Cross-well Seismic Monitoring of Coal Bed Methane (CBM) Production: A Case Study from the Powder River Basin of Wyoming

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Summary

The primary mechanism for Coal Bed Methane (CBM**)** recovery in a typical biogenic, low-rank, shallow and sub-bituminous coal like that of the Powder River Basin (PRB**)** of Wyoming is by dewatering or depressurization of the coal beds. In this case history, cross-well seismic experiments were designed to image changes in seismic signatures associated with the dewatering process. The pre- and post-CBM production cross-well seismic surveys were executed in December, 2002 and August, 2003 respectively in the PRB's Big George formation.

Two-dimensional seismic tomograms show static and time-lapse changes in *P*-wave velocity. Consequently, we identified 4 distinct sub-surface units: shaly-sand, sandy-shale, the low-velocity coal-bearing Big Geroge formation and sandstone. This result is consistent with the qualitative interpretation of the gamma ray logs in the 2 observation wells that were used for the surveys. Moreover, comparison between the two velocity tomograms yields P-wave velocity changes of 5% to 7% due to gas production and changes in pore pressure. These observed changes are corroborated by our theoretically derived velocity models, underscoring the effectiveness and applicability of cross-well seismic experiments in imaging the CBM production process.

Introduction

There has been a recent upsurge of interest in the exploration, exploitation and development of CBM in the PRB, Wyoming. This can be attributed to presumably high-energy resource potential of this veritable resource. The likelihood of coal seams serving as viable sites for subsurface-geologic storage of CO_2 in the foreseeable future constitutes another reason for the growing interest in ECBM exploration in the PRB and other known coal basins worldwide. The Powder River Basin accounts for 800 billion tons of coal and is estimated to produce 25 trillion cubic feet of gas - about 20% of the CBM being produced in the United States. The Big George and the Wyodak coal beds form the major part of the PRB. Cross-well seismic experiments discussed in this study were carried out at the Big George coal sites. Located in the Central part of the PRB of Wyoming and Montana, the Big George is currently one of the world's most established coal fields. The PRB coals are biogenic, permeable, shallow and low-rank coals. They are characterized by higher moisture content and lower carbon content when compared with high-rank bituminous coals.

In a CBM reservoir, the gas is stored primarily within micro pores of the coal matrix in adsorbed state and secondarily in macro pores and fractures as free gas or solution gas in water. The coal structure and cleat system (natural fracture mechanism) play vital roles in the coal gas storage system. Majority of the gas in a CBM reservoir diffuses through the primary storage system, desorbs at the interface between the primary and secondary systems, and then move by Darcy flow through the secondary systems to wells (Schraufnagel, 1993 and Ayers, 2002). At the PRB where the cleats are water saturated, the coal is dewatered or depressurized for several months to enable methane (CH_4) recovery. As the dewatering occurs, CH_4 desorbs from the coal matrix adjacent to the cleat and moves to the well bore.

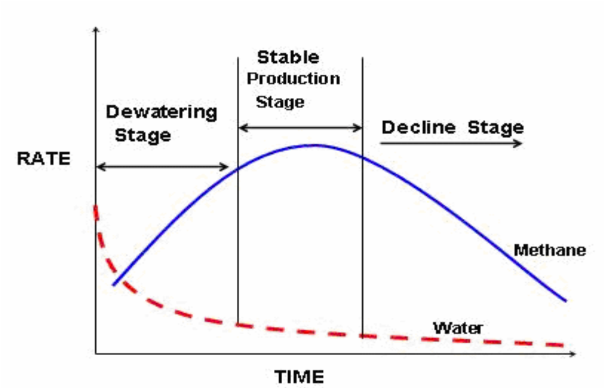

Figure 1: Conceptual CBM production at the PRB (modified from Ayers, 2002 and Schraufnagel, 1993).

As shown in Figure 1, gas production is negligible at the initial stage of depressurization and/or dewatering. As dewatering progresses over an appreciable period, water production diminishes and CH_4 (methane gas) production increases. Hydraulic fracturing may be introduced at the initial stage of CBM development, but early production is poor because the permeable, shallow and sub-bituminous coal may collapse under the influence of overburden pressure after dewatering. Richardson and Lawton (2002) showed that the dewatering process affects the acoustic and elastic properties of the CBM reservoir, causing appreciable acoustic impedance discontinuity within the coal-bearing layer and the surrounding strata. These changes in turn affect the amplitude and travel times of reflected and transmitted seismic waves, paving the way for cross-well seismic mapping of changes that are associated with the dewatering process. Time-lapse cross-well experiments discussed here were executed to map production-induced changes in *P*-wave velocity. The relevance of time-lapse analysis depends on the principle that the seismic response changes in time due only to CH_4 production.

Data Acquisition and Processing

The cross-well field data sets were acquired with a goal of mapping reservoir changes due to CBM production. Two observation wells spanning 150ft and straddling a production well were used. The surveys covered about 800ft to the total depth of the wells at about 1400ft. The baseline and repeat surveys were executed in December 2002 and July 2003 respectively. The data reveal the presence of modal seismic waves such as primary (P) waves and tube waves. The tube waves are conspicuous in the data, making easy identification of primary reflections difficult. They are recognized by their low propagation speed, high amplitude and steep linearity. Also, useful structural and stratigraphic information can be deduced from the raw data (Figure 2).

We pre-processed the data sets to suppress tube waves and conditioned the data for easy identification and picking of P-wave first arrivals. We manually carried out the travel-times picking and processed the data for changes in P-wave velocity (Vp) using TomoxPro 2D tomography algorithm. The algorithm performs non-linear inversion of travel times and reconstructs velocity structures from the first-arrival travel times for any survey geometry. Through an iterative process, it can obtain a reliable velocity model that allows predicted times to fit the data (Zhang and Toksoz, 1998 and Harris et al. 1990). The 2D tomography tasks involve (i) manual construction of a 1-D initial model, and (ii) inversion for a 2-D velocity model using the inversion software. Using the nearest-offset travel times, appropriate survey geometry and model parameters; we build initial velocity models for each of the time-lapse surveys. These models serve as the starting models for the 2-D tomography. The resulting 2-D tomograms are shown in Figure 3. Also, we plotted acquired gamma ray logs for the two observation wells alongside to validate qualitative geologic interpretation of the 2-D tomograms. To permit quantitative estimation of changes in *P*-wave velocity (Vp) due to CBM production, we computed the difference between the 2 tomograms and plotted the output as shown in Figure 4.

Data Interpretation

The baseline and repeat tomograms are shown in Figure 3, with the receiver well on the left side and the source well

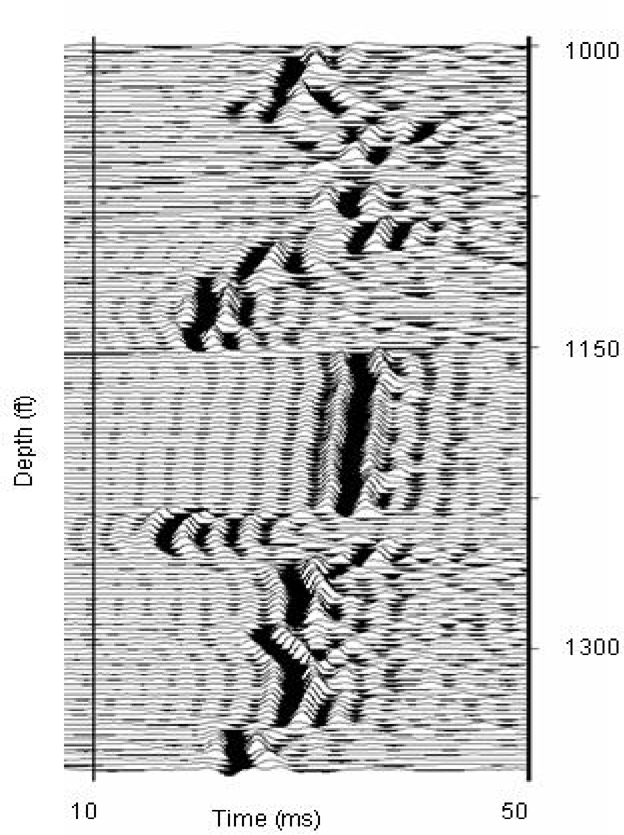

Figure 2: A zero-offset profile from the data showing the coal zone (1150’-1230’) and surrounding/Overlying layers

on the right (150ft away from the receiver well). The production well is 50ft away from the source well. The tomograms show layers with distinct acoustic velocity differences. We observed good correlation between the gamma ray logs and the velocities (Figure 3). This consistency corroborates the quality of the tomographic inversion process. In conjunction with the gamma ray logs, we identified 4 distinct geologic units from the tomography result. They are shaly-sand, sandy-shale, the low-velocity coal-bearing formation and sandstone. Comparison between the 2 tomograms shows that Vp decreases about 5% within the coal-bearing zone (Figure 4). Changes in velocity both above and below the coal zone appear to be negligible within margin of survey error. The dewatering process causes a drop in pore pressure and an increase in gas concentration. The observed changes in Vp (figure 4) are representative of the presence of gas. These changes concur with the result of our numerically derived Vp model, using Gassmann equation (Gassmann, 1951), as shown in Figure 5. In creating the theoretical Vp model, we

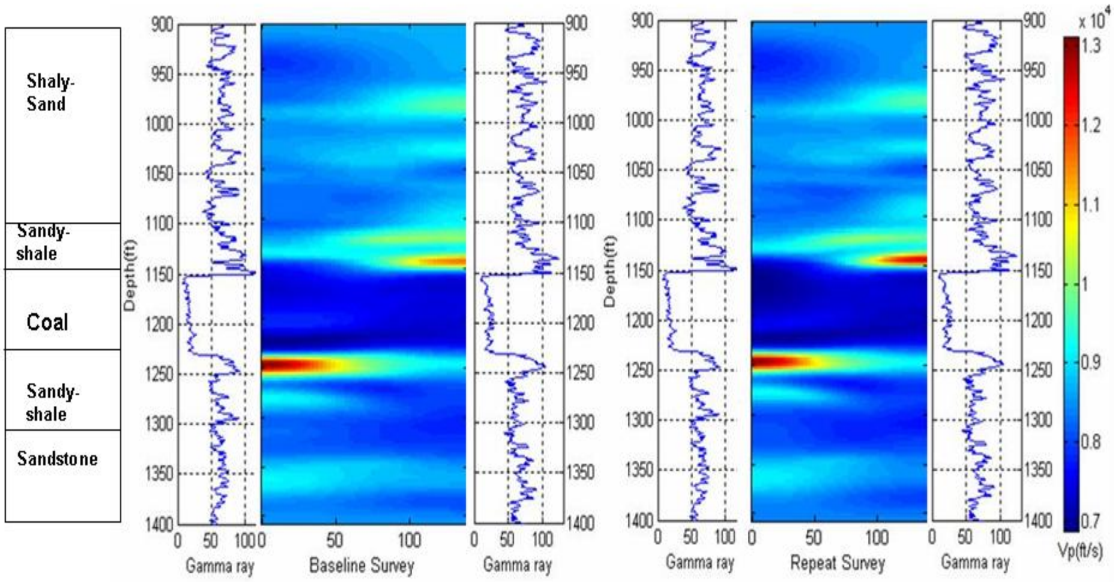

Figure 3: Baseline and repeat velocity tomograms with Gamma ray logs rom the Power River basin.

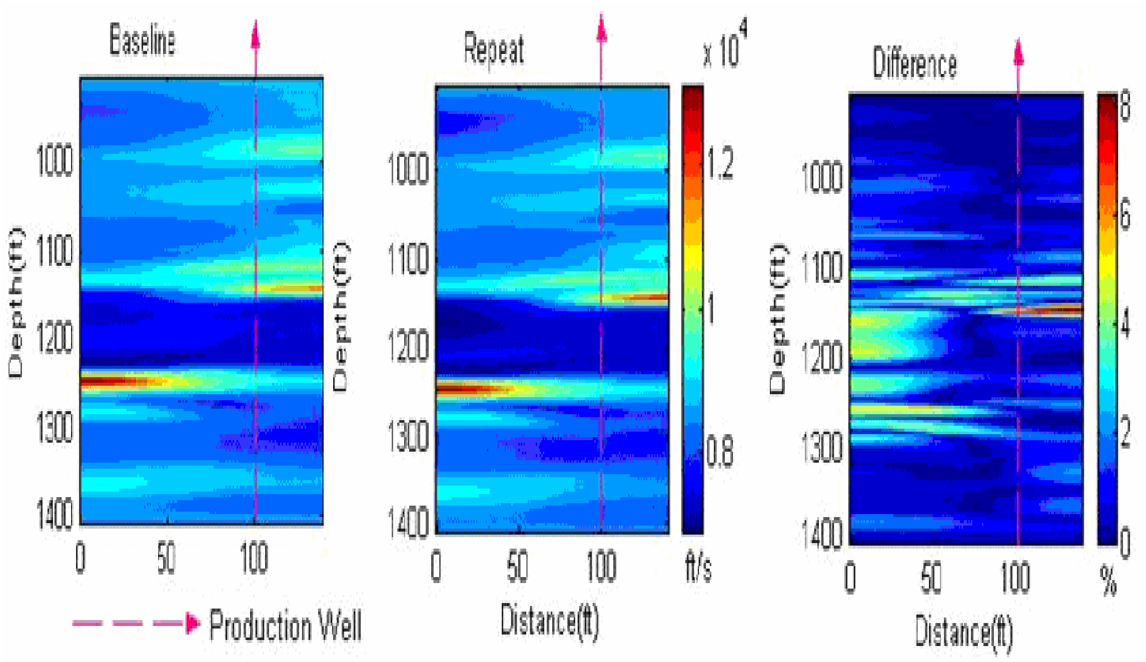

Figure 4: Time-lapse tomograms show that the *P*-wave velocity (Vp) decreases about 5% in the coal zone (1150 ft – 1250 ft). The location of the production well is indicated by the red line.

used laboratory P-wave (Vp) data on a Permian coal sample from Yu et al. (1993) and conditioned the data to reflect the prevailing geo-reservoir conditions at the PRB. We modeled the dry Vp data by applying Gassmann equation and fluid properties of water and methane at varying water/methane saturations. The modeling assumes free gas and not adsorbed gas. The Gassmann-derived Vp model shows that Vp changes by 5% to 15% depending on pore-pressure and the amount of water/methane (H_2O/CH_4) saturation. We envisaged that the effects of changing pore pressure and fluid saturation, occasioned by CH_4 production, produce perturbations in the acoustic and elastic properties (seismic velocities, bulk modulus and density) of the CBM reservoir. These changes make it petrophysically feasible to image and monitor the CBM production process seismically.

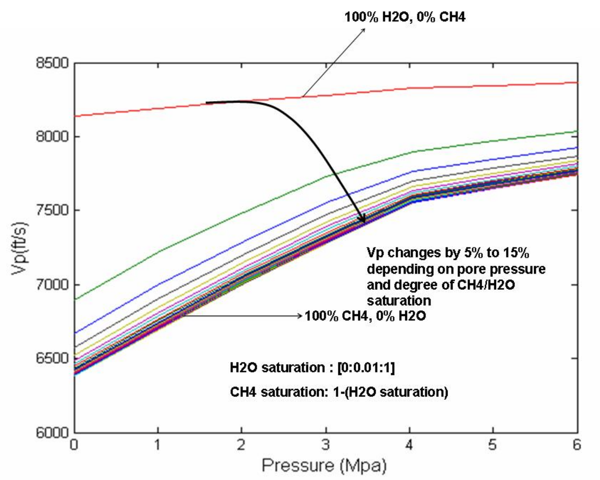

Figure 5: Theoretically derived velocity (Vp) model (Data from Yu et al. 1993).

Conclusions

Dewatering or depressurization of coal beds during CBM production perturbs the reservoir, causing changes in seismic and petrophysical properties. Our results have demonstrated the capability of high resolution cross-well seismic in characterizing the CBM reservoir and mapping production-induced changes in seismic and reservoir properties. Quantitative estimation of these changes is yet to be done but favors effective monitoring and optimization of the CBM production process.

Acknowledgements

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