Jerry M. Harris, Olusoga Martins Akintunde*, Tapan Mukerji and Jaime Urban, Department of Geophysics, Stanford University.

PREDICTING PRESSURE AND SATURATION CHANGES FROM ELASTIC WAVE VELOCITIES IN A CO₂-FLOODED COAL BED METHANE: A MODELING STUDY

SUMMARY

Understanding the effects of changing seismic signatures from fluid saturation and pressure changes is germane to the problem of monitoring the injection and spread of CO_2 . Recent papers on the estimation of changes in reservoir properties as functions of changes in seismic properties have focused mostly on hydrocarbon reservoirs. It is important to develop similar concepts to guide the feasibility of monitoring coal beds undergoing CO_2 injection. Moreover, the basic coal physics and the interactions with CO_2 and methane are still poorly known. To address these issues, physics-based models are developed to predict changes through the CO_2 -ECBM (Enhanced Coal Bed Methane) scenario. We attempted to quantitatively relate the sensitivity of seismic properties to variations in pore fluid saturation (Δ S) and pressure (Δ P) using forward modeling. We used laboratory data on four (4) samples of Australian Permian coal from Yu et al. 1993. and modeled them using Gassmann's equation and appropriate fluid properties.

Our preliminary results show that the Gassmann derived P- and S-wave velocities for the saturated coals are highly pressure dependent. The estimated changes in P-wave velocity, bulk modulus and density are largest at low differential pressures. The modeling study further reveals that the seismic velocities (V_p and V_s) are not highly dependent on changes in saturation. Coal, depending on its rank and geology, exhibits significant variations in porosity and structure. While our results are valid for the Permian coals examined, they may be representative of other coals as well.

INTRODUCTION

Storing CO_2 in to coal seams is one of the most cost-effective and promising geologic sequestration methods for reducing the emission of green house gases, of which CO_2 is a major component. The vast global distribution of coal beds and their frequent locations around power generation plants mitigate the financial burden of CO_2 capture and transportation. Coal regardless of its rank has the tendency to adsorb large volumes of CO_2 , while at the same time releasing Coal Bed Methane. The methane that is derived from this Enhanced Coal Bed (ECBM) scenario can serve as an alternative source of electricity generation, thereby reducing green house gas emissions. The common practice for primary Coal Bed Methane (CBM) production is to depressurize the coal, usually by pumping water out of the reservoir. The ECBM option, though currently being demonstrated only in very limited field tests, has the potential to effectively displace CH_4 while the injected CO_2 is simultaneously being stored in the bed (figure 1). Other

underground geologic repositories being canvassed and tested for CO₂ storage include oil and gas fields, deep saline aquifers, oil shale, mafic rock bodies and mined salt domes (Bachu, 2002, and Mavor et al. 2002).

Porosity in coals varies considerably (1.6% to 20%) depending on the coal's rank. Also, coals exhibit low density and low magnetic susceptibility. The coal structure contains pores with various pore sizes, i.e., macropores, mesopores and micropores. CH_4 is stored in the coal by being adsorbed to the micropores and internal surfaces. The structure and cleat system play vital roles in the coal gas storage system. The ECBM process works by replacing sorbed CH_4 molecules in the primary storage with sorbed CO_2 molecules. The CH_4 molecules are subsequently displaced into the coal natural fracture system and into producing wells (Mavor et al. 2002).





Despite the growing number of studies on CBM reservoirs, adequate field-based and theoretically-derived numerical models on basic coal physics and the physical interactions of coal with CH₄ and other pore fluids are still elusive. In addition, recent papers on the applications of time-lapse monitoring for improved reservoir process observation, optimization and management have focused mostly on hydrocarbon reservoirs (Harris et al. 1995). This underscores the need to apply the same tool to study the feasibility of seismically monitoring primary CBM and ECBM production processes. The primary objectives of this current work are: to predict reservoir changes and relate the variations in seismic signatures to changes in pore-fluid saturations and pressure, caused by primary CBM and ECBM processes (figure 1). We used laboratory data from Yu et al. 1993 for this modeling study.

METHODOLOGY

Dry velocities for compressional wave and shear wave (Vp and Vs) and their pressure dependence were extracted from laboratory measurements on four Permian coal samples

(Yu et al. 1993). The samples are bituminous coals exhibiting low porosities and densities. Calculations for the effects of fluid saturations on the seismic properties of the reservoir (seismic velocities, bulk modulus, impedance and Poisson's ratio) were done using Gassmann's theory (Gassmann, 1951) and other rock physics relationships for Vp, Vs, effective fluid modulus and density of a fluid-saturated rock that are fully described in Mavko et al. 1998. Gassmann theory is a physical expression that relates the fluid-saturated moduli to the known dry moduli and fluid properties of a reservoir process undergoing changes in pore fluid. It allows for calculation of the effect of fluid saturation on seismic velocities in rocks and is valid for low frequencies. Two discrete theoretical modeling cases involving partial homogeneous mixture of: CH_4 and H_2O (for the CBM process) and CO_2 , CH_4 and H_2O (for the ECBM scenario) were considered.

These calculations were done within the effective pressure range of 0 to 15Mpa because seismic velocities are more sensitive to pore fluid changes under lower effective pressure (Wang et al.1998). Figure 2 below relates the computed fluid density (RHOF), fluid bulk modulus (Kf), density of the saturated fluid (RHOBsat) and saturated bulk modulus (Ksat) to water saturation (Sw) for the dry Vp of Sample 1 when saturated with CH₄ and H₂O. These parameters were used to estimate the saturated velocities (Vpsat and Vssat) at a reference pressure of 5Mpa as shown in figures 3 and 4. Changes in Vp and Vs (_Vp and _Vs) as functions of changes in pressure (_P) and water saturation (_S_w) at an assumed reference pressure of 5Mpa and reference saturation of 0.5 were subsequently estimated and plotted as shown in figures 3 and 4. This same approach was used to relate the sensitivity of seismic velocities to variations in pressure and saturation for the ECBM phenomenon as shown in figures 5 and 6. It is pertinent to note that the Gassmann-derived models for the remaining samples generally reflect the results shown in figures 2 to 6.



Figure 2: Plots of computed fluid properties versus Sw for Vpdry at reference pressure of 5Mpa.

RESULTS AND DISCUSSION

The estimated _Vp and _Vs due to CH_4 and H_2O saturations appear to be more sensitive to _P than to _S_w (figures 3 and 4). In general, velocity behavior in coal is pressure dependent because of coal's presumably large concentration of thin cracks. The effect of increasing differential pressure is to close the thin cracks and penny-shaped pores and to allow for better contact between particles in the coal matrix. The observed changes in the velocities are influenced by porosity, mineral composition and crack concentration, and pore structure.



Figure 3: Estimated _Vp as functions of _P and _S_w due to CH₄ and H2O saturations.



Figure 4: Estimated _Vs as functions of _P and _S_w due to CH₄ and H₂O saturations.

The observed changes in Vp are more pronounced at low than at high differential pressure (figure 3). The reduction in the observed _Vp and _Vs values can be attributed to the high compressibility of CH_4 . The calculated changes in Vs (figure 4) are generally very small when compared with _Vp values due to the density effect. Figures 5 and 6 also relate the sensitivity of seismic velocities to variations of seismic velocities to variations in pressure and saturation for the CO_2 -ECBM modeling process.



Figure 5: Estimated _Vp as functions of _P and _S_w due to CO₂, CH₄ and H₂O saturations.



Figure 6: Estimated _Vs as functions of _P and _S_w due to CO₂, CH₄ and H₂O saturations.

As in the CBM case, the theoretically derived _Vp and _Vs exhibit the same sensitivity to changes in pressure (figures 5 and 6). Also, the observed changes in Vp and Vs further

diminish with CO₂ saturation. It is premature to infer from these results the feasibility of seismically monitoring both the CBM and ECBM processes because the current forward models are not based on actual field conditions and are valid only for the assumptions made. Incorporating relevant statistical variability will help account for the observed non-uniqueness and uncertainty in the Gassmann-derived models.

CONCLUSIONS

The results of a coal physics forward modeling study relating quantitative changes in seismic velocities to variations in pressure and saturation due to CBM and CO₂-ECBM production processes have been presented. The observed changes in Vp and Vs of the saturated coals for the selected data sets are pressure dependent, but lack adequate sensitivity to saturation. The estimated changes in seismic signatures especially for the CO₂-ECBM scenario are generally small but tend to be more noticeable at low differential pressure. This theoretical study has provided useful background information about basic coal physics models that are relevant to our understanding of the geophysical dynamics of the seismic changes during CBM and CO₂-ECBM production processes. These modeling results provide a quantitative basis for predicting changes in pressure and saturation from changes in seismic velocities.

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