

Who supported the project and credit:

Gas technology institute, with the support from Illinois Clean coal institute, and cooperation of Illinois State Geological Survey, designed research project aimed at determination of viability of seismic techniques for site selection and monitoring of CO₂ sequestration in Illinois coal.

Why ? This study focused on proving or disproving the applicability of advanced seismic techniques for producing reliable maps of thin Illinois coal seams for selecting the sites for CO₂ sequestration.



Presentation Outline

- **Motivation**
- **Problems**
- **Technology Needs**
- **Project Objectives**
- **Scope of Work**
- **Summary of Results**
- **Future Work**
- **Conclusions and Recommendations**

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Motivation

- Coalbed methane in Illinois is a sizeable natural gas resource (14-21 Tcf)
- Unmineable coal seams offer a safe and permanent target for sequestration of carbon dioxide
- Sequestration of carbon dioxide in coals liberates the adsorbed methane that can be economically produced. (Enhanced Coal Bed Methane recovery – ECBM)

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Problems

Factors influencing CBM production :

- **Uncontrollable:** Thickness, lateral continuity, rank of coal , gas content, permeability, depth, structures, (in-situ conditions)
- **Controllable:** Site selection, well location and well completion techniques.
- **CBM Production to be successful**
 - Coal seams continuity at the site essential.
 - Wells must be placed along high permeability trends.

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Factors:

Thickness, lateral continuity and rank of the coal.

Moderate to high permeability that is controlled by the amount of fracturing or cleats.

Depth of burial and other barriers, such as impermeable layers, or structures, as faults and folds, that keep the gas trapped within the coal seam (Arkansas Geological Commission).



Problems *Continued*

➤ **CO₂ Sequestration**

- **The target seams must extend over a large enough area to accommodate large volume of CO₂ over a long period of time**
- **It is important that the host coal seams be free from faults and dislocations that could cause migration of the injected CO₂ into unintended zones**
- **It is therefore imperative to map the candidate coal seams very accurately prior to site selection and monitor the gas front movement throughout the life of a project**

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As with all greenhouse gas sequestration processes involving injection of greenhouse gases into geologic formations, safety and permanency of the processes require the injected gas to remain within the target zone with no possibility of contaminating water supplies, leaking to unintended zones, or eventually, escaping back into the atmosphere. Diligent site selection and attentive monitoring are thus crucial prerequisites for success. Specifically, the host coal seams must be continuous, extend over a large area, occur in structurally closed geometry, and be free of faults and displacements.



Technology Needs

- **Advanced seismic technology is potentially capable of resolving these issues**
 - **Seismic techniques have been used successfully for reliable subsurface imaging and monitoring of gas cap movements in conventional oil and gas reservoirs, however, because of the internal properties of coal, the degree of applicability of the technology to coal is not certain.**

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Advanced seismic technology has been proven successful in providing detailed subsurface images of conventional oil and gas reservoirs as well as thicker coal seams. However, Illinois coal seams are shallow and thin, with the thickness rarely exceeding 10 feet. The first objective of this project was to establish viability of seismic imaging of thin coal seams in Illinois.



Project objectives

Field Investigation

- Investigate resolution limits of seismic techniques relative to thin coal seams and detection of small discontinuities.

Laboratory Investigation

- Investigate changes in bulk elastic properties of coals due to changes in saturation.

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The resolution of seismic techniques is rarely better than 5m (~16.4 f).

Van Reil (1986) has shown that coal beds as thin as 0.75 m (2.46 f) can be resolved by reflection seismic methods.

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)



Resolution

The resolution of seismic techniques is rarely better than 5m (~16.4 ft).

Van Reil (1986) has shown that coal beds as thin as 0.75 m (2.46 ft) can be resolved by reflection seismic methods.

(Widess et. al., 1986) concluded that the thickness of a bed must be at least 1/8 of the dominant seismic wavelength to be resolvable.

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The resolution of seismic techniques for conventional sedimentary rocks is rarely better than 5m (~16.4 f), Van Reil[1] (1986) 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.

[1] Van Riel, W. 1986. Coal Geophysics: Society of Exploration Geophysicists.



Resolution *Continued*

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 events?

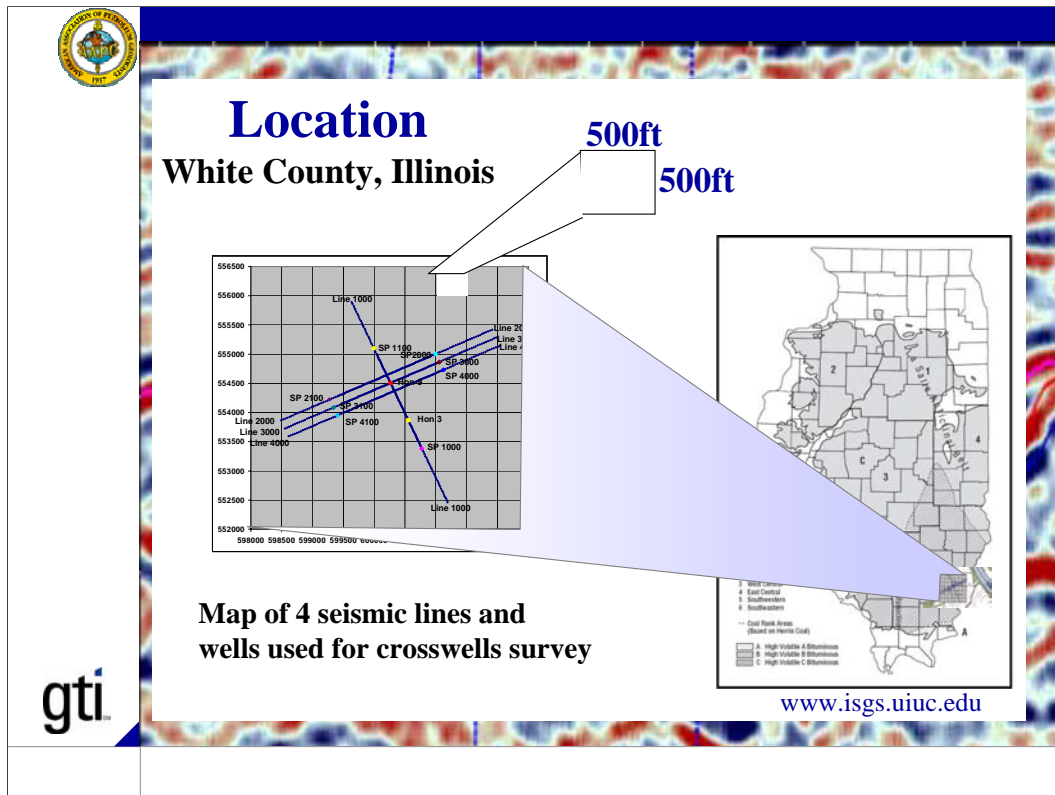
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Scope of Work

- **Developed customized seismic survey techniques for CO₂ sequestration and CBM production site selection**
 - Detailed surface survey
 - VSP
 - Crosshole seismic survey
- **Lab work to investigate the viability of monitoring CO₂ front in coal seams**
 - Measure changes in elastic properties of coal resulting from addition of a gas phase into the cleat system (Wst.)

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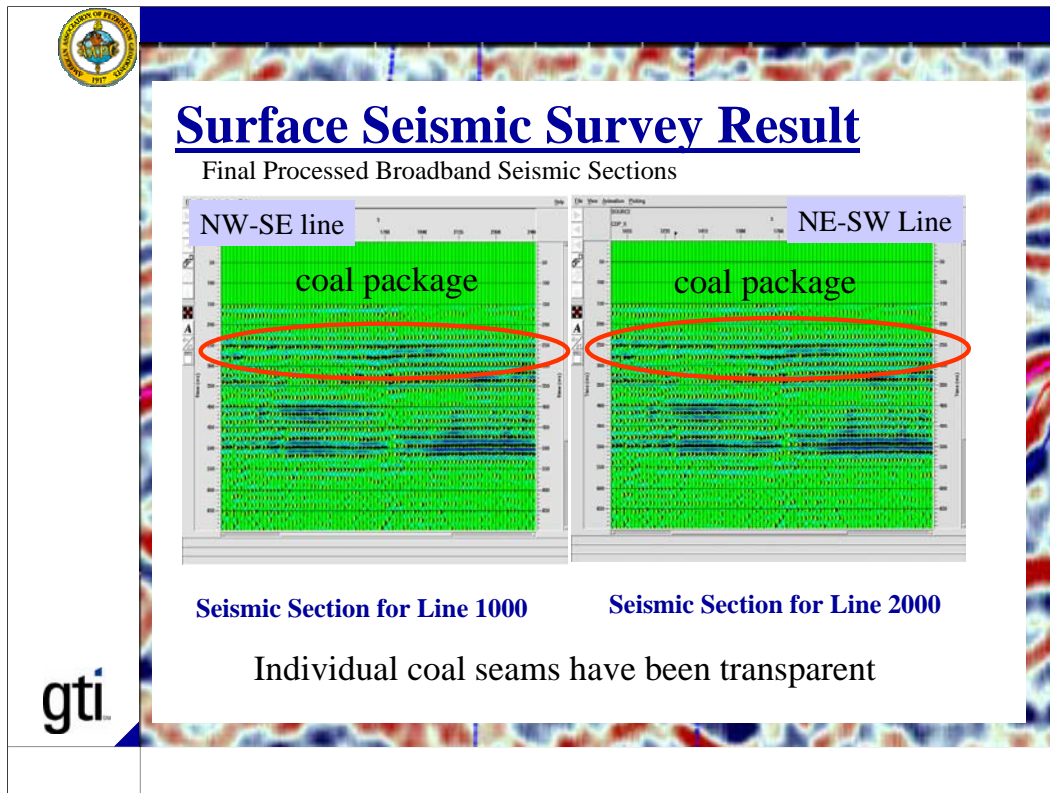
Series of seismic data acquisitions were carried out in the White County, Illinois at the ISGS pilot site.

These were 4 densely populated surface lines plus vertical seismic profiles (VSP) and one crosswell survey.

The location of the seismic lines, wells Hon 3 and Hon 9, and VSP surveys are shown on this slide.

Line 1000, running through the two wells used for the cross-well survey, is the Northwest to Southeast Line shown in Figure 8. Lines 2000, 3000, and 4000 were run perpendicular to Line 1000 for the purposes of understanding 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.



These figures are the final processed seismic sections from surface lines.

Note that although the reflection events from the coal package (inside the red ellipse) are clearly identifiable, individual coal seams have been transparent.

Also note that the coal package as a whole is quite continuous and does not exhibit any discontinuity.

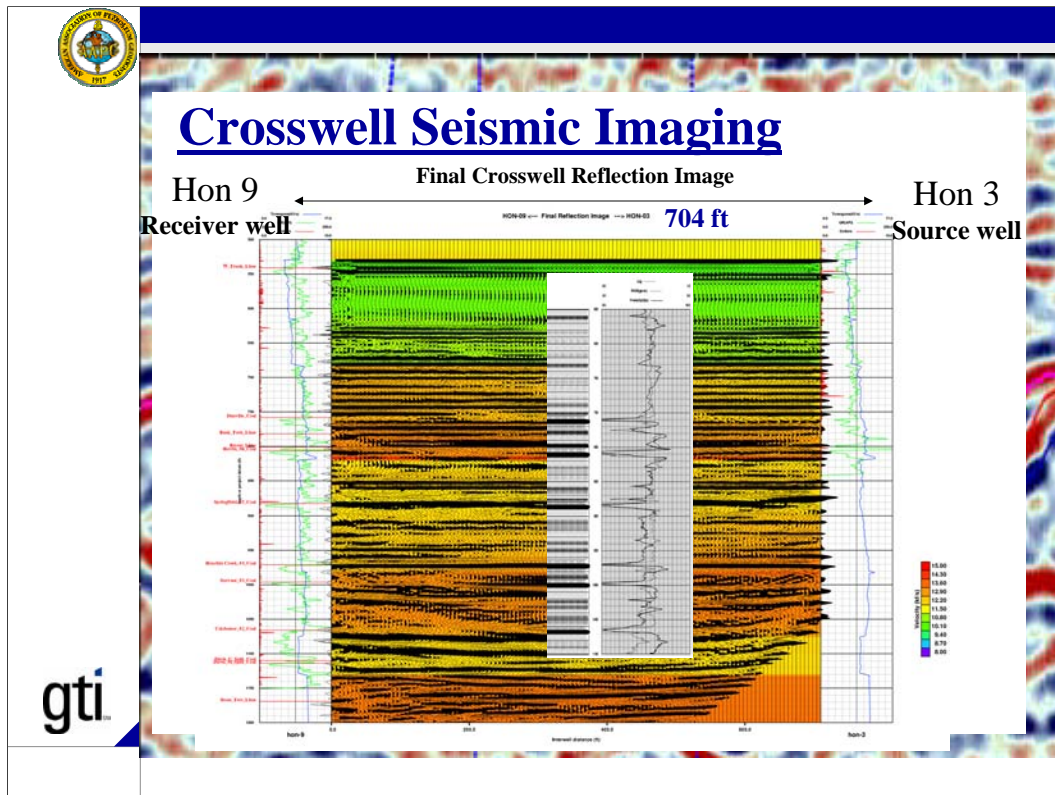
Lower in the section, at about 400 milliseconds, clear discontinuity is observed. These discontinuities do not appear to reach the coal zone and do not cause any concern.

Line 1000, running through the two wells used for the cross-well survey, is the Northwest to Southeast Line shown in Slide 11. Line 2000, as well as Lines 3000 and 4000, run perpendicular to Line 1000 for the purposes of understanding 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.

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.

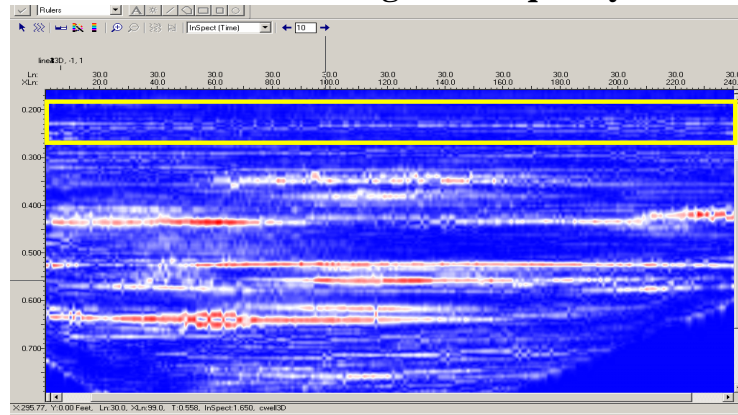


This is the final processed crosswell image. It covers the section between wells Hon 3 and Hon 9. All coal seams present at the site have been clearly imaged, as shown by the superposition of the well log from well Hon 9 on the section.



Advanced Seismic Data Processing

In order to identify the dominant frequency for coal seams and to determine changes in frequency with depth



Spectrally Decomposed Data at 30 Hz

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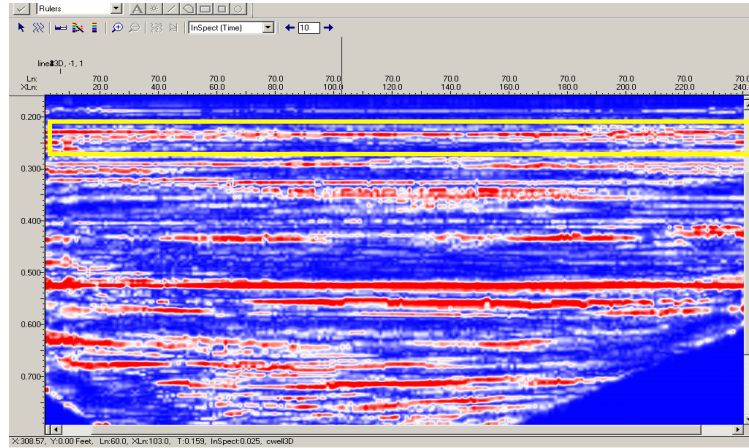
In order to identify the dominant frequency for coal seams and to determine changes in frequency with depth, the data was spectrally decomposed in 10 Hz increments for the entire section. Figures are example frames of results from these analyses.

Note that at 30 Hz (this slide [14]), the resolution at the zone of interest is quite low; it is noticeably enhanced and is at the highest value at 140 Hz (Slide 16).



Advanced Seismic Data Processing

Spectrally Decomposed Data at 70 Hz

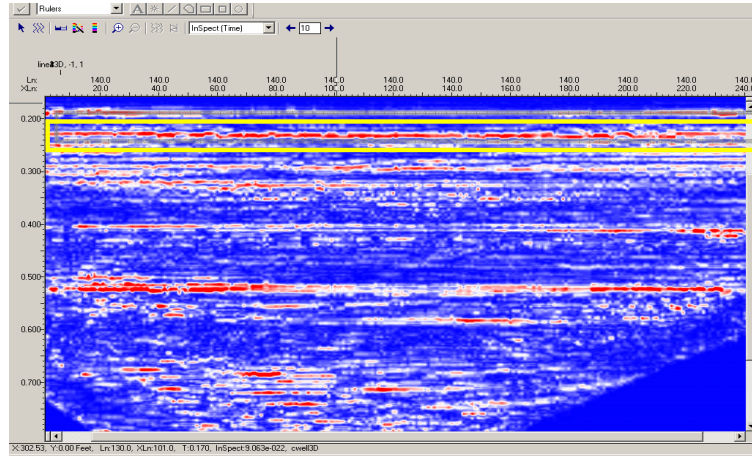


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Advanced Seismic Data Processing

Spectrally Decomposed Data at 140 Hz

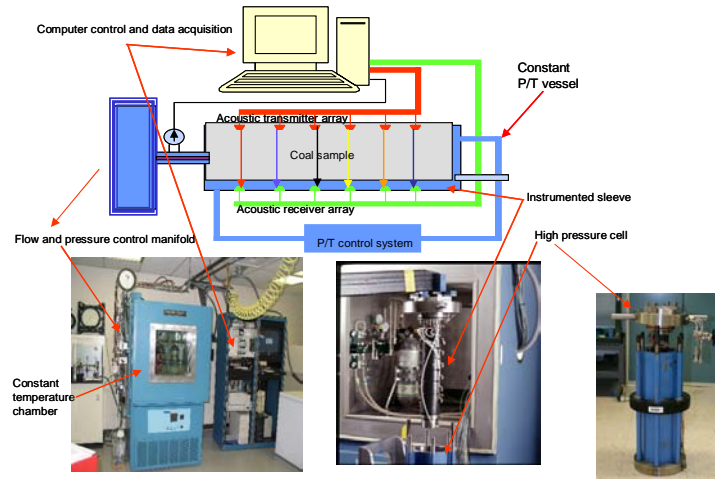


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Laboratory work

Ultrasonic velocity measurement



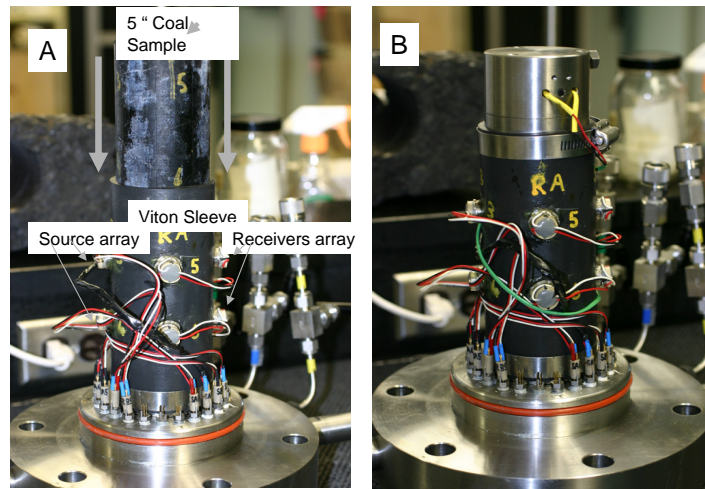
Schematic diagram of experimental apparatus

Our laboratory studies were 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 site where ISGS is implementing a coalbed methane pilot project and one in Central Illinois near Springfield (C in Slide 11).



Laboratory work



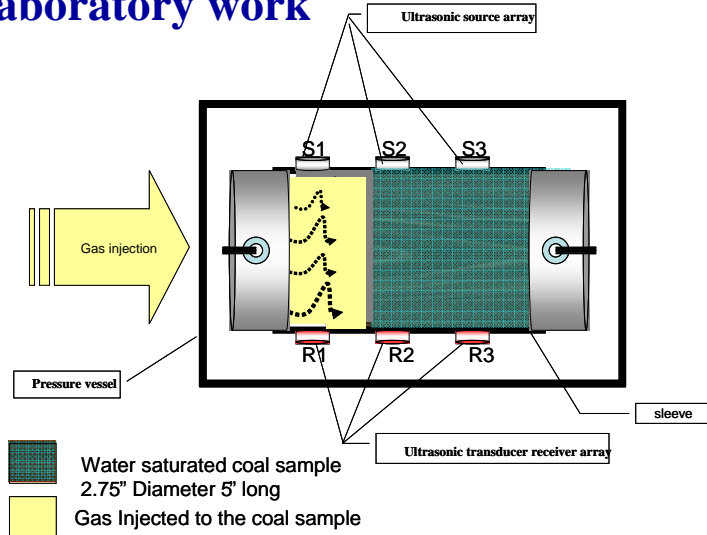
Sample assemblies for measuring ultrasound velocity

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Multiple 70 by 342 millimeter cores (2.75 by 13.5 inches) were cut from these blocks of coal in the lab for acoustic measurements. When the high friability of the coal 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. This slide shows the setup of the core sleeves and source/receiver ultrasonic transducer pairs.



Laboratory work



Schematic diagram of experimental apparatus

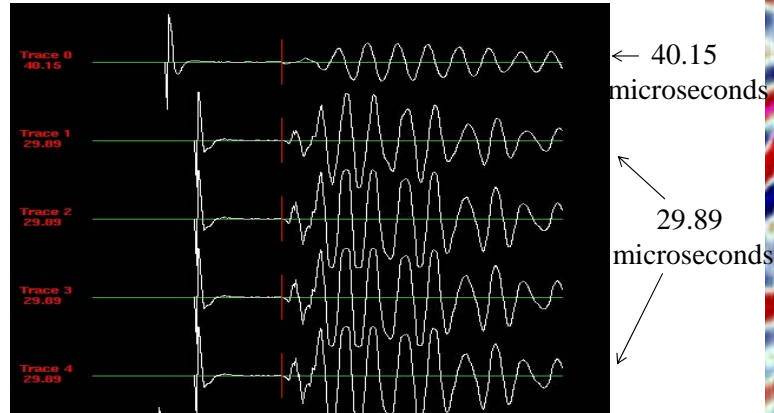
Slides 19 and 20 provide an example of changes in compressional (P) wave velocity resulting from introduction of a gas phase into the water saturated coal. Slide 20 is a screen dump from the data acquisition system and shows the recorded travel times. The image is from a point in time when the injected 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.



Illinois Coal Project

Velocity changes resulting from introduction of a gas phase into the water saturated coal

compressional (P) wave velocity

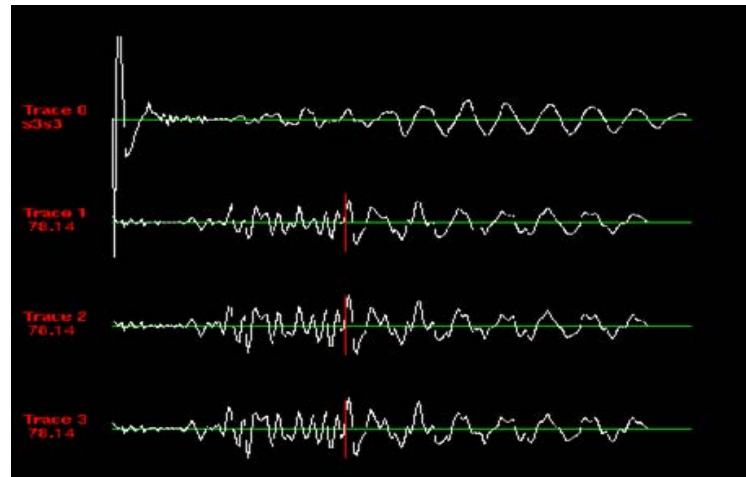


34% decrease in P wave velocity.

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Illinois Coal Project



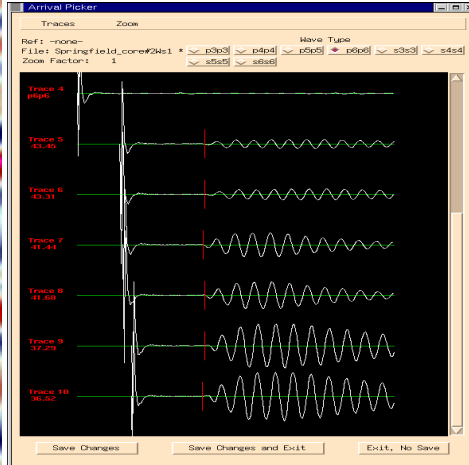
Examples of shear wave arrivals in water saturated coal

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Illinois Coal Project

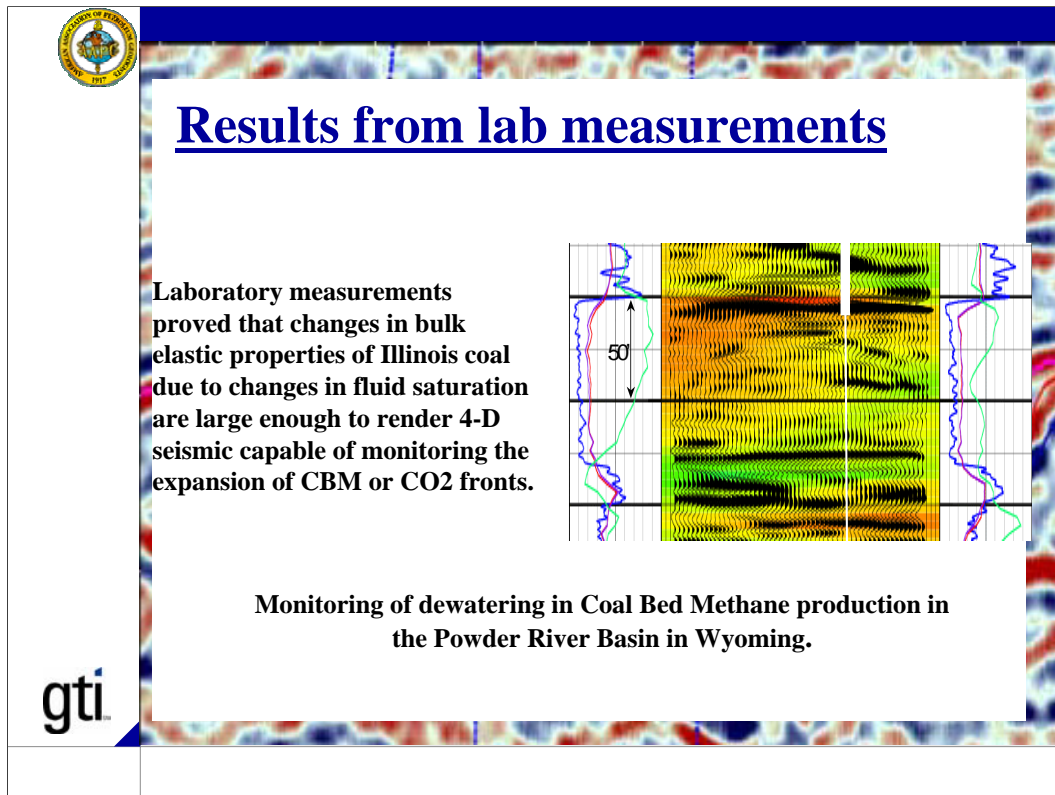
Effects of confining pressure on coal velocity



Springfield # 2,
Water saturated coal
Trace # Confining pressure

4	1 MPa
5 & 6	43.45ms 2 MPa
7 & 8	3 MPa
9 & 10	36.52ms 4 MPa

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Laboratory measurements proved that changes in bulk elastic properties of Illinois coal due to changes in fluid saturation are large enough to render 4-D seismic capable of monitoring the expansion of CBM or CO₂ fronts.

The proposed 4-D seismic is desirable for imaging the expansion of the gas front during CBM production, or prolonged CO₂ injection, for two important reasons.

First, to ascertain that the gas phase remains in the target zone, direction of flow must be determined and the position of the gas front must be projected for the entire life of the project. Second, to produce the desorbed methane the production wells must be placed along the preferred flow path. The direction of progress of the gas front is set by the direction of the least resistance to flow; i.e., the high permeability trend. However, in spite of all recent advances in exploration seismology, no reliable method for determination of permeability from surface seismic, or any other geophysical technique, is presently available.

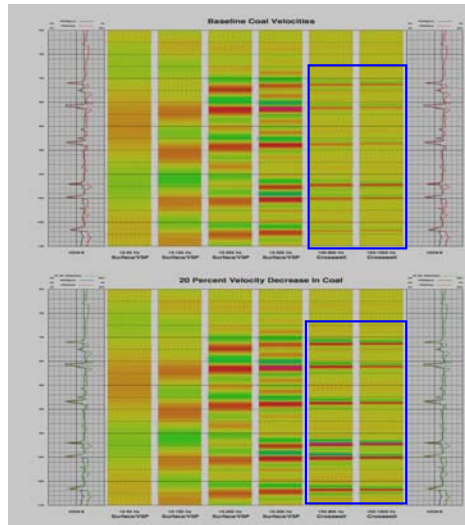
In the absence of any direct measurement tool, the effects of lateral permeability variations may be observable in an after-the-fact manner through time-lapse seismic surveys. In these surveys, the progress of the gas front is mapped after a pre-set period of time, the duration of which is determined on the basis of reservoir engineering studies. Integrating this information with the local geologic framework provides a dependable tool for predicting the direction of flow, which can be used for selecting the location of production wells.



Results from Seismic Surveys

VSP, crosswell, and surface seismic surveys work proved that:

- At lower frequencies (surface seismic) coal packages, but not individual seams, can be reliably mapped.
- It is possible to map thin coal seams and to identify small scale discontinuities using higher frequencies (X-well & VSP)
- Seismic modeling indicated that a 20% velocity reduction due to saturation change can be clearly identified at 100 Hz+ frequencies at the ISGS pilot site.



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Response of individual coal seams to gas saturation.

Following completion of the data analysis and visualization, a series of seismic forward modeling were performed.

The purpose of the modeling was to investigate the feasibility of time-lapse seismic technology for imaging the injected or evolved gas phase within the coal seams.

The line graphs on either side of the colored area represent the well logs from wells Hon 3 and Hon 9. Synthetic seismograms for surface/vsp and crosswell geometries from the Hon 9 logs illustrate the impact of frequency content on resolution.

Coal seams can be clearly identified on these logs.

Each vertical band 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 upper part of the figure exhibits the seismic response of individual seams before velocity reduction, and the lower 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 (area within the blue rectangles).

Results from forward modeling work strongly suggest that accurate monitoring of the injected CO₂ front through repeated crosswell surveys is quite possible.

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.



Conclusions and Recommendations

- 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.
- VSP surveys (10-300 Hz bandwidth) noticeably enhance the resolution.

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Conclusions and Recommendations

- 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.
- 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.

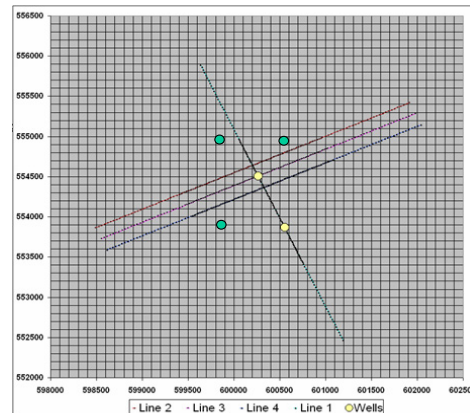
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Future work:

Drill and complete 3 dewatering wells (ISGS)

Repeat crosswell and seismic surveys after gas production has been established to map the position of the gas front



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Acknowledgements

- Gas Technology Institute
- Illinois Clean Coal Institute
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