Measurements of Gas Permeability and Diffusivity of Tight Reservoir Rocks: Different Approaches and Their Applications*

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Abstract

Knowledge of the pore structure of gas shales and other micro-porous rocks is of critical importance in establishing the original gas in place and flow characteristics of the rock matrix. Methods of measuring pore volume, pore size distribution, sorptive capacity, and flow characteristics of shales inherited from the coalbed methane and conventional reservoir rock analyses, although widely applied, are of limited value in characterizing many shales and may yield erroneous results. The use of He as routinely applied to measure porosity, permeability, and diffusivity may result in non-systematic errors due to the molecular sieving effect of the fine pore structure to larger molecules such as reservoir gases. Utilizing gases with larger adsorption potentials than He, including nitrogen and all reservoir gases, to measure porosity or permeability of rocks with high surface area is a viable alternative, but requires correction for adsorption in the analyses.

We expand on several approaches to measure permeability and diffusivity with consideration of gas adsorption, which has not been explicitly considered in previous studies. Our new models explicitly correct for adsorption during pulse decay measurements of core under reservoir conditions, as well as on crushed samples used to approximate permeability or diffusivity. We also present a method to determine permeability or diffusivity from data captured during core desorption as carried out during coal or shale desorption analyses for gas in place determinations. Our new approach utilizes late-time data from experimental pressure decay data, which we show to be more reliable and theoretically (and practically) more accurate than the early-time approach commonly used to estimate gas transport properties.

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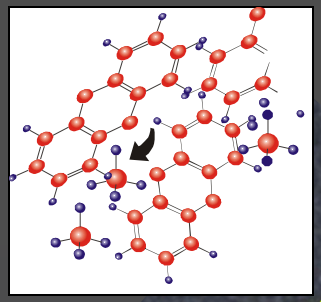
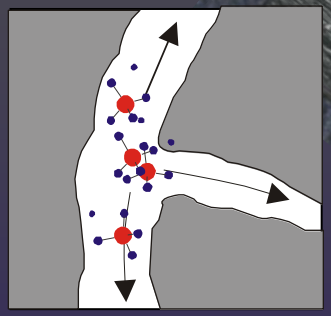
(Geofluids, 2009)

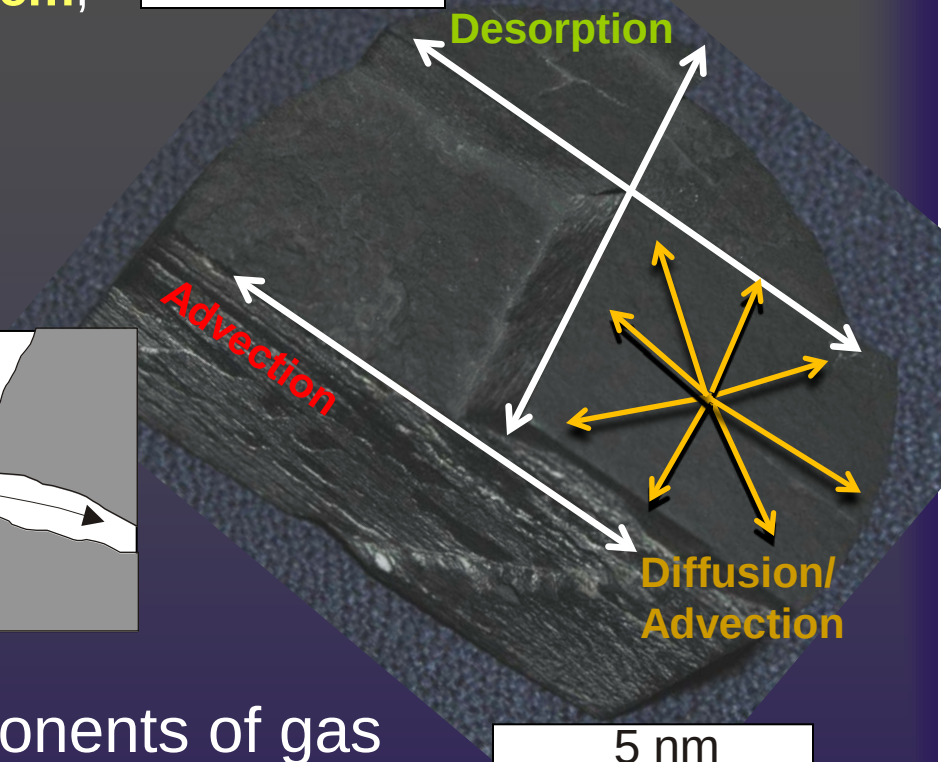
Gas Transport

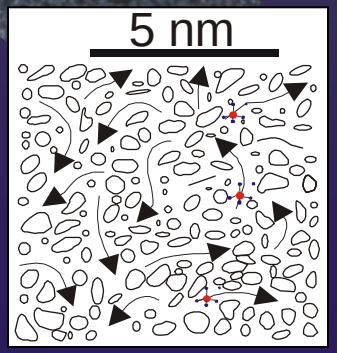
- Results from numerical simulations show that for **$k_m \leq 1\ \ 10^{-5}$ md** and/or **a > 10 cm**, the production limited by:
  - Fracture flow
    - Darcy's law; permeability k
  - Matrix flux
    - Darcy's flow k_m
    - Diffusion k_d
  - Fracture spacing

(Bustin et al. in prep)









- measurement of different components of gas flow critical as input for reservoir simulation

Gas transport- Theoretical Background

- Advection
  - Darcy's law
  - Pressure primary unknown
- Diffusion
  - Flick's law
  - Gas density primary unknown

$$\phi\frac{\partial\rho}{\partial t}+(1-\phi)\frac{\partial q}{\partial t}=\frac{1}{r^m}\frac{\partial}{\partial r}\left(r^m\frac{\rho k}{\mu}\frac{\partial p}{\partial r}\right)$$

$$\phi\frac{\partial\rho}{\partial t}+(1-\phi)\frac{\partial q}{\partial t}=\frac{1}{r^m}\frac{\partial}{\partial r}\left(r^m\phi k_d\frac{\partial\rho}{\partial r}\right)$$

$$\frac{\partial p}{\partial t}=\frac{K}{r^m}\frac{\partial}{\partial r}\left(r^m\frac{\partial p}{\partial r}\right)$$

Assume small p or ρ changes

$$\frac{\partial\rho}{\partial t}=\frac{K_d}{r^m}\frac{\partial}{\partial r}\left(r^m\frac{\partial\rho}{\partial r}\right)$$

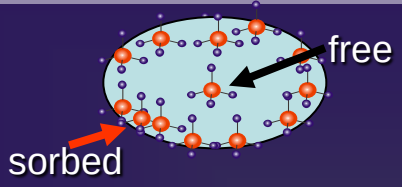
$$K=\frac{k}{\mu c_g[\phi+(1-\phi)K_a]}$$

$$k_d=\frac{k}{\phi\mu c_g}$$

$$K_d=\frac{\phi k_d}{[\phi+(1-\phi)K_a]}$$

$$K_a=\frac{\partial q}{\partial\rho}$$

$K_a > 0$ for adsorptive fluids perm/diffusivity will be underestimated if adsorption effects are not considered



Change in ϕ_a due to Adsorption

microporous rocks - high gas adsorption
gas in liquid-like state - higher density than compressed
kerogen- high adsorptive capacity

adsorption results in increase in total gas capacity:

$$f_a = \frac{\phi_a}{\phi}$$

effective porosity due to gas sorption

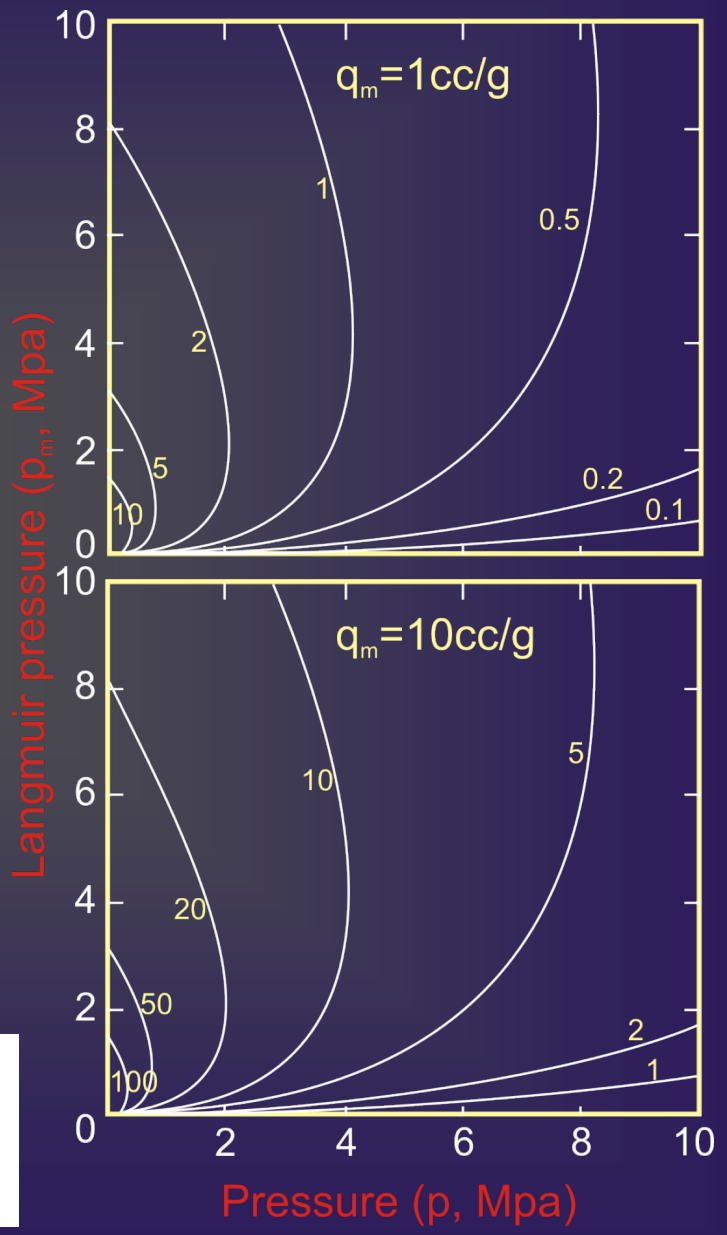
$$\phi_a = (1-\phi)K_a$$

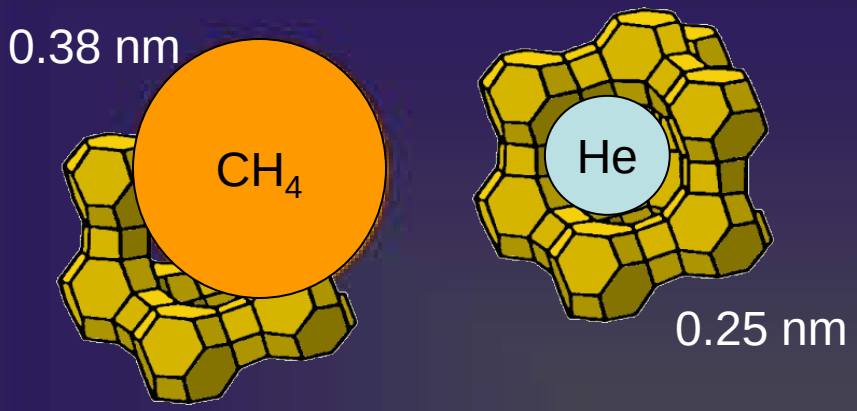
assume gas adsorption follows Langmuir isotherm

$$\phi_a = \frac{\rho_s}{V_{std}} \frac{(1-\phi)}{c_g \rho} \frac{q_L p_L}{(p_L + p)^2}$$

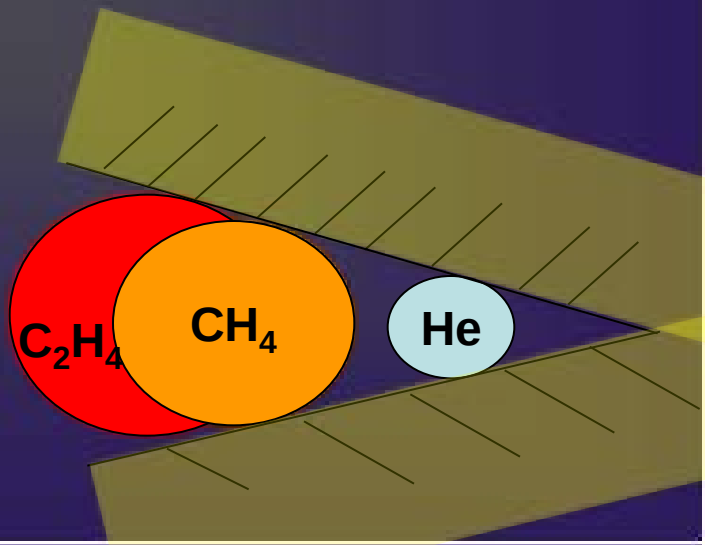
$\therefore$ k_m/k_d depend on the adsorption isotherm and experimental pressure

Even for a weakly adsorptive system, adsorption imposes significant influence on gas transport and thus perm/diffusivity measurements





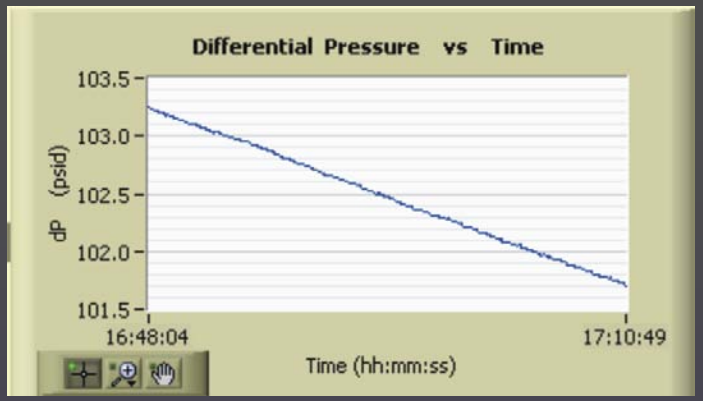
- using He to measure perm/diffusivity, porosity, density results in molecular-sieving
- micropores have unique transport properties for different gases so measurements are specific to individual gases
- correct for adsorption



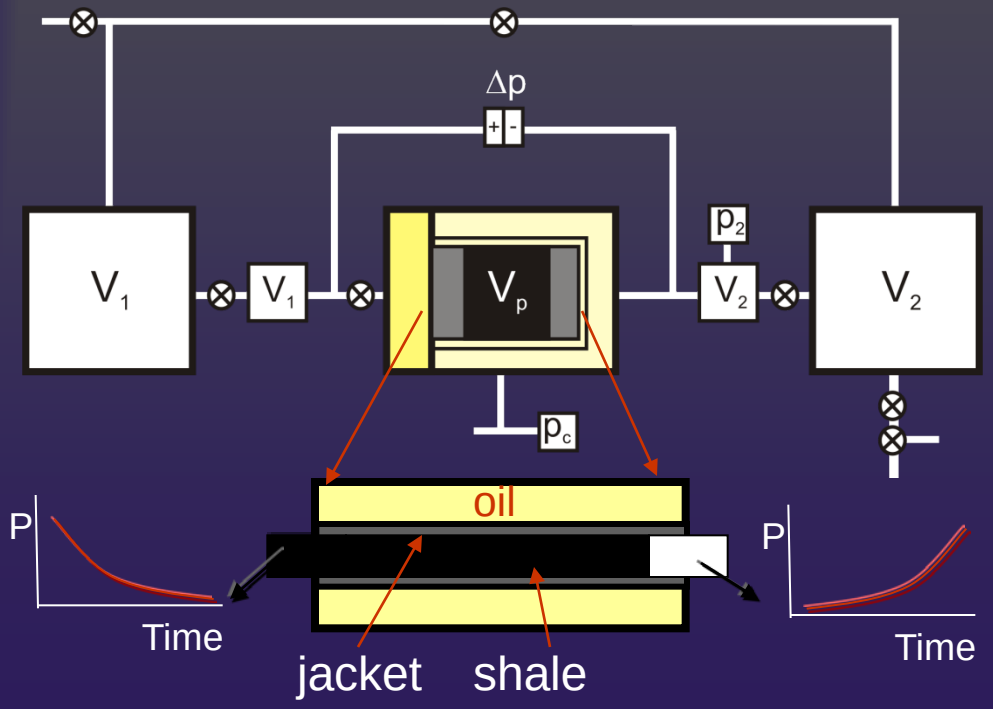
Laboratory Permeability

- cores
  - confined under reservoir conditions
  - pulse decay
    - extend existing method to measure effective permeability /diffusivity of adsorptive gases
- crushed samples
  - unconfined
    - gas-expansion technique
      - use late-time data
    - onsite drill-core desorption tests
      - use late-time data
- mercury intrusion curves
  - unconfined

Pulse-Decay Technique



- Hoek cell
- p transient analysis of pulse
- increasing confining P
- k varies 10 orders of magnitude

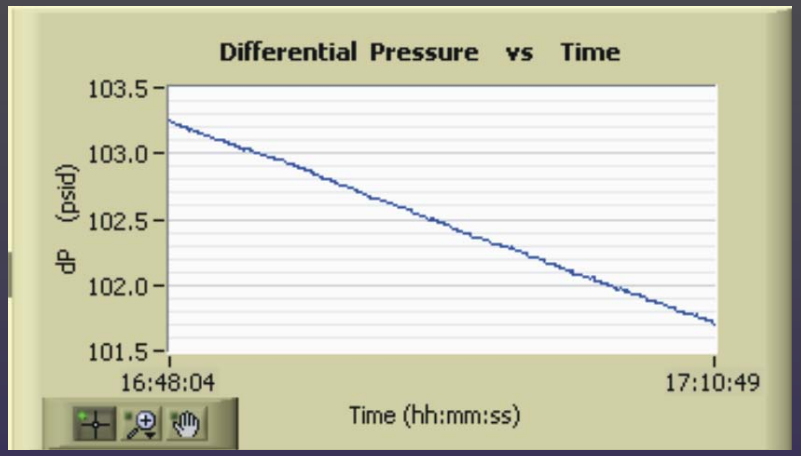


Pulse-Decay Technique

- Δp_d is a single exponential function of time assuming
  - experiment only involves small \pP
  - late-time

$$\ln(\Delta p_d) = \ln(f_0) + s_1 t$$

Plot ln(Δpd) vs time to get slope, s1



$$k = \frac{-s_1 \mu L c_g}{f_1 A\left(1/V_u + 1/V_d\right)}$$

$$f_1 = \frac{\theta_1^2}{a+b}$$

$$\tan\theta = \frac{(a+b)\theta}{\theta^2 - ab}$$

- $f_a = 0$ if no adsorption occurs
- a + b become same ratios previously defined

$$a = \frac{V_p(1+f_a)}{V_u}$$

$$b = \frac{V_p(1+f_a)}{V_d}$$

Pulse-Decay Adsorption Effects

- numerically simulate pulse-decay experiment with pre-specified k
  - FEM
  - calculate k from numerical data using lab approach

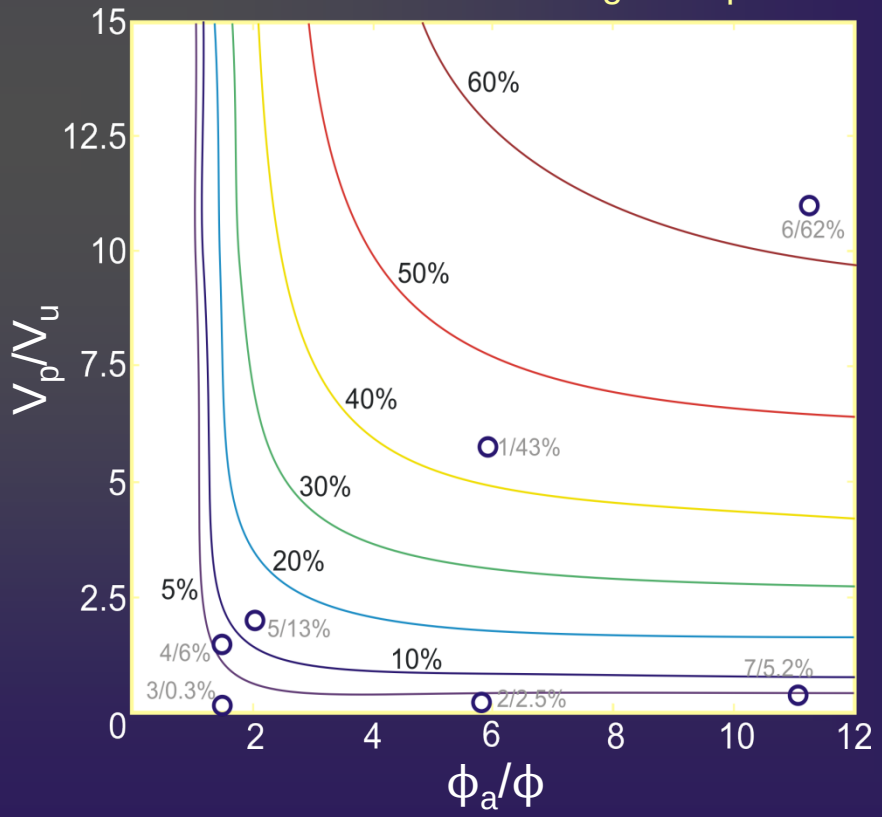
- relative errors < 0.031% for k determined with consideration of adsorption
- underestimation of k if adsorption ignored depends on experimental setup and adsorption isotherm

It is necessary to consider adsorption effects in order to accurately determine perm with the pulse-decay technique

$V_p/V_u < 1$ or $\phi_a/\phi \leq 1 \rightarrow$ underestimation of perm < 10%

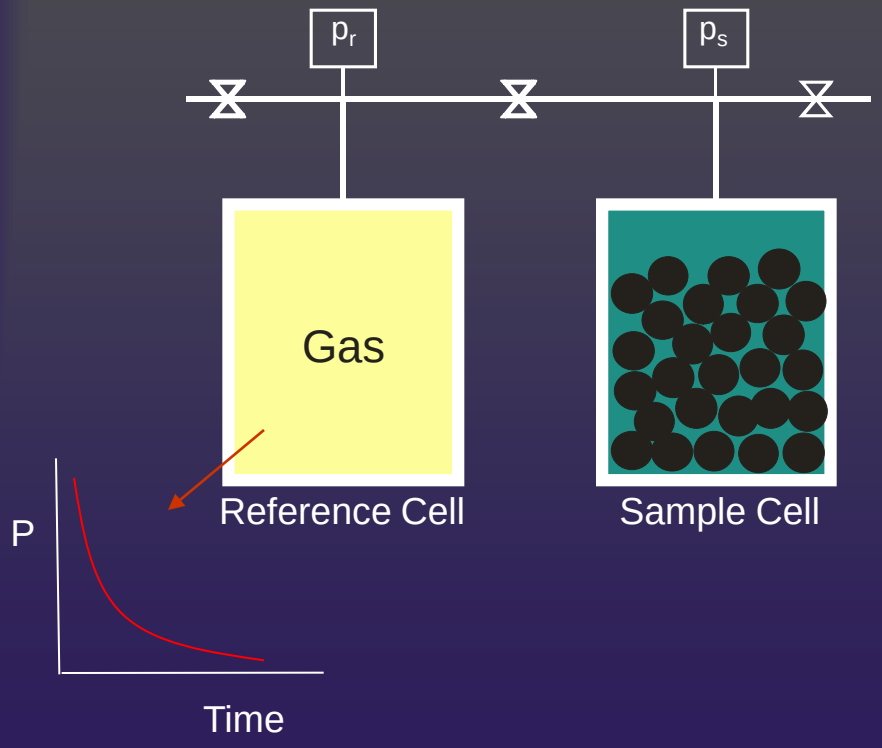
V_p/V_u and/or $\phi_a/\phi > 2 \rightarrow$ significant perm underestimation

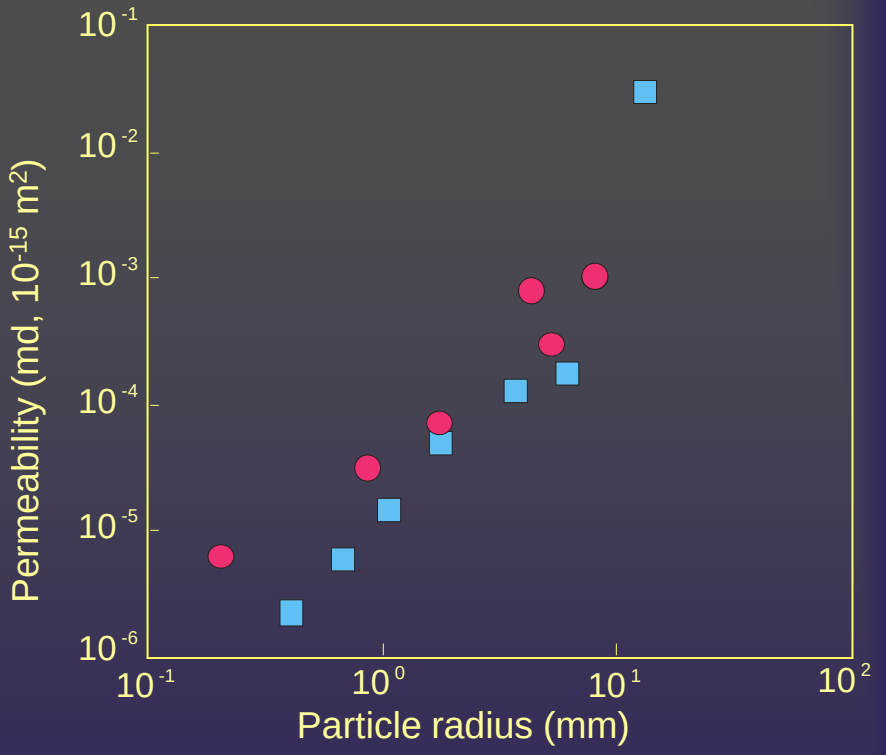
>60% for low P and strong adsorption



Laboratory Permeability on Crushed Samples

- Pressure decay during gas expansion
  - pycnometer
  - crushed samples
    - unconfined – pore compressibility
    - k strongly dependent on particle size





Gas-Expansion Technique Late-Time

Residual gas fraction theoretically given as:

$$F_R = 6K_c(K_c+1)\sum_{n=1}^{\infty} e^{-K\alpha_n^2 t/R_a^2}\frac{1}{K_c^2\alpha_n^2 + 9(K_c+1)}$$

$$K_c = \frac{\rho_b V_c}{M[\phi + (1-\phi)K_a]}$$

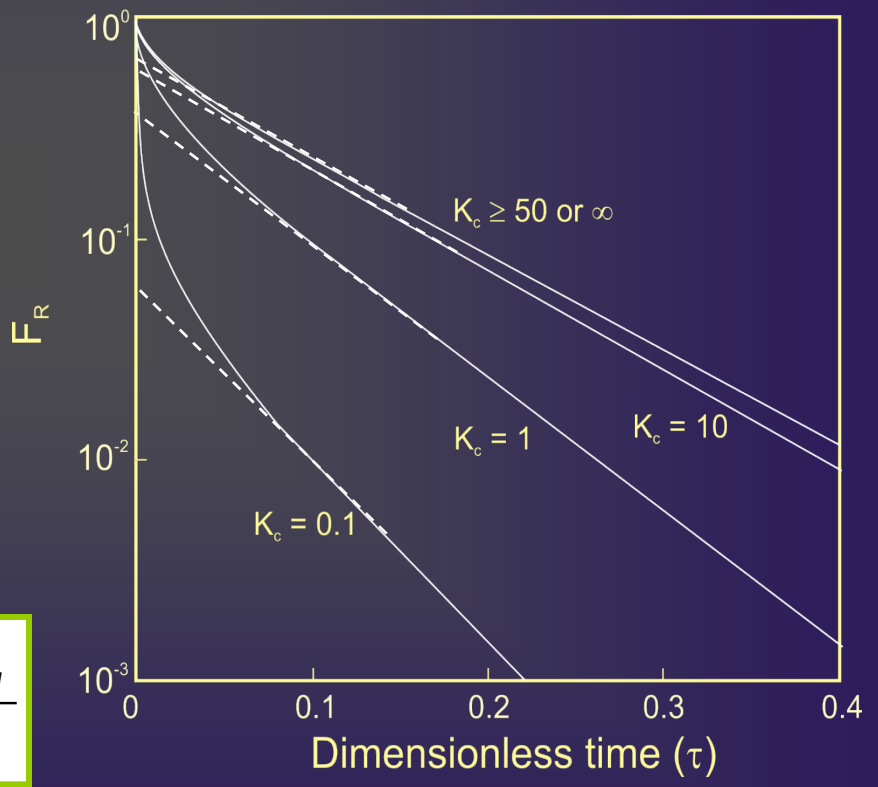
- Mass fraction of gas in V_c that will eventually be taken up by sample particles relative to the total gas that can be taken up by samples
  - Calculated from experimental data
  - particles ~spherical with R_a
  - small experimental p change

- Late-Time
  - Log F_R becomes a linear function of τ for wide range of K_c and $\tau > 0.1$

$$\ln(F_R) = f_0 + s_1 t$$

$$k = \frac{R_a^2[\phi + (1-\phi)K_a]s_1\mu c_g}{\alpha_1^2}$$

$$\tan\alpha = \frac{3\alpha}{3 + K_c\alpha^2}$$



Gas-Expansion Technique Early Time

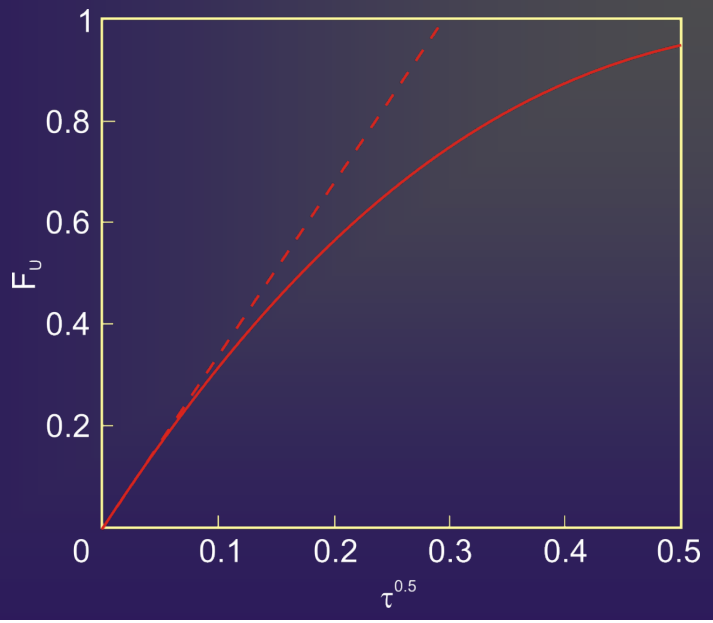
Cumulative gas uptake approximated as:

$$F_U = 1 - F_R = \frac{6\sqrt{K}}{\sqrt{\pi R_a^2}}\sqrt{t}$$

$$k = \frac{\pi R_a^2 \left[\phi + (1-\phi)\right] s_1^2 \mu c_g}{36}$$

- Ratio of the gas that has entered the sample particles to the total gas that eventually will be taken up by the sample

- Early-Time
  - F_U becomes a linear function of $\tau^{1/2}$



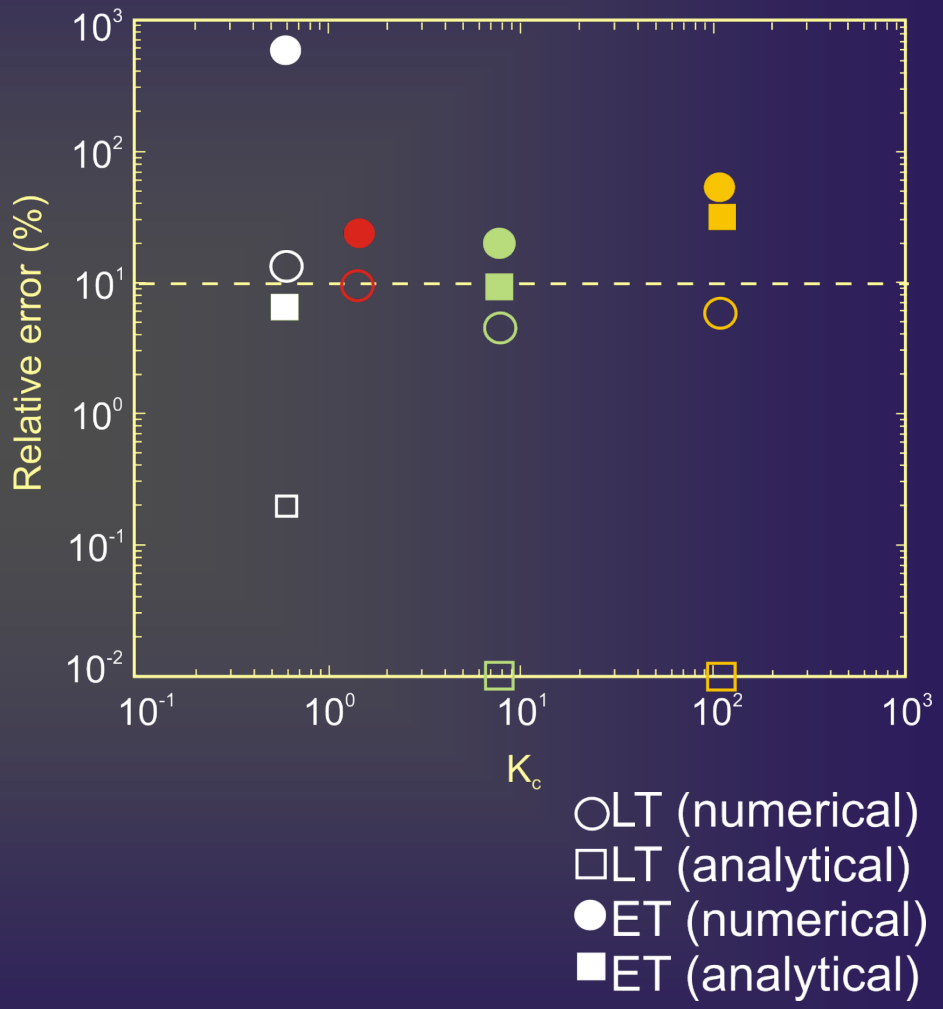
- Only valid for early-time when K_c is large
- Poor quality initial p data
  - Large Δp between V_c and V_p
    - Very rapid gas uptake
  - Fast-penetration into/through macropores first (overestimation)

Late-time technique preferred method based on theoretical analysis

Late Time vs Early Time

- numerically simulate pycnometer experiments with pre-specified k
  - Using both late-time and early-time
- analytical data calculated with constant K_c

- late-time errors systematically lower than early-time errors
  - late-time < 10% for numerical data
  - early-time > 10% even with exact analytical data



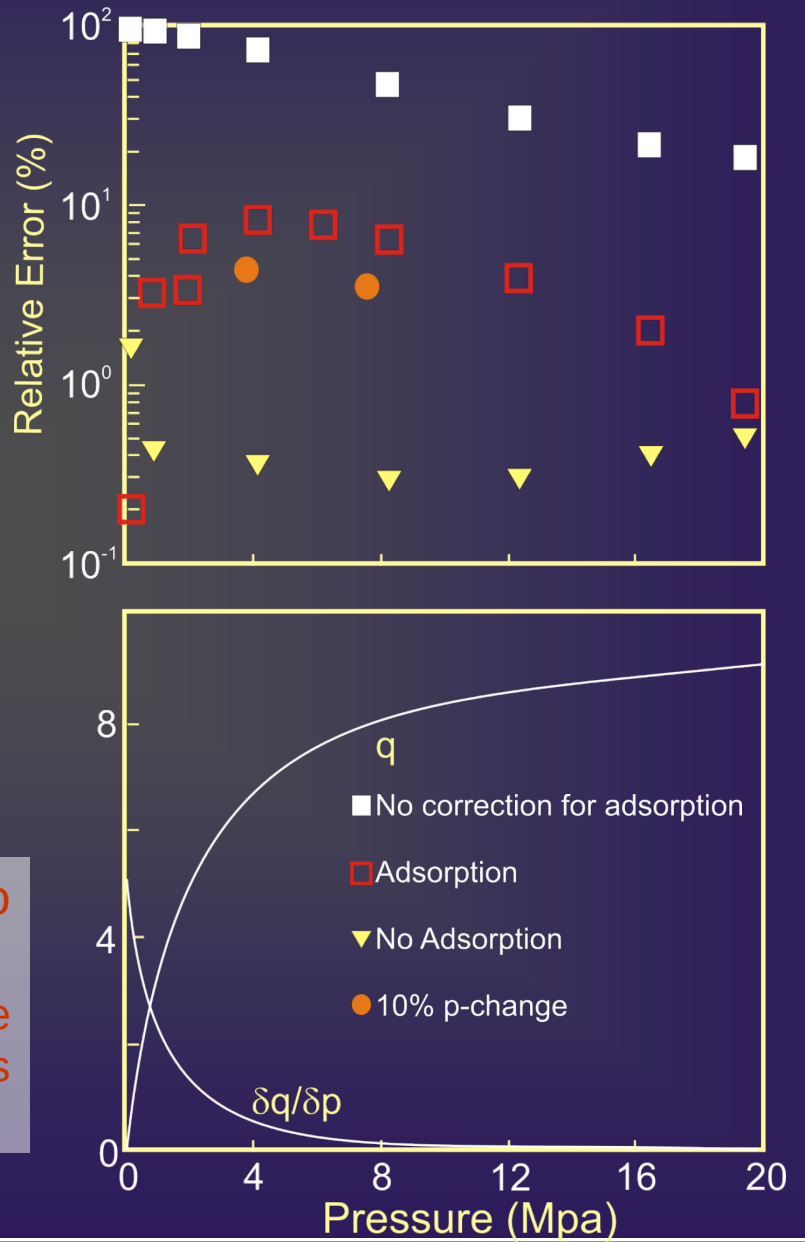
Gas Expansion Adsorption Effects

- numerically simulate pycnometer experiments using CH_4

- without adsorption
  - model errors < 0.5%
  - largest error ~2% at very low p
- with adsorption
  - model errors change systematically with p
  - max ~8% at 4MPa
  - related to adsorption isotherm + δq/δp
    - largest curvature relates to largest model errors
- without consideration of adsorption
  - > 20% at high p
  - 100% at low p

larger errors for adsorptive cases due to strong p-dependence of adsorption

can be reduced by half - p change limited to 10% (smaller changes in fluid properties)



Canister Desorption

desorbed gas fraction, F_d analytically approximated by assuming 1D radial flow out of an ∞-long cylinder

- fraction of cumulative desorbed gas relative to total gas to be desorbed

- Late-Time
  - F_D can be fitted by $\ln(1-F_D) = f_0 + s_1 t$

$$k = \frac{R_a^2\left[\phi + (1-\phi)K_a\right]s_1 \mu c_g}{\xi_1^2}$$

- Early-Time
  - F_D linear function of can be fitted by $\tau^{1/2}$

$$F_D = s_1\sqrt{t}$$

$$k = \frac{R_a^2\left[\phi + (1-\phi)K_a\right]s_1 \mu c_g}{\xi_1^2}$$

Not as accurate because of nature of samples and measurements

Summary

- Use main component of gas reservoirs to measure the permeability/diffusivity
  - Molecular-sieving effect
  - Measurements specific to individual gases
  - Impact of adsorption must be considered
- Pulse-Decay on whole cores under confined pressure preferred
- Late-time technique on crushed samples during pycnometer and canister desorption

Current and Future Work