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INSTITUTO ARGENTINO DEL PETROLEO Y DEL GAS

Experimental investigation of apparent shale permeability with consideration of gas slippage and stress-dependence effects

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Introduction

- Reservoir heterogeneity yields in multiple scales of permeability. Although complex natural and induced fractures may control the reservoir performance at early stages, it is the matrix properties that drive how a well will perform over long periods of time.

- During shale gas production, as pore pressure is decreased, two different effects impact on permeability:

  - Increasing effective stress: leads to lower permeabilities because of the pore throats narrowing.

  - Flow regimes effects: transport of gas through the rock matrix is described as a combination of Darcy´s flow and diffusion flow. Not considering this effect leads to overestimating the intrinsic permeability of the rock.

Objectives

- Experimental measurements were proposed to study the following effects:

  1. Stress dependency of k

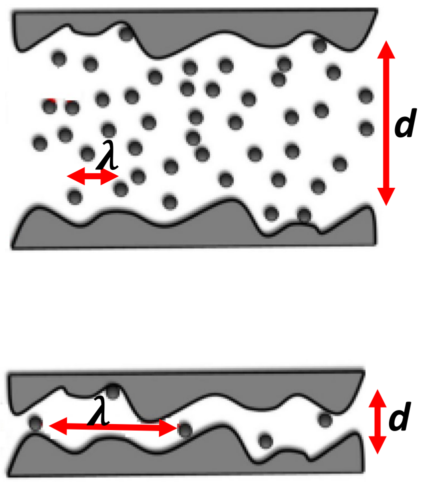
  2. Flow regime effects on apparent k

  3. Adsorption effects

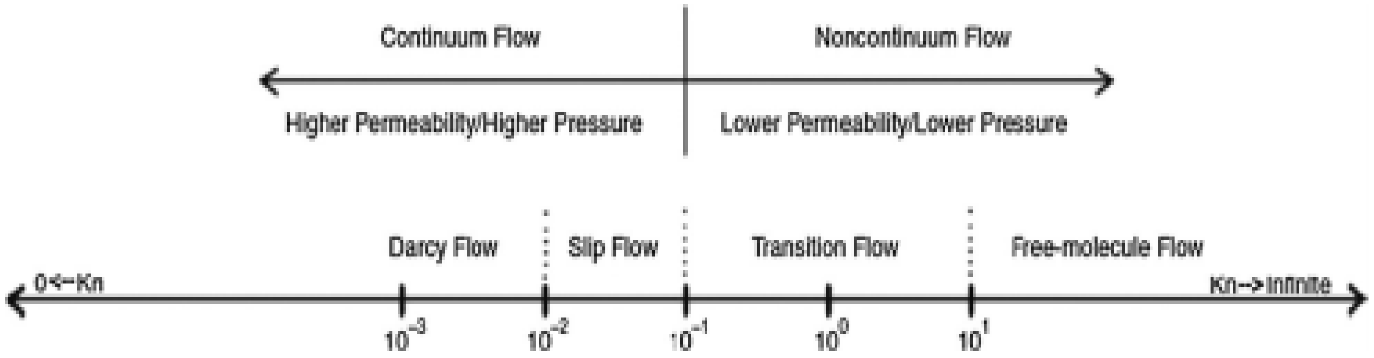
Background

Flow regimes

- Total gas flow in shale rocks is a combination of:
  - Darcy´s flow
  - Diffusion flow
- Knudsen number is used to characterize flow regime:



$$Kn = \frac{\lambda}{D}$$



Background

Slip effect

Gas molecule slippage in pore walls modelled by Klinkenberg:

$$k_g = k_l\left(1 + \frac{b}{p}\right)$$

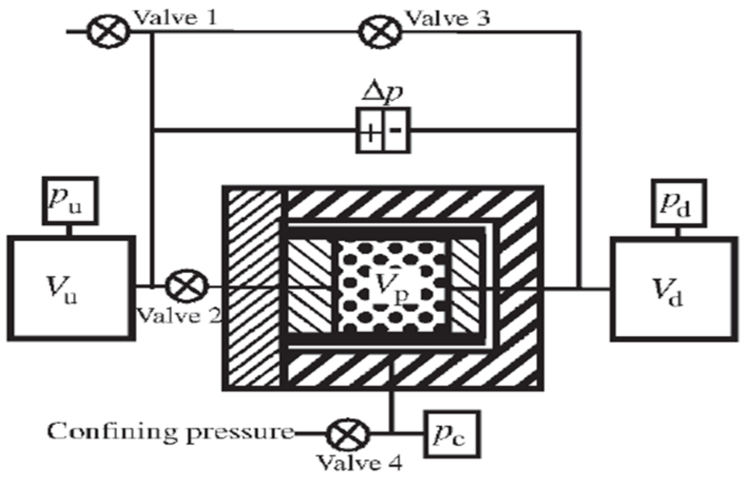
At high pore pressures (>7 Mpa), gas slippage is assumed to be negligible by many researchers

Adsorption

Adsorption effects impact specially on strongly adsorptive rocks such as organic-rich gas shales with high surface areas. Permeability could be underestimated if this is not considered.

Methods

- Permeability measurements were conducted on core samples from Eagle Ford
- Different confining pressures (CP) and pore pressures (PP)
- Methane and helium were used as pore fluids
- Pressure pulse decay technique

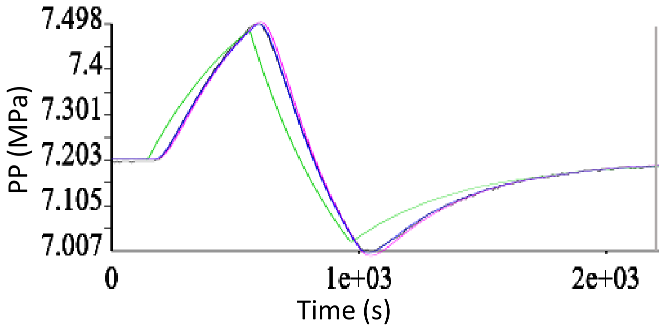


Methods

- As downstream pressure increase and upstream pressure decrease, the differential pressure is fitted with an exponential decay and permeability could be determined.

$$\Delta P(t) = \Delta P_0 e^{-mt} \qquad k = -\frac{m\left(\frac{L}{A}\right)\mu\beta(V_u V_d)}{(V_u + V_d)}$$

- Model data-matching



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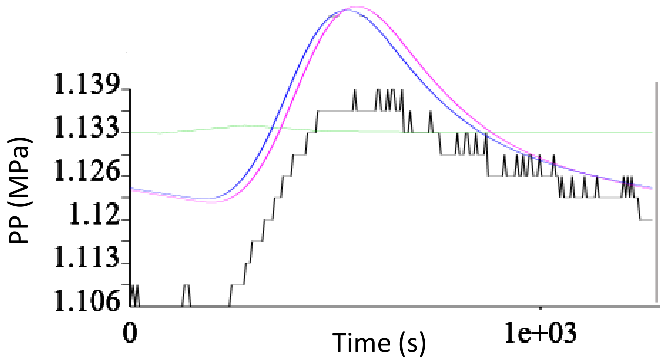


Rejected

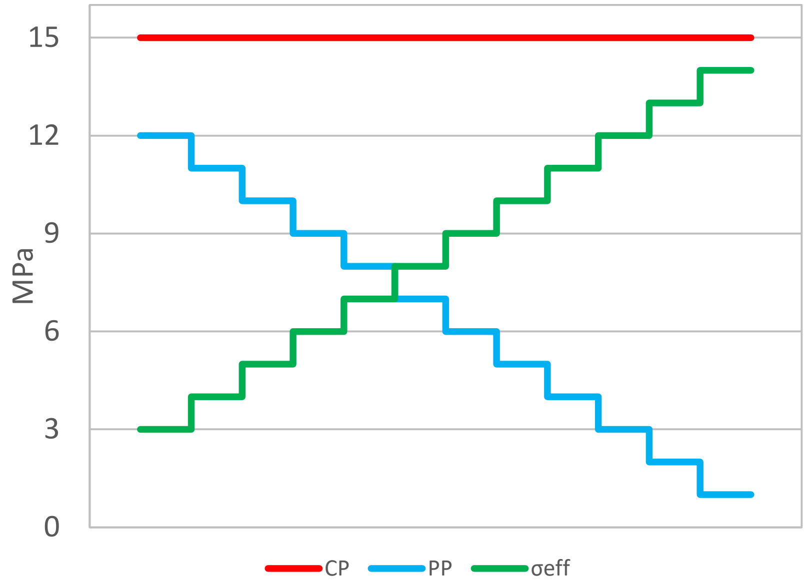
Methods

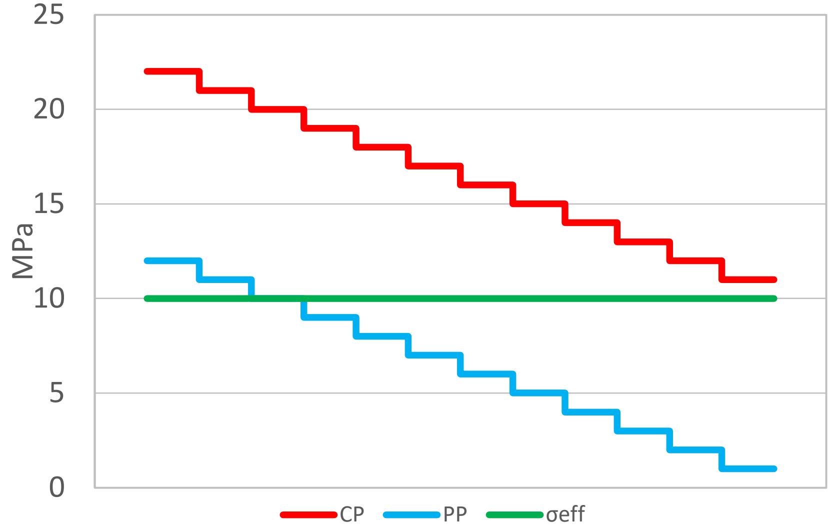
Procedure:

1. To focus on **stress-dependency**:
   - Constant CP =15 Mpa
   - PP from 1 to 12 Mpa

2. To consider **slippage** effect:
   - Constant Effective Stress = 10 Mpa
   - PP from 1 to 12 Mpa
   - CP from 11 to 22 Mpa

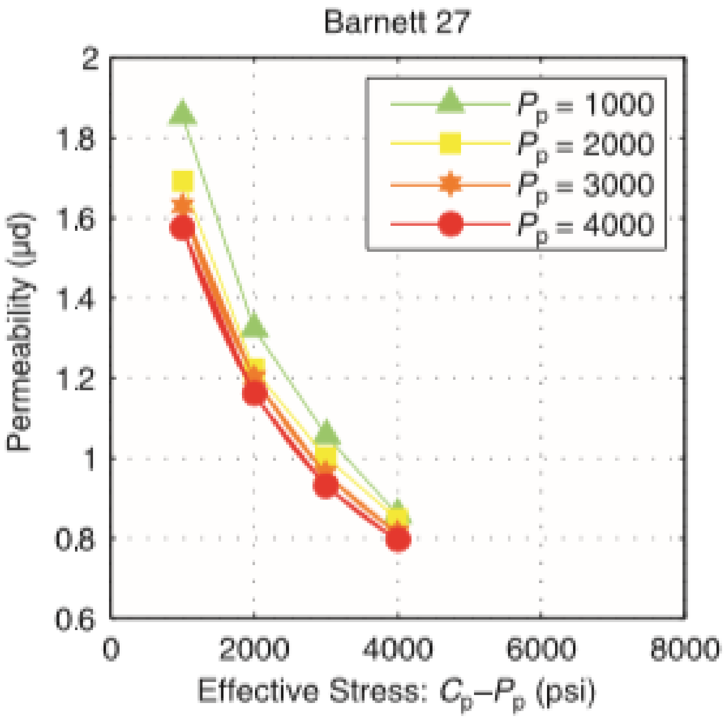
3. To analyze **adsorption** effects:
   - Helium
   - Methane





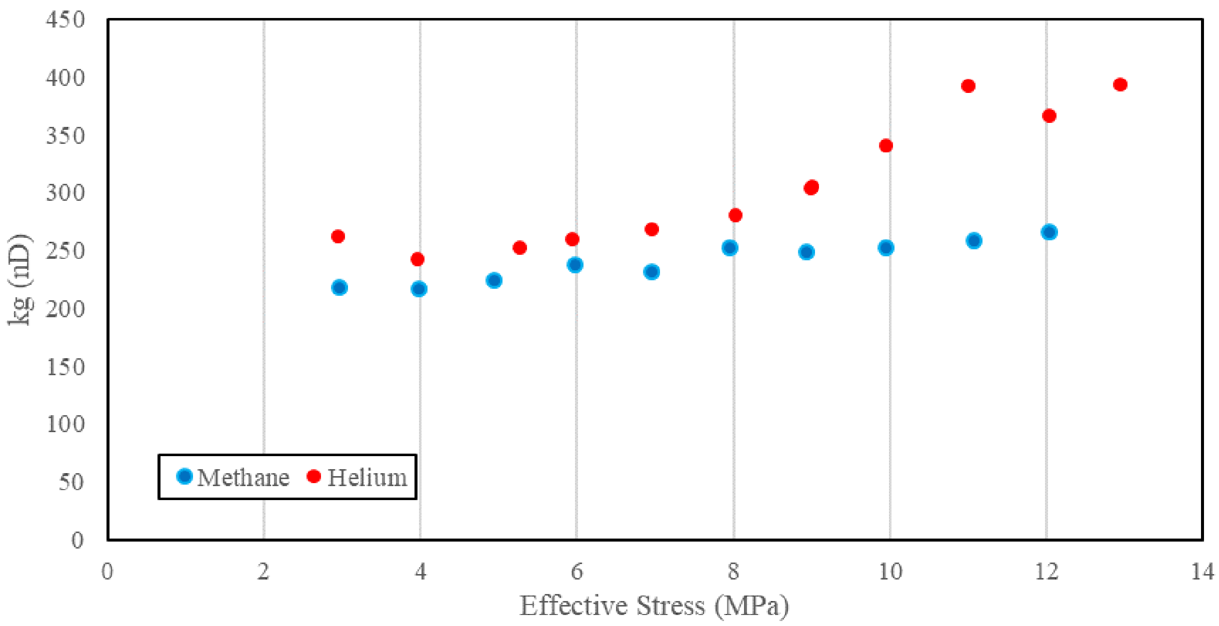
Results and Discussions

Results from Heller et al., 2014



Permeability versus simple effective stress (CP – PP); Heller et al., 2014

Our results



Permeability versus simple effective stress (CP – PP)

Results and Discussions

Stress-dependent permeability

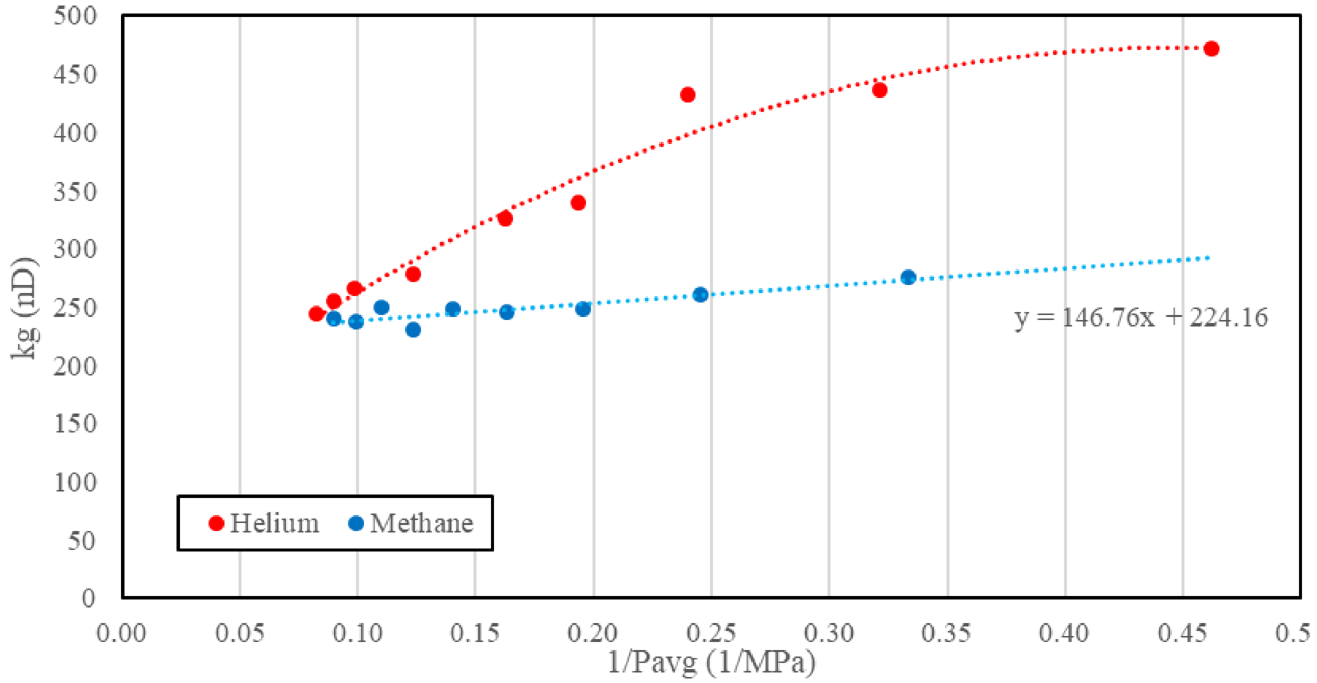
- The measured permeability has an increasing trend, opposite to the behavior expected. Clear and strong slippage effect is present even at high pore pressures (low effective stresses).

- Permeability values for methane are smaller. The reason for this is molecular sieving and methane’s strong adsorption to shale rocks.

- The difference increases at higher effective stress (small pore pressure). This can be also explained by slippage effect.

Results and Discussions

Klinkenberg effect



- Measured permeability with methane as pore fluid align in a straight line. Klinkenberg parameters were calculated by a linear extrapolation.
- Values start to deviate from a straight line at lower pore pressures for helium

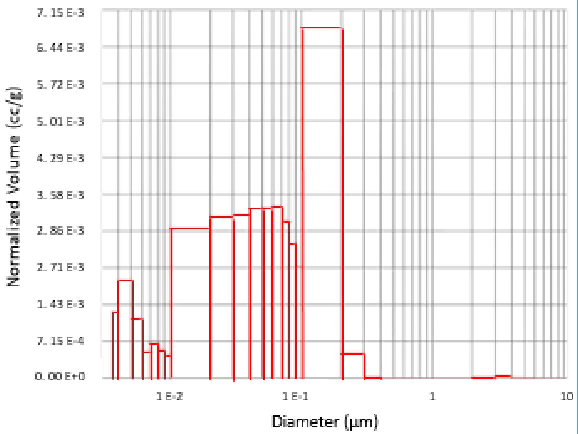
Results and Discussions

Flow Regime Characterization

Knudsen number was calculated for each experiment to verify the flow regime

$$Kn = \frac{\lambda}{D}$$

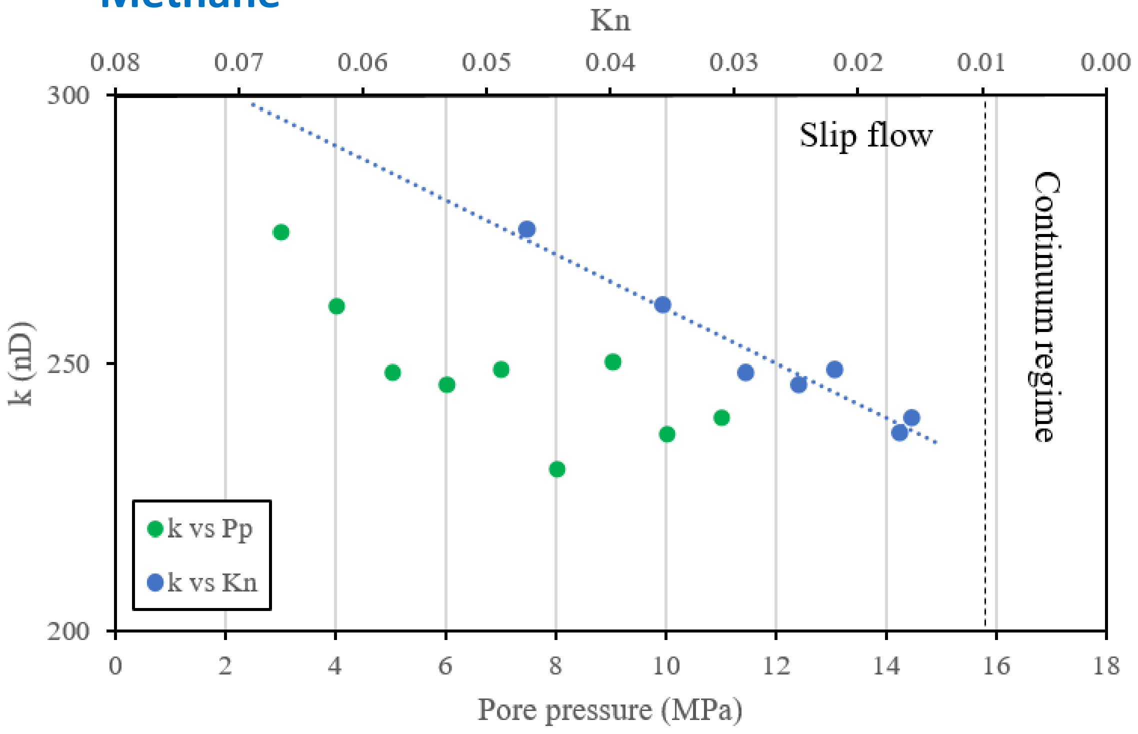
$$\lambda = \frac{k_B T}{\sqrt{2}\pi\sigma^2 P} \quad ; \quad \sigma^2 = \frac{2\sqrt{m k_B T}}{3\pi^{3/2}\mu}$$

Mercury injection test	Analytical approximation	Bibliography references
	$k = \underbrace{\boxed{\frac{w^4}{12A}}}_{k_l}\left[1 + \frac{1}{P}\underbrace{\boxed{\frac{16c\mu}{w}\left(\frac{2RT}{\pi M}\right)^{1/2}}}_{b}\right]$ $w = \sqrt{3\pi k_l}$	• Nazari *et al.* (2016) • Pang *et al.* (2017) • Nelson (2009)

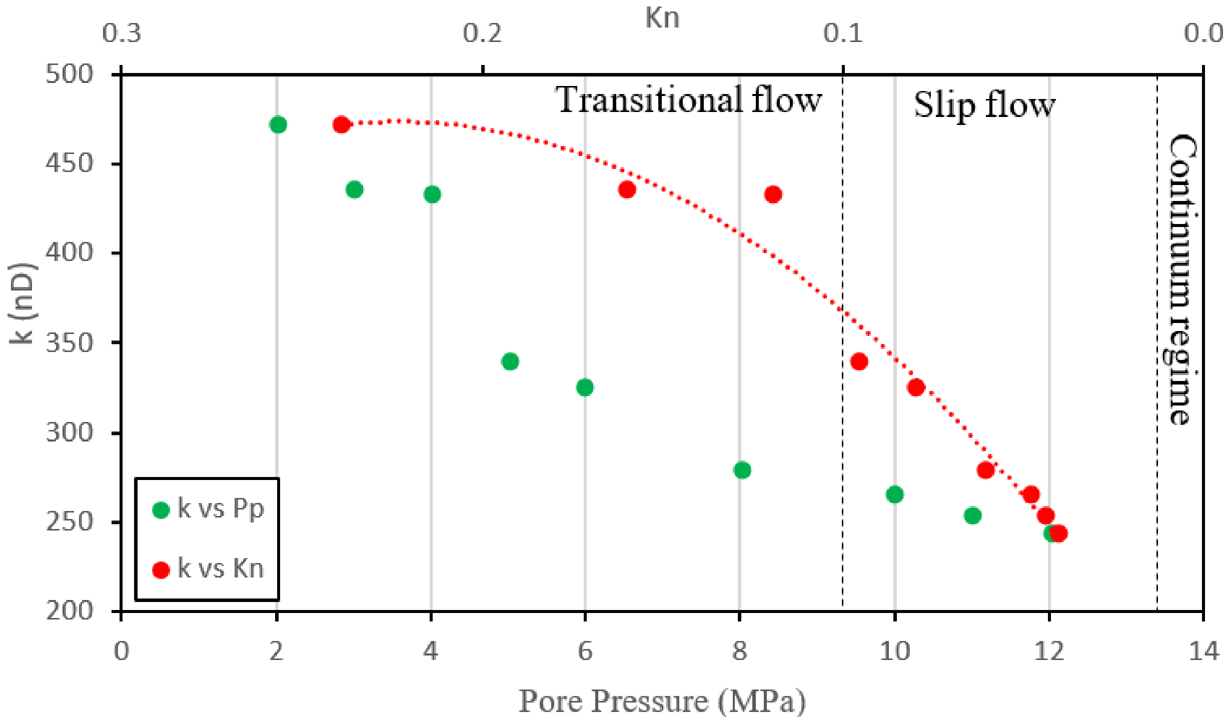
Results and Discussions

Flow Regime Characterization

Methane



Helium



- The permeability measurements versus Knudsen number for methane lie close to a straight line.
- Measured permeability with helium does not follow a linear relationship. Klinkenberg effect does not work in these regions.

Results and Discussions

Flow Regime Characterization

- Transitional flow regime is the reason for the linear trend deviation, opposite to Klinkenberg theory
- Klinkenberg model was used only were the slip flow regime was dominant

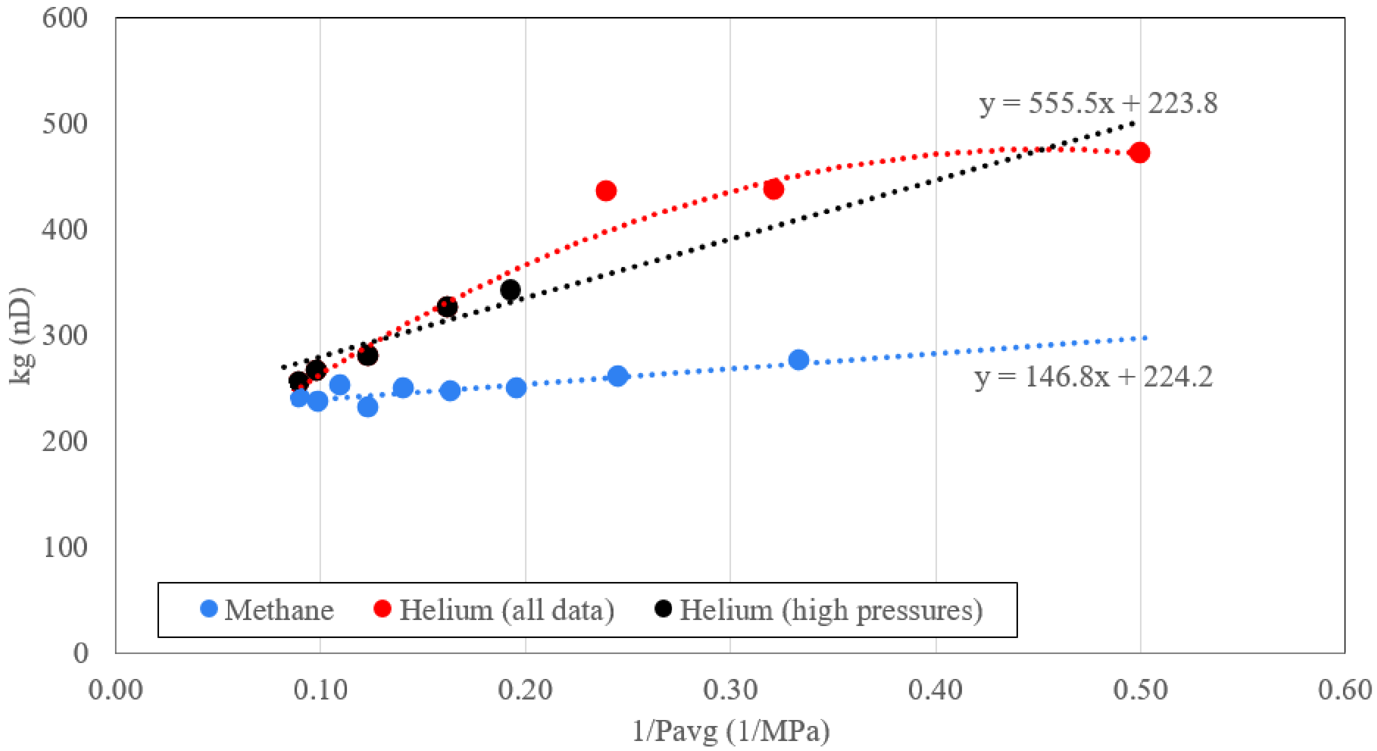


Table 2 - Results for intrinsic permeability and slip factor		
Symbol	Methane	Helium
kl **(nD)**	224.2	223.8
b **(MPa)**	0.65	2.5

Conclusions and Recommendations

- Commonly used assumption that gas slippage can be neglected at pore pressure higher than 7 MPa is not always accurate. The measurements were so affected by slippage that a tendency of effective stress effect could not be determined.

- Permeability is significantly enhanced at low pore pressures due to slippage effects.

- The best model for correcting permeability due to slippage depends on the predominant flow regime, which may be diagnosed by calculation of the Knudsen number. Klinkenberg model should only be applied when the slip-flow is present.

- Adsorption and molecular sieving effect of the fine pore structure contribute to the difference between permeability values for methane and helium.

- For future works, we recommend measurements of the rock pore compressibility to validate if this is a possible cause for the anomalous behavior. We also suggest measurements and calculation of the adsorption factor for a more accurate value of permeability.

Thank you!