representation of water saturated and gas saturated acoustic wave velocity (Magenta and purple bars correspondingly) under ~3 MPa confining pressure

The data in Table 2 also shows the pressure dependency of acoustic velocity for all coal samples. In many cases, this relationship is almost perfectly linear, as shown in Figure 15. However, it was not possible to establish an analytical relationship between velocity and confining pressure for cases of highly fractured coal samples.

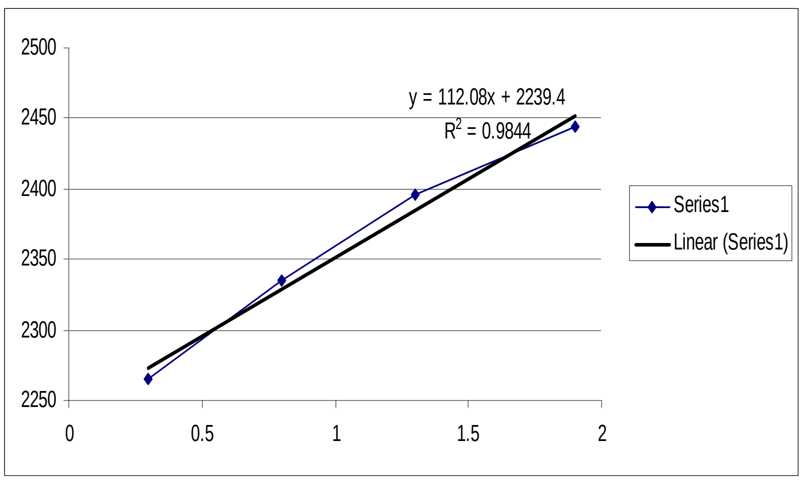


Figure 15. Graphic representation of velocity/pressure dependency

Velocity reduction in sedimentary rocks due to gas saturation is a well established phenomenon. Considering the compressibility of coal, the question was whether the same phenomenon occurs in coal seams. Our laboratory experiments proved that the phenomenon does occur in coals as well.

In the course of our data analysis we frequently noticed substantial velocity differences for two adjacent points of seemingly uniform samples. To investigate the matter, CT scan imaging was performed on one sample (Figure 16-A). Removing the pixels corresponding to coal material through image processing produced the image of the open and filled cleats (Figure 16-B).

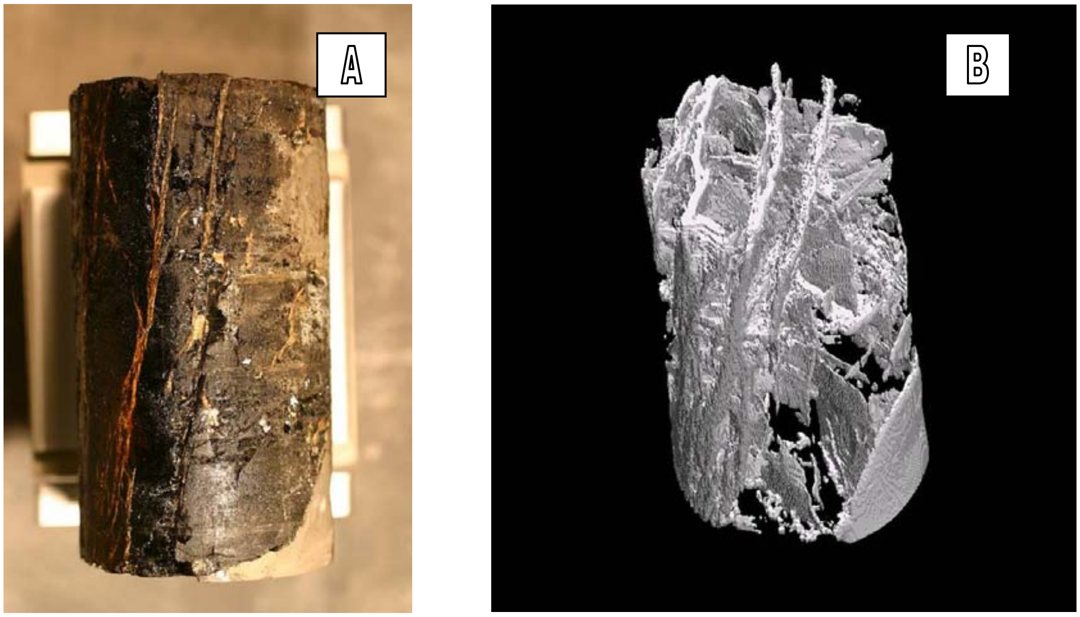


Figure 16. Photograph of coal sample (A) and CT image of cleat system (B)

The CT image clearly shows the abundance and non uniform distribution of cleat filling material (predominantly calcite) and helped us understand the discrepancy in the data. In light of this observation, it is clear that application of results of single core measurements to modeling of large bodies of coal would be error prone and should not be attempted. Instead, average values from a sufficient number of samples, checked against sonic logs if available, can be used more reliably for forward seismic modeling.

Task 2. Data Analysis and Modeling

A - Seismic Analysis and Modeling

Data analyses included all conventional seismic analysis techniques to produce the final cross sections. The success of the project was keyed to development of accurate cross sections by integrating the results from all three surveys. Examples of results from conventional data processing are shown on figures 17 and 18.

In order to identify the dominant frequency for coal seams and to determine changes in frequency with depth, the data was spectrally decomposed in 10 Hz increments for the entire section. Figures 19 through 21 are example frames of results from these analyses. Note that at 30 Hz (Figure 19), the resolution at the zone of interest is quite low; it is noticeably enhanced at 70 Hz (Figure 20), and is at the highest value at 140 Hz (Figure 21).

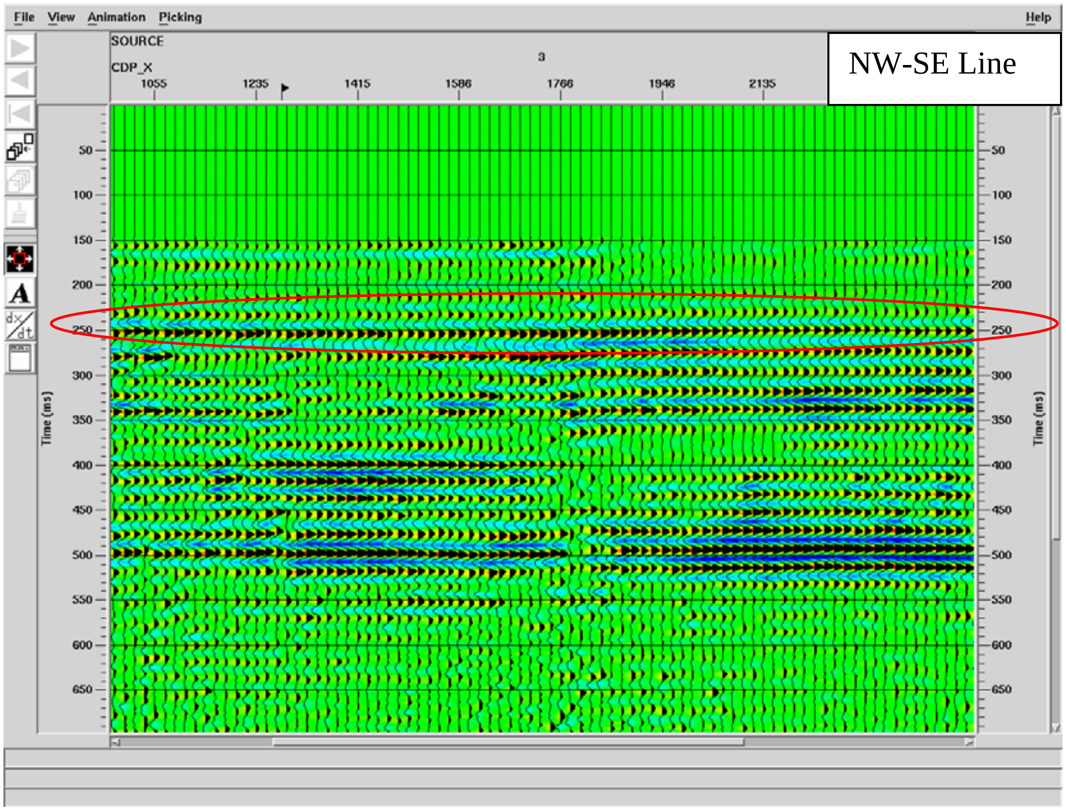


Figure 17. Processed Seismic Section for Line 1000

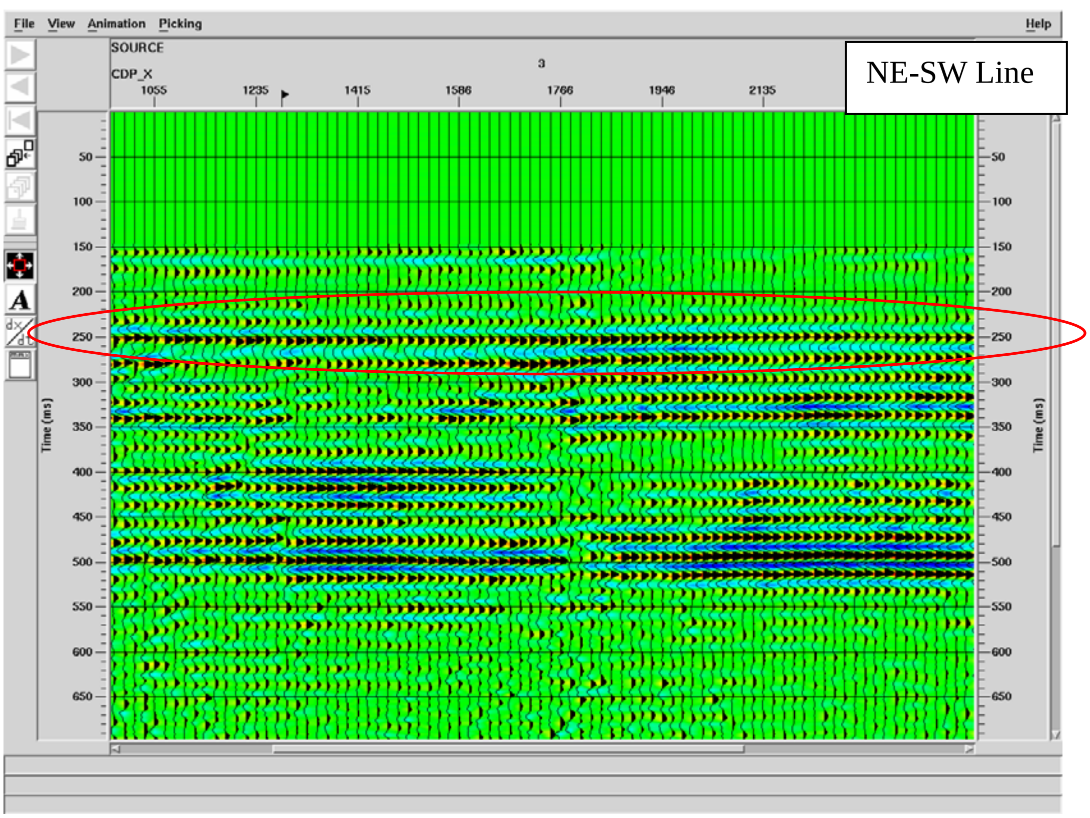


Figure 18. Processed Seismic Section for Line 2000

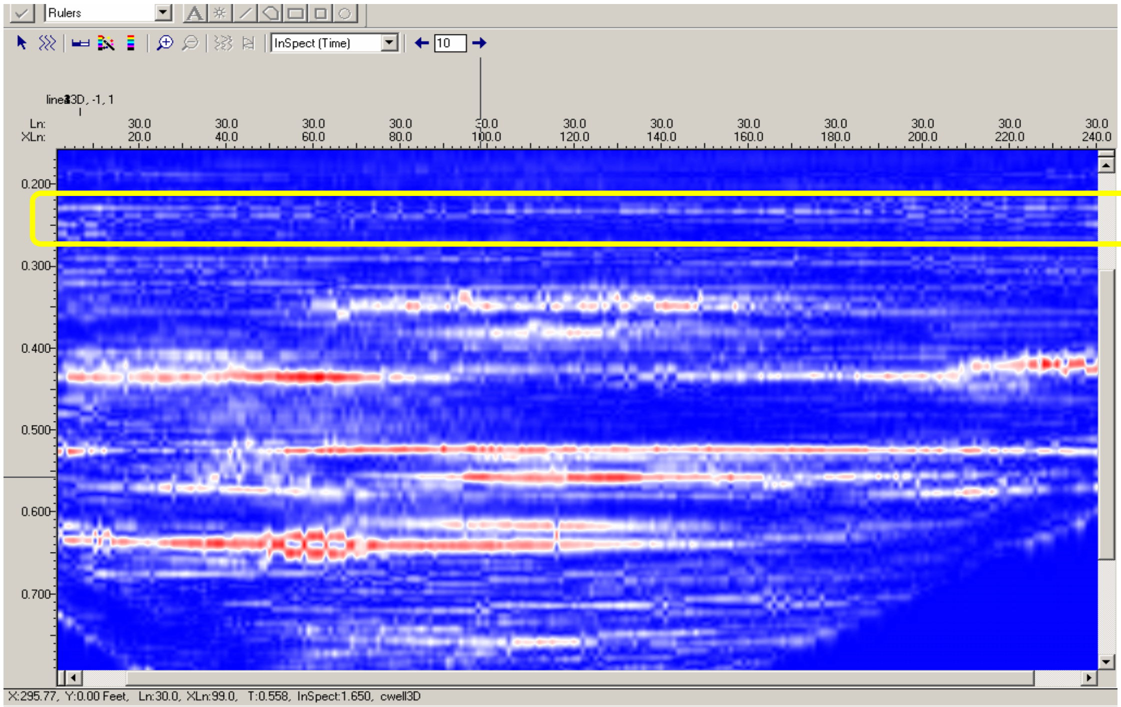


Figure 19. Spectrally Decomposed Data at 30 Hz

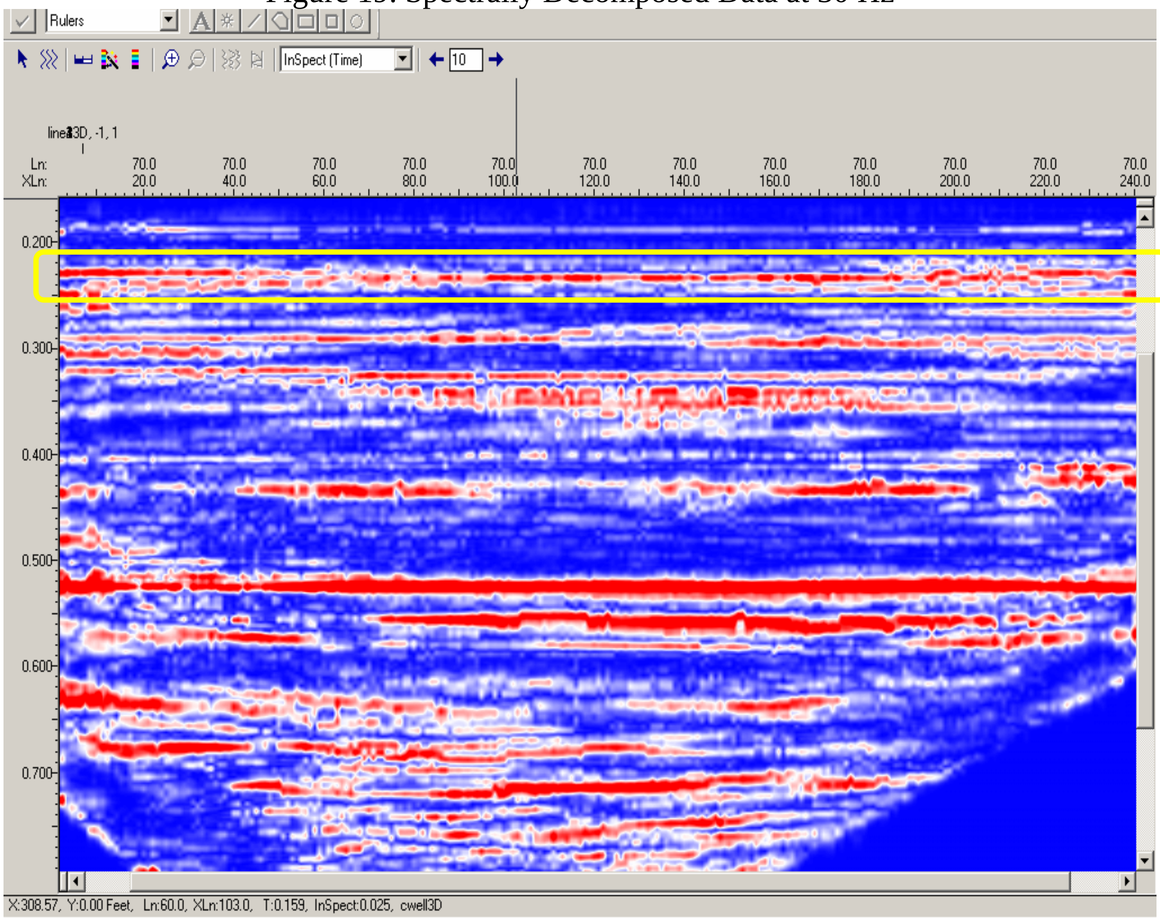


Figure 20. Spectrally Decomposed Data at 70 Hz

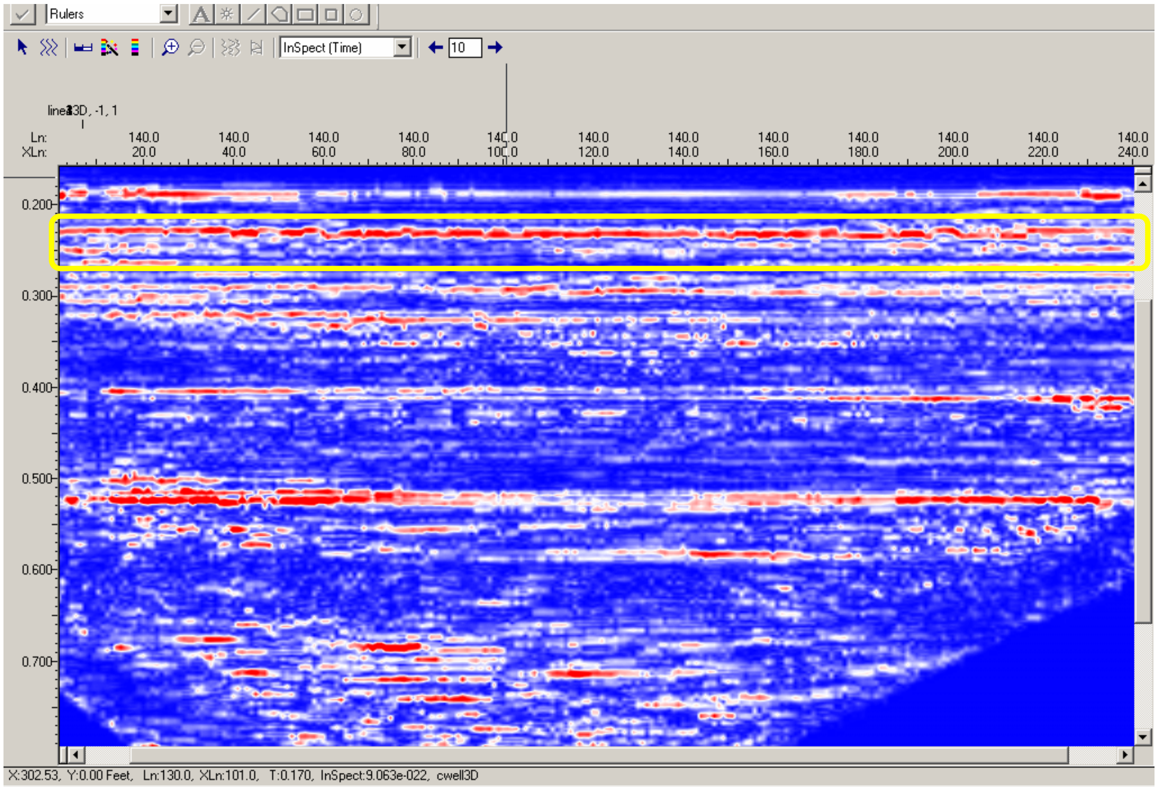


Figure 21. Spectrally Decomposed Data at 140 Hz

Figure 22 is the final processed crosswell image. This image covers the section between wells Hon 3 and Hon 9. All coal seams present at the site have been clearly imaged, as shown by the superposition of the well log from well Hon 9 on the section.

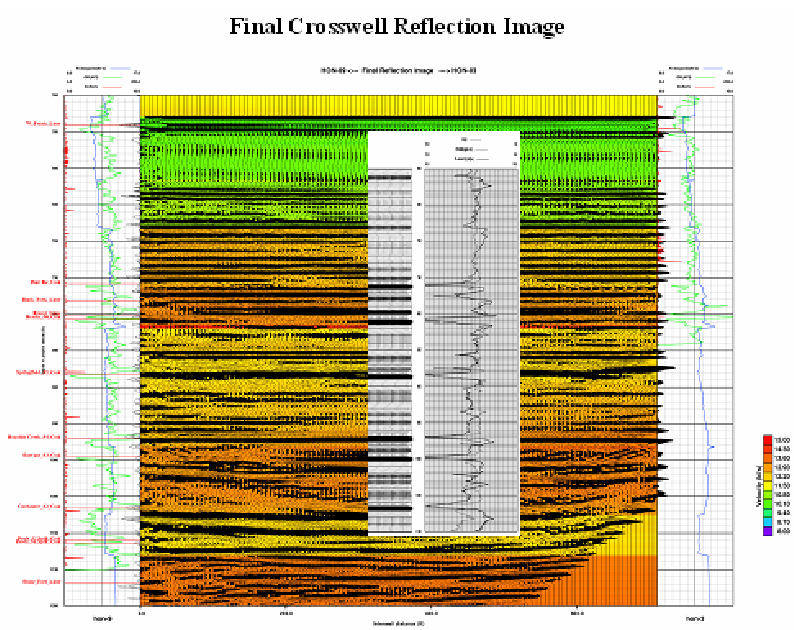


Figure 22. Final crosswell reflection section at well Hon #9

Following completion of the data analysis and visualization, a series of seismic forward modeling were performed. The purpose of this modeling exercise was to investigate the feasibility of time-lapse seismic technology for imaging the injected or evolved gas phase within the coal seams. Results from laboratory measurements had shown that addition of a gas phase to initially water saturated coals would cause substantial decrease in the compressional wave velocity. However, in our modeling, a conservative 20% velocity reduction was assumed. Results from these modeling efforts are shown on Figure 23.

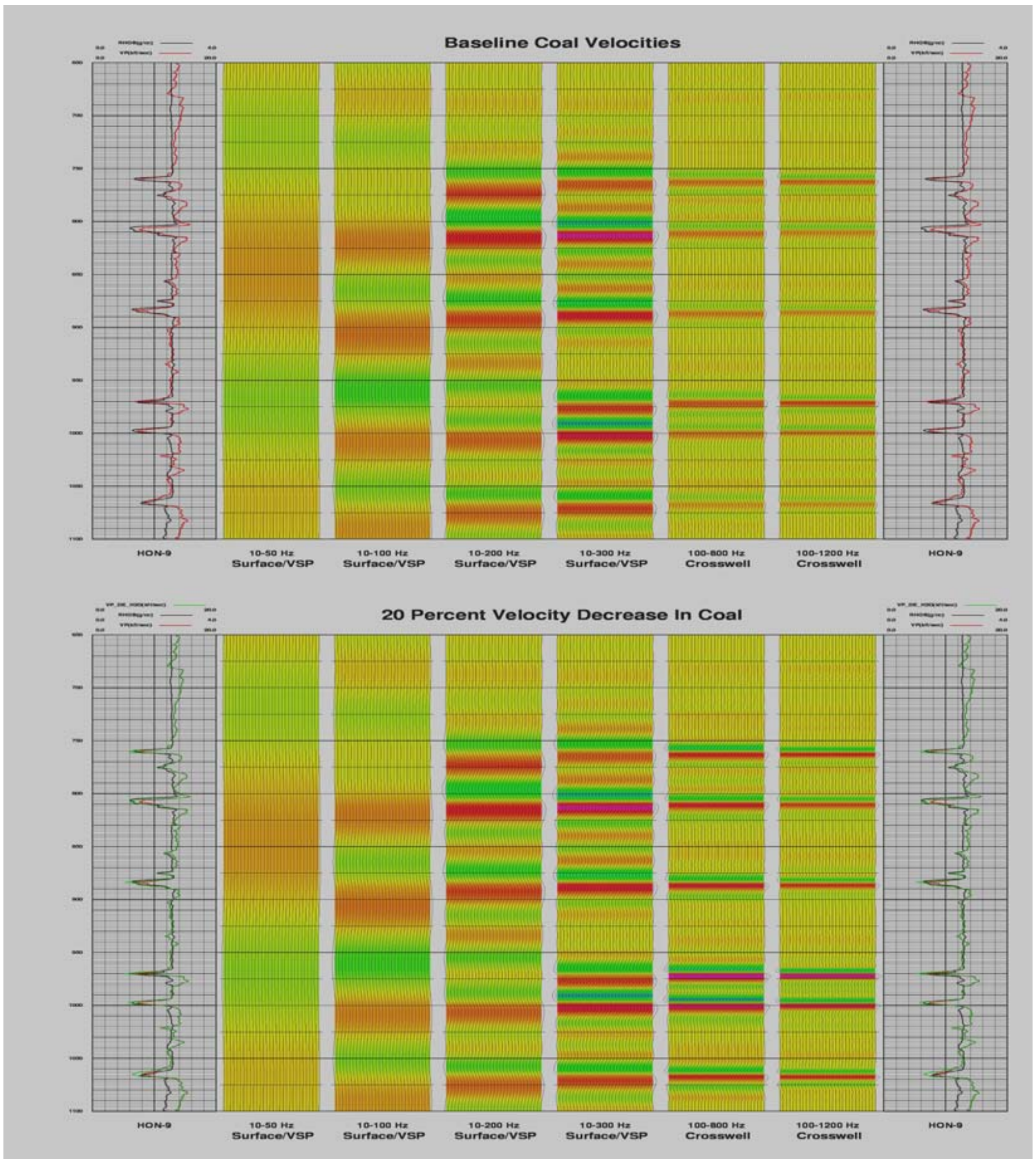
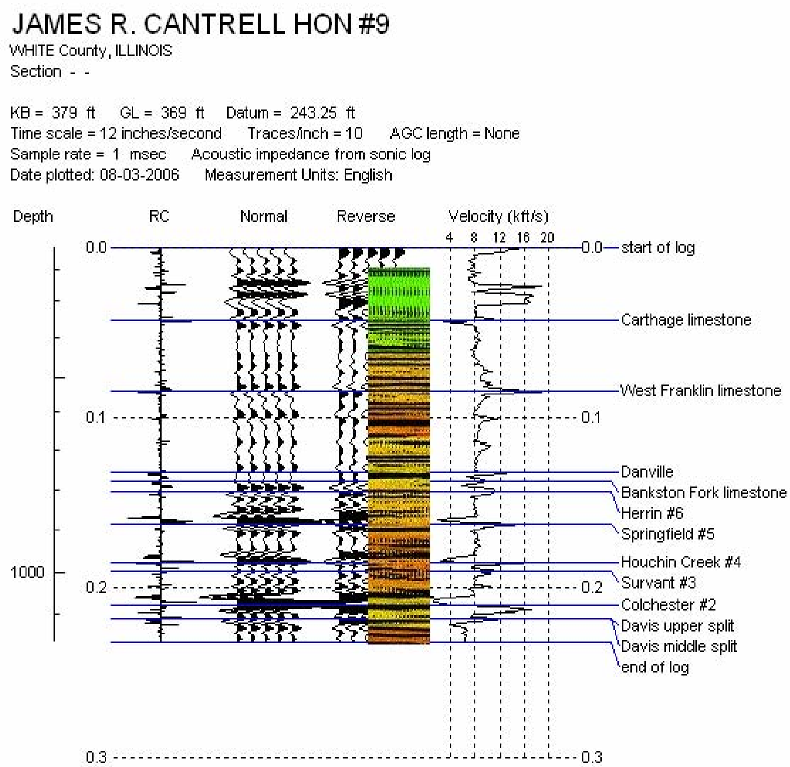


Figure 23. Response of individual coal seams to gas saturation

In Figure 23, the line graphs on either side of the colored area represent the well logs from wells Hon 3 and Hon 9. Coal seams can be clearly identified on these logs. Each vertical band on the main figure is for a range of frequencies that increases to the right, i.e., low frequency band on the left (10-50 Hz) and high frequency band (100-1200 Hz) on the right. The top part of the figure exhibits the seismic response of individual seams before velocity reduction and the bottom part shows the response after 20% velocity reduction. Note that changes in the seismic response resulting from injection of carbon dioxide or evolution of coalbed methane can only be observed at frequencies in the 100-800 Hz and 100-1200 Hz bandwidths. Results from forward modeling work strongly suggest that accurate monitoring of the desorbed methane front through repeated crosswell surveys is quite possible.

Seismic modeling included development of synthetic seismograms with data from Hon #9 wells at the ISGS site, Figure 24. Note the close correspondence between the synthetic trace, the crosswell data, and coal seams as cored in this well.



Horizon	Depth	Subsea	Time	Ave V
start of log	136	243	0.000	-----
Carthage limestone	357	22	0.043	10385
West Franklin limestone	541	-162	0.085	9551
Danville	758	-379	0.133	9389
Bankston Fork limestone	782	-403	0.138	9381
Herrin #6	806	-427	0.143	9346
Springfield #5	882	-503	0.163	9152
Houchin Creek #4	971	-592	0.185	9017
Survant #3	996	-617	0.191	9031
Colchester #2	1066	-687	0.211	8834
Davis upper split	1110	-731	0.218	8938
Davis middle split	1114	-735	0.219	8948
end of log	1159	-780	0.232	8823

Int H	Int T	Int V
221	0.043	10385
184	0.042	8710
217	0.048	9100
24	0.005	9170
24	0.006	8506
76	0.020	7732
89	0.022	8025
25	0.005	9536
70	0.020	6964
44	0.007	11900
4	0.001	12480
45	0.013	6780

Wavelet

5-10-140-200 Hz

Phase = 0 degrees

Length = 0.080 Sec

QuickSyn © 1996-2006 by GeoTools

Figure 24. Synthetic seismogram for the sequence at well Hon # 9

B - Fracture Modeling

Using Pinnacle Technologies FracPro PT, a series of fracture modeling were performed. Petrophysical data from wells Hon #9 and Shelby #7; and actual fracturing parameters from Shelby #7 (e.g.; schedule time, rate, pressure, fluid viscosity, and proppant concentration) were used in these model runs. Modeling was carried out for all individual seams. Figures 25 and 26 are sample outputs of these model runs. Modeling showed that in all cases the vertical fractures grow out of zone and individual fractures cut across the neighboring coal seams.

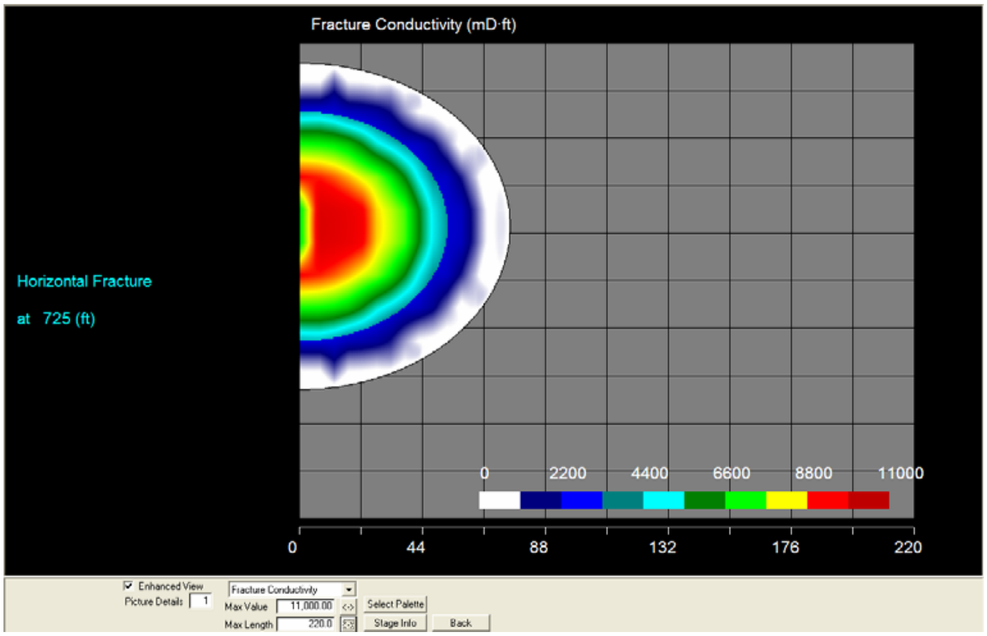


Figure 25. Model of a horizontal fracture at an approximate depth of 725 feet

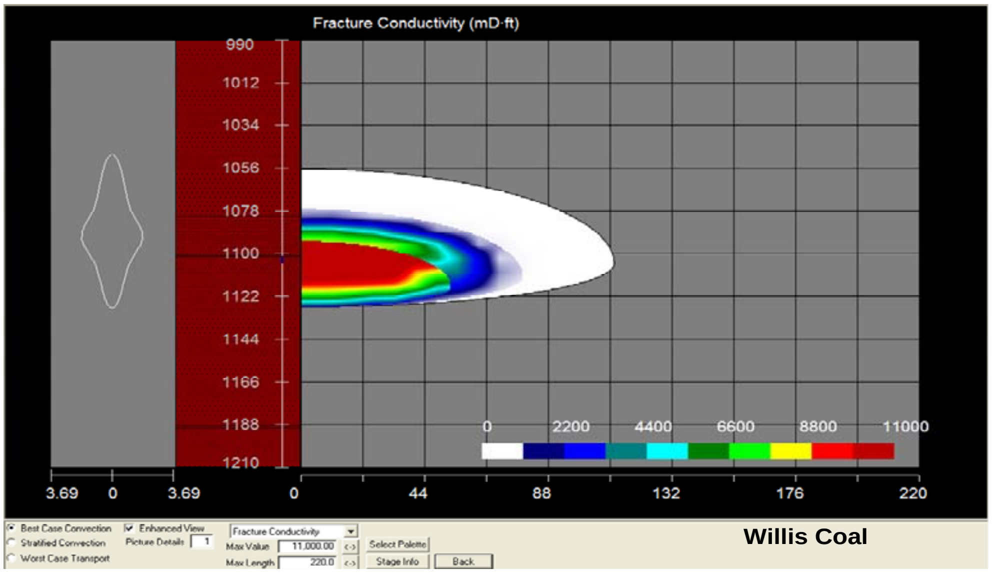


Figure 26. Model of a vertical fracture at the depth of about 1100 feet

Task 3. Field Data Acquisition

Seismic data acquisition included recording of four densely instrumented surface lines, a Vertical Seismic Profile (VSP), and a cross-well survey, as described in the Experimental Procedures section. The major finding from the field data acquisition task was that, under the ISGS site conditions, conventional seismic recording provides images of coal 'package' ;i.e., a number of coal seams in proximity of one another represented by a single reflection signal, but falls short of identification of individual coal seams. This is mainly due to the overburden (Tick River Fill) at the site and the incompetent nature of the overburden causing severe attenuation of the high frequency content of the seismic waves. In contrast, cross-well signals and to a lesser extent VSP data were rich in high frequencies. It is therefore recommended that under similar conditions, cross-well seismic surveys should be used to provide the most reliable images of the subsurface. These images can also be used for identification of refection horizons on surface sections. It was further observed that although VSP data is more reliable than surface data, the signals are still subject to surface related attenuation.

It was also concluded that because of poor surface coupling, vibroseis should not be the source of choice for seismic surveys. Instead, impulsive sources (such as small explosive charges) placed at about 10 feet below the surface would be much preferred. In this fashion, in addition to starting with a wide band of energy at the source, coupling of the source energy to the ground would be greatly enhanced.

Field data acquisition for fracture diagnostic surveys did not deviate from the sate-of-the-art techniques.

Task 4. Integration, Report, and Technology Transfer

Compilation of data and preparation of reports continued throughout the project and will continue albeit at a lesser extent. Although no new funding is presently available for continuation of efforts, we believe pursuing the development of coalbed methane production has the promising of turning a portion of the 14 trillion cubic feet of gas resource in Illinois to a substantial producible reserve.

Our technology transfer efforts included presentations at the Pittsburgh Coal Conference, the annual meeting of the American Association of Petroleum Geologists, and publication in two issues of GasTips, a GTI-DOE publication featuring the major results from the ongoing research and development.

CONCLUSIONS AND RECOMMENDATIONS

Combining the results from the actual surveys, spectral decomposition, and forward modeling, the following conclusions can be drawn:

- At 10-50 Hz bandwidth the resolution is very low and results from surface seismic surveys are not reliable.
- At 10 -200 Hz bandwidth, high resolution imaging is possible and surface seismic data would be reliable for mapping of the "coal seam packages" as a whole.

- The use of impulsive sources for surface seismic surveys is strongly recommended.
- VSP surveys (10-300 Hz bandwidth) noticeably enhance the resolution.
- Under geologic conditions similar to those at the ISGS pilot site, position of the injected or evolved gas can only be imaged at higher frequencies through cross-well seismic applications.

Laboratory measurements proved that changes in acoustic properties of coal resulting from the addition of a gas phase into the cleat and pore spaces is substantial and therefore, seismic monitoring of the injected CO_2 would be quite feasible. Furthermore, monitoring of methane production from coal seams of Illinois appears to be quite practical and can be used as means for determination of the high permeability trends and development of de-watering and production well patterns.

Fracture modeling and fracture diagnostic survey proved the following issues:

- Hydraulic fractures at depths less than 750 feet grow horizontally.
- Fractures at depths between 750 and 1100 feet grow in a complex mode with one minor vertical component and at least one major horizontal component.
- Under conditions similar to the BPI site, it is safe to assume a circular drainage pattern for coalbed methane wells.
- Vertical fractures under these and similar field conditions grow out of zone and staged fracturing of neighboring well does not appear to be required.

ACKNOWLEDGEMENTS

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