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# On the relationship between effective permeability and stress for unconventional rocks: Analytical estimates from laboratory measurements

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ABSTRACT

Permeability measurements show that unconventional rock is considerably stress sensitive because the matrix permeability is likely controlled by micro cracks and bedding structures in unconventional reservoirs. While there are a number of laboratory studies in the literature on the dependency of core-scale permeability on effective stress for unconventional rocks, how to determine the corresponding large-scale stress-dependency relationship (of more interest to practical applications) from the laboratory measurements has not been systematically investigated. This work proposes a method to estimate such a large-scale relationship from laboratory measurements.

Based on the stochastic approach commonly used for parameter upscaling, we derived relationships between the large-scale effective permeability and the stress for the two- and three-dimensional isotropic porous media. The development is based on the empirical observation that at core scale permeability is an exponential function of effective stress. The developed large-scale relationships can be written in terms of the same mathematical form as the local-scale relationship except parameters in the large-scale relationships correspond to effective ones. The effective stress sensitivity parameter (that characterizes the stress-dependency) is simply the expected value of that at the local scale, or the arithmetic average of local values, for the two-dimensional flow problem and a function of effective stress for the three-dimensional problem.

Because of its dominant two-dimensional flow along beddings (resulting from the fact that vertical permeability is significantly smaller than the horizontal one), the relationship for the two-dimensional flow case is valid for unconventional rocks. Nevertheless, we demonstrate that for typical local-scale parameter values from unconventional rocks (e.g., Barnett shale and a carbonate source rock), the relationships obtained for two- and three-dimensional problems give the essentially same results.

## 1. Introduction

Oil and natural gas from unconventional reservoirs have become major hydrocarbon energy resources in Northern America and worldwide. This has been largely owing to the development of two technologies, drilling of long horizontal wells and hydraulic fracturing, that significantly enhance the reservoir contact areas such that an economically feasible production rate can be achieved for a low-permeability reservoir. A number of researchers (e.g., Liu et al., 2016; Heller et al., 2014; Patzek et al., 2013; Ozkan et al., 2011) have identified formation permeability as the key parameter controlling the production rate because the permeability determines how easily the hydrocarbon can flow from the formation to the hydraulic fractures and then to the production wells. Liu et al. (2016) even speculated that the next big technology breakthrough in developing unconventional resources likely occurs in the area of using economical ways to stimulate reservoir matrix permeability.

It is well documented in the literature that the permeability of unconventional rock samples is significantly stress sensitive, probably because micro-cracks and the alike are important for determining the rock permeability (e.g., Liu, 2017; Zheng et al., 2015; Wasaki and Akkutlu, 2015; Heller et al., 2014). With increasing effective stress (or the decreasing pressure for a given confining stress), micro cracks and the related features in the matrix, unlike a rounded pore, close quickly such that rock permeability declines significantly. Among a number of different factors, this stress sensitivity may be a key contributor to the well-known fact that the early production rate declines very rapidly with time as micro cracks are closing with pore pressure evolution during the production. Thus, the stress dependency of permeability is critical for predicting the performance of unconventional reservoirs and for optimizing the reservoir management strategies, such as the management of pressure drawdown in production wells.

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The stress dependency of permeability has been investigated in laboratory on the core scale under controlled conditions of pore pressure and confining stress (e.g., Bhandari et al., 2015; Heller et al., 2014). Because of the subsurface heterogeneity, upscaling is generally needed to determine large-scale (or effective) flow parameters from laboratory measurements, while the former should be used for reservoir simulations. In the last two or three decades, the upscaling has been intensively investigated and the related results have been summarized in several books (Bear, 2018; Zhang, 2002; Dagan and Neumann, 1997; Gelhar, 1993). The upscaling is based on the stochastic method that treats core-scale permeability as a spatially distributed random variable and then relates effective flow parameters to the statistics of local-scale measurements. At the same time, the uncertainty of an effective parameter can also be quantified. Most of the stochastic studies mentioned above, however, have exclusively focused on cases in which permeability is not dependent on the effective stress. To the best of our knowledge, studies on upscaling a stress-dependency relationship for permeability are very rare in the literature if they exist.

The objective of this study is to develop a method to determine an analytical relationship between effective permeability and stress for unconventional rocks based on the stochastic approach. This paper is organized as follows. It first presents the core-scale relationship between permeability and effective stress that has been observed in laboratory for unconventional rocks. Next, the stochastic approach is briefly reviewed to determine effective permeability from statistics of core-scale measurements. This is followed by a presentation of the newly developed relationship between effective permeability and stress. Finally a discussion of the implications of this work is included.

## 2. Core-scale relationship between permeability and effective stress

A number of researchers have investigated the relationship between permeability and effective stress for unconventional rock samples in the laboratory (Bhandari et al., 2015; Heller et al., 2014; Vermylen, 2011; Dong et al., 2010; Bustin et al., 2008; Kwon et al., 2004). The permeability measurements are generally made with the pressure pulse-decay method that estimates the core permeability by analyzing pressure evolution in the two gas reservoirs connected to the inlet and outlet of a rock core sample, respectively, as a small pressure pulse goes through the sample (e.g., Jones, 1997; Cui et al., 2009).

Bhandari et al. (2015) studied the effects of anisotropy and stress dependence of permeability in the Barnett shale and also reviewed the related measurements from Vermylen (2011), Bustin et al. (2008) and Kwon et al. (2004). They found that both vertical and horizontal permeability are stress dependent, with the permeability anisotropy, or the ratio of the horizontal to the vertical permeability, being about two orders of magnitude as a result of preferential flow along the horizontal bedding (more permeable layers). Bhandari et al. (2015) indicated that the related measurements on permeability as a function of stress can be represented by the following equation:

$$k = k^0 \exp(-\alpha S_{eff}) \quad (1)$$

where $k$ is permeability, superscript "*0*" refers to zero stress condition, $\alpha$ is the stress-sensitivity factor, and $S_{eff}$ is the effective stress.

The experimental data from Bhandari et al. (2015) imply that there is no or a very weak correlation between measured permeability values and the stress-sensitivity factor $\alpha$. For example, they found that vertical and horizontal cores correspond to significantly different permeability measurements, but have similar $\alpha$ values. This is further supported by the experimental results from Vermylen (2011) and Kwon et al. (2004) that were compiled in Fig. 8 in Bhandari et al. (2015) that do not show a clear trend between permeability values from different rock samples (at a given stress) and the corresponding stress-sensitivity factors. As will be discussed later, this point is important for developing the theoretical relationship between effective permeability and stress based on the stochastic approach.

Heller et al. (2014) presented permeability measurements as functions of both effective stress and pore pressure for core samples from the Barnett, Eagle Ford, Marcellus, and Montney shale reservoirs. They again found that core permeability declines rapidly with increasing effective stress for a given pore pressure. They also reported that the permeability is enhanced by Knudsen diffusion and slippage flow at low pore pressures for a given confining stress, which is consistent with other related studies in the literature (e.g., Darabi et al., 2012; Ziarani and Aguilera, 2012; Civan et al., 2012). Shale pores generally have sizes on the order of nano meters up to micro meters and therefore gas molecules within these pores can have mean free paths larger than the pore diameters at low gas pressures. This makes diffusion (called Knudsen diffusion) an important factor determining gas flow. Slippage gas flow results from the fact that gas flow velocity at the pore solid surface, unlike that assumed in the classic viscous fluid mechanics, is not always zero. Thus, the slippage flow, unlike Knudsen diffusion, is not related to the pore size and can occur for gas flow in both conventional and unconventional reservoirs. While the physical mechanisms of Knudsen diffusion and slippage flow, their impacts on permeability measurements and the correction of the impacts have been well documented in the literature (e.g., Darabi et al., 2012; Ziarani and Aguilera, 2012; Civan et al., 2012), the focus of this communication is on the relationship between stress and permeability at different scales.

Zheng et al. (2015) developed a theoretical relationship between permeability and the effective stress for low-permeability sedimentary rock, based on the two-part Hooke's model (TPHM) (Liu et al., 2009; Liu, 2017). The TPHM was developed based on the two major hypotheses. It conceptualizes an intact rock into a soft part and a hard part, while the soft part consists of a combination of micro cracks, bedding structures and the alike and the hard part comprises of the rest of the rock body. In addition, it postulates that the elastic strain is an exponential function of stress, rather than the linear function; the modified Hook's model is reduced to the conventional form of Hooke's law for small elastic strains. The TPHM considers the total rock deformation to be a summation of the deformations of the two parts corresponding to different elastic mechanical parameters. The TPHM has been intensively validated with literature data from different sources (Liu, 2017). The concept of the TPHM is essentially consistent with the dual-porosity model proposed by Wasaki and Akkutlu (2015) that divides the shale pore space into slit-shaped pores in inorganic matter and rounded pores in organic matter. Note that slit-shaped pores are relatively easy to deform under stress compared with rounded pores.

Based on the TPHM, Zheng et al. (2015) derived that permeability is a summation of the two exponential functions of the effective stress that correspond to the soft and hard parts, respectively. When ignoring the contribution from the hard part, the relationship of Zheng et al. (2015) is reduced to Eq. (1). The relationship is verified by the experimental data collected by Dong et al. (2010) for silt-shale samples from a deep drilling project in the Western Foothills of Taiwan. Fig. 1 shows that the theoretical relationship agrees well with the experimental data for a large range of effective stresses. Both the theoretical relationship and experimental data in Fig. 1 indicate that the soft-part is responsible for the significant permeability reduction in low stress levels and the high stress-sensitivity of permeability is mainly attributed to the micro-crack (soft-part) closure in the intact rock.

In the following sections, we will develop the large scale relationship between effective permeability and stress based on its core scale counterpart with spatially variable parameters. Eq. (1) is used for this purpose based on the following considerations. Although the TPHM gives an accurate representation of stress-dependency of permeability for a large range of stress (e.g., Fig. 1), Eq. (1) seems to be adequate within stress ranges of practical interest for several shale reservoirs because the matrix permeability is mainly determined by the "soft