Apparent Permeability Effective Stress Laws: Misleading Predictions Resulting from Gas Slippage, Northeastern British Columbia

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Introduction

Northeastern British Columbia hosts a tremendous oil and gas resource trapped in fine-grained, unconventional reservoirs (shale oil and shale gas). To efficiently harness the potential economic benefit this resource represents, basin-scale inventories and distributions of gas and liquid hydrocarbons need to be determined. Equally important to inventories and distributions is petrophysical characterization of the host strata's storage and transport properties, which in large part govern production potential.

Thorough, accurate, petrophysical characterization of shale-oil and shale-gas reservoir rocks has been hampered by lack of suitable equipment and techniques for analyzing heterogeneous, low-permeability, nanoporous rocks. Development of new techniques and refinement of existing techniques, successfully applied to the analysis of conventional reservoir rocks, will yield the capacity to evaluate important petrophysical parameters of fine-grained rocks, and ultimately the ability to predict shale hydrocarbon production potential.

A multifaceted study supported by Geoscience BC and industry partners is underway at the University of British Columbia. The study seeks to better predict the areal distribution of natural gas-liquid–bearing shale in northeastern BC and its production potential. One component of the study is development of better methods for quantifying shale-oil– and shale-gas–matrix flow characteristics. This paper reports some of the progress to date for this particular component of the study. Specifically, the impact of gas slippage on experimentally derived permeability effective stress laws is investigated.

Gas Slippage in Shales

A defining characteristic of shale-oil and shale-gas reservoirs is their fine grain size and therefore smaller pores and pore throats in comparison to conventional hydrocarbon reservoir rocks. Inherent to rocks with smaller pores and pore throats is the increased significance of gas slippage (Klinkenberg, 1941). Gas slippage enhances transport efficiency relative to that predicted by Darcy's law when the mean free path of a gas (average distance a gas molecule travels before colliding with another molecule) approaches the size of the pores and pore throats through which it is flowing. Hence, gas slippage is more pronounced in shale-oil and shale-gas reservoir rocks with nanometre-scale pore systems than in conventional reservoir rocks with larger pores and pore throats.

Mean free path of a gas is controlled by temperature, pressure and the size of the individual gas molecules that comprise the gas. Mean free path is larger (and therefore gas slippage is more pronounced) at higher temperature and/or lower pressure and/or for a gas composed of smaller gas molecules. Typical reservoir pressures in conventional reservoir rocks are high enough and pore throats large enough that gas slippage is unlikely to be of practical significance for reservoir modelling; nowhere in a conventional reservoir is the mean free path of the gas being produced large enough that flow is in the slip-flow regime (Klinkenberg, 1941). Gas slippage, however, can be responsible for significant permeability variation in conventional reservoir rocks in the laboratory, where permeability measurements are often made at lower-than-reservoir pore fluid pressures (for instance a flow-through permeameter with atmospheric pressure on the downstream end of the core). In this case, laboratory measurements need to be 'corrected' for gas slippage (slip-corrected or Klinkenberg-corrected permeability) in order to be used in reservoir models.

Unlike in conventional reservoir rocks, gas slippage can significantly influence permeability in shale-gas reservoirs in situ (e.g., Clarkson et al., 2012). In the near-wellbore region during the later stages of production and pore fluid pressure (pore pressure herein) drawdown, the mean free path of the gas being produced can be large enough that flow takes place in the slip-flow regime. Gas slippage will be most significant in ultratight (nanodarcy permeability) dry gas reservoirs, which have the smallest gas molecules and, characteristically, the smallest pores.

Keywords: *shale, fine-grained, gas slippage, effective stress, permeability*

Gas slippage can significantly influence matrix permeability when analyzing shale-oil and shale-gas reservoir rocks in the laboratory. Laboratory measurements of matrix permeability are often made at lower-than-reservoir pore pressure using gaseous probing fluids. Helium, an essentially inert gas, is commonly used as a probing fluid to avoid complications associated with adsorption when using a hydrocarbon gas (e.g., methane) as a probing fluid (Cui et al., 2009). However, helium gas molecules are smaller than any hydrocarbon gas molecules, and therefore will have a larger mean free path at any given temperature and pressure. A larger mean free path results in more gas slippage.

Although it has been recognized in the literature that gas slippage is far more pronounced in shale-oil and shale-gas reservoir rocks than in conventional reservoir rocks, the full extent to which gas slippage influences laboratory matrix permeability measurements has not yet been realized. This paper highlights the fact that gas slippage can have a significant effect on permeability effective stress laws for shale-oil and shale-gas reservoir rocks, even when permeability measurements are made at high pore pressures (>7 megapascals [MPa]), where gas slippage is assumed to be negligible by many researchers.

Impact of Gas Slippage on Experimentally Derived Permeability Effective Stress Laws

An effective stress law is used to predict a rock property that varies with confining pressure and pore pressure. Application of an effective stress law combines confining pressure and pore pressure into a single variable: effective stress. This variable can be used to predict the value of the measured rock property outside the ranges of confining pressures and pore pressures at which the property was measured at in the laboratory (Robin, 1973). For instance, permeability at high confining pressure and pore pressure could be predicted using measurements made at lower pressures.

In its most basic form, effective stress laws can simply be the difference between confining pressure and pore pressure:

$$\sigma'_{eff} = P_C - P_P \qquad (1)$$

where σ'_{eff} is effective stress, P_C is confining pressure and P_P is pore pressure. Slightly more complicated effective stress laws invoke an effective stress law coefficient, α:

$$\sigma'_{eff} = P_C - \alpha P_P \qquad (2)$$

Equations 1 and 2 are examples of linear effective stress laws. Effective stress laws can also be nonlinear, in which case their utility is severely limited, as permeability needs to be measured over the particular pressure range of interest in order to predict permeability within that range (Robin, 1973). Schematic examples of linear and nonlinear effective stress laws are presented in Figure 1.

Development of an effective stress law assumes that the variation of the rock property being quantified is solely the result of changing pore structure that has resulted from changes in confining pressure and pore pressure. If another process is in part responsible for variation of the rock property, it will be captured quantitatively by the effective stress law, but not theoretically (i.e., the variation is assumed to be controlled by effective stress, some function of confining pressure and pore pressure). The result would be a misleading effective stress law.

Permeability varies with confining pressure and pore pressure because pore structures are not fixed and change in response to varying stress. Increasing confining pressure constricts pores and pore throats, thereby decreasing permeability. Increasing pore pressure has the opposite effect, as increased pressure applied to the pore walls from within the pores expands the pore structure. Permeability effective stress laws are meant to capture the variation in pore structure and therefore permeability resulting from changing confining pressure and pore pressure. If a gaseous probing fluid is used for permeability measurements and the magnitude of permeability variation due to gas slippage is significant in comparison to permeability variation due to stress changes alone, misleading permeability effective stress laws would result. In this case, it would not be possible to use the effective stress law to predict permeability to a liquid or another species of gas with either bigger or smaller gas molecules, or to extrapolate the effective stress law to pore pressure–confining pressure combinations other than

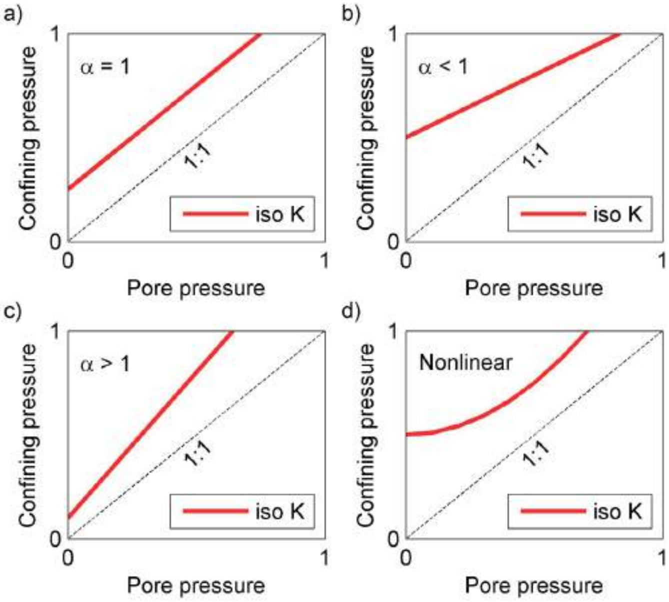

Figure 1. Schematic plots of **a–c)** linear and **d)** nonlinear permeability effective stress laws using permeability contours (iso-K lines) in confining pressure–pore pressure space (modified from E.A. Letham and R.M. Bustin, unpublished paper, 2015).

those measured during development of the effective stress law. Previous studies have been conscious of the misleading impacts gas slippage could have on experimentally derived permeability effective stress laws (Warpinski and Teufel, 1992; Li et al., 2009; Heller et al., 2014), but have assumed that gas slippage is negligible at pore pressures higher than ~7 MPa. To test the validity of this assumption, the permeability of a Montney Formation sample to helium was measured at a wide range of pore pressures and confining pressures, including pore pressures low enough to easily recognize gas slippage.

Experimental Method

Permeability measurements were performed using the pressure pulse decay technique (Brace et al., 1968). Permeability was measured over a confining pressure range of 8.6–65.5 MPa and a pore pressure range of 1.7–17.2 MPa, as per the pressure schedule presented in Figure 2. Permeability measurements at higher confining pressures were not possible with the experimental setup due to limitations of the confining cell, and permeability measurements at higher pore pressures were not possible due to limitations of the permeameter.

Results and Discussion

One of the most characteristic symptoms of gas slippage is the linear relationship between apparent permeability (not Klinkenberg corrected) and inverse pore pressure (Figure 3; E.A. Letham and R.M. Bustin, unpublished data, 2015). Because mean free path decreases linearly with decreasing inverse pore pressure, gas slippage and therefore apparent permeability also decreases linearly with decreasing inverse pore pressure. Permeability data in the present study was first analyzed under the simplest assumption that effective stress was the difference between confining pressure and pore pressure (referred to as simple effective stress herein, Equation 1), and Klinkenberg plots were generated for each simple effective stress (Figure 4). The strong linear

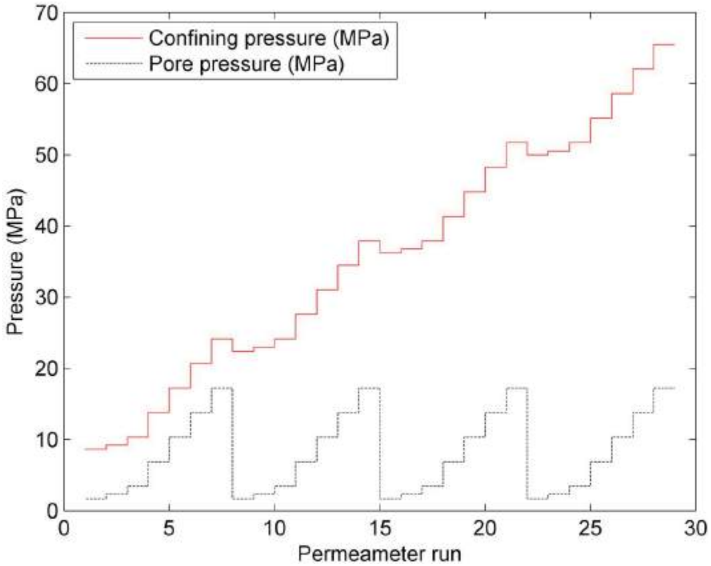

Figure 2. Schedule of confining pressure and pore pressure conditions for permeability measurements (modified from E.A. Letham and R.M. Bustin, unpublished paper, 2015). Abbreviation: MPa, megapascal.

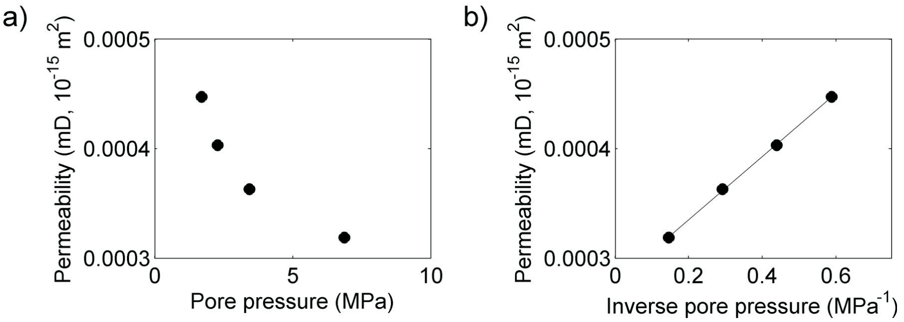

Figure 3. Data for a sample from the Eagle Ford Formation, Texas, U.S. (E.A. Letham and R.M. Bustin, unpublished data, 2015). **a)** Permeability variation with pore pressure. **b)** Klinkenberg plot that shows linear relationship of inverse pore pressure and permeability. The mean free path of the gas varies linearly with the inverse of pressure, which is why permeability varies linearly with inverse pore pressure. Abbreviations: mD, millidarcy; MPa, megapascal.

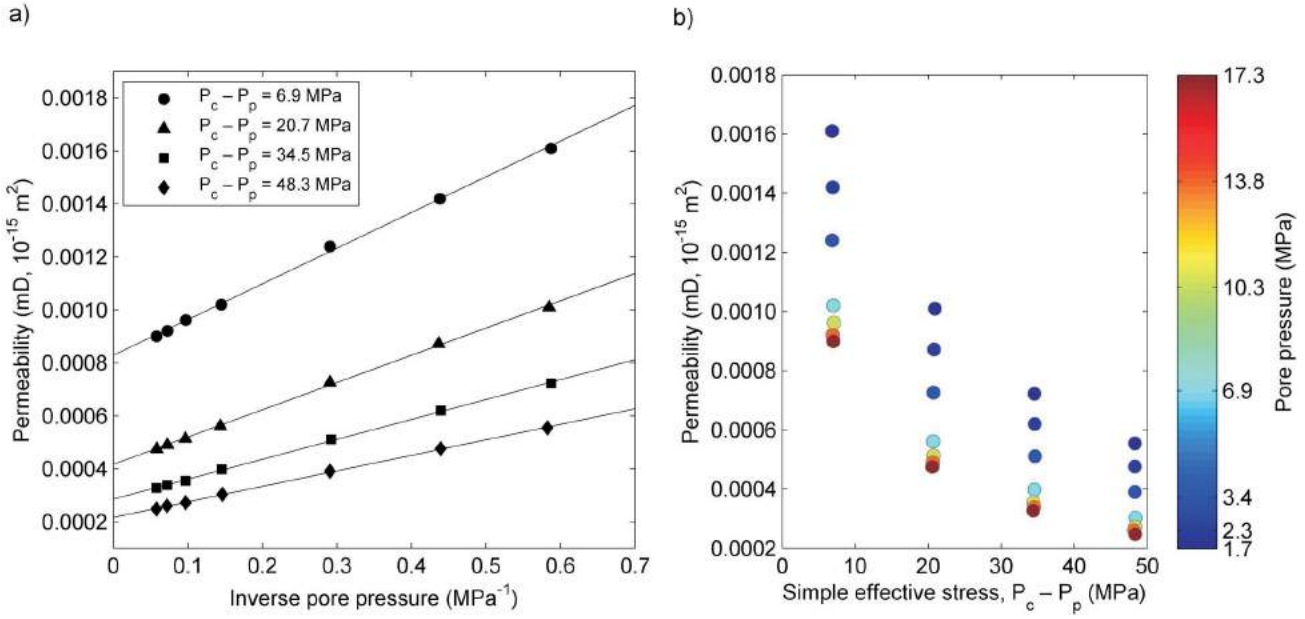

Figure 4. a) Klinkenberg plots for permeability measurements at each simple effective stress. **b)** Permeability variation due to gas slippage at each simple effective stress (modified from E.A. Letham and R.M. Bustin, unpublished paper, 2015). Abbreviations: mD, millidarcy; MPa, megapascal; P_C, confining pressure; P_P, pore pressure.

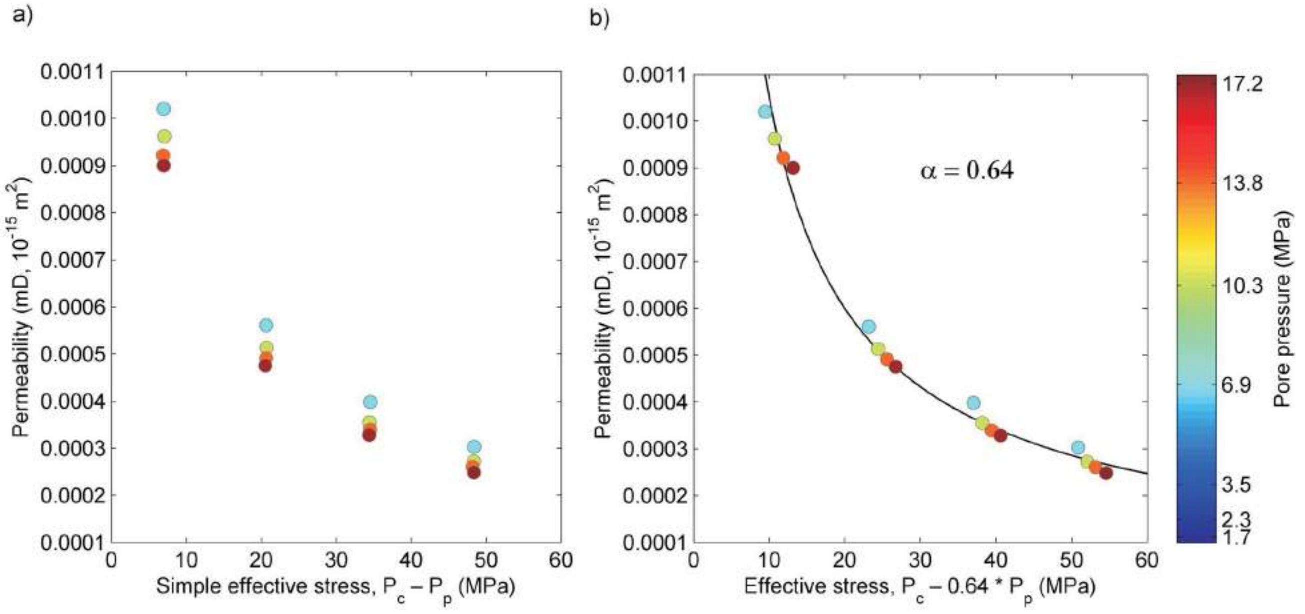

Figure 5. **a)** Permeability variation resulting from gas slippage at individual simple effective stress states for permeability measurements made at pore pressures ≥7 megapascals (MPa). **b)** Apparent permeability effective stress law for data fit to a power function (modified from E.A. Letham and R.M. Bustin, unpublished paper, 2015). Abbreviations: mD, millidarcy; P_C, confining pressure; P_P, pore pressure.

relationships indicate gas slippage is the cause of permeability variation at each simple effective stress. If the assumption was incorrect and pore structure varied significantly at different combinations of confining pressure and pore pressure that equate to the same simple effective stress, then nonlinear Klinkenberg plots would be expected. The simplest form of permeability effective stress law (Equation 1) therefore holds for this particular sample.

Having concluded gas slippage was the cause of permeability variation at each individual simple effective stress, high pore pressure (>7 MPa) data was then analyzed without correcting for gas slippage to determine the impact of gas slippage on what would be the experimentally derived permeability effective stress law (Figure 5). Curve fitting of a power law yielded a permeability effective stress law with an α value of 0.64 (Figure 5b). This is an apparent permeability effective stress law, as the permeability variation that the fitted curve represents is a combination of both apparent permeability variation due to gas slippage at each single simple effective stress, and permeability variation due to pore structure change when stepping from one simple effective stress to the next. Using the apparent permeability effective stress law to determine input values for reservoir models would hence result in inaccurate production predictions.

Conclusions

Gas slippage was found to significantly impact an experimentally derived permeability effective stress law for a shale-gas sample from the Montney Formation, even when only high pore pressure (>7 megapascals) data was analyzed. The resulting apparent permeability effective stress law would lead to inaccurate matrix permeability estimations and therefore inaccurate production predictions if the matrix permeability estimations were used in a reservoir simulator. The common assumption that gas slippage can be neglected at pore pressures higher than 7 megapascals when determining a permeability effective stress law using a gaseous probing fluid needs to be abandoned for fine-grained rocks and previous studies that utilized this assumption should be thoroughly re-examined.

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