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# Implications of stress re-distribution and rock failure with continued gas depletion in coalbed methane reservoirs

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ABSTRACT

Significant increases in permeability of coal with continued production of coalbed methane (CBM) is a well-accepted phenomenon, particularly in the San Juan basin in the US and Surat basin in Australia. Modeling this increase is either based on the resulting increase in fracture porosity of coal or the associated changes in stresses as a result of the sorption-induced strain. This paper combines the experimental results of a study that measured sorption-induced coal matrix volumetric strain with depletion and a model proposed to estimate the associated changes in stress. The overall changes in stress, resulting from the combined effect of the poro-mechanical behavior and sorption-induced strain, were estimated by introducing a Biot-like coefficient. Plotting the stress path followed during depletion along with the failure envelope for the coal-type clearly showed that shear failure of coal is possible due to anisotropic loading resulting from a large reduction in the horizontal stresses. This would explain the large increases in permeability, typically observed in CBM operations. Finally, a permeability model was developed using the Biot-like coefficient, and assuming transversely isotropic behavior of coal. A comparison of the experimental and modeled permeability results showed that the model works well as long as coal does not fail. However, it demonstrates that a permeability model, incorporating failure of coal, is warranted for reliable prediction of permeability variation.



## 1. Introduction

US coalbed methane (CBM) production was 1.4 trillion cubic feet (TCF) in 2014 and proven reserves at the time were estimated to be 15.7 TCF (EIA, 2015). Leading in production in the US were the states of Colorado, Wyoming, New Mexico, Virginia, Utah and Oklahoma. Although production has dipped from the all-time high of 1.9 TCF in 2010, CBM continues to be an important source of energy in the US.

The controlling mechanism when producing CBM is accepted to be coal permeability, typically believed to decrease with increasing depth (Unconventional Oil and Gas Production, 2010). However, coal exhibits a unique behavior, termed "matrix shrinkage", associated with desorption of gas, resulting in increased permeability (Harpalani and Chen, 1997; Levine, 1996; Mitra et al., 2012; Singh, 2014). The outcome is a negative declining production trend when producing CBM. With continued production, there is an associated drawdown in gas pressure, which eventually changes the stress environment in the reservoir. The horizontal stress in CBM reservoirs has been reported to decrease with pressure drawdown (Mitra et al., 2012; Liu and Harpalani, 2013; Singh, 2014), the rate of decrease being 50% higher than the corresponding drop in pore pressure. This is significantly higher than the response reported for conventional reservoirs (Hillis, 2001; Teufel et al., 1991). Theoretically, based purely on conventional poro-elasticity, this ratio cannot be higher than unity (Zoback, 2007). Such a large decrease in horizontal stress, together with the well accepted uniaxial strain conditions in reservoirs, results in anisotropic loading conditions of coal and ultimately failure (Singh, 2014; Espinoza et al., 2015a).

This paper attempts to model the experimental data acquired recently (Singh, 2014) in order to explain the sorption-induced reduction in the horizontal stress with depletion of gas using a model proposed by Espinoza et al. (2015a). The model is based on shear failure of coal with depletion in CBM reservoirs. Although primary effort is aimed at validating this model, validation of an intermittent model relating sorption strain and stress (Espinoza et al., 2013), which included a Biot-like coefficient, became inevitable and this is included. As a final step, a permeability model using the Biot-like coefficient and transversely isotropic nature of coal was developed. This model is shown to work well for coal as long as there is no failure. However, the permeability model needs to be extended for conditions leading to coal failure. Such modeling would present a complete picture of permeability variation with pressure, especially for deeper coals, such as, the Greater Green River

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basin, where CBM production is practically non-existent due to the burial depth and the associated stress conditions prevalent *in situ*.

## 2. Sample characterization

The coal tested in this study was retrieved from southwestern part of the San Juan basin. The rank of coal was sub-bituminous. The ash and moisture content was 5.1% and 7.9% respectively. For sorption experiments, powdered sample (0.0425–0.0149 cm) was used. For matrix shrinkage experiments, coal quadrants were prepared by trimming off the ends of the coal core. Each sample was, therefore, approximately 0.75 in. thick and one inch in radius. The remaining portion of the coal core, of diameter two inches and three inches long, was used for the pressure-dependent-permeability (PdK) experiment. The bulk density of the coal core was 1.34 g/cm$^3$.

## 3. Experimental work and results

### 3.1. Experimental work

Experimental data for the analysis presented in this paper was obtained from a laboratory-based study aimed primarily at establishing the pressure-dependent-permeability (PdK) of CBM reservoirs in the San Juan basin (Singh, 2014). Three different experiments were carried out as a part of the overall study. First, sorption characteristics for methane were established. Using the sorption data, the Langmuir Constants, $P_L$ and $V_L$, were estimated. Second, quadrants of end pieces of the coal core used for flow tests were utilized to measure the volumetric shrinkage/swelling strains under incremental hydrostatic pressure for unconstrained condition (unjacketed). This was first carried out for a non-sorbing gas (helium) and then repeated for a sorptive gas (methane). Third, a flow experiment was carried out replicating the *in situ* reservoir stress and uniaxial strain condition during drawdown. As a part of this experiment, stresses, volumetric strains and flowrates were measured for a step-wise decrease in pore pressure for each step of depletion, for both sorptive and non-sorptive gases independently. As a final step, triaxial strength of the coal type was estimated under incremental confining stress to establish the failure envelope for the coal type. Details of all experimental setups used and testing procedures are presented in Singh (2014).

### 3.2. Experimental results

The matrix shrinkage experiments included measurement of strains in the three principal directions for unconstrained coal using helium and methane. Helium results provided the change in matrix volume due to de-compression of solid coal associated with depletion (pressure decrease), while methane results provided the overall strain resulting from the combined effects of solid de-compression and volumetric strain associated with matrix shrinkage. The two results are shown in Figs. 1 and 2. With helium depletion, the volume of solid coal increased as the pressure decreased from ~10 MPa (1500 psi) to atmospheric. For methane, on the other hand, the volume of solid coal decreased with depletion due to the dominant effect of sorption-induced matrix shrinkage.

For permeability experiments, the coal sample was initially stressed to *in situ* condition of the reservoir (total vertical stress: 20 MPa (2900 psi); initial total horizontal stress prior to depletion: 12.8 MPa (1850 psi); and pore pressure: ~10 MPa (1500 psi)). Gas was then depleted in a step-wise manner for declining pressure, recording the strain and stresses continuously, and measuring the flowrate for each step under equilibrium conditions. Using the flowrate, permeability was calculated for each step, thus establishing the pressure-dependent-permeability trend for depletion. Throughout the experiment, uniaxial strain condition was maintained, that is, the horizontal strain was maintained zero and vertical stress was maintained constant. In order to compensate for the horizontal strain associated with matrix shrinkage, the horizontal stress was adjusted throughout the experiment. The results showing the change in horizontal stress for the two experiments are shown in Fig. 3. Relevant experimental statistics for the pressure-dependent-permeability experiment is presented in Table 1.

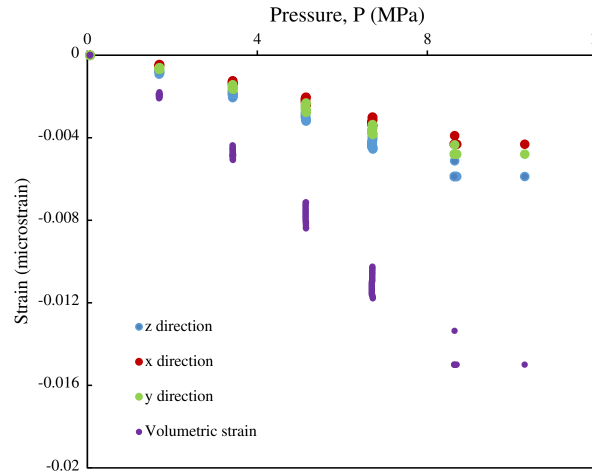


**Fig. 1.** Measured strain with changes in pressure (unconstrained (unjacketed), helium).

In addition to the flow and matrix shrinkage experiments, sorption isotherms for the coal type were established. The values of $V_L$ and $P_L$ were estimated to be 1.407 mol/l (749 scft) and 2.69 MPa (391 psi). Finally, triaxial strength testing was carried out on coal samples to establish the failure envelope for the coal type. The results are summarized in Table 2.

## 4. Analysis

### 4.1. Coal transverse isotropy

The results obtained from shrinkage/swelling experiment using helium, shown in Fig. 1, suggest that coal behaves like an orthotropic rock. However, it can be approximated to be transversely anisotropic since the behavior in x- and y-directions is similar. This is not anomalous behavior for rock of sedimentary origin and has been suggested by Moore et al. (2014). Other experimental studies have also reported

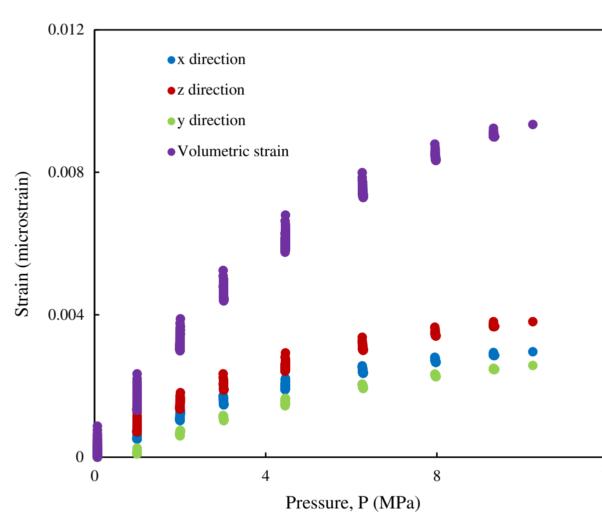


**Fig. 2.** Measured strain with changes in pressure (unconstrained (unjacketed), methane).