Evidence for a variable Archie porosity exponent “m” and impact on saturation calculations for Mesaverde tight gas sandstones: Piceance, Uinta, Green River, Wind River, and Powder River basins

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US DOE Project Summary

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

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- project website is [http://www.kgs.ku.edu/mesaverde](http://www.kgs.ku.edu/mesaverde)
Objectives of this task

- Characterize Mesaverde electrical properties as a function of porosity and salinity
  - Archie porosity (cementation) exponent “m”
  - Investigate behavior at low porosity end (<6%) not previously studied
  - Evaluate excess conductivity effects
- Methods to compute accurate Sw from logs
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
Permeability vs Porosity

- Samples collected over a wide range of porosity and permeability across 6 basins
- 0-24% porosity, spanning 1 nD to >100 mD
Archie’s equation

\[ S_w^n = \left( \frac{a}{\phi^m} \right) \times \left( \frac{R_w}{R_t} \right) \]

- completely empirical – no theoretical basis
- “m” is the porosity or cementation exponent
  - loosely related to tortuosity of the current flow path, better thought of as electrical efficiency of the path
- “n” is the saturation exponent
  - related to change in conductivity path with changing saturation
Archie porosity exponent

- for a simple bundle of capillary tubes oriented parallel to current flow direction: $m \to 1$
  - insensitive to cross section shape, so fractures act like capillary tubes
- as porosity increases and less of it participates in the conductive path, $m \uparrow$
- for an “average” sandstone comprised of spherical grains, $m \to 2$
Resistivity of a simple rock model

For rock with tortuous pores:

\[ F = \frac{R_o}{R_w} = \frac{1}{\phi^m} \]

(after Doveton, 2005)
Capillary tube model for m

Conductivity = \( C_w \)

\( m = 1 \)

Conductivity = \( C_w\phi \)

\( m > 1 \), ~2, > 2

Porosity

after Herrick & Kennedy, 1993, SPWLA Paper HH
Core measurement of the formation factor, $F$

Start with core plug saturated with brine of known $R_w$ & $\Phi$

then we measure $R_0$. $F = R_0/R_w$. 

A $R_w$

$\Phi$ $L$
When $F$ and $\phi$ are plotted log-log

\[ \log F = -m \log \phi \]
Observed porosity dependence of “m”

- Empirical: \( m = 0.676 \log \phi + 1.22 \)  \( R^2 = 0.63 \) (RMA)
- each salinity is different
  - 40Kppm dataset is largest and used for base case
  - cap m at 1.95

\[ y = 0.5377x + 1.3313 \]
\[ R^2 = 0.6331 \]
Dual porosity model

- \( m = \log[(\phi - \phi_2)^{m_1} + \phi_2^{m_2}]/\log \phi \)
  - \( \phi \) expressed as V/V
  - \( \phi_2 = 0.0035, m_1 = 2, m_2 = 1; \ SE \ both = 0.11 \)
  - rock behaves like a mixture of matrix porosity and cracks, with cracks dominating low porosity end
- cap at \( m = 1.95 \) (\( \phi \sim 16\% \))
- both models fit data

\( \phi = \) bulk porosity
\( \phi_2 = \) fracture porosity
\( m_1 = \) matrix cementation exponent
\( m_2 = \) fracture cementation exponent

![40K ppm brine data](image)
And a third way to look at it....

- Why is the minimum $m \sim 1.2$, instead of 1?
- $A$ – for a distribution of cracks of different cross-sectional area, the largest (widest) cracks will dominate the conductivity.
- The high tail of the distribution determines the bulk conductivity,
- while the rest of the cracks act like “excess” porosity that do not participate (significantly) in the conductivity.
- Therefore $m \uparrow$
And are the “cracks” all fractures?

- Probably not..............
- Slot-like pores oriented preferentially parallel to bedding also act like conductive cracks
- Thin parallel laminae of slightly coarser, more permeable sand will be crack-like
Salinity dependence of “m”

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

\[ n = 335 \]
All data, all salinities

In situ Porosity (%) vs. Archie Cementation Exponent (m, a=1)
Salinity dependence of “m”

- $m = a \log \phi + b$
- Intercept $b$ drops with decreasing salinity
- Slope is ~ constant

![Graphs showing the relationship between salinity and porosity for different salinity levels (20K ppm, 40K ppm, 80K ppm, 200K ppm).](image)
Simple procedure to compute $Sw$

- determine $Rw$ @ $Tf$ conventionally
  - Pickett plots – focus on the lower porosity, wetter sandstones
  - produced waters
  - your best guess

- convert $Rw$ to 75°F by chart lookup or Arps equation
Pickett Plot example

Rw = 0.306

pick m at low porosity end, where BVW_{irr} \sim BVW

Williams PA 424-34
Piceance basin
Kmv above “top gas”
Pickett plot

\[ R_w \text{ ohmm } @ 160^\circ F = 0.7 @ 75^\circ F \text{ (9K ppm)} \]
Our new procedure

- compute m at 40K ppm from RMA regression:
  \[ m_{40k} = 0.676 \log \phi + 1.22 \]
  e.g. for 10% \( \phi \): \( m = 0.676 + 1.22 = 1.896 \)
- correct m for salinity effect by
  \[ m = m_{40k} + (0.0118 \phi - 0.355) \cdot (\log R_w + 0.758) \]
  e.g. for 10% \( \phi \), \( R_w = 0.7 @ 75^\circ F \)
  \[ m = 1.896 + (-0.237 \cdot 0.603) = 1.753 \]
- cap m at 1.95 (~12% porosity)
Practical impact

- Nominally, most of us use an \( m \) close to 2, but usually slightly less, for tight gas sand evaluations (e.g. 1.85, 1.90)
- Variable \( m \) that DECREASES with decreasing porosity leads to lower \( S_w \)’s
- Therefore, there is more gas in the tight rocks than we thought.
- Above 10% porosity there is very little difference
Example: Low porosity, wet zone
“High” porosity gas zone

$m$ is HIGHER than base case, so $Sw$ is higher
30K ppm example, Wamsutter
Summary & Conclusions

- 335 Kmv samples run at multiple salinities
- Archie porosity exponent $m$ varies with
  - porosity: $m \downarrow$ as porosity $\downarrow$
  - salinity: $m \downarrow$ as salinity $\downarrow$
- Behavior is consistent with increasing electrical efficiency with decreasing porosity, whatever the pore scale architecture
variable m model can be implemented with a simple equation relating m to porosity and formation water salinity

- m is constant above ~12% porosity at 1.95
- lowering m at 5-12% $\phi$ increases GIP
- see no impact below ~5% porosity
  - $BVW_{irr}$ is typically 3-5%
  - no longer calculate Sw's $>> 1$
  - $Sw = 1$ at low $\phi$ validates $Rw$
Visit our project website

http://www.kgs.ku.edu/mesaverde

Questions?

The Discovery Group, Inc.