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 emanating from the dewatering process. Quantitative estimation of these changes is vital to the technical viability of the CBM reservoir process optimization and monitoring. The pre- and post-CBM production cross-well seismic surveys were executed in July, 2002 and August, 2003 respectively at the PRB's Big George coal beds, Wyoming.

Following 2D tomography of the acquired time-lapse data sets, the resulting tomograms manifest rocks with different seismic velocities and petrophysical properties. Consequently, we identified 4 discrete sub-surface layers: shaly-sand, sandy-shale, the low-velocity coal-bearing 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 travel times-inverted tomograms yields P-wave velocity changes of 5% to 7% due to gas production. 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 at 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 CBM exploration at 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 the 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.

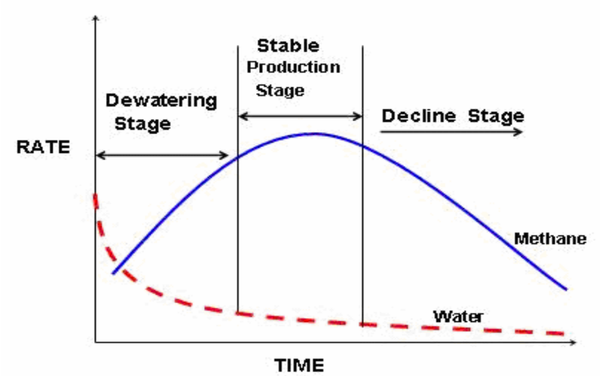

Figure 1: Conceptual CBM production at the PRB (modified from Ayers, 2002 and Schraufnagel, 1993).

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 was also introduced at the initial stage of CBM development at the PRB, but the production was poor because the permeable, shallow and sub-bituminous coal collapsed 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 seismic reflections, paving the way for cross-well seismic mapping of changes that are triggered off by 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. And quantitative estimation of these perturbations can be used to maximize the CBM production rate. The reasoning is based on the premise that seismic experiments are repeatable in all earth domains outside the reservoir.

Data Acquisition and Processing

The cross-well field data sets were acquired with a view to mapping reservoir changes due to CBM production at the PRB. Two observation wells spanning 150ft 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, shear (S) waves, head waves, tube waves and guided 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).

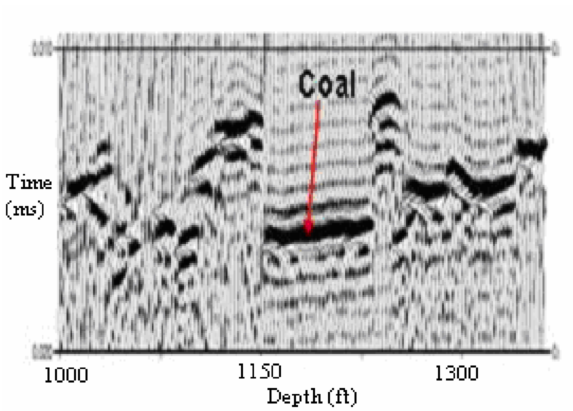

Figure 2: A zero-offset profile from the data showing the coal zone and surrounding/Overlying layers

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) construction of the 1D velocity model and (ii) construction of the 2D velocity model using the 1D velocity model as the starting model. Using the nearest-offset travel times, appropriate survey geometry and model parameters; we build the initial velocity models for each of the time-lapse surveys. These models serve as the starting models for the 2D tomography. The resulting 2D tomograms are shown in Figure 3. Also, we plotted acquired gamma ray logs of the two observation wells alongside to validate qualitative geologic interpretation of the 2D velocity models. 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 tomograms are shown in Figure 3, with the receiver well on the left side and the source well on the right (150ft away from the receiver well). The production well is 50ft away from the source well. The tomograms show similar layers with distinct acoustic impedance discontinuity, implying rocks having different seismic and petrophysical properties. We observed good correlation between the gamma ray logs and the velocity models (Figure 3). And this consistency serves as a tomographic inversion quality control tool. In conjunction with the gamma ray logs, we identified 4 discrete geologic layers 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 and the vicinity of the production well (Figure 4). However, changes in seismic signatures both above and below the coal zone appear to be negligible. 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 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 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.

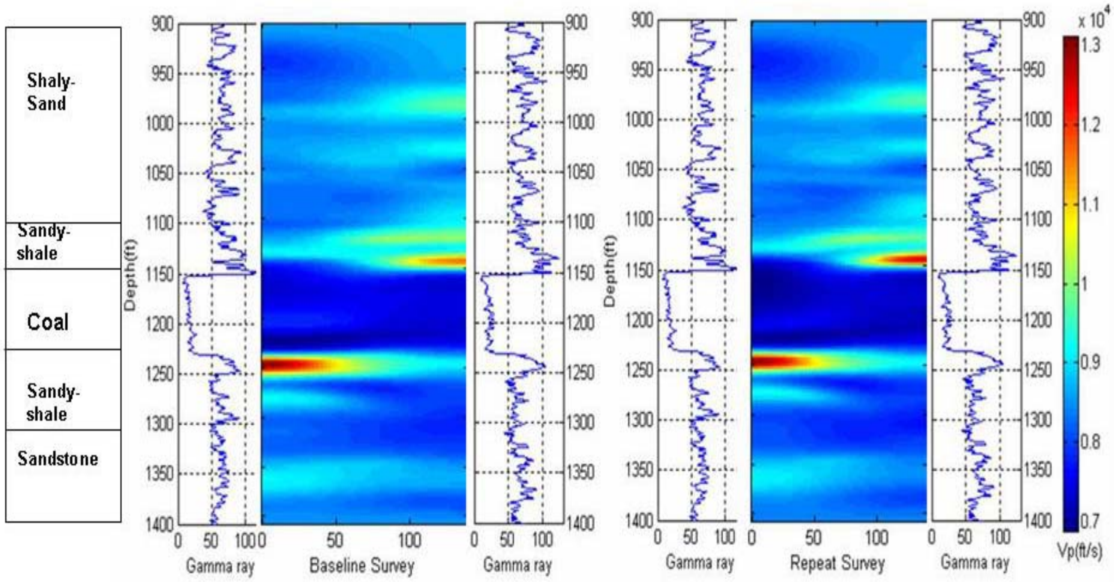

Figure 3: Time-lapse Tomography in Coal with Gamma ray logs

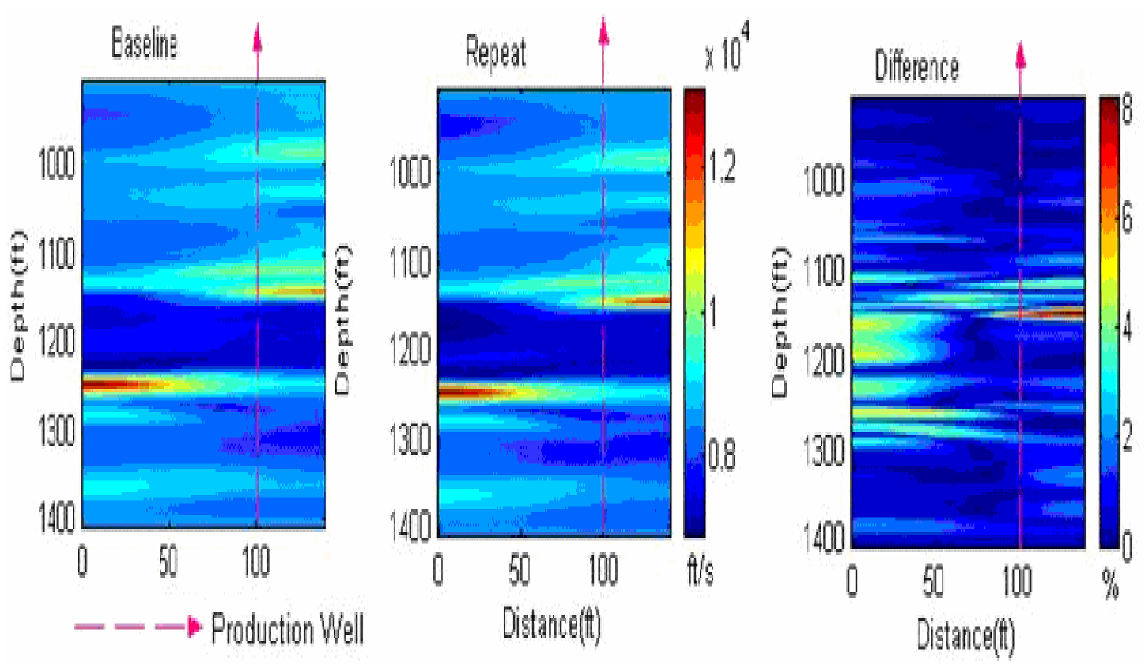

Figure 4: Time-lapse surveys show that the P-wave velocity (Vp) decreases about 5% in the coal zone. Vp changes by about 5% to 8% in the vicinity of the CBM production well.

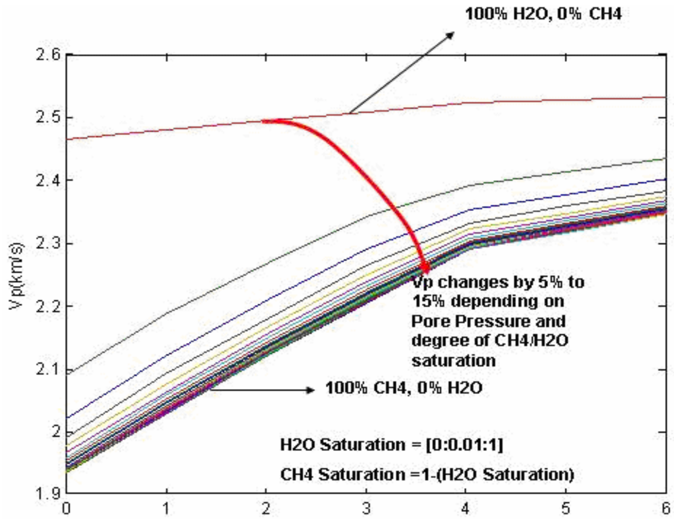

Figure 5: Theoretically-derived velocity (Vp) model (Data from Yu et al. 1993).

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 usefulness 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 favors effective monitoring and optimization of the CBM production process.

Acknowledgements

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