Capillary Pressure Properties of Mesaverde Group Low-Permeability Sandstones in Six Basins, Western U.S.

Alan P. Byrnes  
(KGS- now Chesapeake Energy)  
Robert M. Cluff  
John C. Webb  
(The Discovery Group Inc)  

(KGS Student Research Assts.)  
Daniel S. Osburn  
Andrew Knoderer  
Owen Metheny  
Troy Hommertzheim  
Joshua Byrnes  

The Discovery Group, Inc.  
http://www.kgs.ku.edu/mesaverde  
US DOE # DE-FC26-05NT42660
US DOE Project Summary

• Solicitation DE-PS26-04NT42072-0
  – subtopic area 1: Understanding Tight Gas Resources
  – Award Date: October 1, 2005
  – Completion Date: June 30, 2008
  – Contract # DE-FC26-05NT42660
• Organization: University of Kansas, Kansas Geological Survey
• Principal Investigator: Alan P. Byrnes, KGS
• KGS-Discovery Group, Inc. co-participants
• DOE share $411,030 (80%)
• Industry share $102,804 (20%)
Objectives

• The project will provide petrophysical tools that address:
  – 1) minimum gas flow, critical and residual gas saturation, \( S_{gc} = f(\text{lithofacies, } P_c, \text{architecture}) \)
  – 2) capillary pressure, \( P_c = f(P) \), \( P_c = f(\text{lithofacies, } k, \phi, \text{architecture}) \)
  – 3) electrical properties, \( m^* \)
  – 4) facies and upscaling issues
  – 5) wireline log interpretation algorithms
  – 6) providing a web-accessible database of advanced rock properties.
Sampling

- 44 wells/6 basins
- Describe ~7000 ft core
- 2200 core samples
- 120-400 advanced properties samples
Sampled across wide range of lithofacies
Sampled over wide range of porosity and permeability

$\text{In situ}$ calc Porosity (%) vs. Klinkenberg Permeability (4,000 psi, mD)

- Green River
- Piceance
- Powder River
- Uintah
- Washakie
- Wind River

LogK = 0.3$\Phi$ - 3.7
LogK = 0.3$\Phi$ - 5.7
Capillary Pressure in Uniformly Variable Capillary

- \( P_c = 2\tau \cos\theta/r \)

- \( P_c \) = capillary pressure
- \( \tau \) = interfacial tension
- \( \theta \) = contact angle
- \( r \) = pore radius

(after Lake, 2005)
Mercury Capillary Pressure

(after Jennings, 1981)
Depth

Pressure

Buoyancy pressure

$$(\rho_w - \rho_o)h$$

Hydrostatic gradient

Pressure

Cp

Zones with lower porosity & permeability

Zones with higher porosity & permeability

FREE WATER LEVEL (FWL)

0 Water saturation 100%

100% Oil saturation 0

(after Doveton, 1999)
Capillary Pressure Equations

- \[ P_c = \frac{2\tau \cos\theta}{r} \]
- \[ r = \frac{2\tau \cos\theta}{P_c} \]

where:
- \( P_c \) = capillary pressure
- \( \tau \) = interfacial tension
- \( \theta \) = contact angle
- \( r \) = pore radius

- \[ H = \frac{P_{c_{\text{res}}}}{(\sigma_{\text{brine}} - \sigma_{\text{oil,gas}}) \times 0.433} \]
- \[ P_{c_{\text{res}}} = P_{c_{\text{air-Hg}}} \frac{\tau \cos\theta_{\text{res}}}{\tau \cos\theta_{\text{air-hg}}} \]

*after Wright and Woody, 1955*
Capillary Pressure Measurement

- Three different air-Hg measurements
  - Unconfined (n=150)
  - In situ
    - Drainage-imbibition (n=37)
    - Drainage only (n=90)
    - NES = 4000 psi
Unconfined Capillary Pressure

- Capillary Pressure Varies with Lithofacies and associated pore size distribution and permeability
Pc Normalization - Leverett J function

- $J(S_w) = C \frac{Pc}{k/\phi}^{0.5}/\tau\cos\theta$
  - $J = $ dimensionless Pc function, function of $Sw$
  - $C = $ conversion constant = 0.2166
  - $Pc = $ capillary pressure (psi)
  - $\tau\cos\theta = $ interfacial tension (dyne/cm) X cosine of the contact angle (degrees)
  - $k = $ permeability (md)
  - $\phi = $ porosity (fraction)
Normalization: Leverett J Function

- J function works poorly for mixed lithofacies and between basins
- Does work OK for single lithofacies in a small area
Normalization: Brooks-Corey Capillary Pressure

- Transform taking logarithm of $P_c$ and $S_w$
- $\lambda$ represents pore throat size distribution
- Standard unimodal curves can be reduced to intercept ($P_{ce} = $ extrapolated threshold entry) and slope ($\lambda$)
Stress effect on Pc

- no significant difference in high-low pairs at high K
- increasing Pce separation with decreasing K
- merging of curves at 35-50% Sw
  - smaller pores are in protected pore space
- users of Winland R35 need to adjust for confining stress
• threshold entry pressure is predictable from $\sqrt{K/\phi}$ at any confining pressure

• correct unconfined Pce to insitu Pce based on perm change with stress
Brooks-Corey Slope

Leverett $J(S_w) = P_c \left(\frac{k}{\phi}\right)^{0.5}/\tau \cos \theta$

Implicitly assumes $P_{c_{slope}} = \text{Constant}$

Poor fit because $P_{c_{slope}} \neq C = f(k, \text{lith})$

- PSD expressed by $P_{c_{slope}}$
- $P_{c_{slope}} = f(k)$
- $P_{c_{slope}} \downarrow \text{with } P \uparrow$

![Graph showing Brooks-Corey Capillary Pressure Slope vs. In situ Klinkenberg Permeability (mD)].

- $y = -0.0304 \ln(x) + 1.87$
  - $R^2 = 0.0216$

- $y = -0.037 \ln(x) + 1.256$
  - $R^2 = 0.052$
Modeled Pc Curves

Pc properties evolve over time as diagenesis changes porosity and pore architecture.
Drainge-Imbibition

- what is the residual trapped gas when a reservoir leaks or along a gas migration path?
Trapping increases with increasing initial saturation

(after Lake 2005)
Residual Gas Saturation

\[ C = 1/[(Snwr - Swi) - 1/(Snwi - Swi)] \]
\[ Snwr = 1/[C + 1/Snwi] \]

\[ C = 0.55 \text{ (min } \varepsilon \text{); } Swi = 0 \]

\[ \text{Land } C = 0.66, \text{ Swi} = 0 \]
\[ \text{Land } C = 0.54, \text{ Swi} = 0 \]
Residual gas saturation

- Trapping constant, C consistent with cemented sandstone
Conclusions

• Drainage capillary pressure (Pc) can be modeled using equations for threshold entry pressure (Pte) and Brooks-Corey $\lambda$ slopes.
• Confining pressure decreases largest pores consistent with permeability decrease but has little influence on smaller pores (pores largely protected by matrix)
• $S_{nwr} \uparrow$ with $S_{nwi} \uparrow$ Land-type relation: $S_{nwr} = 1/[0.55 + 1/S_{nwi}]$
• Mesaverde Project website is http://www.kgs.ku.edu/mesaverde