Laboratory Measurements of Matrix Permeability and Slippage-enhanced Permeability in Gas Shales*

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Abstract

We are conducting laboratory experiments on gas shales samples examining the effects of confining stress, pore pressure and pore fluid type on permeability. Experiments were carried out on intact core plugs from the Eagle Ford, Haynesville, Marcellus, Montney and Barnett shale reservoirs. We developed a methodology to separate the decrease of permeability with increasing effective stress (the difference between hydrostatic confining pressure and pore pressure) and the increase of permeability at very low pore pressure due to molecular slippage effects. These effects are also known as Knudsen diffusion or Klinkenberg effects. In addition, by isolating the Klinkenberg effect we are able to estimate the effective size of the flow paths within each sample. Our measurements show that the permeability of the rock is significantly enhanced at low pore pressures (<1000 psi) due to slippage effects. Preliminary results suggest the effective flow paths of the samples investigated are on the order of tens of nanometers to about 100 nanometers in a high-permeability sample. These results are in close agreements with pore size estimates from SEM images. From the magnitude of the Klinkenberg gas slippage effect, an effective Knudsen diffusivity was also calculated. These estimates can be used in reservoir simulation to more accurately predict the long-time production behavior of these shales. Finally, the relative contribution of Knudsen Diffusion to total flow is calculated. We show that the contribution is likely to be negligible at initial reservoir pressures, but becomes increasingly more important as flowing pressure declines

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Sondergeld, C.H., K.E. Newsham, T.E. Comisky, M.C. Rice, and C.S. Rai, 2010, Petrophysical considerations in evaluating and producing shale gas resources: SPE-131768, SPE Unconventional Gas Conference, Pittsburgh, Pennsylvania, February 23-25, 2010.

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STANFORD UNIVERSITY
GEOPHYSICS
SCHOOL OF EARTH SCIENCES

talk outline

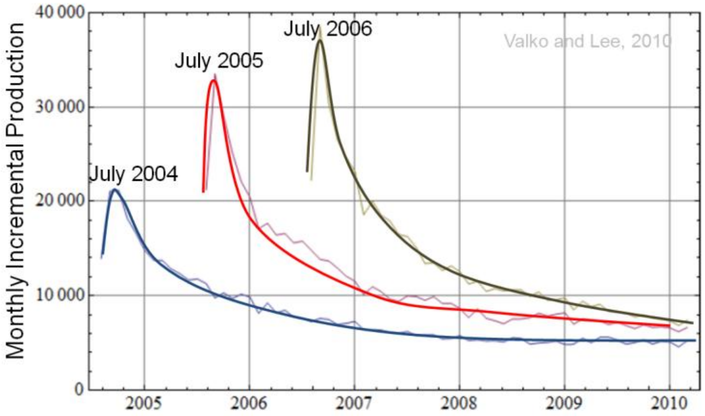
- Research motivation and background

- Laboratory apparatus and procedure

- Results
    - Permeability effective stress law (6 samples)
    - Magnitude of the Klinkenberg effect (3 samples)
    - Pore width estimates (3 samples)
    - Relative contribution of diffusion and Darcy flow (3 samples)

- Summary and conclusions

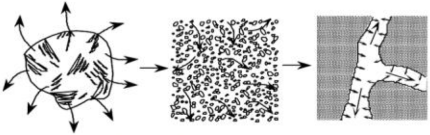
research motivation: flat production tails?



- ☐ Monthly incremental production from groups of wells drilled in the Barnett Shale in 2004, 2005 and 2006
- ☐ Production peaks higher due to better completions methods and technology
- ☐ All curves exhibit similar production tails, characterized by relatively flat, plateau-like production

research motivation: matrix permeability

Conceptual model for flow in gas shales

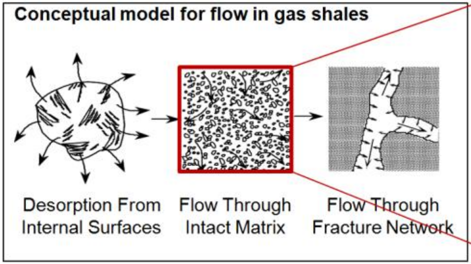


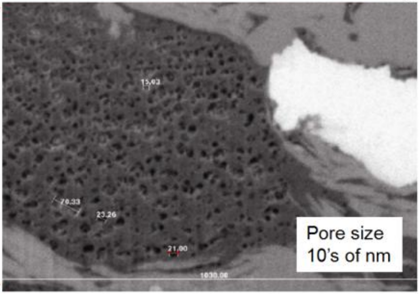
Desorption From Internal Surfaces | Flow Through Intact Matrix | Flow Through Fracture Network

- Multiple scales of porosity and permeability exist, all potentially evolving with time during production
- This study focuses specifically on flow through the matrix

research motivation: matrix permeability

Conceptual model for flow in gas shales





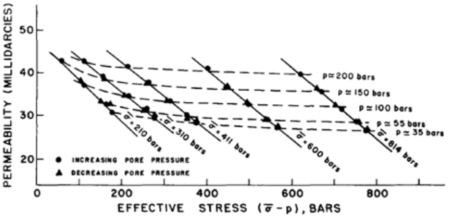
Pore size 10's of nm

Image from Sondergeld, et al. 2010

1. How does matrix permeability evolve during production?
    - Stress effects
    - Flow regime effects

matrix permeability influenced by:

Stress Effects



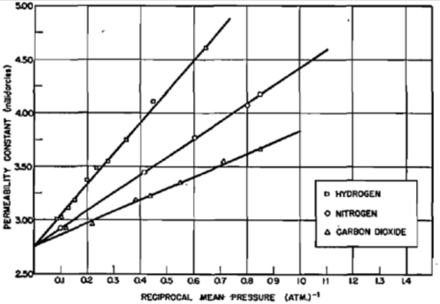
Zoback and Byerlee, 1975

- At a given pore pressure, permeability decreases with confining stress
- At a given confining stress, permeability increases with pore pressure

$$k(\sigma_{eff})$$

$$\sigma_{eff} = C_p - xP_p$$

Flow Regime Effects



Klinkenberg, 1941

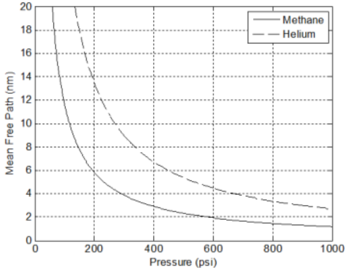
- Apparent increase in permeability at low pore pressure due to gas slippage

$$k_a = k_0\left[1 + \frac{b_k}{p}\right]$$

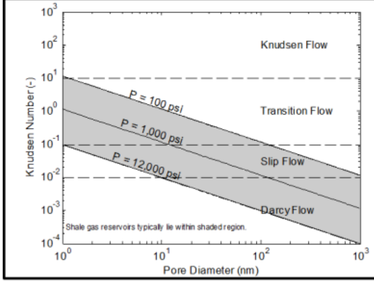
Presenter's notes: Under steady state and laminar flow condition, Klinkenberg demonstrated that the permeability to gases is approximately a linear function of the reciprocal pressure.

However, Klinkenberg's formulation ignores the transition flow region, where neither molecule-molecule nor molecule-wall interactions can be neglected because both are playing relevant roles.

Under what conditions is slip flow important?



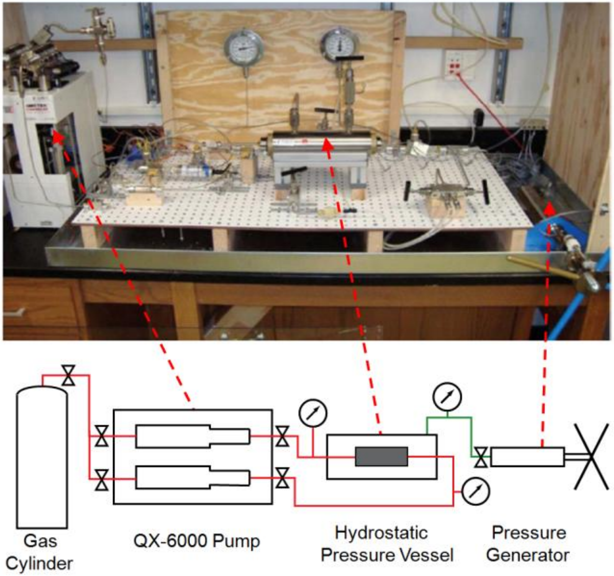
- As pore pressure decreases, distance between molecular collisions (mean free path) increases



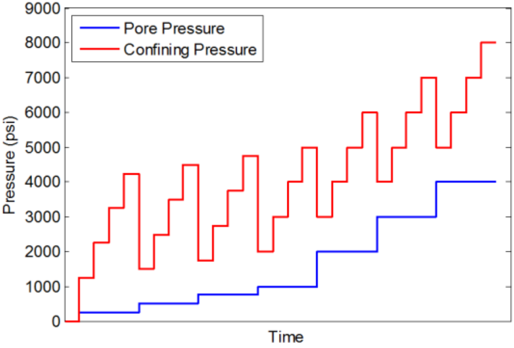
- For a given pore size, as pressure decreases, ratio of mean free path to pore size (Knudsen number) increases

- At low Knudsen numbers, other transport mechanisms become increasingly more important

permeability system setup



sequence of confining pressure and pore pressure steps



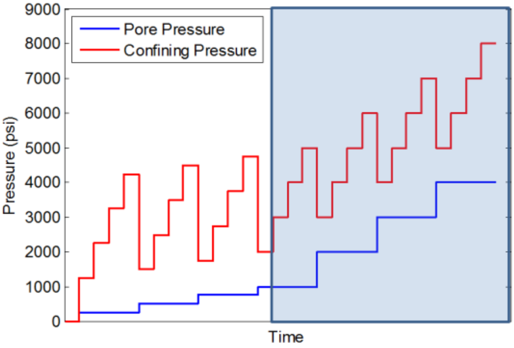
- Covered broad range of confining pressure (Cp) and pore pressure (Pp) steps

$$k(\sigma_{eff})$$

$$\sigma_{eff} = C_p - xP_p$$

Presenter's notes: Techniques to formalize an effective stress law for low permeability rocks have been well established. Chi determines the relative sensitivity of permeability to changes in confining pressure and pore pressure.

sequence of confining pressure and pore pressure steps



- ☐ Covered broad range of confining pressure (Cp) and pore pressure (Pp) steps
- ☐ Measure permeability of 6 shales samples within this range and fit data to an effective stress law

$$k(\sigma_{eff})$$

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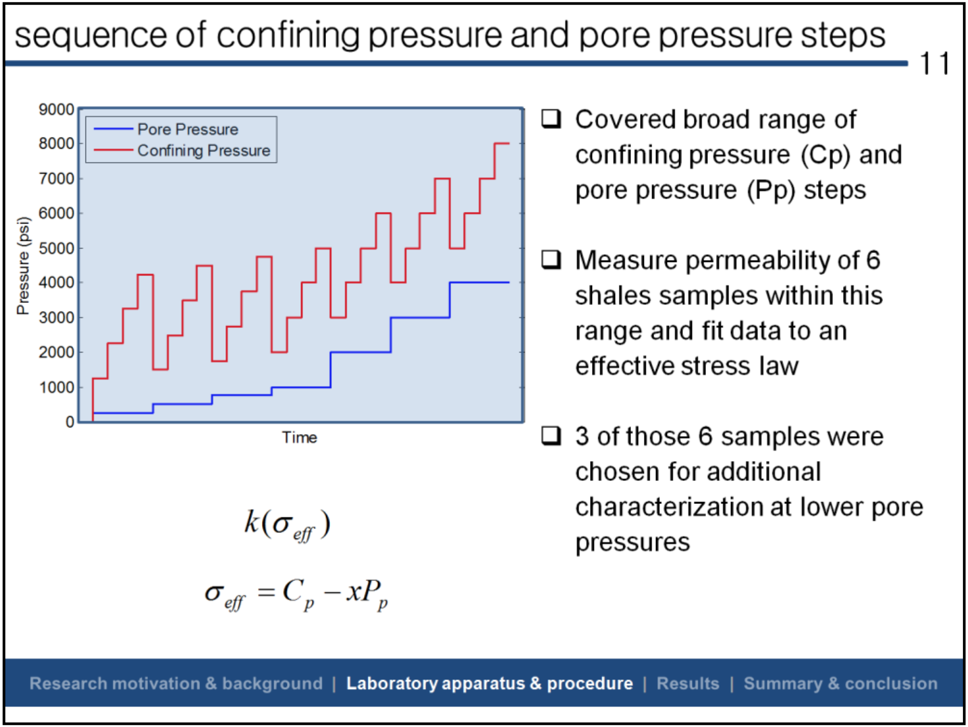

sequence of confining pressure and pore pressure steps

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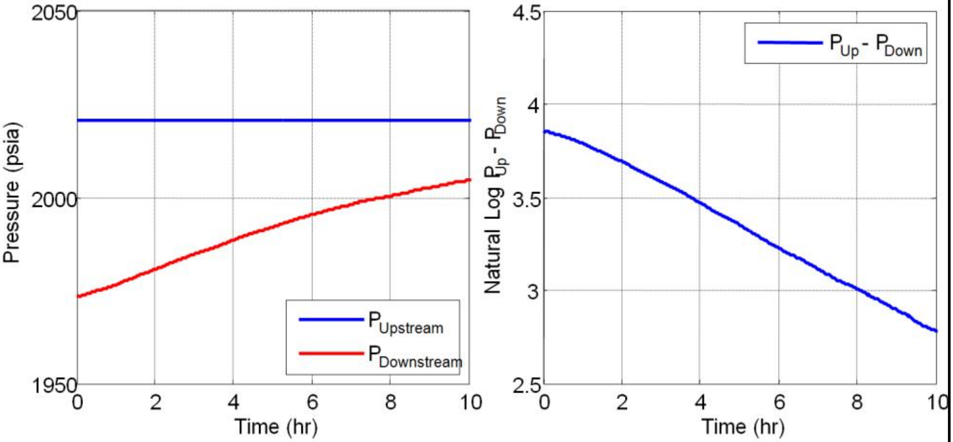
- ☐ Covered broad range of confining pressure (Cp) and pore pressure (Pp) steps
- ☐ Measure permeability of 6 shales samples within this range and fit data to an effective stress law
- ☐ 3 of those 6 samples were chosen for additional characterization at lower pore pressures

Presenter’s notes: Techniques to formalize an effective stress law for low permeability rocks have been well established. Chi determines the relative sensitivity of permeability to changes in confining pressure and pore pressure.

pulse permeability method

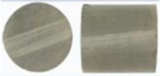


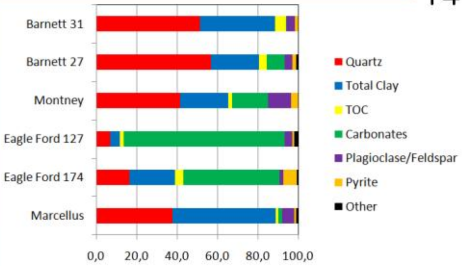
$$\left.\begin{aligned}\Delta P(t) &= \Delta P_0 e^{-\alpha t} \\ \alpha &= \frac{kA}{\beta V_{down} L \mu}\end{aligned}\right\}\text{Brace et al., 1968}$$

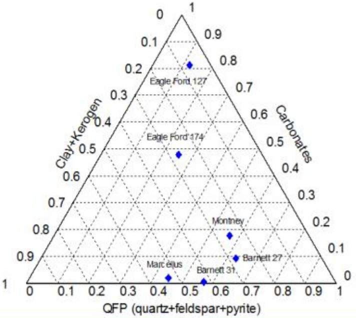
experimental notes

- Samples were subjected to a hydrostatic stress of 6000 psi for 48-72 hours prior to each experiment
- 2 data points/day ➔ ~60 points per experiment ➔ ~1 month/sample
- Significant effort to minimize system leaks were made, including:
  - Fitting adjustment
  - Infinite upstream volume boundary condition
  - Relatively large downstream volume to minimize loss of pressure from leaks
- Measurement repeatability was monitored

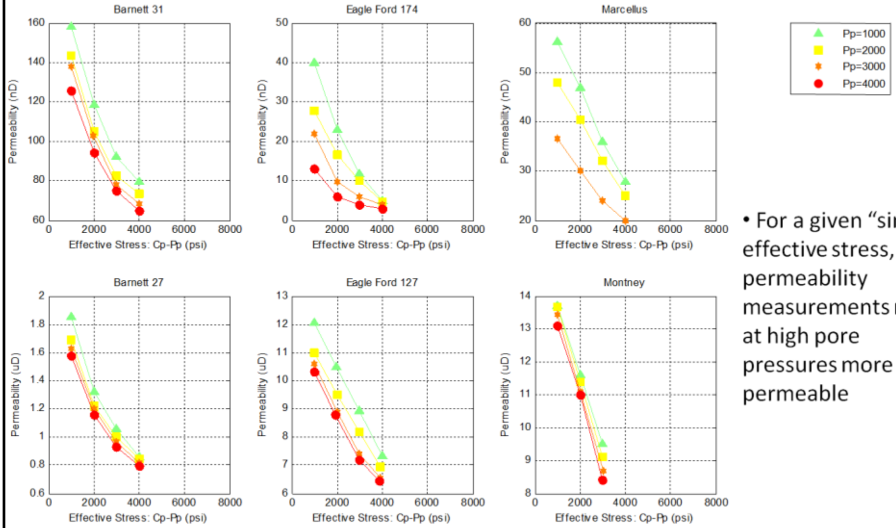
summary of samples measured

Sample	Photo	Perm Range (nD)
Barnett 31		**60-160**
Barnett 27		**800-1800**
Montney		**1000-5000**
Eagle Ford 127		**1500-3500**
Eagle Ford 174		**5-90**
Marcellus		**20-180**



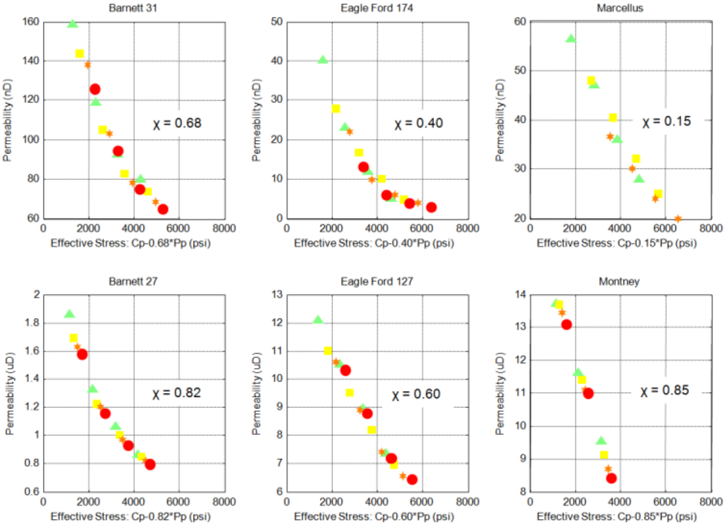


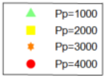
permeability vs. Cp – Pp



- For a given “simple” effective stress, permeability measurements made at high pore pressures more permeable

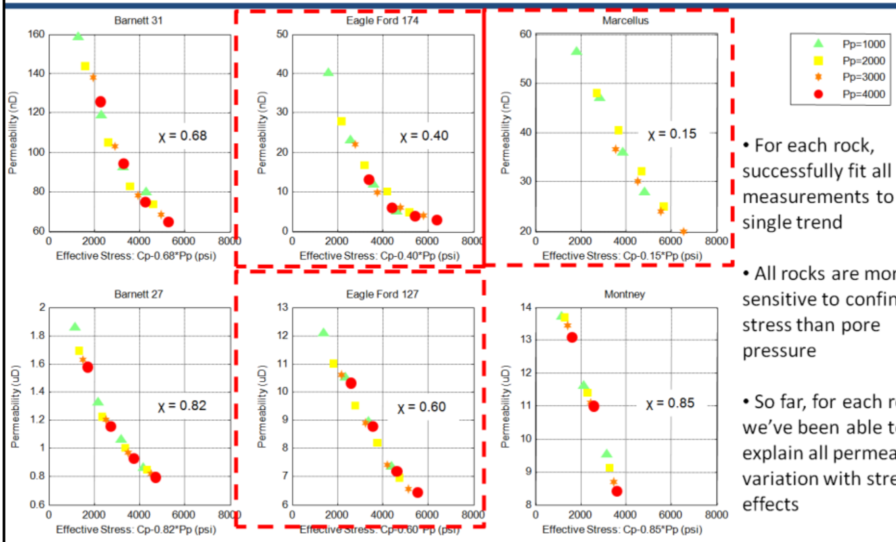
permeability vs. Cp – χ Pp





- For each rock, successfully fit all measurements to a single trend
- All rocks are more sensitive to confining stress than pore pressure
- So far, for each rock, we've been able to explain all permeability variation with stress effects
- What about lower pore pressures?

permeability vs. Cp – χ Pp



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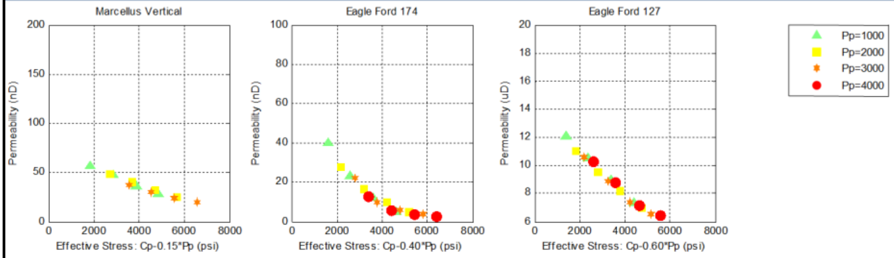
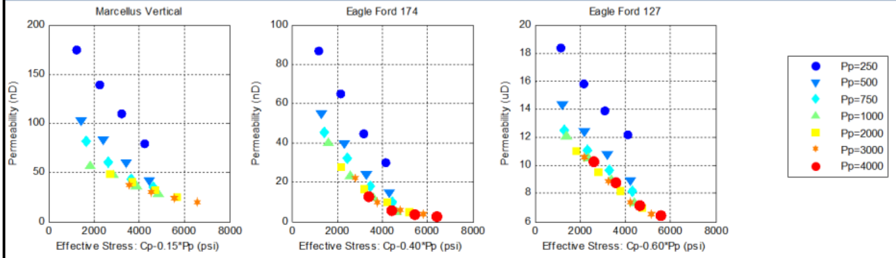
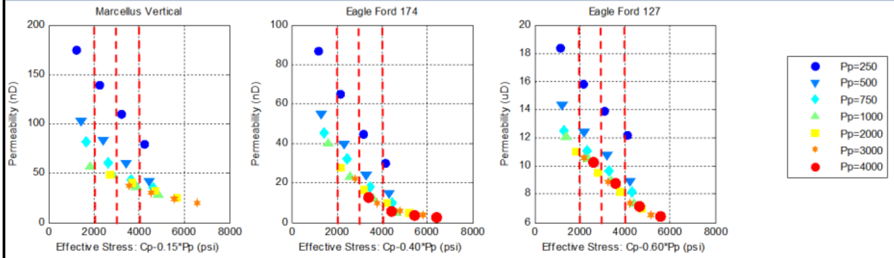
permeability vs. $Cp - \chi Pp$



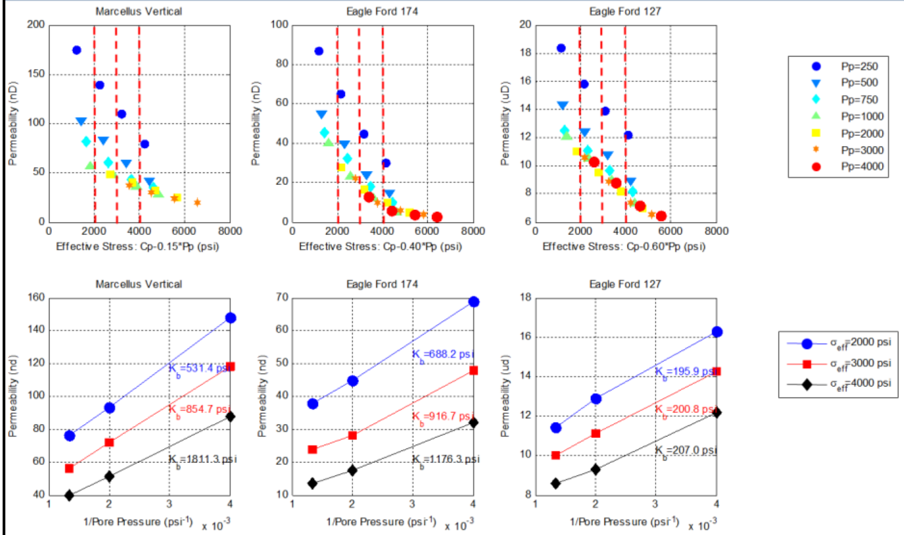
permeability vs. Cp – χPp



permeability vs. Cp – χPp



permeability vs. Cp – χPp



effective pore size from Klinkenberg slope

Assumptions:

- Total mass flow is sum of viscous (Darcy) flow and Knudsen/slip flow
- Slit shaped pore geometry
- Model viscous flow using Poiseuille equation

$$Q = \frac{w^3 P}{12 \mu L} \Delta P + c \frac{4}{3\rho} \left(\frac{2M}{\pi R T} \right)^{1/2} \frac{w^2}{L} \Delta P$$

$$Q = \frac{kA}{\mu L} \Delta P$$

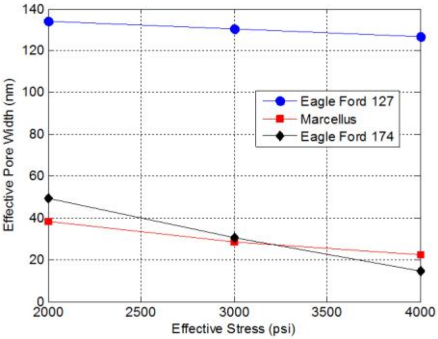
$$k = \frac{w^3}{12A} \left[1 + \frac{16 c \mu}{w \overline{P}} \left(\frac{2RT}{\pi M} \right)^{1/2} \right]$$

$$k_a = k_0 \left[1 + \frac{b_k}{p} \right]$$

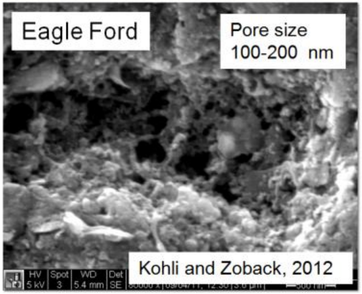
$$k_b = \frac{16 c \mu}{w} \left(\frac{2RT}{\pi M} \right)^{1/2}$$

$$\boxed{w = \frac{16 c \mu}{k_b} \left(\frac{2RT}{\pi M} \right)^{1/2}}$$

effective pore size vs. effective stress



- Pore width decreases with increasing effective stress
- Pore widths range from 20-40nm in Marcellus samples, ~130nm in Eagle Ford
- Klinkenberg pore sizes consistent with SEM images


Eagle Ford

Pore size
100-200 nm

Kohli and Zoback, 2012

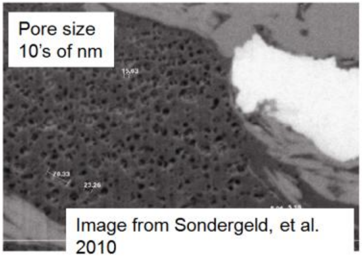
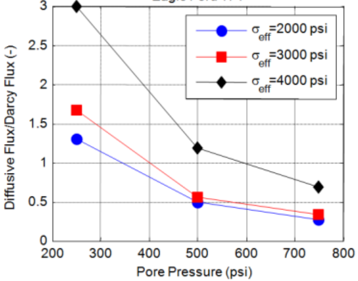
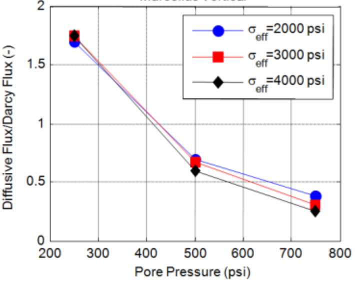

Pore size
10's of nm

Image from Sondergeld, et al. 2010

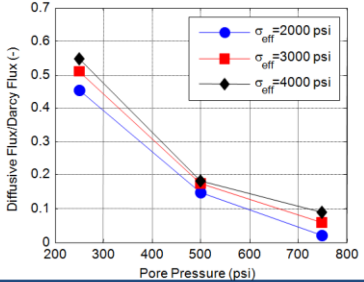
To what extent does Knudsen diffusion contribute to flow?



Eagle Ford 174



Marcellus Vertical



Eagle Ford 127

- Diffusive flow contributes appreciably to total flow at pore pressures < 800 psi
- Diffusive flow is sometimes more important than Darcy flow at pore pressure < 500 psi
- As we increase effective stress for a given pore pressure, we narrow the pore aperture and the relative contribution of diffusion decreases

summary of what has been presented:

1. Measured permeability over a wide range of pore pressure/confining pressure combinations
2. Determined permeability-effective stress law using measurements made at high pore pressures
3. Plotted permeability vs. effective stress for all data; low pore pressures deviated from trend ➔ created Klinkenberg plot for three effective stresses
4. Used magnitude of Klinkenberg effect to interpret effective pore widths and estimate contribution of slip flow relative to Darcy flow

conclusions

☐ Permeability and effective stress:
  - $\chi < 1$, indicating that samples are more sensitive to changes in confining stress than pore pressure

☐ Klinkenberg effect:
  - Gas slippage seems to enhance permeability at low pore pressure
  - Effective pore widths are estimated to be 10-150nm, consistent with SEM images
  - At low pore pressures, Knudsen diffusion (or “slip flow”) becomes increasingly more important, in some cases surpassing Darcy flow

acknowledgements

- ☐ Financial support from RPSEA and DOE
- ☐ Samples donated from ConocoPhillips and BP

Thank you!