Lithofacies and petrophysical properties of Mesaverde tight-gas sandstones in Western U.S. basins

Alan P. Byrnes  
KGS- now Chesapeake Energy

John C. Webb  
Robert M. Cluff  
Daniel A. Krygowski  
Stefani D. Whittaker  
The Discovery Group, Inc

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Organizations
- University of Kansas Center for Research, Inc.
- Kansas Geological Survey, Lawrence, KS
- The Discovery Group Inc., Denver, CO

Principal Investigator: Alan P. Byrnes, KGS

project website is
http://www.kgs.ku.edu/mesaverde
Project objectives

- investigate minimum gas flow, critical and residual gas saturation, $S_{gc} = f(\text{lithofacies, } P_c, \text{architecture})$
- investigate capillary pressure, $P_c = f(P)$, $P_c = f(\text{lithofacies, } k, \phi, \text{architecture})$
- investigate electrical properties, $m = f(\phi, \text{salinity})$
- characterize lithofacies and upscaling issues
- develop advanced wireline log interpretation algorithms
- providing a web-accessible database of advanced rock properties
- this is the last of our overview presentations – from here on they will be topic specific deep dives.........
Sampling

- systematic characterization of Kmv lithofacies over entire Rocky Mtn region
- 44 wells/6 basins
- Described 7000 ft core (digital)
- 2200 core samples
- 120-400 advanced properties samples
Digital Core Description

- To provide lithologic input to equations and predict lithology from logs used 5 digit system
  - 1 basic type (Ss, Ls, coal)
  - 2 grain size/sorting/texture
  - 3 consolidation
  - 4 sedimentary structure
  - 5 cement mineralogy

- Property continuum - not mnemonic or substitution cipher

- Similar to system used in 1994 and subsequent studies
Core description

- rock typing at 0.5 ft frequency to match log data resolution
- lithology, color, grain size, sed structures
- sample locations
- important cements
- EOD
Porosity consists of poorly to moderately connected moldic and secondary intergranular mesopores and traces of pore-lining ML/IS(?) clay containing microporosity. Quartz cement is prominent, ferroan calcite is sparse. Pore-lining clay cement causes elevated Swi and reduced relative permeability.

Williams PA 424, 6148.8’ 15276
9.9%  2.66 g/cc  Ka=0.0237 mD
Porosity consists almost entirely of sparse, poorly connected, clay-filled intergranular microporosity.
Quartz cement is prominent, ferroan calcite is sparse.
Pore-filling clay cement causes elevated Swi and reduced relative permeability.

Williams PA 424, 4686.4’  15286
7.9%   2.65 g/cc  Ka=0.211 mD
Petrophysical property distributions are generally normal or log-normal.

Sub-distributions = \( f \) (basin, lithofacies, marine/non-marine, etc.)
Pore Volume Compressibility

- Previously documented in literature
- No large datasets in public domain
- 113 Samples
- Log-linear pore volume change seen in EVERY sample, avg. $R^2 = 0.99$
- Characteristic of cracks/sheet-pores
- Slope and intercept increase with increasing porosity
Stress dependence of permeability

- Known for many years that low-K sandstones are stress sensitive
- Generalized = \( f \left( P_{pore}, \text{Lith} \right) \)
- 1997 Byrnes equation:
  \[
  k_{ik} = 10^{\left[1.34 \left( \log k_{air} \right) - 0.6 \right] - 0.6
  \]
- This study:
  \[
  k_{ik} = 10^{\left[0.0088 \left( \log k_{air} \right)^3 - 0.072 \left( \log k_{air} \right)^2 + 1.37 \log k_{air} + 0.46 \right]}
  \]
- Statistically similar except for \( k > 1 \text{ mD} \)
- no meaningful stress dependence over 10 mD
Overall trend allows prediction of Kik from porosity with 10X error
Breaking into two subtrends at \( \phi \sim 12\% \) improves to 5X error
Different \( k-\phi \) trends among basins
Beyond common \( k \uparrow \) with grain size \( \uparrow \), lithologic influence changes are complex and nonlinear
Permeability vs Porosity

- \( \log k_{ik} = 0.234\phi_i + 0.12R^2 - 4.71 \) (±4X; \( \phi < 12\% \))
- \( \log k_{ik} = 0.265\phi_i + 0.11R^2 - 4.80 \) (±5X; 0<\( \phi < 24\% \))
- Artificial Neural Network ±3.3X
Capillary pressure

- investigating $P_c$ as $f(\text{lithology}, \phi, K)$
  - 120 high-low pairs
  - sampled across basins, permeability range, & lithology
- stress sensitivity of $P_c$
  - most MICP curves are run under laboratory conditions, but given stress dependence of permeability we expect $P_c$ to also be stress sensitive
- relationship between initial and residual non-wetting phase saturations ("scanning curves")
  - only published data are for conventional reservoir rocks
Stress effect on Pc

Stress effect on Pc is entirely predictable from \( \sqrt{K/\phi} \) ratio at any P
Residual Gas Saturation

- $S_{ni}$ and $S_{wr}$ are $\sim 0.5$ for $Sw > 80$
- e.g., for $S_{ni}$ of 30%, $S_{wr}$ is $\sim 50$

![Graph showing residual gas saturation](image-url)

- $C = 0.66$, $S_{ni} = 0$
- $C = 0.54$, $S_{ni} = 0$
Critical Gas Saturation

- Experimental work indicates $S_{gc} < 10\%$ often $< 5\%$

- **but** krg curves extrapolate to $35\% < S_{gc} < 0\%$

- **Issues**
  - little krg data at $Sw > 65\%$
  - two different ways to model the data, which is better?
Critical Nonwetting Phase Saturation

- Electrical conductivity and Pc inflection indicate 0% < Sgc < 22%
- Higher Sgc as bedding complexity increases
Sgc and percolation theory

- Critical gas saturation strongly controlled by sedimentary structures/rock fabric
- Any bedding parallel laminations result in low Sgc

Experimental results can be explained using four-pore network architecture models

1) Percolation Network ($N_p$) - Macroscopically homogeneous, random distribution of bond sizes, e.g., Simple Cubic Network ($z=6$)

2) Parallel Network ($N_p$) - Preferential orientation of pore sizes or beds of different $N_p$ networks parallel to the invasion direction.

3) Series network ($N_s$) - Preferential sample-spanning orientation of pore sizes or beds of different $N_s$ networks perpendicular to the invasion direction.

4) Discontinuous series network ($N_{sp}$) - Preferential non-sample-spanning orientation of pore sizes or beds of different $N_{sp}$ networks perpendicular to the invasion direction. Represents continuum between $N$ and $N_s$.

![Graph showing gas-water capillary pressure vs. water saturation for different permeabilities (0.001 md, 0.1 md)]
Archie porosity (cementation) exponent

- Nearly all cores exhibit some salinity dependence
- Tested plugs with 20K, 40K, 80K, and 200K ppm brines

![Graphs showing the relationship between Brine Conductivity, Core Conductivity, Brine Resistivity, and In situ Archie Cementation Exponent.](image)
Porosity dependence of “m”

- Empirical: \( m = 0.234 \ln \phi + 1.33 \)
- Dual porosity: \( m = \log\left[\left(\phi - \phi_2\right)^{m_1} + \phi_2^{m_2}\right]/\log \phi \)
  - \( \phi_2 = 0.35\% \) \( m_1=2, m_2=1; \) SE both = 0.11
  - rock behaves like a mixture of matrix porosity and cracks or fractures
- both models fit data

\[ \phi = \text{bulk porosity} \]
\[ \phi_2 = \text{fracture porosity} \]
\[ m_1 = \text{matrix cementation exponent} \]
\[ m_2 = \text{fracture cementation exponent} \]
Salinity dependence of “m”

- $m = a \ln \phi + b$
- $a, b = f(\text{salinity})$
- low porosity rocks hold more gas than we thought

\[ y = 0.2267\ln(x) + 2.2979 \quad R^2 = 0.6619 \]

\[ y = 0.2328\ln(x) + 2.409 \quad R^2 = 0.6547 \]

\[ y = 0.2149\ln(x) + 2.4354 \quad R^2 = 0.5132 \]

\[ y = 0.1621\ln(x) + 2.3222 \quad R^2 = 0.3633 \]
Log modeling

- ran a “basic” log analysis on every study well
  - total and effective porosity
  - optimize grain density, matrix values
  - Archie and Dual Water Sw using “standard” tight gas electrical parameters from earlier work
  - Timur equation absolute permeability estimate
- imported digital rock numbers, routine core data, KGS SCAL data, and converted all routine to *in situ* using standard equations
- Core data depth shifted using rock number curve
core rock number vs. GR

grain density

alternative porosity models

Kabs

Sw model
Advanced log modeling

- variable grain density model as $f(\text{lith})$
- improved permeability model
- improved Sw model, including variable $m$, $n$
- rock typing
  - really, really tough. May not be possible with conventional “triple combo” log suites
  - Looking at NMR, other options to improve predictability
- Work is still in progress
Conclusions

- Average grain density for 2200 samples is 2.654+0.033 g/cc (+1sd)
  - but grain density distributions differ slightly among basins & lithofacies.
- Pore volume compressibility shows a log-linear relationship characteristic of sheet like pores and cracks
- Stress dependence of permeability is consistent with prior work (Byrnes, 1997)
- Porosity-permeability data exhibit two subtrends with permeability prediction approaching 5X within each
  - Adding rock types or using an ANN model improves perm prediction to 3.3X – 4X
Capillary pressure ($P_c$) is stress sensitive as expected
- threshold entry pressure is entirely predictable from $\sqrt{K/\phi}$ at any confining pressure
- Minimal impact at low Sw’s (high capillary pressures)

Residual gas saturation increases with increasing initial gas saturation
- Land-type relation: $(1/S_{nwr})-(1/S_{nwi}) = 0.55$

Critical gas saturation is low ($S_{gc} < 0.05$) in laminated sandstones but tends to increase in rocks with more complex bedding
- Percolation theory provides a tool for predicting limits.
Archie porosity/cementation exponent (m) decreases with decreasing porosity below 10%
- Can predict using empirical or a dual-porosity model
- Little impact over 10-12% porosity (constant m)

Project completion within 70 days

Watch our website for new data – most project results will be posted this summer

Detailed topic-specific presentations begin in July.
Forthcoming presentations

- AAPG-Rocky Mtn Section meeting, Denver, July 9-11th
  - Cluff & Byrnes: Evidence for a variable Archie porosity exponent “m” and impact on saturation calculations
  - Webb et al: Lithofacies and petrophysical properties of Mesaverde tight-gas sandstones
  - Byrnes et al: Capillary pressure properties of Mesaverde Group low-permeability sandstones
Questions?