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# INFLUENCE OF VERTICAL DEVIATORIC STRESS ON PERMEABILITY CHANGES IN COAL

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# INFLUENCE OF VERTICAL DEVIATORIC STRESS ON PERMEABILITY CHANGES IN COAL

by

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A Paper
Submitted in Partial Fulfillment of the Requirements for the
Masters of Science in Mining Engineering

Department of Mining and Mineral Resources Engineering
in the Graduate School
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# RESEARCH PAPER APPROVAL

# INFLUENCE OF VERTICAL DEVIATORIC STRESS ON PERMEABILITY CHANGES IN COAL

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A Research Paper Submitted in Partial

Fulfillment of the Requirements

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Masters of Science in Mining Engineering

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Approved by:

Dr. Satya Harpalani, Chair

Dr. Bruce DeVantier

Dr. A.J.S. Spearing

Graduate School
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8/26/2014

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# INTRODUCTION AND BACKGROUND

## Introduction

During the last three decades, coalbed methane (CBM) has become an important component of the world's natural gas resource (Liu, 2012). CBM reservoirs have been classified as "unconventional reservoirs" by the energy industry since the gas storage and transport mechanisms of CBM reservoirs are different from other conventional reservoirs (Liu, 2012). In CBM reservoirs, the gas may be stored as a free gas in the secondary porosity system and natural fracture network, similar to the conventional reservoirs; it is also stored at near liquid densities on the internal surfaces of coal matrix by physical adsorption. The adsorbed gas is generated as a by-product during coalification process, typically accounting for more than 90% of the gas-in-place (Gray, 1987). In CBM reservoirs, the migration of methane starts with desorption of gas in the coal matrix. This leads to a concentration gradient between the coal matrix and matrix cleat interface, which results in the migration of desorbed gas towards the cleat system by the process of diffusion. Finally, the gas reaches the naturally occurring fracture (cleat) present in coal, where the flow is controlled by the permeability of coal (Liu & Harpalani, 2012). Hence, gas production from a CBM reservoir depends primarily on the diffusion and permeability of coal. Permeability is, therefore, one of the most important parameters controlling the flow of gas in a CBM reservoir.

The commercial production of CBM is typically carried out by pressure depletion, also known as the primary recovery technique. As the name suggests, this involves depressurizing the coal. Since most US CBM reservoirs are initially water saturated, depletion is initiated by dewatering the reservoir. This lowers the reservoir pressure and leads to desorption of methane and its movement, first towards the cleat network, and then in the cleat towards the producing wells. This is shown in Figure 1-1.

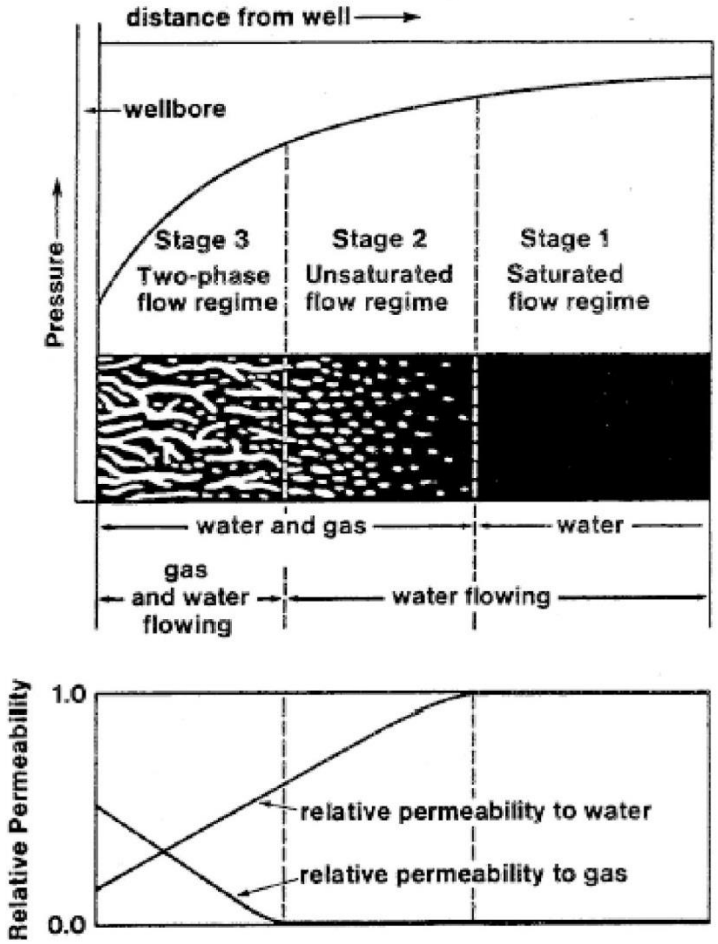

Figure 1-1: Three stages of coalbed gas production (McKee, et al, 1987)

## Changes in Stress with Depletion

As a result of depletion and continued production, the stress conditions in the reservoir change continuously, leading to reservoir deformation. This deformation is typically divided into three categories: cleat deformation, linear elastic deformation of coal matrix due to stress variation, and coal matrix non-linear elastic deformation due to the matrix shrinkage effect induced by desorption of gases (Liu & Harpalani, 2013a). It is well accepted that coal is a typical porous medium and the effective stress, defined as the difference between the principle stress and pore pressure, therefore, links these volumetric deformations. Depletion of pressure in coal reservoir changes the stress that is carried by the load-bearing grain framework of the coal, as well as decreases the reservoir pressure, which causes coal matrix shrinkage induced by gas desorption (Liu et al., 2012). Researchers have found that stress and shrinkage deformation behavior of pores and fractures present in coal are key factors that influence the permeability which, in turn, eventually controls the long-term production from CBM reservoirs (Gray, 1987; Palmer & Mansoori, 1998; Palmer et al., 2007; Ma et al., 2011; Liu & Harpalani, 2012).

Typically, the permeability of coal to water and gases decreases with increasing effective stress prior to the generation of new fractures within the coal matrix that are not visible (Wang et al., 2013). Several researchers have established relationships between coal permeability and changes in effective stress during pressure depletion. However, most of the investigations were conducted under a triaxial state of stress, allowing the sample to deform in the lateral direction. Little evidence is present in the literature for permeability measurements conducted under uniaxial strain condition, which require the horizontal dimension to remain constant, allowing sample deformation in the vertical direction only (Mitra, 2010). The uniaxial strain condition, believed to best replicate *in situ* condition, requires that the horizontal dimension remain constant. Coalbeds in situ are confined laterally and are, therefore in uniaxial strain condition. The vertical stress remains constant due to the unchanged overburden load (Mitra, 2010; Liu, 2012). The concept of methane producing coalbed being a constant volume reservoir was mentioned by Harpalani and Chen (1997) although no effort was made to justify this idea or develop a model based on this philosophy. However, Massarotto et al. (2009) suggested that coalbed reservoirs act as a constant volume condition. He stated that the volume of the coal reservoir is 99.72% to 99.95% of the original volume and is maintained by the flexural and tensile strength of the overburden across the reservoir.

The variation in the permeability of coal with continued production was established by Mitra (2010) and Liu (2012). To date, researchers have mostly investigated the permeability changes due to non-linear elastic deformation caused by a matrix shrinkage associated with methane desorption (Liu & Harpalani, 2013b). However, the effect of linear elastic deformation of coal matrix due to stress variation has not been considered. The vertical deviatoric stress, defined as the difference between principle stress and mean stress, is partly responsible for the linear elastic deformation of anisotropic rock (Lockner & Stanchits, 2002). Most rocks in nature are anisotropic to some extent. The common case of anisotropic rocks includes sedimentary rock, like coal, since the elastic properties along and perpendicular to the bedding planes are different (Jaeger et al., 2007). In the literature, there are a couple of investigations for instantaneous gas outbursts in underground coal mines, which have discussed the influence of applied vertical deviatoric stress, defined as the difference between two principle stresses, on coal permeability (Wang and Elsworth, 2010; Wang et al., 2013). In the presence of sorbing gases (methane and carbon dioxide), and under applied external stress, the permeability changes with increasing vertical deviatoric stress. As vertical deviatoric stress increases, cleats oriented perpendicular to the axial stress close and new dilatant cracks grow parallel to the axial stress. This weakens the coal and accelerates the rate of desorption, which, in turns, increase the permeability (Wang and Elsworth, 2010; Wang et al. 2013). Unfortunately, in the case of CBM reservoirs, this relation is not clearly defined. Yang et al. (2011) suggested a stress-damage-flow coupling model and applied it to pressure relief in deep coal seams. Chen et al. (2013) used X-ray CT scan to see the permeability changes in coal while unloading, thus decreasing the effective confining stress. They concluded that decreasing effective confining stress, along with the decrease in differential stress (that is, difference between the two principle stresses), increase the damage and accelerate the permeability. It is not clearly defined how the vertical deviatoric stress with pressure depletion is related to changes in permeability. This uncertainty highlights the importance of understanding the relationship between vertical deviatoric stress-induced internal fracturing (within coal matrix) and the resulting permeability variation. This paper focuses on the evaluation of changes in permeability as a result of stress changes that are caused by vertical deviatoric stress (effective vertical deviatoric stress).

## Vertical Deviatoric Stress

There is a significant amount of controversy in defining the vertical deviatoric stress in rock mechanics. Past researchers were prone to use the definition of differential stress as vertical deviatoric stress (Wang and Elsworth, 2010; Wang et al. 2013). In reality, it is entirely different. The differential stress is simply the difference between two principle stresses. If the two principle stresses are $\sigma_1$ and $\sigma_3$, then the differential stress is given as (Deb, 2006):

$$\sigma_{\mathrm{diff}} = \sigma_1 - \sigma_3 \qquad (1\text{-}1)$$

The definition of vertical deviatoric stress is quite different. Unlike mean stress, pressure, or differential stress, vertical deviatoric stress is not a single number, but a tensor, denoted commonly by $\sigma_{\mathrm{dev}}$. In Figure 1-1, a three dimensional stress tensor is shown.

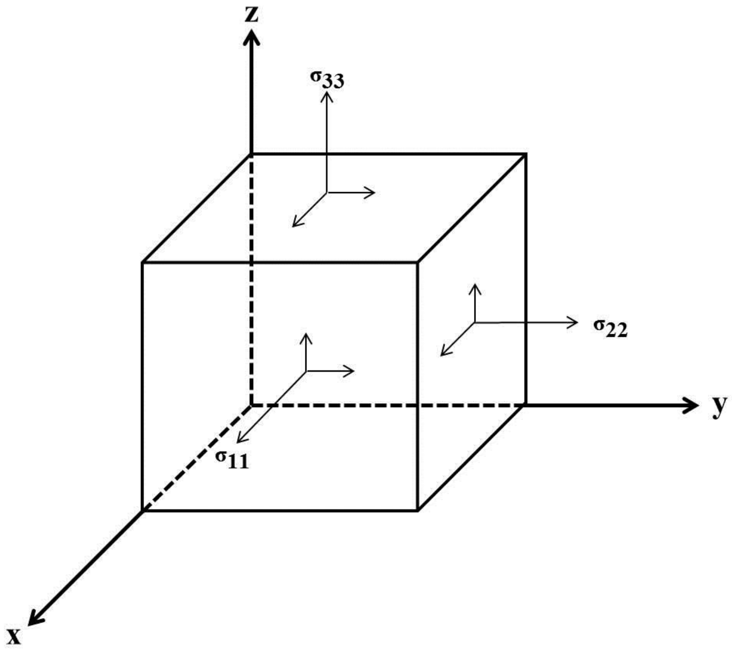

Figure 1-2: A three dimensional stress tensor.

As per Deb (2006), assume stress at a point in the coordinate matrix system:

$$\sigma_{ij} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix} \tag{1-2}$$

Where i = j, the stress the principle stress. For $\sigma_{ij}(i \neq j) = 0$,

$$\sigma'_{ij} = \begin{bmatrix} \sigma_{11}' & 0 & 0 \\ 0 & \sigma_{22}' & 0 \\ 0 & 0 & \sigma_{33}' \end{bmatrix} = \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{bmatrix} \tag{1-3}$$

Mean of the three principle (normal) stresses becomes,

$$\sigma_{mean} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \tag{1-4}$$

This mean stress is also known as the non-vertical deviatoric, or isotropic, component.

Vertical deviatoric stress in the matrix form can be written as:

$$\sigma_{dev} = \begin{bmatrix} \sigma_1 - \sigma_{mean} & 0 & 0 \\ 0 & \sigma_2 - \sigma_{mean} & 0 \\ 0 & 0 & \sigma_3 - \sigma_{mean} \end{bmatrix} \tag{1-5}$$

For full stress tensor, it becomes:

$$\sigma'_{ij} = \begin{bmatrix} \sigma_{11}' & 0 & 0 \\ 0 & \sigma_{22}' & 0 \\ 0 & 0 & \sigma_{33}' \end{bmatrix} = \begin{bmatrix} \sigma_{11} - \sigma_{mean} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} - \sigma_{mean} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} - \sigma_{mean} \end{bmatrix} \tag{1-6}$$

Therefore, vertical deviatoric stress (at a point) is derived by subtracting the mean of principle stresses from each principle stress. By definition;

$$\sigma_{dev} = \sigma - \sigma_{mean} \tag{1-7}$$

It can also be shown with a simplified diagram, shown in Figure 1-2.

$$\sigma_{total} = \sigma_{mean} + \sigma_{dev} \tag{1-8}$$

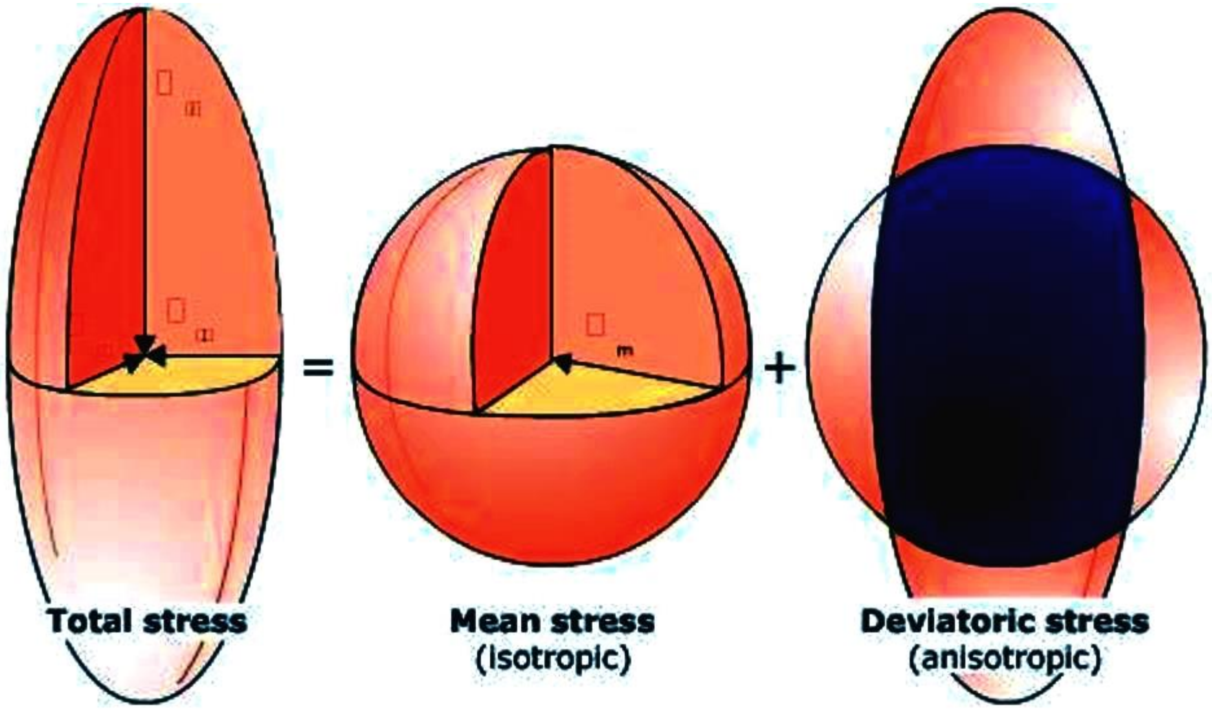

Figure 1-3: Graphical illustration of mean and vertical deviatoric stress (Fossen, 2010).

## Sample Example of Vertical deviatoric Stress

The vertical deviatoric stress tensor is important, as its components cause viscous deformation of rocks. Since the experimental work was carried out under uniaxial strain condition, horizontal deviatoric stress was assumed not to play a significant role given that no strain was permitted with changes in the state of stress. Furthermore, the magnitude of horizontal deviatoric stress took a negative value.  The absolute magnitude of the vertical deviatoric stress tensor components indicates how rapidly a rock will deform. A rock will extend in the direction in which the vertical deviatoric stress components are negative (negative is tensional in the earth science convention), even if all the principal stresses indicate compression. Thus, when making a sketch of field terrain, it is always very instructive to sketch arrows for the principal components of the vertical deviatoric stress tensor onto them, as their magnitude and direction corresponds to what is observed kinematically in the field (Stüwe, 2007).

Two rocks from different crustal levels can have the same vertical deviatoric stress (and therefore deform similarly) but they may be in completely different states of total stress.

For example: if three principle stresses are defined as;

$\sigma_1$ = 2200 psi, $\sigma_2$ = 1400 psi, and $\sigma_3$ = 1400 psi, then

$$\sigma_{\text{mean}} = \frac{2200 + 1400 + 1400}{3} = 1667 \text{ psi}$$

Now,

$\sigma_{1(\text{dev})} = \sigma_1 - \sigma_{\text{mean}} = 2200 - 1667.67 = 523.33$ psi

$\sigma_{2(\text{dev})} = \sigma_2 - \sigma_{\text{mean}} = 1400 - 1667.67 = -267.67$ psi

$\sigma_{3(\text{dev})} = \sigma_3 - \sigma_{\text{mean}} = 1400 - 1667.67 = -267.67$ psi

The rock will contract in the $\sigma_1$ direction since the vertical deviatoric $\sigma_1$ is positive. It will extend in $\sigma_2$ and $\sigma_3$ directions since the vertical deviatoric $\sigma_2$ and $\sigma_3$ are negative.

## Coal Strain under Reservoir Conditions

For an isotropic porous medium, which does not have any shrinkage and swelling, the general tensor expression for strain in terms of stresses and pore pressure can be written as (Nur & Byerlee, 1971; Detournay & Cheng, 1993):

$$\varepsilon_{ij} = \frac{1}{2G}\left(\sigma_{ij} - \frac{\sigma_{kk}}{3}\delta_{ij}\right) + \frac{1}{9K}\delta_{ij}\sigma_{kk} - \frac{1}{3H}\delta_{ij} \qquad (1\text{-}9)$$

where $\delta_{ij}$ is the Kroenecker's delta, $\varepsilon_{ij}$ is the small strain tensor, $\sigma_{ij}$ is the Cauchy stress tensor, K and G are identified as the bulk and shear modulus of drained elastic solid, p is the pore pressure, and H is solid phase modulus (Biot, 1955). In addition, the convention used is that compression is positive where $\sigma_{kk}$ is defined as:

$$\sigma_{kk} = \sigma_{11} + \sigma_{22} + \sigma_{33} \qquad (1\text{-}10)$$

The isotropic compressive stress, denoted as P, is defined as:

$$P = \frac{1}{3}\sigma_{kk} = \frac{1}{3}(\sigma_{11} + \sigma_{22} + \sigma_{33}) \qquad (1\text{-}11)$$

Generally, in literature, the isotropic compressive stress is also termed as “mean stress”.

The first term on the right side of eq. 1-9 represents the strain due to vertical deviatoric stress, which depends only on the shear modulus (G) of rock, without any pore pressure. The second term is the strain due to hydrostatic stress alone, which depends only on the bulk modulus (K) of the rock, without pore pressure. The last term represents the strain due to pore pressure and depends on the effective modulus (H) (Nur & Byerlee, 1971; Detournay & Cheng, 1993; Liu & Harpalani, 2013b).

For CBM reservoirs, there is an extra strain due to desorption/adsorption-induced matrix strain. Biot (1955) stated that the general tensor expression for strain (in terms of the other stresses and pore pressure) can be represented as:

$$\varepsilon_{ij} = \frac{1}{2G}\left(\sigma_{ij} - \frac{\sigma_{kk}}{3}\delta_{ij}\right) + \frac{1}{9K}\delta_{ij}\sigma_{kk} - \frac{1}{3H}\delta_{ij}p + \frac{1}{3Z_p}\delta_{ij}p \tag{2-12}$$

where, $Z_p$ is called the effective shrinkage/swelling modulus (Biot, 1955; Levine, 1996; Harpalani & Mitra, 2010; Liu & Harpalani, 2013b).

This equation suggests that the CBM reservoir permeability associated with this strain should be influenced by the vertical deviatoric stress in the calculation. To date, researchers have focused on the last three components of this strain equation for calculation of permeability primarily because, when calculating the normal strain of coal in the presence of shrinkage/ swelling effect, the strain due to deviatoric stress cancelled out. The vertical deviatoric stress part has not been focused on in the strain calculation, which, in turn, is related to the permeability. In this paper, effort is made to identify whether there is a relationship between permeability and vertical deviatoric stress.

# EXPERIMENTAL DATA

The experimental data used in this paper was obtained from the experimental work included in a recent doctoral dissertation (Liu, 2012). The experiments to measure the variation in permeability with depletion were conducted under uniaxial strain condition. In order to replicate uniaxial strain condition, the horizontal stress was reduced to compensate for matrix shrinkage, ensuring that the sample was not allowed to shrink in the lateral direction with reduction in reservoir pressure. Since the overburden depth remains unchanged during production, the vertical stress was maintained constant throughout the experiment. The experimental setup (triaxial cell) consisted of a circumferential extensometer to measure and control horizontal strain, a linear variable differential transducer (LVDT) to measure vertical strain, and a means to monitor and measure the flowrate. The setup was capable of applying both confining and axial stress initially to replicate the *in situ* condition. Details of the experimental setup and procedure can be found in Liu (2012).

# RESULTS AND DISCUSSIONS

In this section, the variation in permeability with the changes in vertical deviatoric stress at various pore pressures under replicated *in situ* condition is discussed. The sample was stressed vertically and horizontally at 2100 and 1400 psi, respectively, to represent the *in situ* stress condition. After this, helium was injected into the sample at 1100 psi to represent the initial *in situ* reservoir pressure condition. The pore pressure was then reduced gradually from 1100 psi to 50 psi in a step-wise manner and permeability was estimated. For each step, the horizontal stress was adjusted to ensure zero horizontal strain. The vertical stress was maintained constant throughout ensuring uniaxial strain conditions.

After completion of helium cycle, the sample was flooded with methane to expel the residual helium using the huff-and-puff technique. Next, the sample was saturated with methane at 1100 psi. After attaining strain equilibrium, flowrate was measured and the permeability was estimated. The pressure was then brought down in a step-wise manner, measuring the flowrate at each pressure step. After completing the methane cycle, the sample was saturated with carbon dioxide at 850 psi and the pressure depletion cycle was repeated. This level of carbon dioxide pressure was believed to be adequate since the partial pressure of carbon dioxide in coalbed methane reservoirs rarely exceeds 400 psi. Furthermore, at pressures higher than ~850 psi, carbon dioxide enters the supercritical phase. Hence, pressure-dependent-permeability was established for the coal type for helium, methane and carbon dioxide.

## Horizontal Stress with Pore Pressure Depletion Results

As stated earlier, in order to maintain uniaxial strain condition, the horizontal stress was adjusted throughout the experiment. The changes in horizontal stress with pressure decline for the three gases are presented in Figure 3-1. The figure shows that, at complete depletion, the horizontal stress decreased to 458 psi for helium, 110 psi for methane and zero for carbon dioxide. With increased sorptivity of gases ($CO_2$>$CH_4$), matrix shrinkage phenomenon dominates at low pressures, resulting in significant reduction in the horizontal stress. This is in agreement with the results reported by a previous researcher (Mitra, 2010).

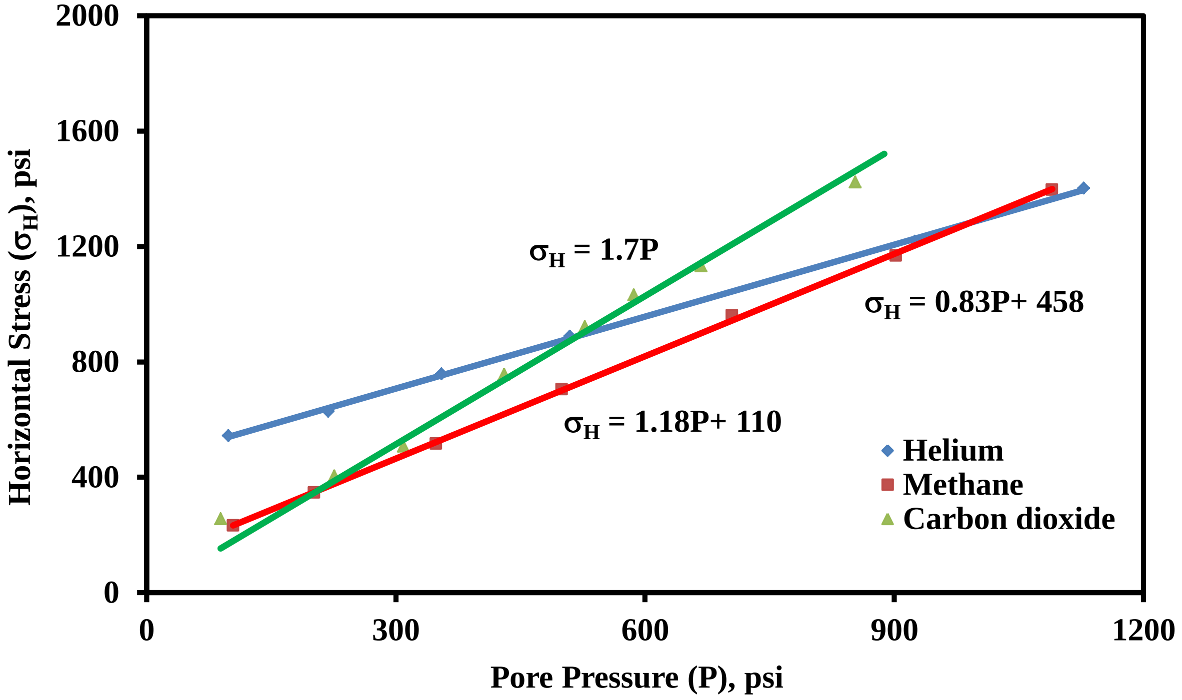

Figure 3-1: Changes in horizontal stress with the change in pressure for helium, methane and carbon dioxide.

In order to investigate the influence of changes in vertical deviatoric stress with pore pressure depletion, deviatoric stress was calculated using the measured stress and pressure conditions for each step. A discussion of this is presented in the next section of this chapter.

### Vertical Deviatoric Stress and Pore Pressure Results

Figure 3-2 shows that the vertical deviatoric stress increased with depletion of helium. The trend is also the same for methane and carbon dioxide, as shown in Figures 3-3 and 3-4.

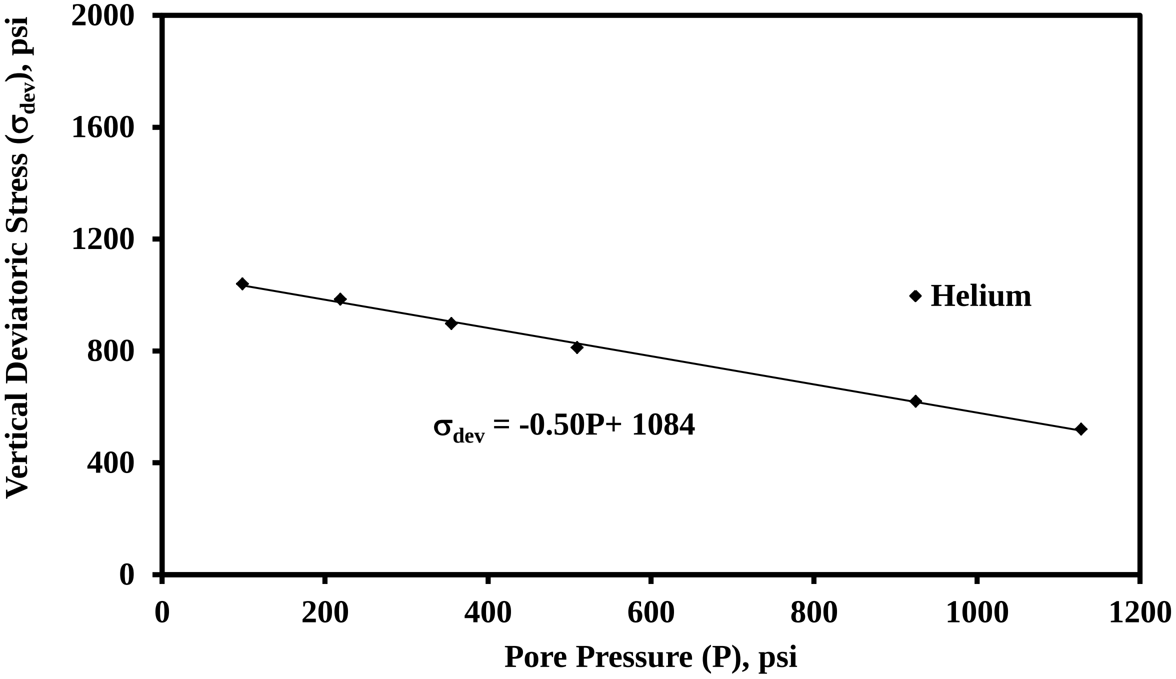

Figure 3-2: Changes in vertical deviatoric stress with pressure depletion for helium.

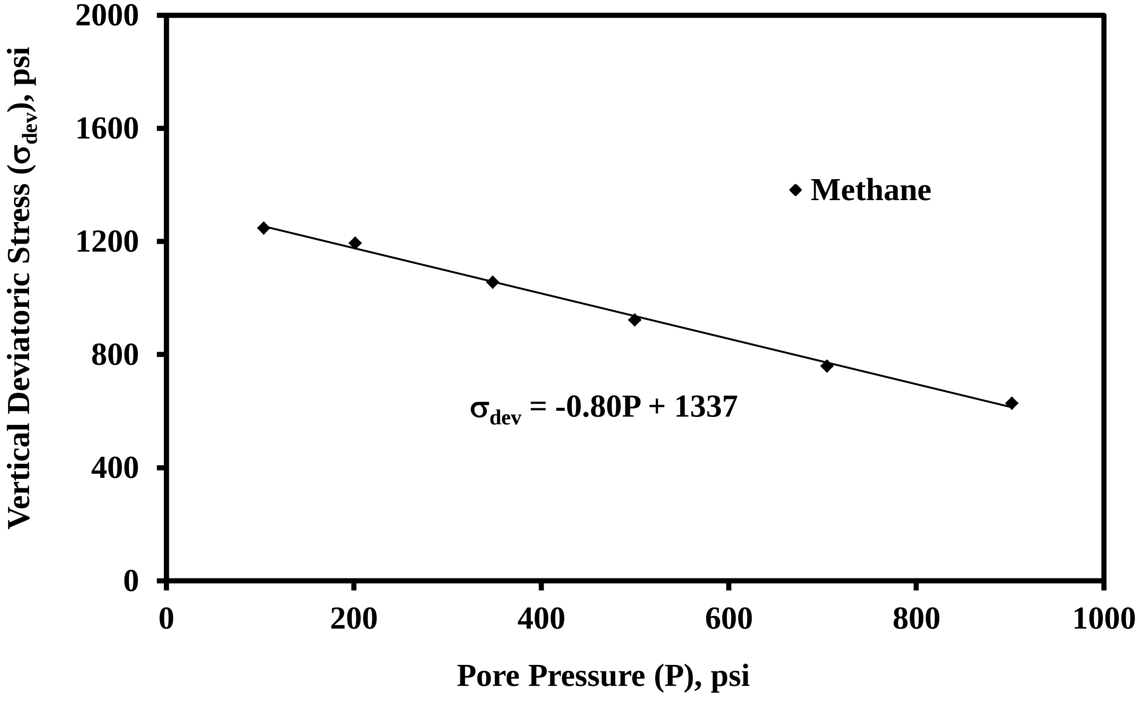

Figure 3-3: Changes in vertical deviatoric stress with pressure depletion for methane.

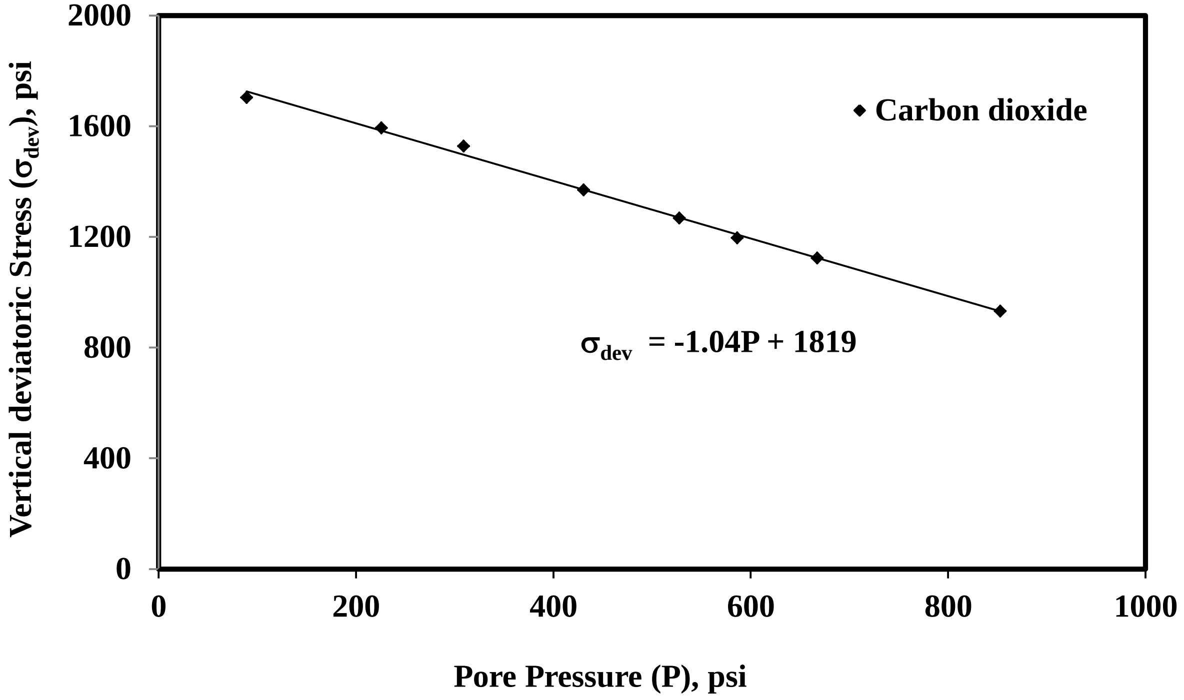

Figure 3-4: Changes in vertical deviatoric stress with pressure depletion for carbon dioxide.

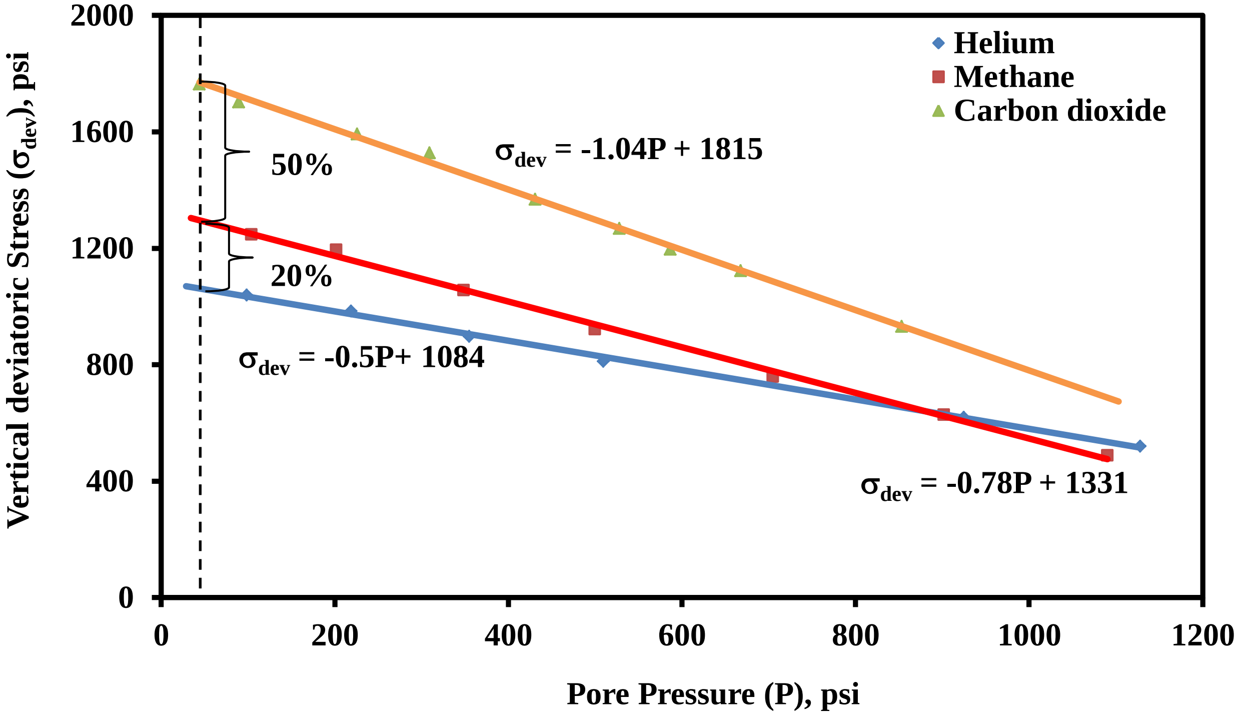

Figure 3-5: Vertical deviatoric stress change with pressure depletion for helium, methane and carbon dioxide.

Figures 3-2, 3-3, and 3-4 clearly show that, for the same changes in pressure, the vertical deviatoric stress increases continuously for all three gases used. However, the variation in vertical deviatoric stress with depletion is different for different gases.

For ease of comparison, Figure 3-5 shows the three plots together. The figure depicts that, in the low pressure region, vertical deviatoric stress differs significantly for all three gases. At complete depletion, the vertical deviatoric stress was 1084 psi for helium, 1331 psi for methane and 1869 psi for carbon dioxide.

**Analysis of Vertical Stress, Mean Stress and Vertical Deviatoric Stress with Pore Pressure**

In this section, relationship between changes in vertical stress, mean stress and vertical deviatoric stress with pressure depletion is discussed.

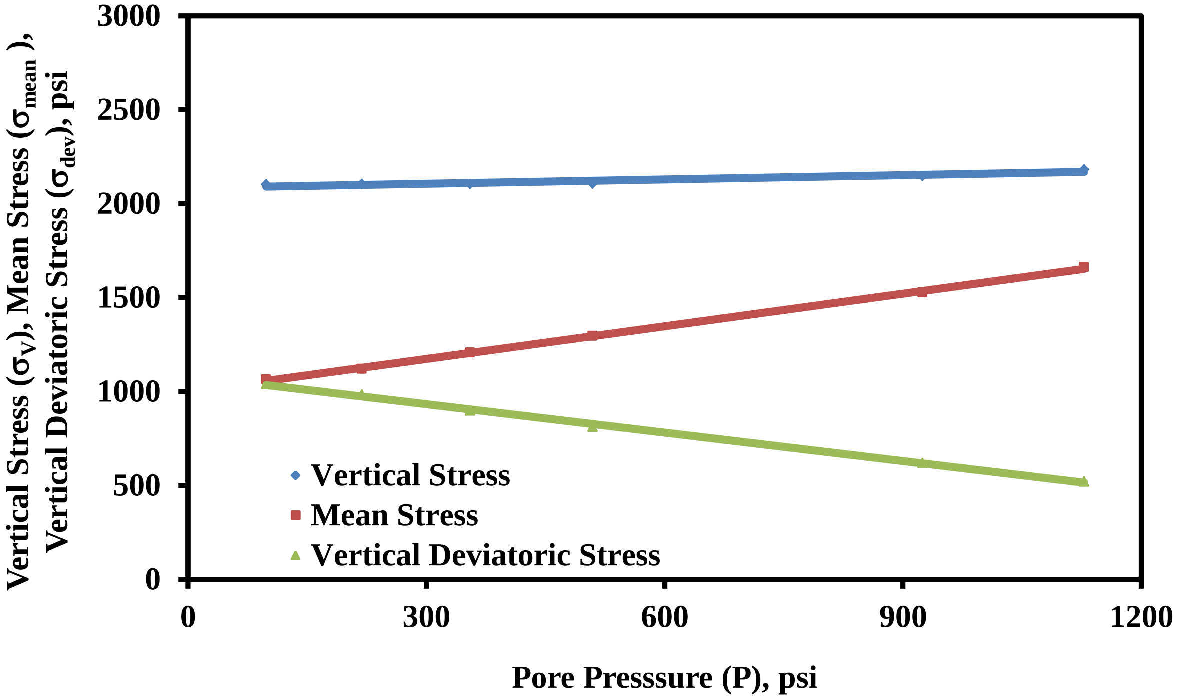

Figure 3-6: Comparison of vertical tress, mean stress, and vertical deviatoric stress for helium depletion.

Figure 3-6 shows the changes in the total vertical stress, mean stress and vertical deviatoric stress with helium depletion. As expected, the applied vertical stress remained constant throughout the depletion period. The decrease in mean stress was also expected since the horizontal stress decreased continuously. The vertical deviatoric stress, on the other hand, increased. At complete depletion of helium the mean stress and vertical deviatoric stress barely touched each other.

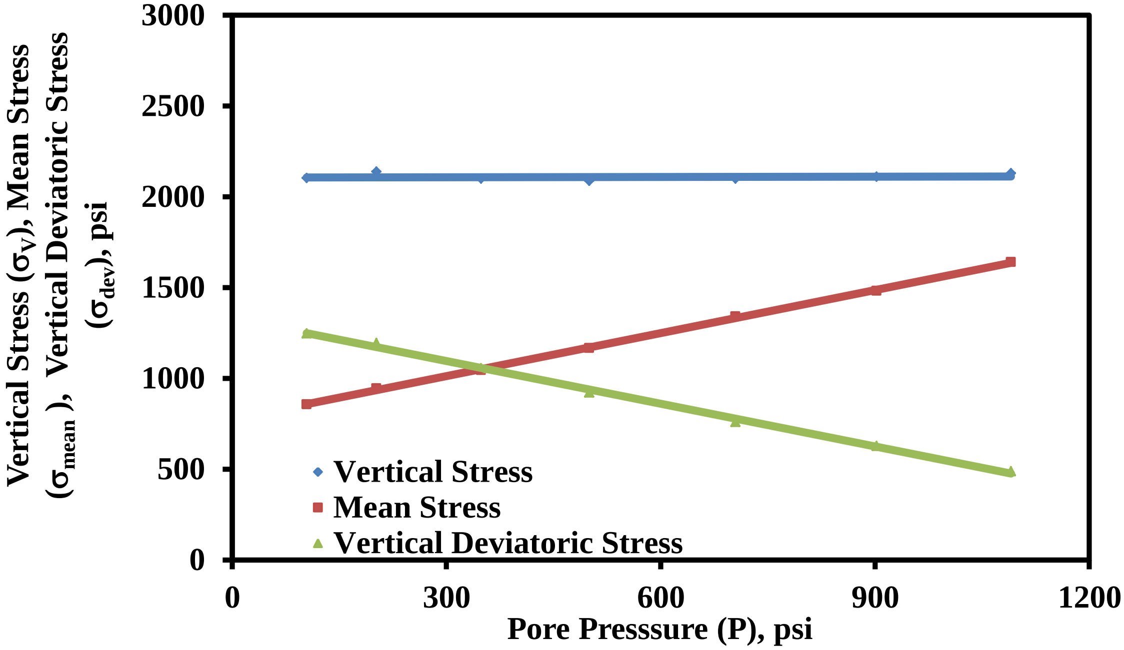

Figure 3-7: Comparison of vertical stress, mean stress, and vertical deviatoric stress for methane depletion.

Figures 3-7 and 3-8 show the relationship between the total vertical stress, mean stress and vertical deviatoric stress with methane and carbon dioxide depletion. It can be seen that, with methane and carbon dioxide depletion, the mean stress and vertical deviatoric stress actually intersected and deviatoric mean stress exceeded the mean stress. Furthermore, the point of intersection of the two plots shifted to higher pressure with increasing gas sorptivity. Literature provides no explanation for this behavior for coal and its implications for CBM reservoirs.

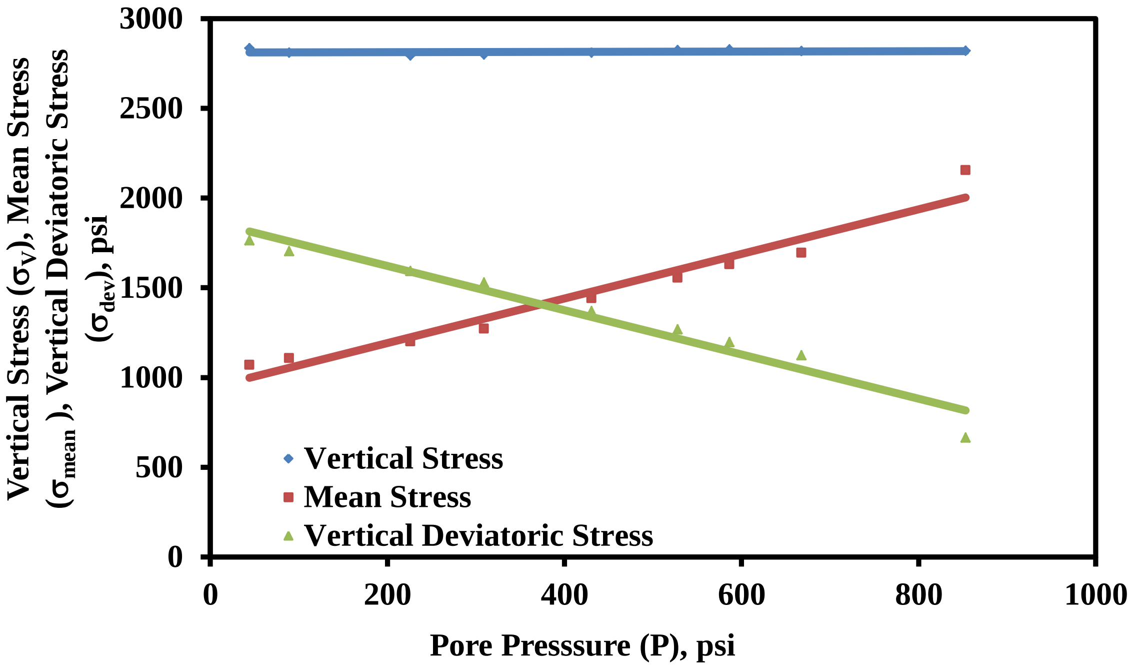

Figure 3-8: Comparison of vertical stress, mean stress, and vertical deviatoric stress for carbon dioxide depletion.

The mean stress, by definition, is responsible for changes in the solid volume whereas the vertical deviatoric stress is responsible for shapes in the shape of the solid (Deb, 2006). Since these experiments were conducted under uniaxial strain condition, it can be concluded that the vertical deviatoric stress also contributes to the sample strain although the distribution of the strain between the solid coal and cleat is not clear. It is well accepted that the permeability of coal is a direct function of the cleat volume. Hence, effort was made to establish a relationship between stresses and permeability and this is further discussed in the following section.

### Permeability Results  and Comparison with Vertical, Mean and Vertical Deviatoric Stress With Pore Pressure)

In this section, a relationship between the total vertical, mean, and vertical deviatoric stress with pore pressure depletion and the permeability variation is established. Instead of permeability, the permeability ratio, defined as the ratio between permeability estimated at each pressure step (k) and the initial permeability ($k_0$), is used since this better displays the intensity of permeability change with pressure reduction. Figure 3-9 shows that the changes in the permeability ratio for methane along with the changes in the three stresses.

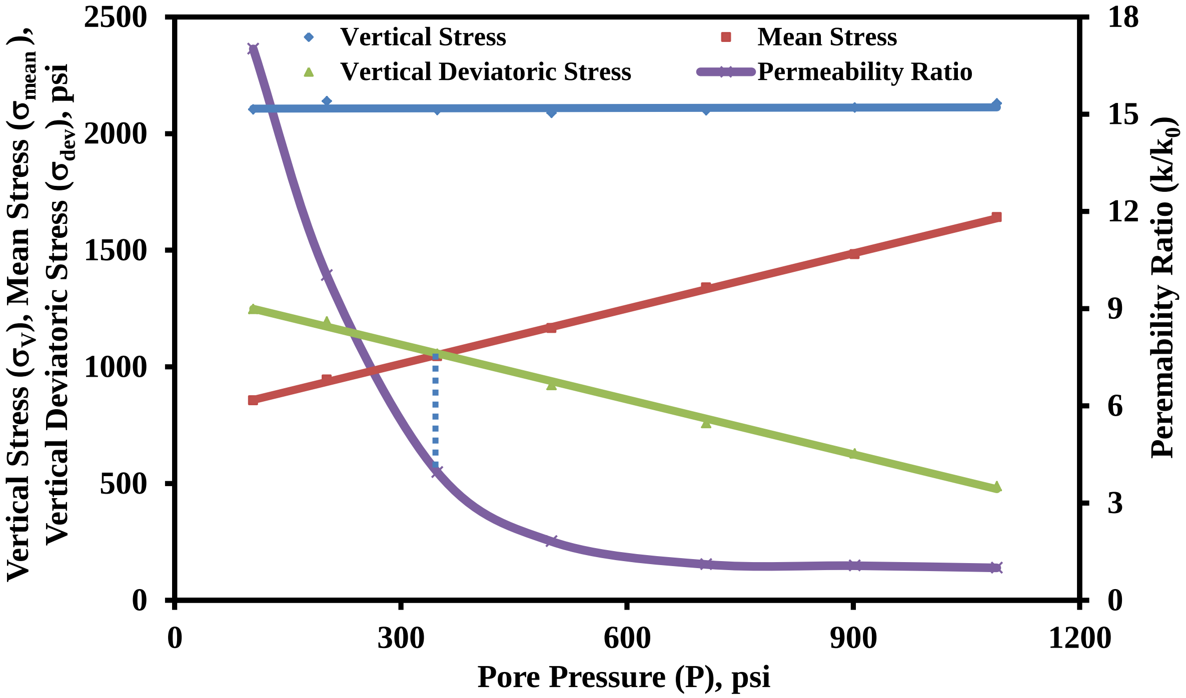

Figure 3-9: Changes in permeability to methane with variation in vertical stress, mean stress, and vertical deviatoric stress.

The permeability starts to increase when the deviatoric stress approached the mean stress. Figure 3-10 shows the permeability increase for carbon dioxide depletion. The same pattern is exhibited for carbon dioxide as well, except that the permeability increase is initiated after the deviatoric stress exceeds the mean stress.

Figure 3-9 and 3-10 show that, as the sorptivity of gas increases ($CO_2$>$CH_4$), the permeability starts increasing at low pore pressure when deviatoric stress exceeds the mean stress.

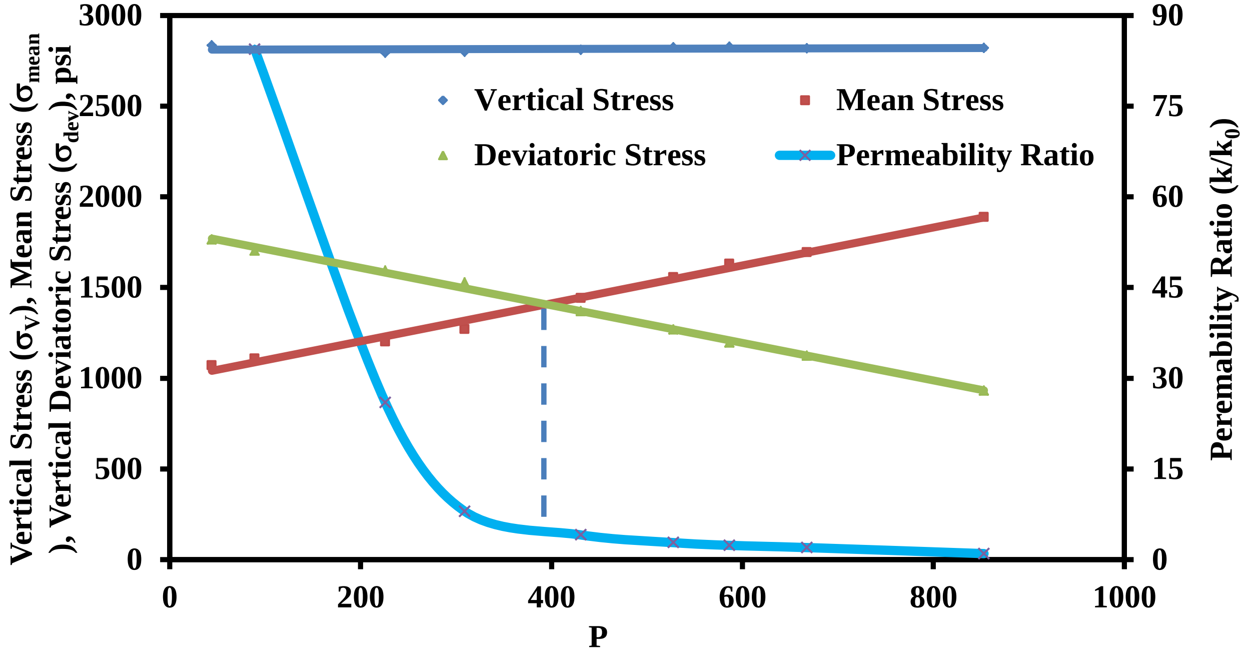

Figure 3-10: Changes in permeability to carbon dioxide with variation in vertical stress, mean stress, and vertical deviatoric stress.

These results require additional analysis to explore any potential relationship between the vertical deviatoric stress and permeability.

In an experiment on rock salt, it was found that, when the vertical deviatoric stress is higher than the mean stress, there is an inelastic brittle mechanism activated within the rock. This induces micro-cracks within the rock, resulting in a volume increase, or dilation (Pfeifle et al., 1998). Although coal behaves elastically when stressed hydrostatically (Harpalani & McPherson, 1985), it is not clear whether the vertical deviatoric stress is responsible for the sudden increase in permeability. There is preliminary evidence that microfractures are created due to increase in the deviatoric stress, or initiation of coal failure with continued depletion.

## Strain Results and Permeability

In this section, the volumetric strain as a function of vertical deviatoric stress is discussed. Effort has also been made to establish a relationship between the variation in permeability and vertical deviatoric stress as a function of volumetric strain. The relationship, however, is purely judgmental.

Figure 3-11 shows the changes in permeability and vertical deviatoric stress as a function of axial strain for the three gases. Under uniaxial strain condition, the sample strain is permitted only in the vertical/axial direction, thus equating the axial and volumetric strains. The measured volumetric strains are the result of changes in the micro-pore volume, elastic strain of solid grains and sorption-induced matrix shrinkage (Liu & Harpalani, 2013). It is apparent that the volume of coal decreases with continued depletion of all three gases although the decrease for helium is significantly lower than that for methane and carbon dioxide. It is also apparent in the plot that there is an increase in permeability with decrease in the axial length/volume of the sample for the two sorbing gases, the increase being higher for carbon dioxide, which is more sorbing than methane. However, there is a decrease in the permeability for the non-sorbing gas, that is, helium.

The interesting feature of the results shown in Figure 3-11 is that, for helium depletion, sample volume decreases with increase in deviatoric stress and this causes a decrease in the permeability. This is in agreement with the results presented by other investigators (Mitra, 2010; Liu, 2012). Typically, permeability decreases with depletion in a conventional reservoir, where sorption of gas plays no role in gas production. This reduction in permeability is purely due to increased effective stress as a result of decreasing pore pressure, which results in closure of flow

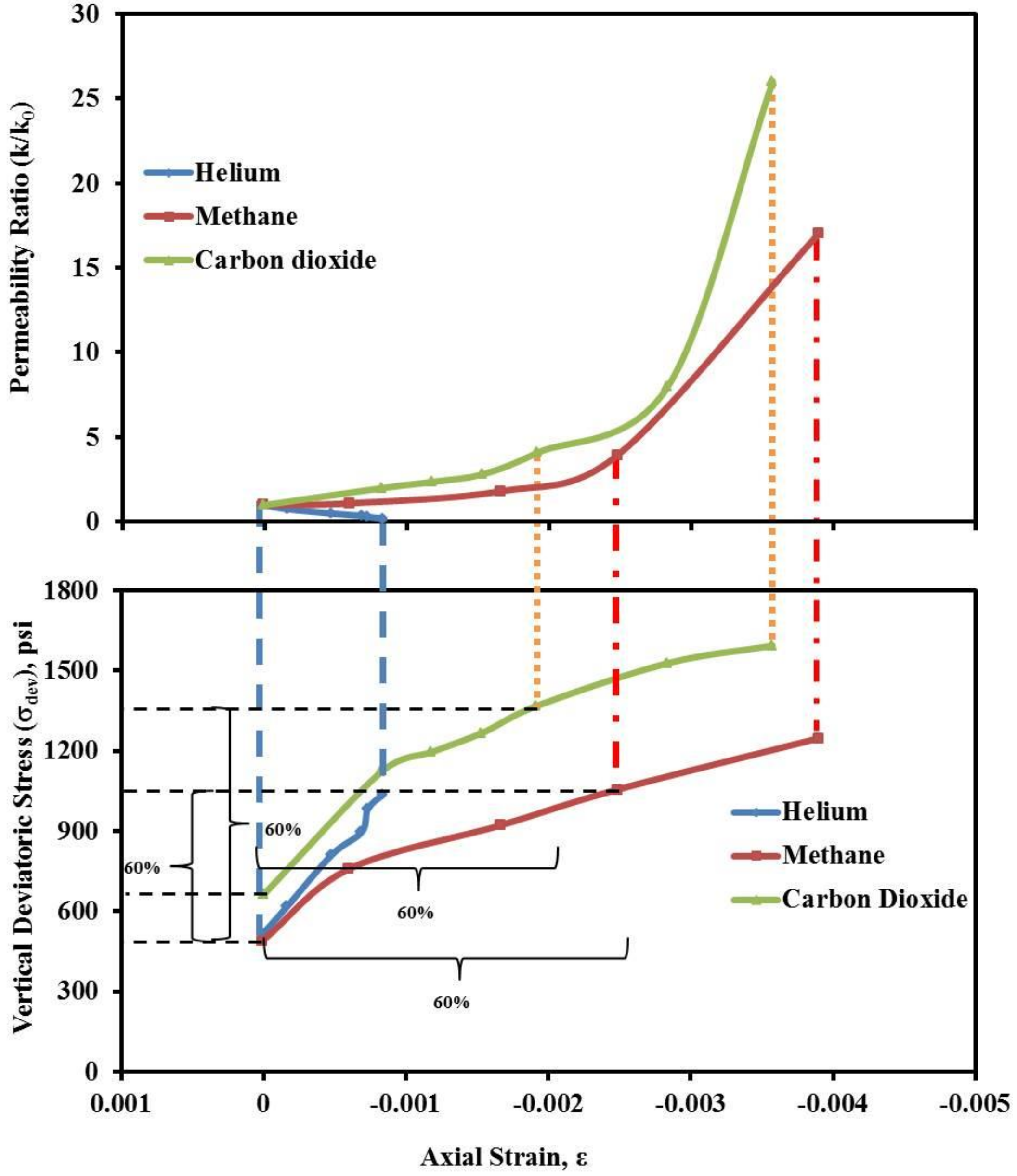

Figure 3-11: a) Vertical deviatoric stress versus axial strain, and b) Permeability versus axial strain.

paths oriented transversely to the axial stress direction, as suggested by Mitra (2010) and Liu (2012).

The second interesting finding is that, for both sorbing gases ($CH_4$ and $CO_2$), the sample volume decreases with depletion, just as it does for helium. However, once the vertical deviatoric stress becomes ~60% of the total vertical deviatoric stress, the permeability starts increasing significantly. In addition, for both of the sorbing gases, the stage at which the permeability starts to increase appears to be when the axial strain achieves ~60% of the total strain. Finally, the permeability increase appears to start only after the volumetric strain of the sample exceeds that caused by complete helium depletion. As long as the strain is above the helium depletion induced strain, there is very little permeability increase. However, once the strain becomes lower than that caused by helium, the permeability starts to increase and continues to increase at accelerated pace. Although the results of only one study are analyzed here, it can be concluded that the effect of depletion alone does not result in increased permeability. It is only after the strain exceeds that caused due to depletion that the permeability increase is initiated.

Wang et al. (2013) investigated the changes in coal permeability induced by internal damage with depletion of a sorbing gas. They showed that, with constant confining stress and application of incremental vertical deviatoric stress, permeability increased by almost three times. They determined that this would probably happen before shear cracks are generated within the sample due to vertical deviatoric loading. In comparison, the experimental results presented in this paper using sorptive gas ($CH_4$ and $CO_2$) showed that the permeability increased significantly more than three times that of initial permeability. It has been documented by researchers that, under uniaxial strain condition, the rise in permeability are influenced by the shrinkage of coal matrix with depletion of sorbing gases (Mitra, 2010; Liu, 2012). Therefore, it can be concluded that the vertical deviatoric stress alone cannot be responsible for the sudden permeability rise. The increase in deviatoric stress is accelerated due to matrix shrinkage, as is apparent from Figure 3-11, thus resulting in permeability increase.

Wang et al. (2013) mentioned that when a coal sample which, for their work was obtained from Gilson Seam of Book Cliffs, Utah, was saturated for twenty-four hours in methane, the sorption process is nearly complete prior to the initiation of vertical deviatoric loading. They described that, with increasing vertical deviatoric stress, new fractures, favorably oriented along the direction of the maximum principal stress, will be created and will contribute to a large amount of desorption of gas. They concluded that sorption induced shrinkage was not significant for the permeability increase. This conclusion is, of course, controversial. However, it should be borne in mind that the thrust of the work presented by Wang et al. (2013) was outbursts in underground coal mining operations. Hence, if vertical deviatoric stress is a factor contributing to permeability increase, the exact magnitude of the responsibility is not known.

# CONCLUSIONS AND RECOMMENDATIONS

Based on the knowledge gained in this study, the following conclusions are made:

1. With depletion of methane and carbon dioxide, when the vertical deviatoric stress of the sample approaches and exceeds the mean stress, permeability starts increasing significantly. As long as the deviatoric stress is below the mean stress, as was found to be the case for helium depletion, permeability does not increase.
2. With depletion of sorbing gas, the point of intersection of vertical deviatoric stress and mean stress shifts forward as the sorptivity of gas increases ($CO_2$>$CH_4$).
3. As the vertical deviatoric stress reaches to ~60% of the total vertical deviatoric stress, permeability starts increasing significantly. This 60% fraction also holds for volumetric strain since the permeability of coal started increasing only after the strain was ~60% of the total.
4. A decrease in pore pressure results in a significant decrease in horizontal stress and a significant increase in the vertical deviatoric stress. Since it is well accepted that lower horizontal stresses result in increased permeability, it can also be concluded that higher vertical deviatoric stress results in increased permeability under uniaxial condition.

Based on the knowledge gained in this paper, the following recommendations are made:

1. It is not clear whether, under uniaxial strain condition, the vertical deviatoric stress alone contributes to permeability increase. This requires further investigation.
2. If the vertical deviatoric stress is a factor contributing to permeability increase, its magnitude is not known. This should be investigated further.
3. Sorption induced shrinkage may be contributing to the increase in vertical deviatoric stress, resulting in generation of new fractures, which may be responsible for the changes in permeability. Additional research needs to carry out to split the permeability increase into

these two components in order to facilitate improved modeling of gas flow in coal. Alternatively, the two effects should be coupled to develop a model that incorporates both the effects simultaneously.

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