Time-lapse seismic imaging of enhanced coalbed methane production: a numerical modelling study

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ABSTRACT

Coalbed methane (CBM) production relies on dewatering coal seams to allow gas flow, and the injection of carbon dioxide to maintain effective reservoir pressure. Injection of carbon dioxide into CBM strata also serves as an effective method of subsurface greenhouse gas sequestration. Both dewatering and gas injection alter the acoustic impedance and hence reflectivity of coal strata. Physical tests and numerical modelling suggest that time-lapse seismic imaging may be used effectively to image the changes in a coalbed methane reservoir that result from CBM production. Seismic responses of coal seams change due to differences in the acoustic impedance of the coal, and decreased velocities within coal zones results in delayed reflections from deeper horizons. Modelling provides "proof of concept", and provides parameters to be considered in survey design prior to a field trial involving the Ardley coal zone in Alberta.

INTRODUCTION

Coalbed methane production is found worldwide, including large developments in the USA, where it accounts for 7% of the nation's daily gas production (Avery, 2001). American coalbed gas-in-place resources are estimated at nearly 750 trillion cubic feet (TCF), of which approximately 95 TCF is estimated to be recoverable (Gas Technology Institute, 2001). Alberta is the most promising CBM development site in Canada, with an estimated 412 TCF in place (Gas Technology Institute, 2001). Being a large producer and processor of hydrocarbons, Alberta also has a high volume of greenhouse gas emissions, which may be sequestered into CBM reservoirs, enhancing production. Recent high gas prices have driven CBM exploration and development in the province, and the search for CBM within the Western Canada Sedimentary Basin is at an all-time high (Canadian Gas Potential Committee, 2000), with several pilot projects underway and the first commercial production announced in February 2002 (Avery, 2002).

Increasing levels of greenhouse gases in Earth's atmosphere may contribute to climate change, including drought, heavy storms, and heat waves (Chadwick et al., 2000). Subsurface sequestration of CO_2 in depleted oil and gas reservoirs, coal beds, and aquifers is a potential method of reducing emissions into the atmosphere (Wawerski & Rudnicki, 1998). Injection of gases into coalbeds also stimulates the production of coalbed methane, a valuable energy source currently being tested for viability in the Western Canada Sedimentary Basin.

Whether accompanied by methane production or not, any suggested CO_2 removal strategy will need to provide a system of quantifying the amount of CO_2 initially sequestered, and monitoring the reservoir over time, ensuring no leakage back to the atmosphere (Chadwick et al., 2000).

A site in Alberta has been selected to test both coalbed methane production and geological sequestration of CO_2 by injection into the Ardley coal zone at a depth of approximately 300 m below surface. The late Cretaceous Ardley coal zone contains a series of seams, each up to 10 m thick, and is believed to be one of Alberta's most attractive CBM targets (Dawson et al., 2000). Time-lapse seismic imaging of the coal reservoir may prove useful to monitor successful storage of greenhouse gas, track dewatered zones within coal seams, and select locations for development wells. Numerical modelling and physical tests provide "proof of concept" for the feasibility of time-lapse seismic monitoring as a method of tracking dewatered zones in coalbeds in Alberta. Such proof is necessary to ensure a successful field test.

BACKGROUND

Geological Background

Unlike typical clastic and carbonate reservoirs, gases are not stored in the matrix porosity of a coal seam, but are adsorbed onto the surface of micropores (Figure 1). The average microporosity of a coal seam is less than 0.01 (Langenberg, 1990). This unusual storage system is much more efficient than conventional reservoirs, and a coal seam may hold up to twenty times the volume of gas found in a conventional reservoir of similar size, temperature, and pressure (Rice, 1993). The exact quantity of sorbed gas is controlled by the confining pressure and surface area of the micropore system.

The macroporosity of coals is the cleat system. Cleating is a mining term that describes the naturally occurring fractures found in coal seams. Face cleats are more continuous, and control the flow of gas to a wellbore. Butt cleats, less continuous cleats that form perpendicular to face cleats, are associated with the diffusion of gas from the coal to the face cleats. Cleating is related to both the compaction of the coal and to any tectonic forces acting on it. Permeability is controlled by the cleat system, and is generally low, less than 10 mD (Langenberg, 1990).

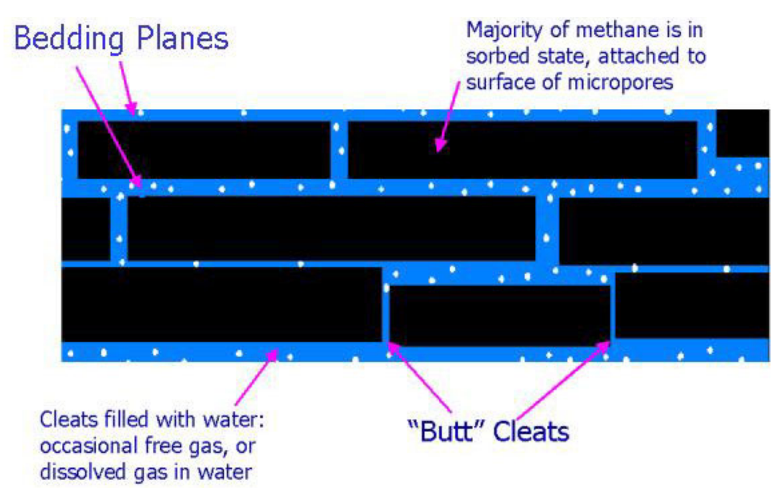

FIG. 1: Typical coal reservoir. Methane is in a sorbed state, attached to the surface of micropores within the coal, and may also be present dissolved in the water filling the cleat system. Plane of view is the face cleat.

The degree of cleating within a coal seam is the single most important geological factor affecting CBM development. Hydraulic communication is necessary throughout the reservoir for successful production. As the cleat system is the only pathway via which gas can travel through the reservoir, it is essential to have conductivity between the cleat system and the wellbore. Reservoir depth is another geological control, as seams must be at depths greater than 200 m to reach sufficient pressure for methane production. Below 1500 m depth, however, overburden pressure may seal off cleats, restricting permeability (Canadian Discovery Ltd, 2001).

Coalbed methane production

Virgin CBM reservoirs exhibit water-filled cleats, with water pressure greater than gas pressure. In order for methane to be desorbed (and thus, be produced), the pressure exerted by the water must be reduced to equal that exerted by the gas. This crossover point is called the desorption pressure, and represents the point at which a free gas phase may exist within the reservoir. In order to accomplish this reduction in pressure, the coal is dewatered. Water is produced and pressure lowers until gas desorbs from the matrix into the adjacent cleat system (Metcalfe et al., 1991).

The relative permeability curve for the Warrior Basin coals (in Alabama) illustrated in Figure 2 shows the dramatic increase in the relative permeability of gas with a reduction in water permeability. Water saturation must be reduced prior to gas production, as seen at the right-end side of the graph. As water saturation decreases, more volume becomes available within the cleat system for gas to travel, increasing the relative permeability of gas. As gas fills this portion of the cleats and the water saturation decreases, relative permeability to water continues to decrease.

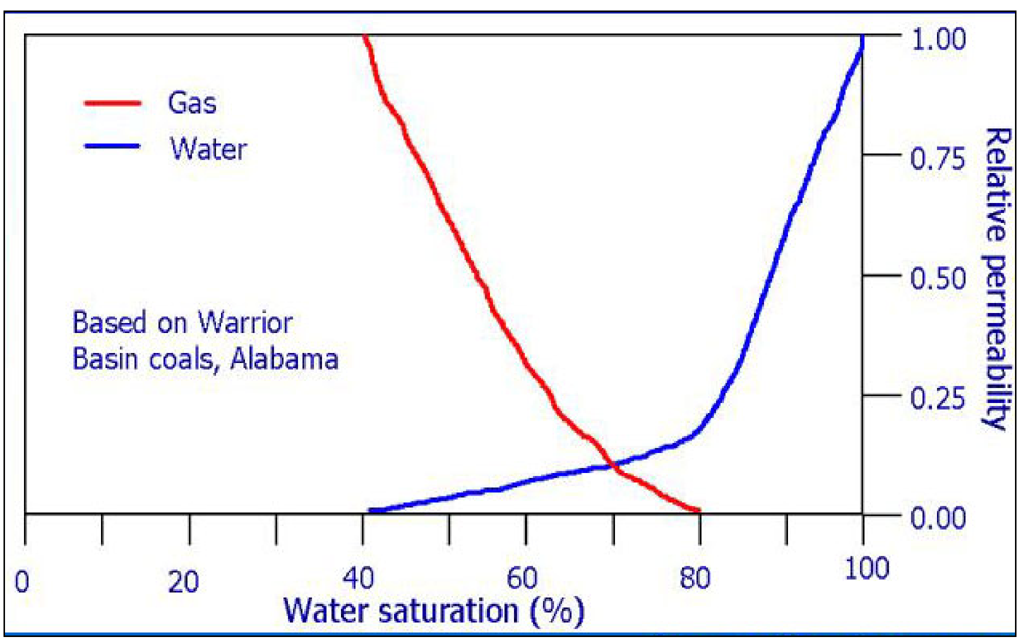

FIG. 2: Graph of relative permeability of gas and water vs. water saturation within coal seams of the Warrior Basin, Alabama. As water saturation decreases, gas production improves as the relative permeability to gas improves substantially (Alberta Geological Survey, 1990).

Two key issues present themselves in CBM production. Often, dewatering a coal seam reduces reservoir pressure to such a degree that economic flow rates of methane are not possible. Operators must also face the issue of long dewatering periods during which little or no methane is produced, while also incurring costs associated with water disposal (Hitchon et al., 1999).

Two possible solutions exist to solve the problem of low production pressures. One method of addressing this issue is to inject a lower-adsorbing gas to reduce the partial pressure of methane without lowering reservoir pressure (Seidle et al., 1997). Another method is to physically displace methane by introducing a higher-adsorbing gas. Gas injection early in production life maintains reservoir pressure, and reduces the delay time associated with methane production.

The total quantity of gas that may be adsorbed by any coal seam is dependent not only on system pressure, but also on the composition and microporosity of the coal. For pure gases at the same pressure and temperature, the ratio of adsorption for carbon dioxide, methane, and nitrogen is 4:2:1 (Bachu, 2000). As it will not be adsorbed, nitrogen is a suitable gas for reducing the partial pressure of methane. With an adsorption ratio of 2:1 over methane, carbon dioxide is an ideal choice for displacement of methane within the reservoir. Coal has a higher affinity for carbon dioxide, and it replaces methane within the micropores, forcing the methane to be desorbed and diffuse into the cleat system.

Comparative production using various injection gases is illustrated in Figure 3. Assumptions are injection pressure of 2000 psi, reservoir pressure of 1500 psi, permeability of 10 mD, porosity of 0.5%, thickness of 10 feet and drainage area of 46 acres (slightly more than one Alberta LSD). Coal is assumed to be 100% gas-saturated.

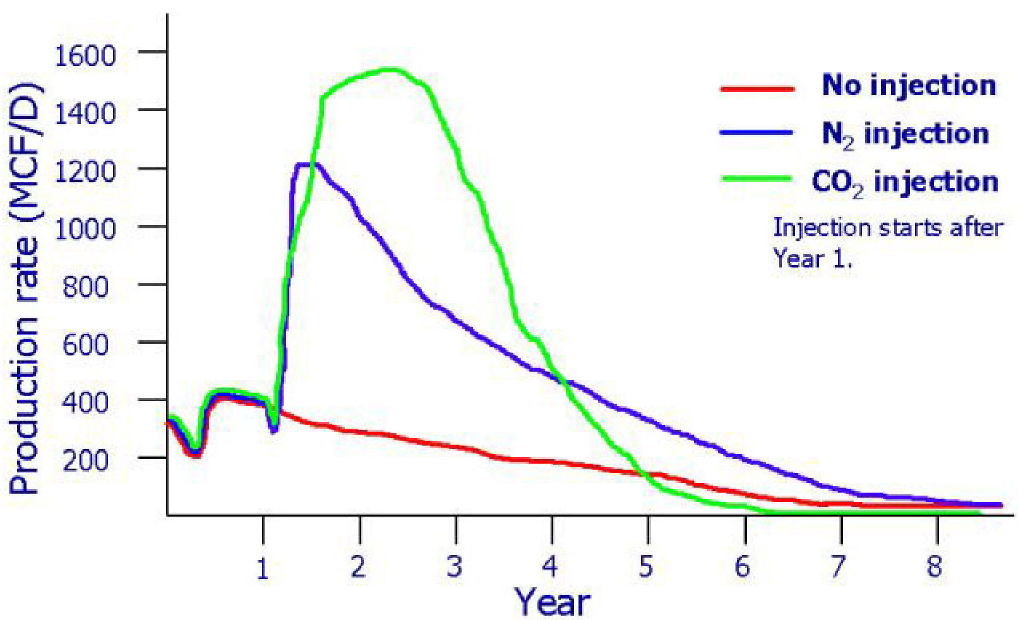

FIG. 3: Graph illustrating difference in production rate by varying injected gas. The red line represents production with no injection whereas the blue line represents injection of N_2, and the green line represents the injection of CO_2. Injection and production wells were arranged in a five spot pattern (Gunter et al., 1997).

In each case, cumulative methane production is more than doubled, with a greater quantity of methane produced much earlier compared to primary pressure depletion methods. When water is present, it is co-produced; its production is also enhanced. Thus, injection of greenhouse gases into CBM reservoirs not only reduces CO_2 emissions, but also enhances production of another clean energy source. Gunter et al. (1997) even propose the possibility of a zero-emission energy source, where CBM is used to power a coal-burning power plant, whose CO_2 emissions are injected back into the reservoir.

Time lapse seismic imaging

Time-lapse reservoir monitoring is a technique that involves the comparison of seismic images taken of the same strata at different time intervals. No published data have discussed the use of time-lapse monitoring of CBM fields, but the technique has been successfully applied to the Sleipner field of Norway, where greenhouse gas sequestration in a subsurface aquifer has been effectively imaged. A heterogeneous CO_2 saturation pattern within the aquifer has been observed as well as successful containment of the gas (Eiken et al., 2000). Injection of carbon dioxide into the strata has altered the acoustic impedance of the strata, resulting in increased reflectivity within the formation, amplitude variations, and a velocity push-down effect (i.e. increased traveltime) for reflections from all horizons beneath the top of the aquifer.

Carbon dioxide injection and the removal of water, the necessary steps in enhanced CBM recovery, affect the bulk density and seismic velocity within a geological formation. Gassman (1951) and Domenico (1976) show that only a few percent incrase in gas saturation will significantly reduce P-wave velocities. The changes in density and velocity in turn affect the amplitude and traveltimes of reflected seismic waves (Gunter et al., 1999). It is believed similar effects to those noted at Sleipner will be imaged at the proposed Alberta study site, but on a different scale, owing to different rock properties of the coal and the sandy aquifer imaged at Sleipner.

METHODS

Digital dipole shear-sonic, compressional sonic, and density well-logs from a number of wells penetrating the Ardley coal zone were used to generate both compressional and converted-wave synthetic seismograms prior to CBM production. Density and velocity values within the coal were altered to simulate the effects of production, after which new synthetic sections were created. The expected change in the seismic response of the coal zone is illustrated by examining the difference between the seismograms. Although the exact change in velocity and density values resulting from dewatering and gas injection is not yet well known, initial models were based on reducing the compressional velocity and density were decreased by 5%. Shear-wave velocities were not altered, as shear waves are impervious to changes in reservoir fluid.

Physical property tests were conducted on coal samples from the Ardley coal zone, measuring the difference between “wet” and “dry” coal densities and velocities. Calculated results were used to alter original well-logs by more realistic values, rather than simply using a 5% standard. New synthetic seismograms were created, and the difference between original and time-lapse seismograms was examined. All of the synthetic seismograms generated for these tests used the Matlab "SYNTH" and "LogEdit" modules.

RESULTS/DISCUSSION

The wells used for modelling are located in the Pembina field of West-central Alberta, and penetrate three separate layers of the Ardley coal, informally named "Ardley A", "Ardley B", and "Ardley C" from uppermost to lowermost seams. In this area, the upper contact of the Ardley coal is at a depth of approximately 400 m, and seam thicknesses range from 5 to 10 m (Figure 4). Offset synthetic seismograms were created for both compressional and converted-waves.

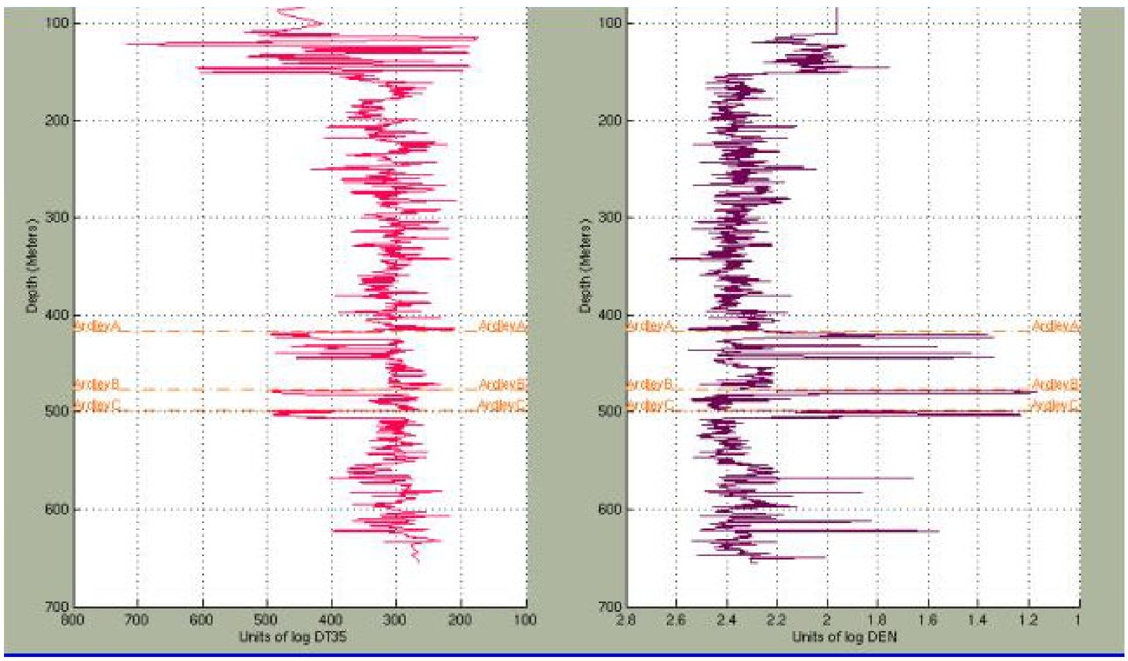

FIG. 4: Well logs of 6-22-50-11W5, indicating three zones of Ardley coal. Compressional sonic-log is on the left; density log is on the right.

Dewatering and carbon dioxide injection will affect both coal density and velocity. If density and velocity are both reduced by 5%, the difference between baseline and time-lapse sections (Figure 5) shows a change in coal reflectivity and a delay in all underlying formations. The amplitude of the coal response is greater after time-lapse, because of the increased acoustic impedance contrast with surrounding strata. Reduced velocity within the coal seams has changed the reflection times of all events underlying the coal zone. The magnitude of this time change is not easily detectable at this scale, but the change is evident on the difference plot.

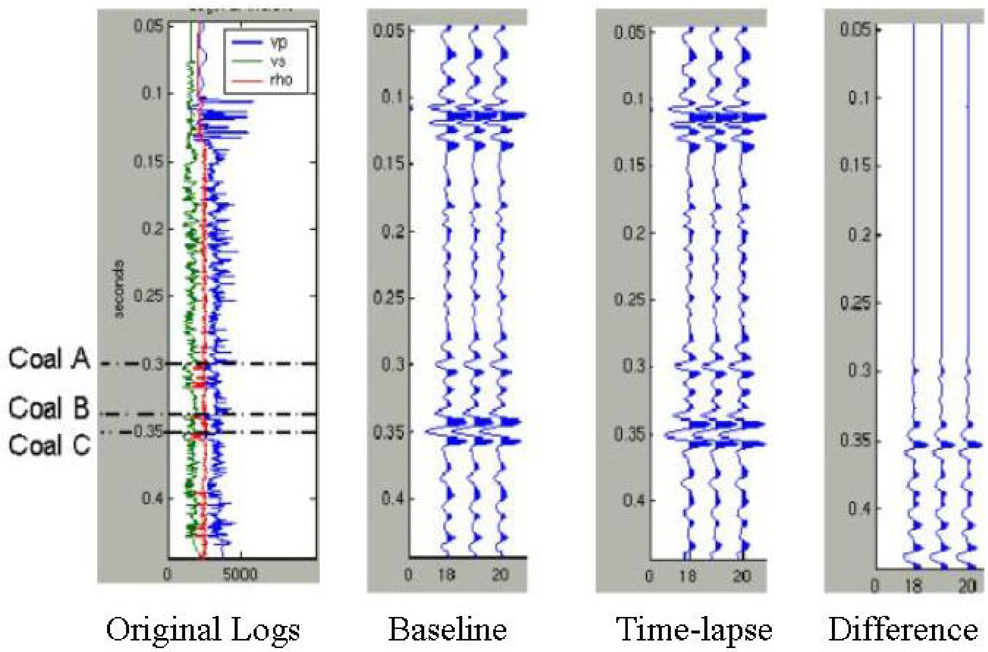

FIG. 5: Baseline, time-lapse, and difference P-P synthetic seismograms using convolution with a 60 Hz Ricker wavelet. After time-lapse, coal reflectivity is increased, and all events underlying the uppermost coal zone are delayed in time.

It stands to reason that if variations in density and velocity values result in a difference on a P-P section, a similar difference should be noted on a P-S section. This is indeed the case, illustrated in Figure 6, in which a small amplitude variation is noticed in reflections from the coals. Although shear-wave velocities are not affected by fluid contained within a formation, compressional waves are sensitive to fluid variations. Thus, the reflection time for a converted wave will be slightly altered, as the downgoing wave (the P-wave) will have reduced velocity through the coals, whereas the upgoing wave (S-wave) will have the same velocity as in the baseline model. Events underlying the coal are expected to arrive at later times, but the magnitude of this change is less than the magnitude of the equivalent P-P change, as traveltime is only affected in one direction.

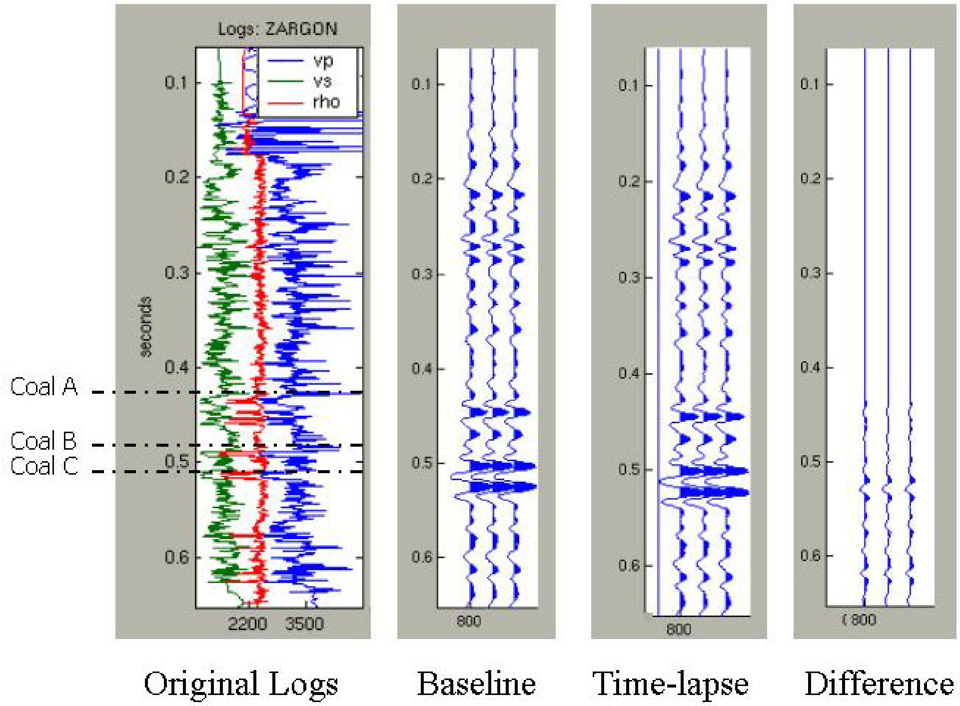

FIG. 6: Baseline, time-lapse, and difference P-S sections. Convolution is with a 40 Hz Ricker wavelet. As in the compressional-wave case, coal reflectivity is altered by the increase in acoustic impedance that accompanies a change in acoustic impedance. Velocity push-down is noted in all events underlying coal.

The results for converted-wave modelling are particularly notable because converted-waves are not typically considered when examining changes in reservoir fluid. It must be remembered that, although the S-wave velocity is not altered by fluid content, the reservoir properties of the strata being imaged are indeed affected. These changes in turn affect acoustic impedance, resulting in changes in reflection amplitude. Additionally, as the P-wave velocities are affected by fluid changes, the converted-wave traveltimes will be different, resulting from the altered (increased, in this example) traveltime of the downgoing P-wave.

Preliminary results suggest that variations in density and velocity as small as 5% will be detectable using time-lapse reservoir imaging, and the velocity push-down effect noted at Sleipner will also be imaged in CBM reservoirs. Prior to a field test, it is important to create synthetic seismograms that more accurately reflect the anticipated changes resulting from dewatering of coal and injection of carbon dioxide. To quantify this change, physical tests on coal samples were conducted.

Physical testing

The Whitewood coal mine in Wabamun, Alberta (Figure 7) produces coal from the Ardley coal zone. Samples were collected at this site for physical property testing.

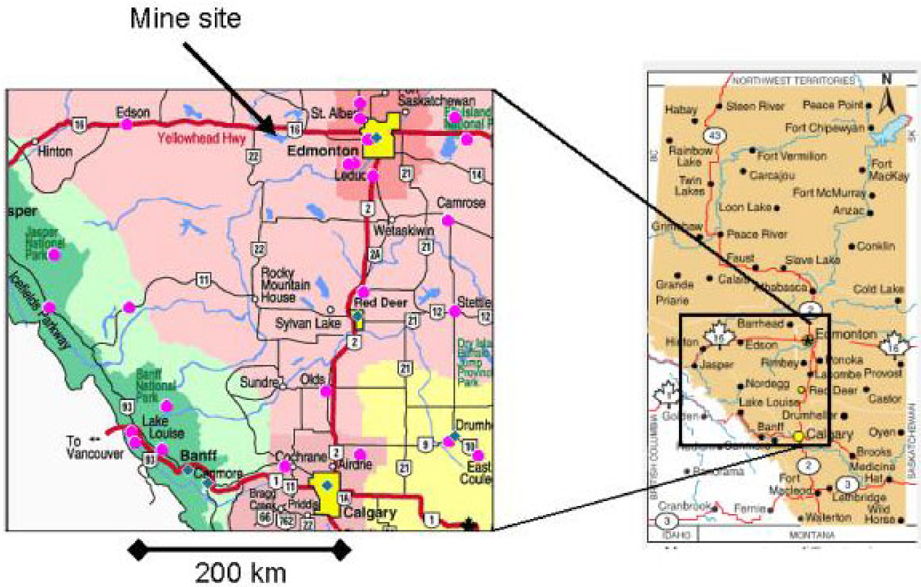

FIG. 7: Location map of the Whitewood mine coal sampling site. (Source: http://discoveralberta.com)

Measuring mass and using the water-displacement method to measure volume, the density of each wet sample was calculated. P-wave transducers were used to find compressional traveltimes through each sample. Calipers were used to measure the path length to calculate velocities. Results of testing wet coal samples are summarized in Table 1.

Table 1: Comparison of physical properties measured from wet coal samples. Average calculated compressional velocity is 2135 m/s, average density of wet coal is 1430 kg/m^3.

Sample #	*Average Vp (m/s)*	*Density (kg/m^3)*
1	2327	1440
2	2314	1440
3	2336	1430
4	2743	1430
5	2153	1460
6	2653	1400
7	1899	1480
Average	2135	1430

P-wave velocities were found to be very consistent, averaging 2135 m/s. Densities were also found to be consistent, with an average of 1430 kg/m^3. Small variations in velocity and density are likely related to small variations in composition, such as variable vitrain or ash content. After allowing samples to dry thoroughly, dry mass was measured and volume assumed to remain unchanged, such that dry densities could be calculated. Transducers were again used to measure P-wave traveltimes across each axis of each sample. Dry velocities were calculated, and results compared with those of the wet samples (Table 2).

Table 2: Comparison of wet and dry coal results. Values from well logs through Ardley coal also provided for comparison to wet coal values. Average decrease in velocity resulting from dewatering is 26%, whereas density decreases 18% with dewatering.

	Wet Coal	*Dry Coal*	*Log Values*	*Average Change*
Average V_p (m/s)	2315	1690	2400	-26%
Average ρ (kg/m^3)	1430	1240	1500	-18.2%

P-wave velocities for dry coal show a marked decrease from wet coal velocities. The average dry coal velocity is 1690 m/s, representing a 26% decrease in velocity with dewatering. The proportion of density loss that accompanies dewatering is relatively constant in each sample, averaging 18.2%. The calculated wet compressional velocities and densities correlate well with average values observed on well logs. Velocities through the Ardley coal zone on compressional sonic logs average 2400 m/s, and density values average 1500 kg/m$^{3.}$ The strong correlation adds further evidence to the validity of this testing.

It is important to note that this experiment does not simulate true reservoir conditions. Dewatering will certainly decrease the water saturation of the coal, but not to the extent possible at surface conditions. Dewatering not only results in the removal of water, but also in the introduction of methane into the system. Any gasification (even very small quantities) will affect velocity values within the reservoir (Gassman, 1951). It is yet to be determined to what extent the desorption of methane will affect each of the "time-lapse" physical and elastic parameters.

Each of the original sets of three-log suites was modified to reflect a 20% decrease in velocity values and a 15% decrease in density. Differenced synthetic seismograms were once again calculated to test for the visibility of the changes using more accurate data values. In all wells, the difference after simulated dewatering is immediately evident (Figures 8, 9). The amplitude of the coal response is significantly increased, and traveltime to underlying events is increased in both P-P and P-S sections. In each of the following figures, the time-lapse seismogram was created using a 20% reduction in velocity and a 15% reduction in density.

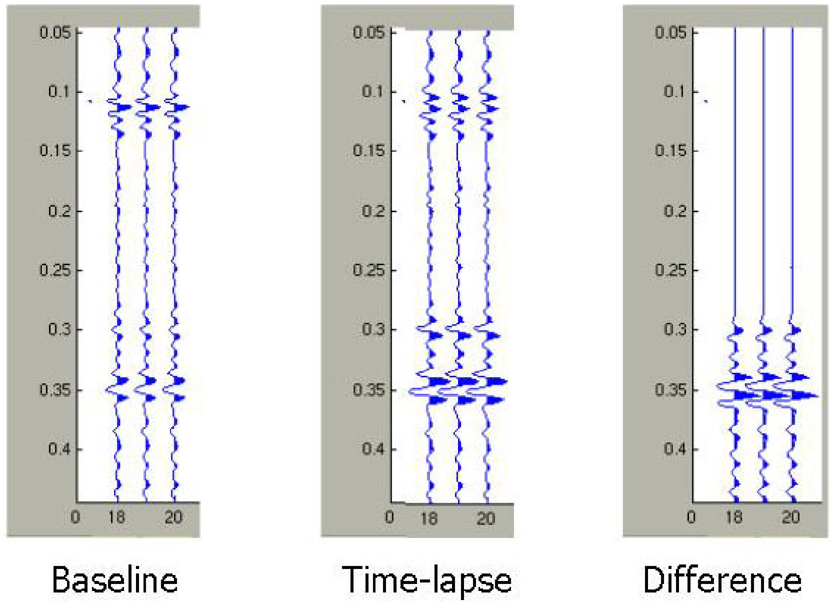

FIG. 8: P-P synthetic seismograms of well 06-22. Convolution is with a 60 Hz Ricker wavelet. A substantial increase in coal reflectivity is noted on the time-lapse section, and velocity push-down effects are noted on the difference plot.

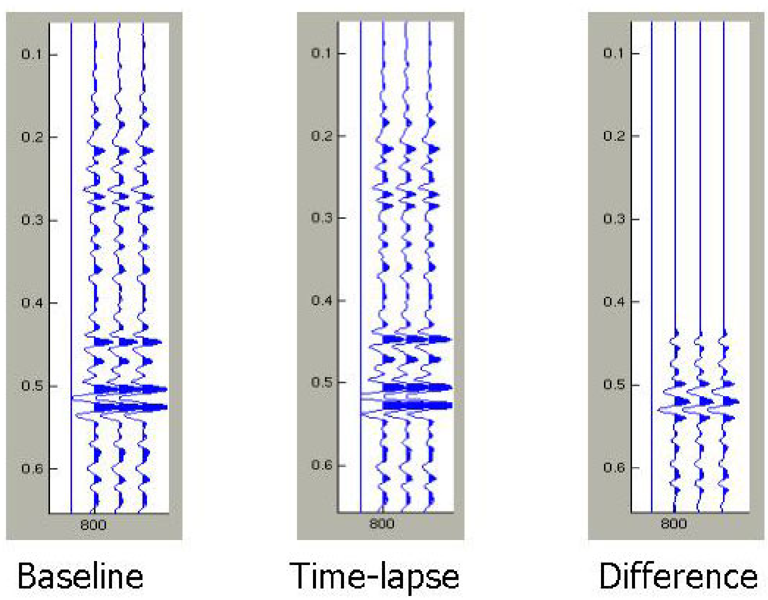

FIG. 9: Converted-wave synthetic seismograms of well 06-22. Convolution is with a 40 Hz Ricker wavelet. Once again reflectivity changes are noted within the coal seams, and push-down effects are seen in all events underlying the uppermost coal.

The use of data from physical testing has led to a more marked difference when simulating the effects of dewatering in coal seams and in comparison to the original synthetic seismograms. This modelling suggests that a field study will be successful in imaging the physical change within coal seams resulting from CBM production strategies. This change should be detectable using both compressional- and converted-wave surveys.

CONCLUSIONS AND FUTURE WORK

Numerical modelling and physical tests have provided proof of concept that time-lapse seismology should be an effective method of imaging changes in reservoir properties associated with enhanced CBM production. Initial physical tests suggest that the magnitude of velocity-decrease associated with dewatering is approximately 20%, whereas the magnitude of density decrease is approximately 15%. Time-lapse differencing is effective in imaging changes in reflectivity resulting from changes in density and velocity. Decreased velocity within the coal zone also results in a velocity push-down effect for deeper reflectors.

It is necessary to estimate the changes that will result from methane gasification within the coal seam, using Gassman's equation. The question remains whether or not an injected plume of carbon dioxide can be imaged in a methane-saturated reservoir. Modelling will be done to test this prior to the field test.

Other future work includes shear-wave testing to analyze Vp/Vs, test for azimuthal anisotropy, and to determine the effect of reduced water saturation of the coals on S-wave velocities. P- and S-wave velocities will be measured on samples under pressure to more accurately simulate reservoir conditions and provide the most accurate representation of field data possible.

Results of this study suggest that a successful field study may be undertaken using time-lapse seismic imaging to aid in the development of a coalbed methane reservoir and the successful identification of dewatered zones. A test site near Red Deer has been selected, and the most exciting aspect of future work is the application of these concepts to a real-world data set. The baseline study is being shot in November, 2002, phase 2 will image the dewatered coal, and phase 3 will image injection carbon dioxide. Additional details on the planned study are reported in this volume by Lawton et al. (2002).

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