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

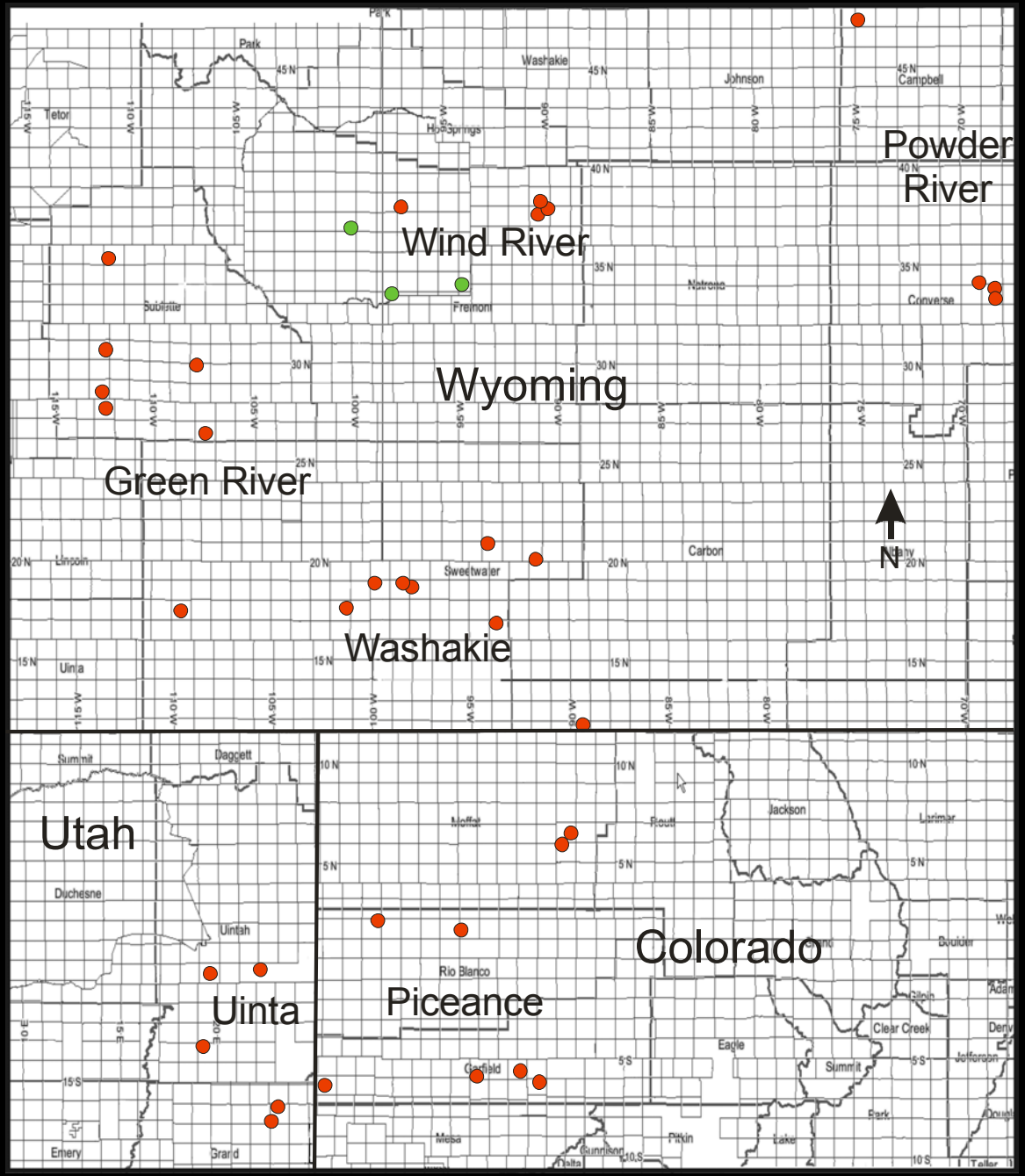
- DOE Contract # DE-FC26-05NT42660
  - completion date 30 June 2008
- Organizations
  - University of Kansas Center for Research, Inc.
  - Kansas Geological Survey, Lawrence, KS
  - The Discovery Group Inc., Denver, CO
- Principal Investigators: Alan P. Byrnes, KGS; Bob Cluff, Discovery Group
- project website is *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

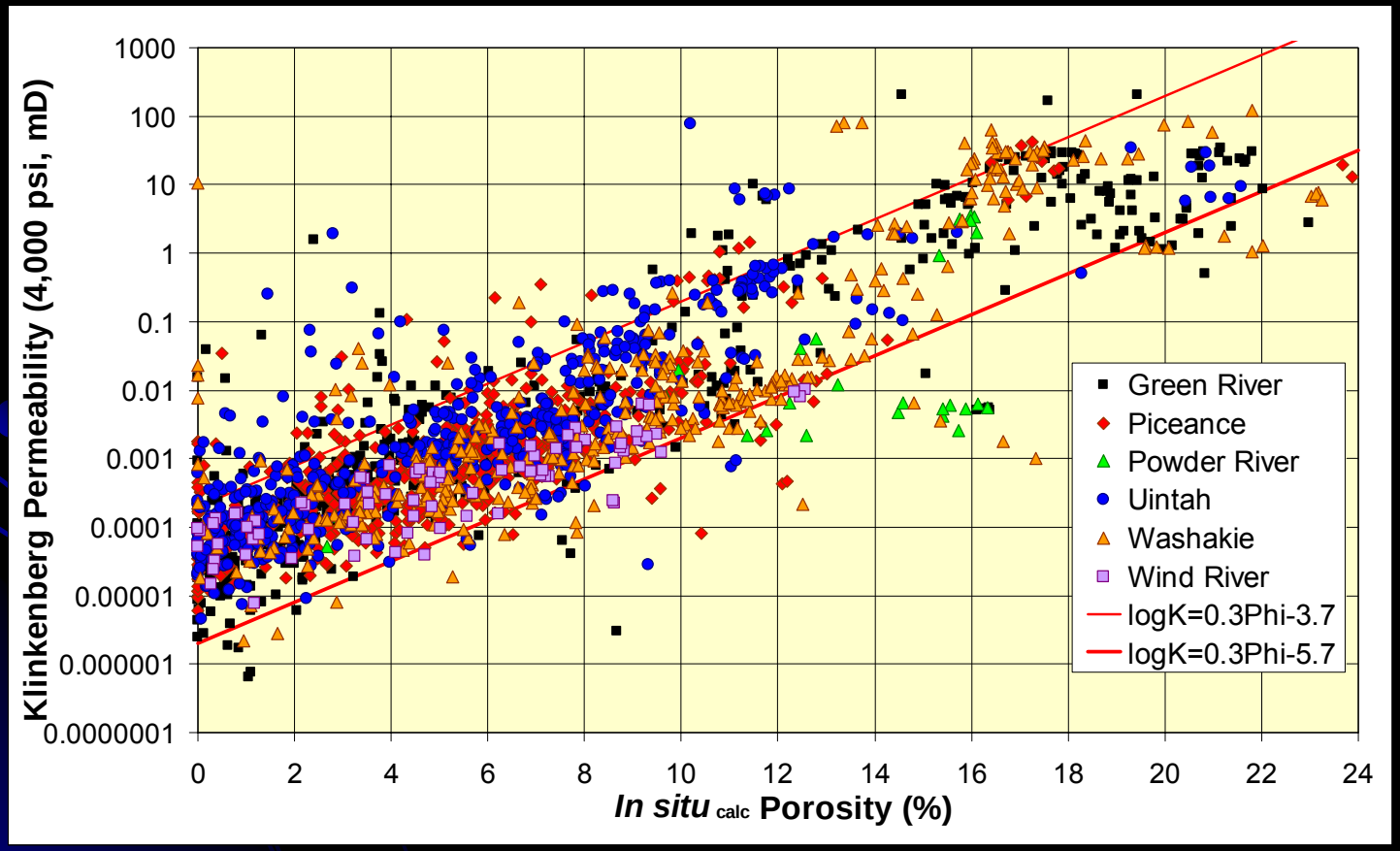
Sampling

- 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

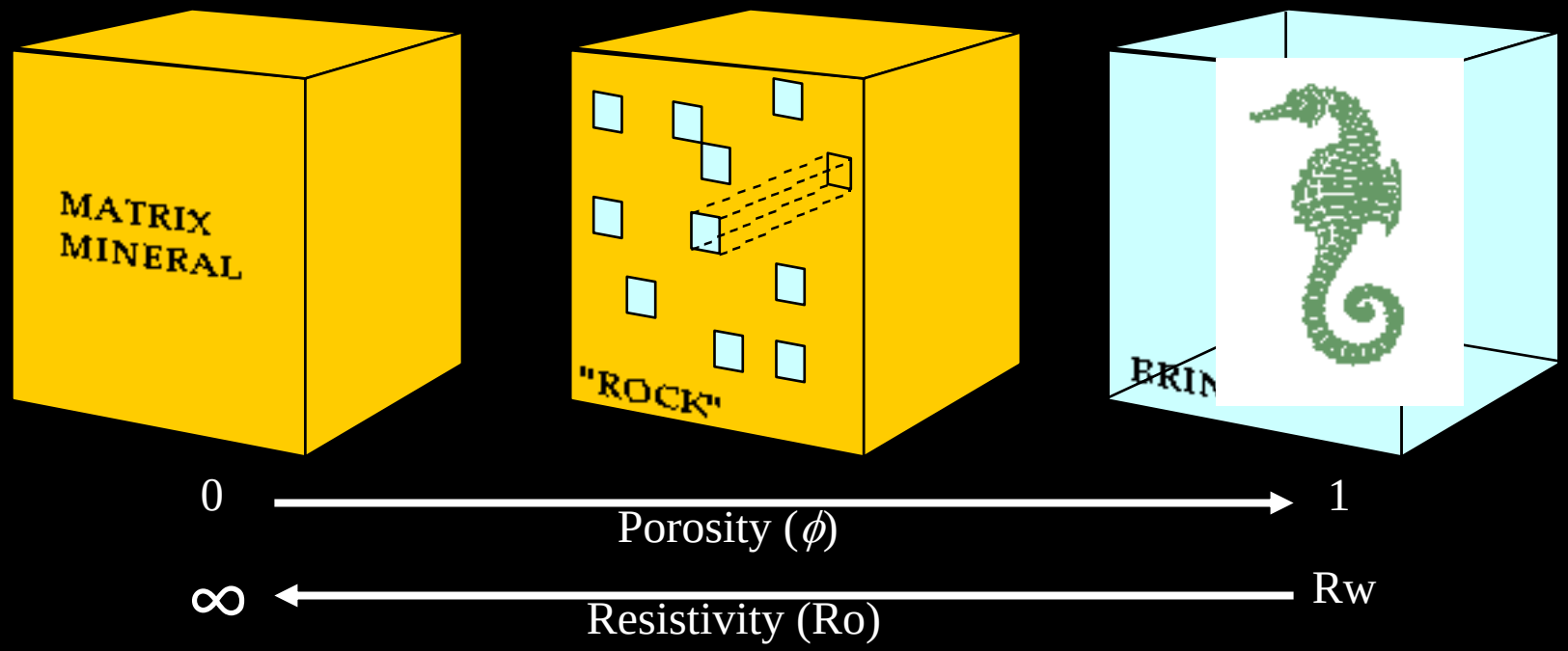
$$S_w^n = (a / \phi^m) * (R_w / R_t)$$

- 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: $m \rightarrow 1$
  - 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, $m \rightarrow 2$

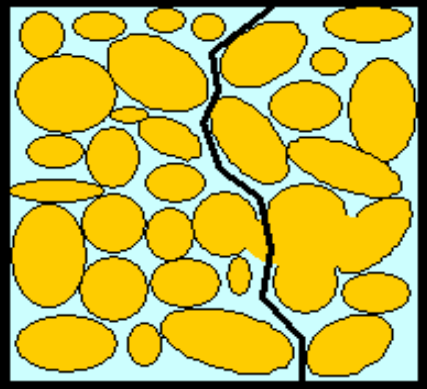
Resistivity of a simple rock model



For straight capillary tubes: $F = Ro/Rw = 1/\phi$

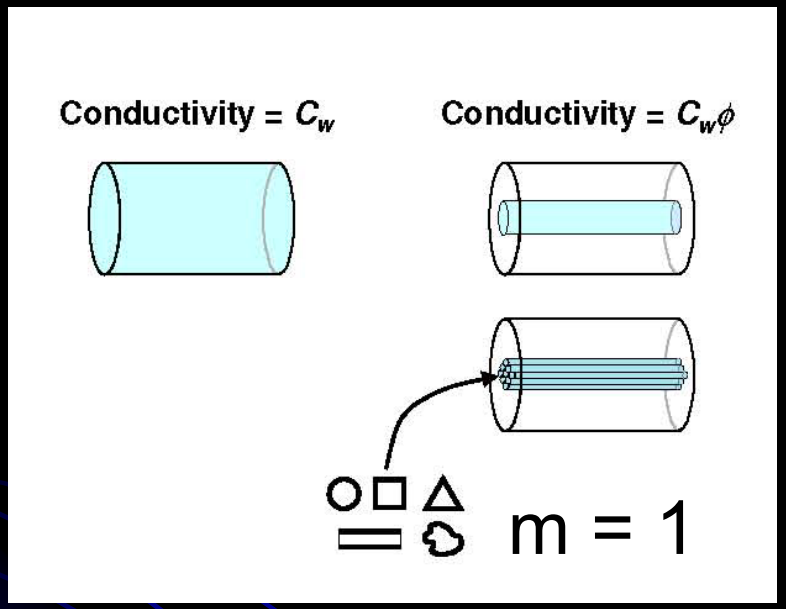
For rock with tortuous pores:

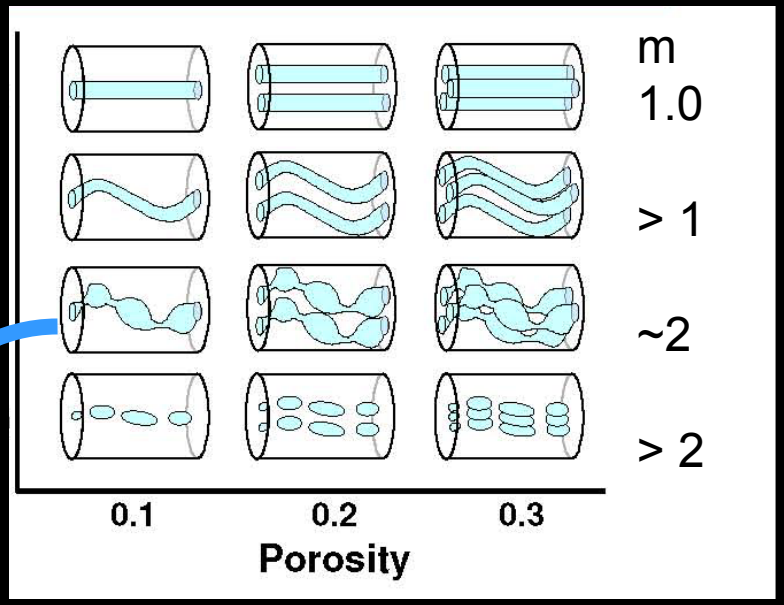
$$F = Ro/Rw = 1/\phi^{m}$$

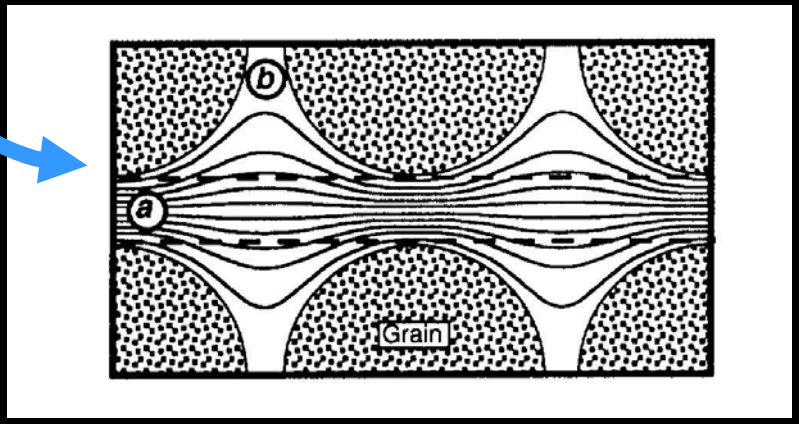


(after Doveton, 2005)

Capillary tube model for m



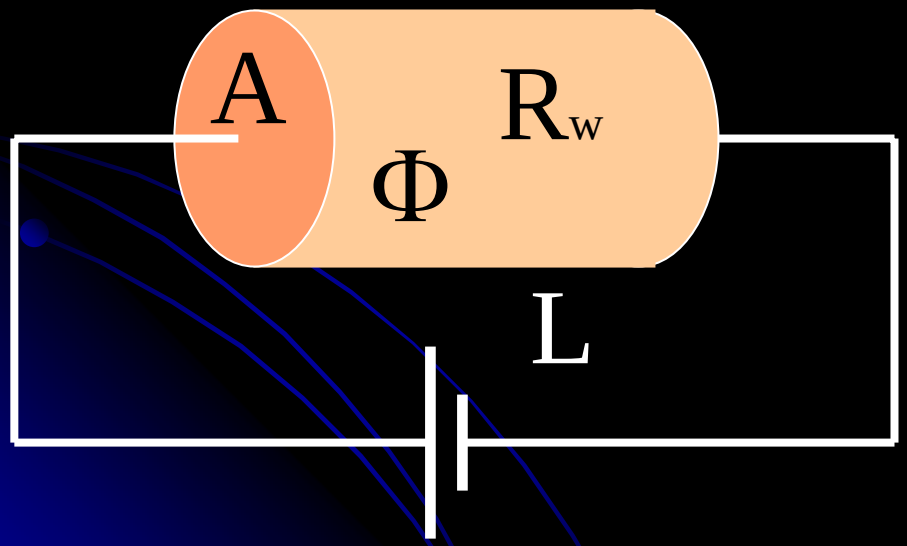




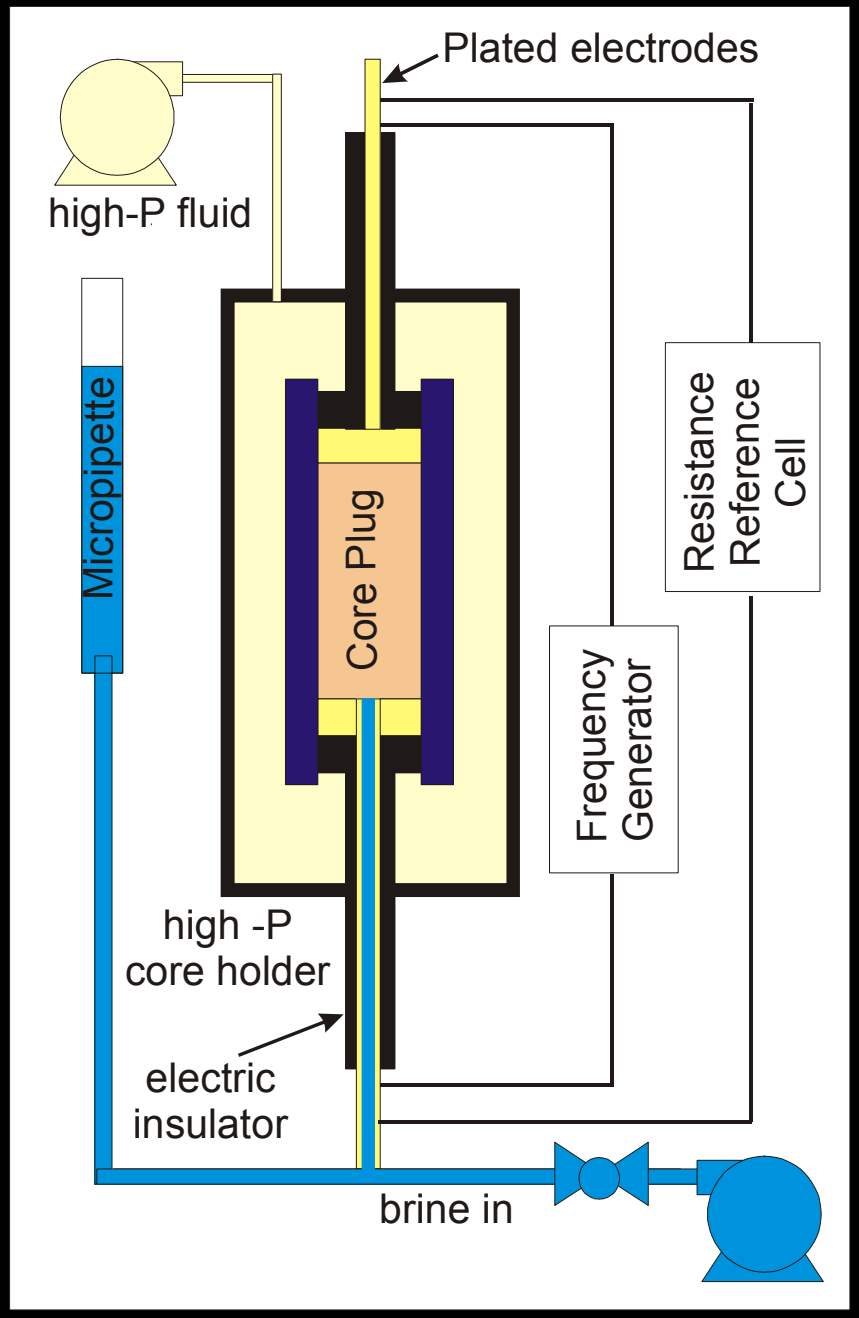
after Herrick & Kennedy, 1993, SPWLA Paper HH

Core measurement of the formation factor, F

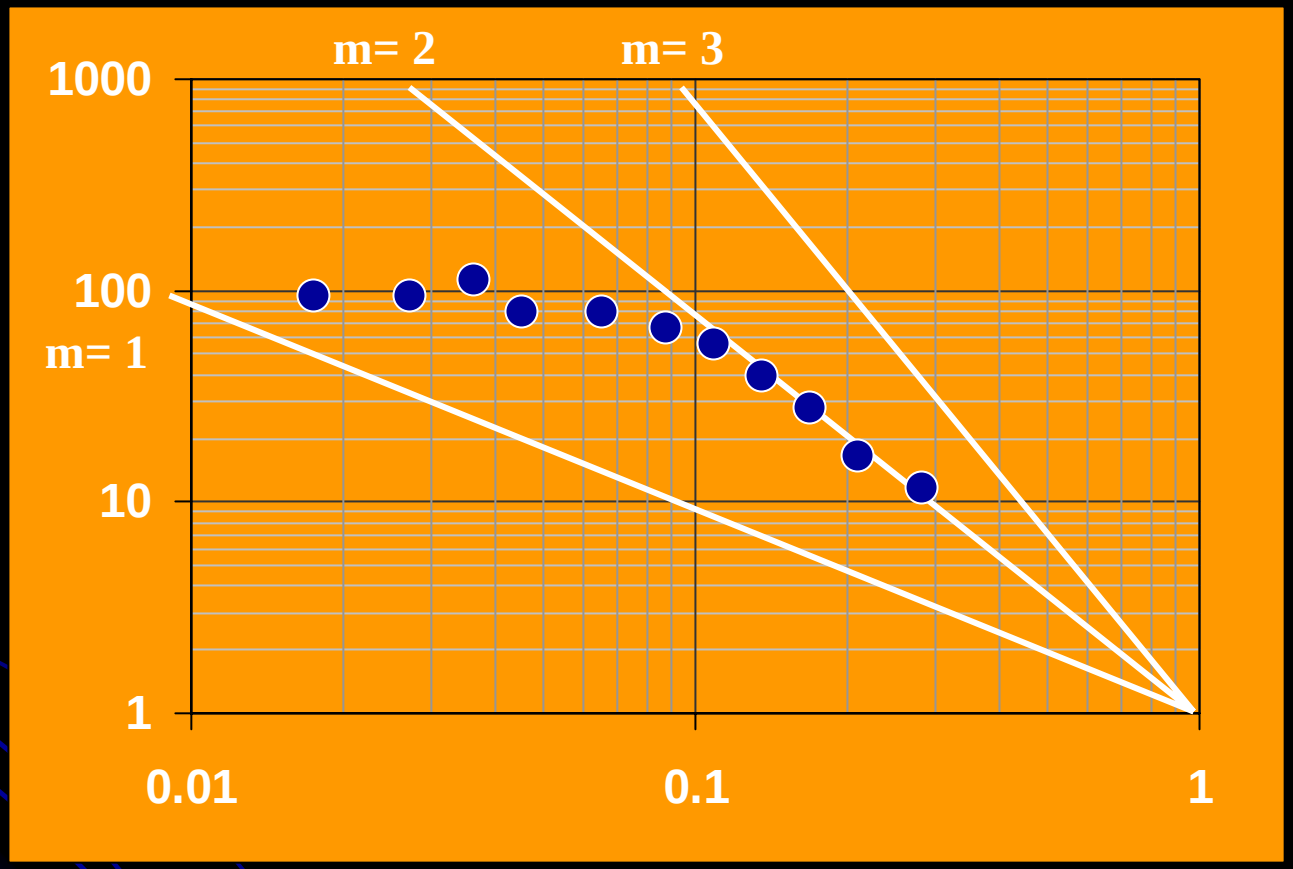
Start with core plug saturated with brine of known Rw & ϕ



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



When F and ϕ are plotted log-log



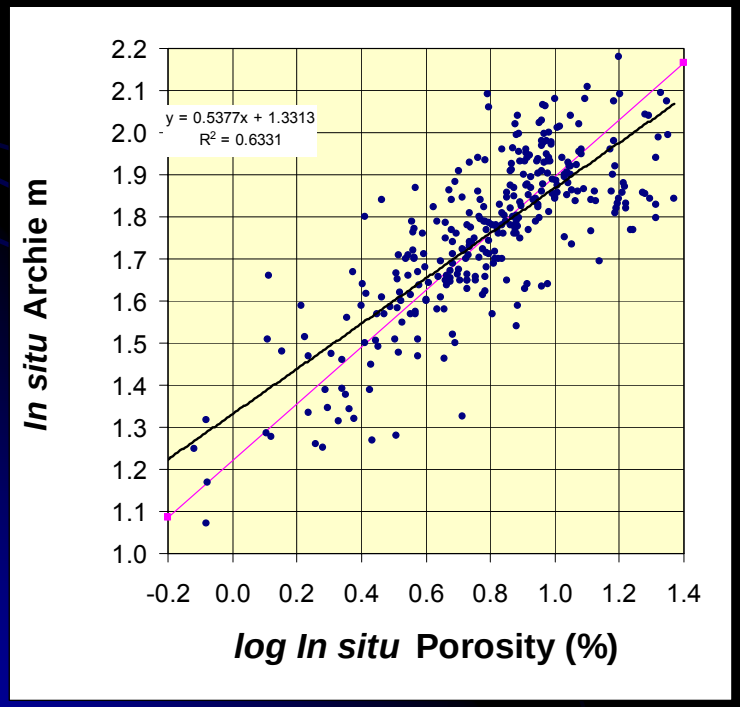
F

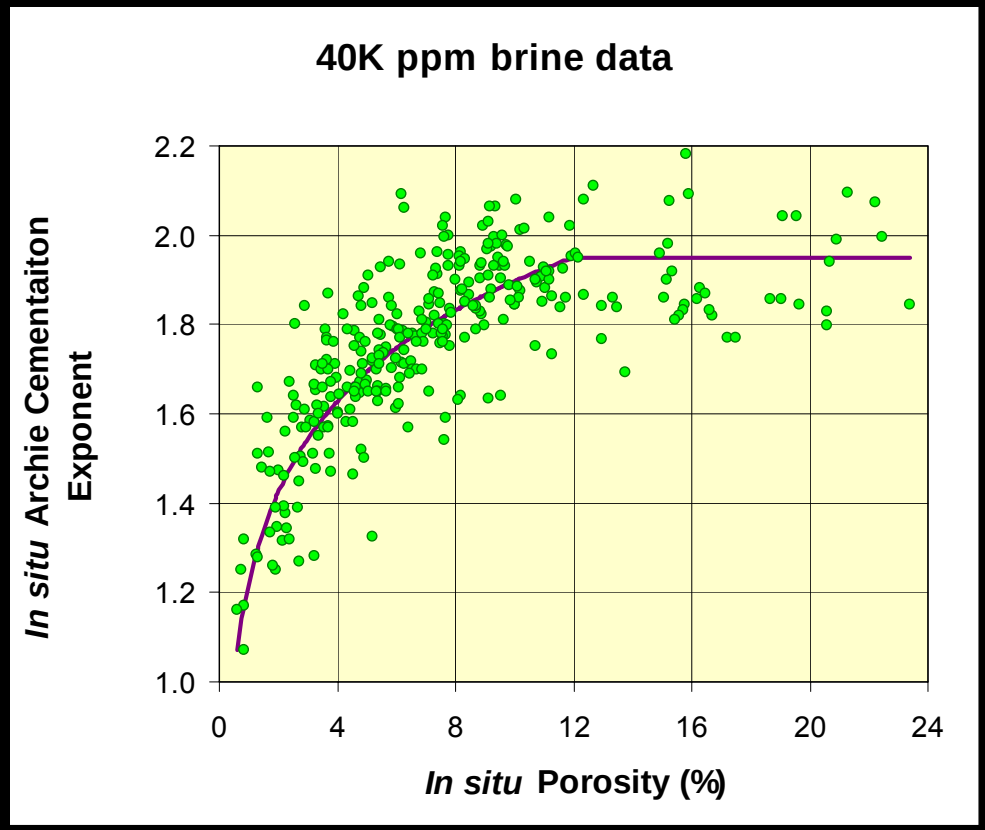
ϕ

$$\log F = -m \log \phi$$

Observed porosity dependence of "m"

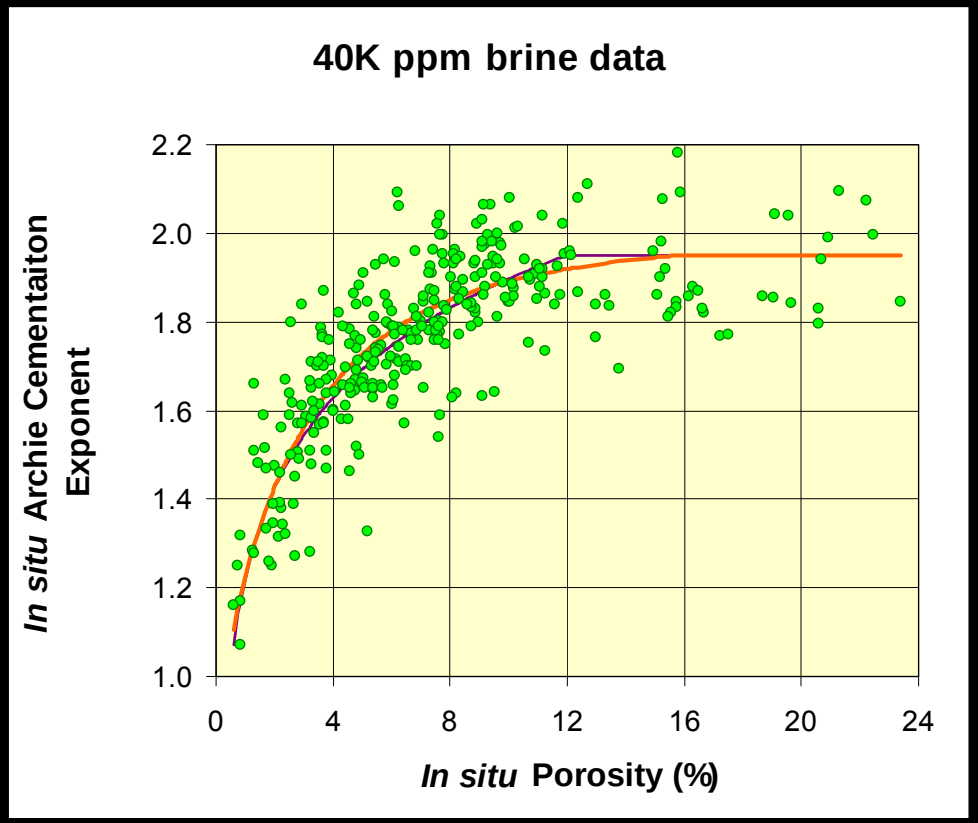
- Empirical: $m = 0.676 \log \phi + 1.22$ $R^2 = 0.63$ (RMA)
- each salinity is different
  - 40Kppm dataset is largest and used for base case
  - cap m at 1.95





Dual porosity model

- $m = \log[(\phi-\phi_2)^{m1} + \phi_2^{m2}]/\log \phi$
  - ϕ expressed as V/V
  - ϕ_2 = 0.0035, m1=2, m2=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 (ϕ ~ 16%)
- both models fit data



ϕ = bulk porosity
ϕ_2 = fracture porosity

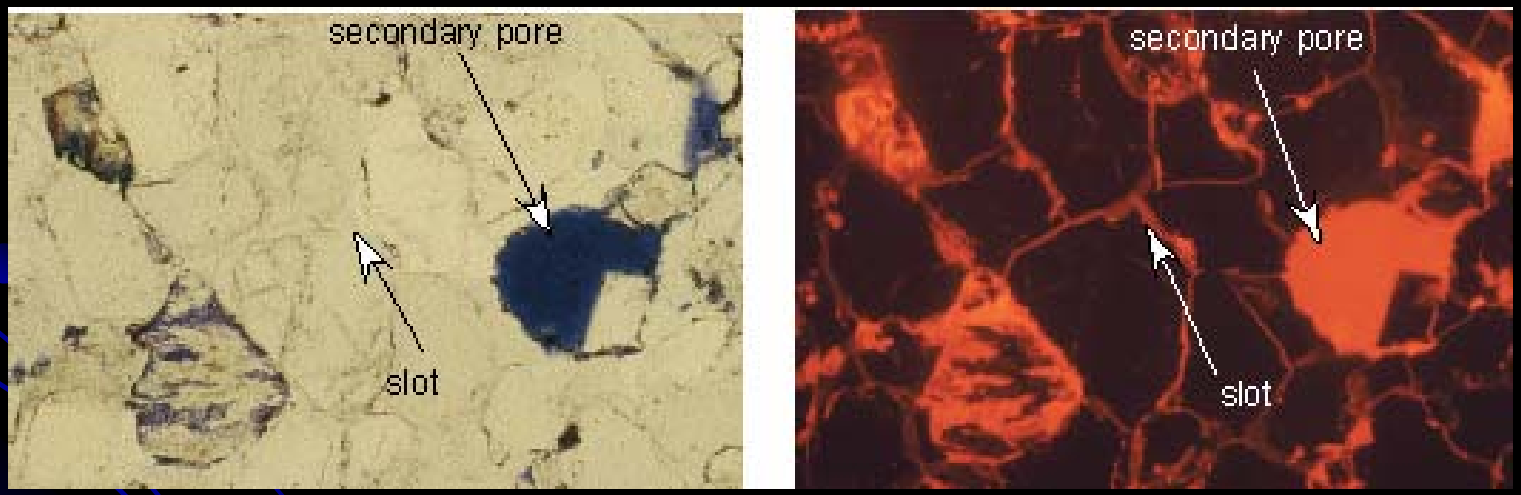
m_1 = matrix cementation exponent
m_2 = fracture cementation exponent

And a third way to look at it....

- Why is the minimum m ~ 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 ↑

And are the “cracks” all fractures?

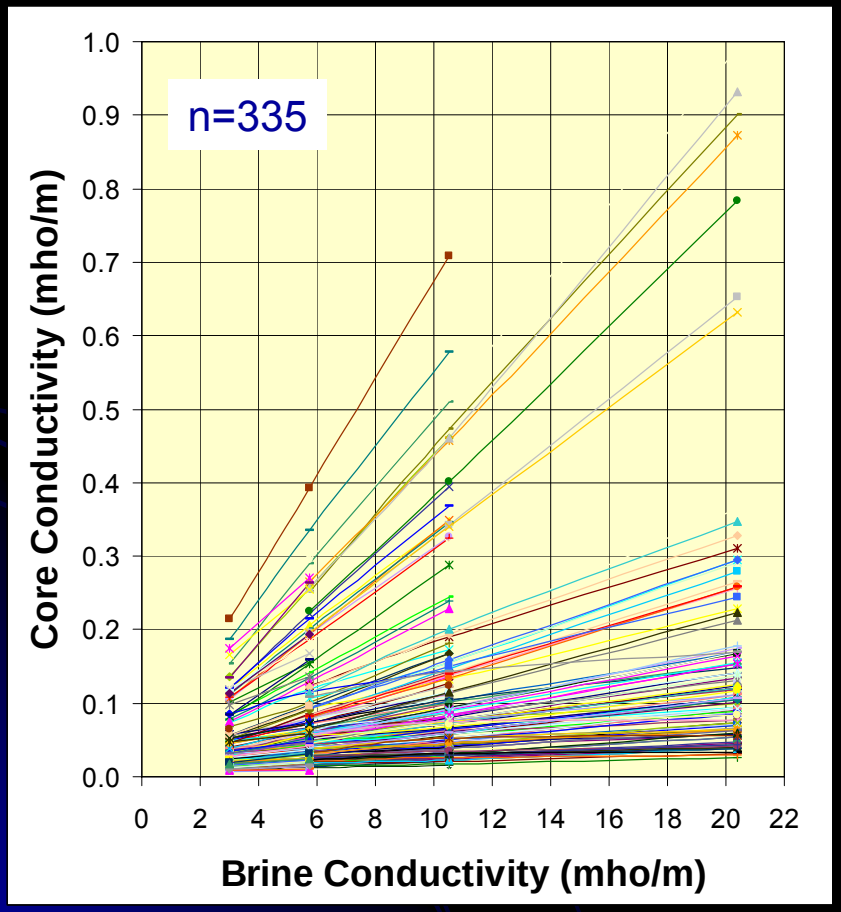
- Probably not.....
- Slot-like pores oriented preferentially parallel to bedding also act like conductive cracks

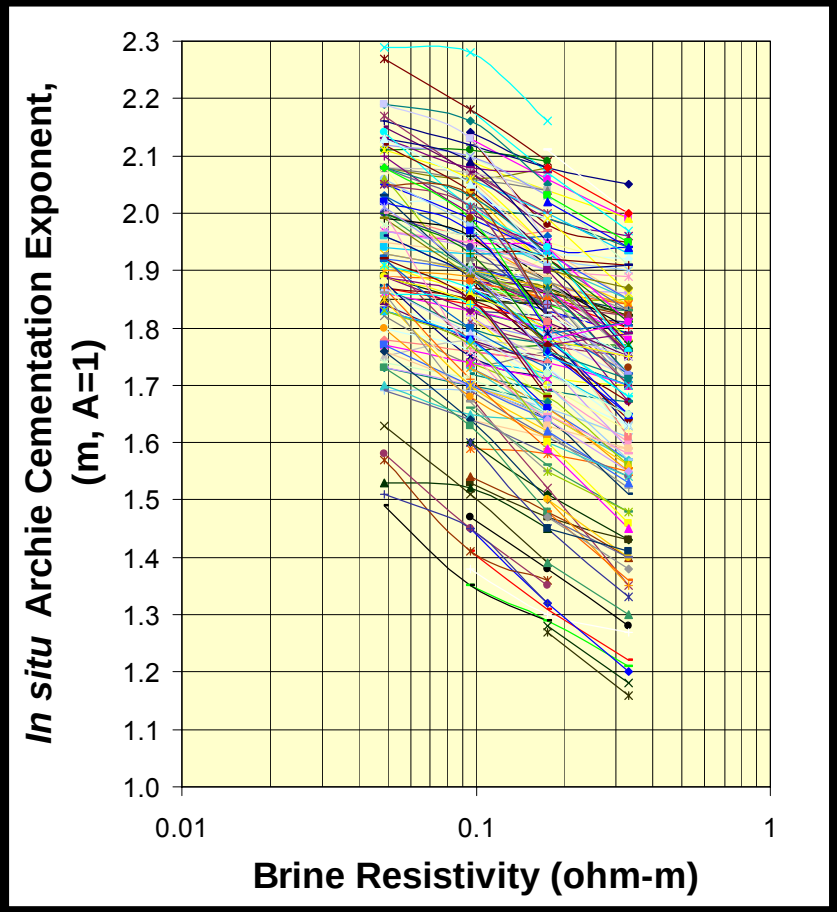


- Thin parallel laminae of slightly coarser, more permeable sand will be crack-like

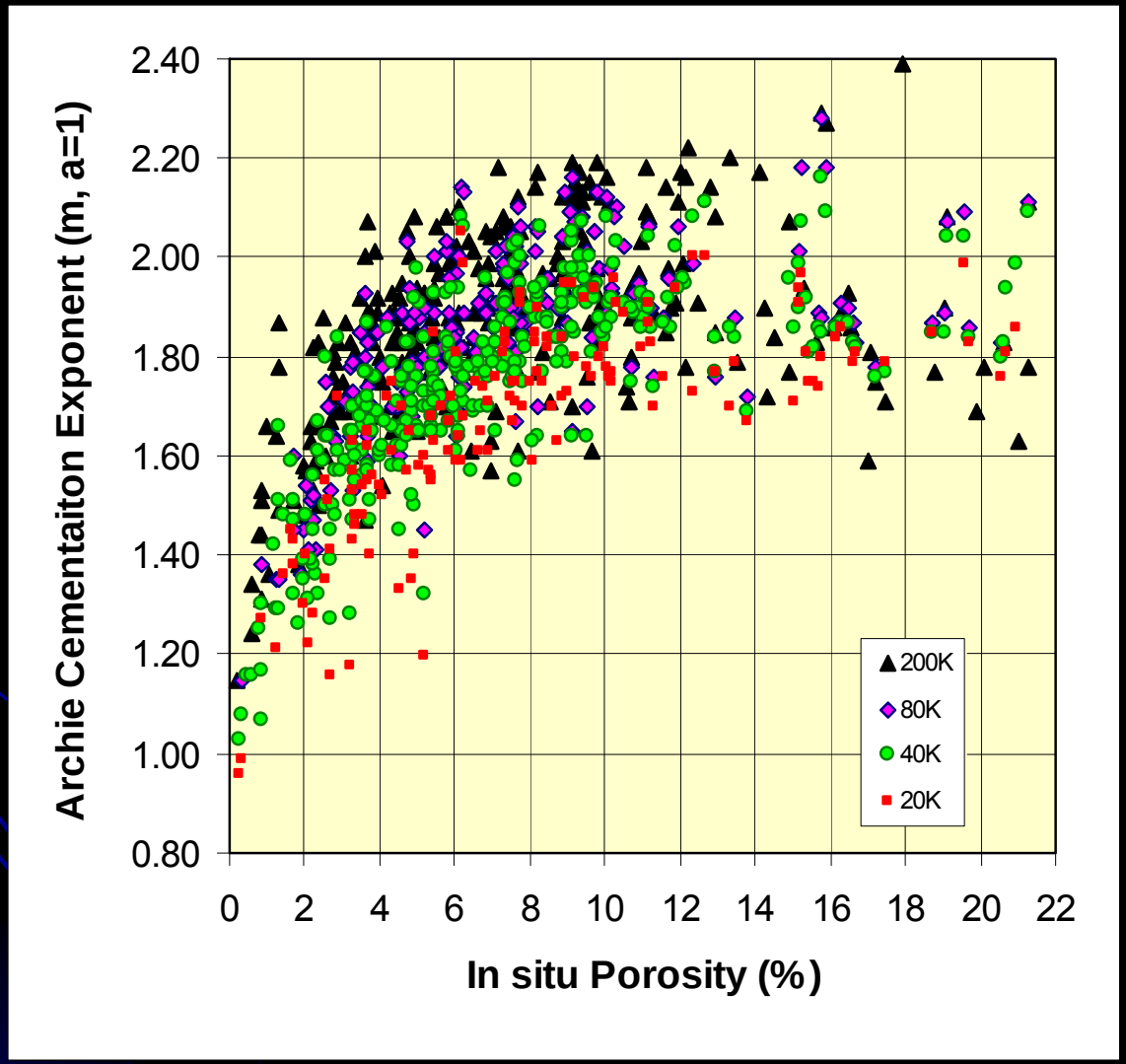
Salinity dependence of "m"

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

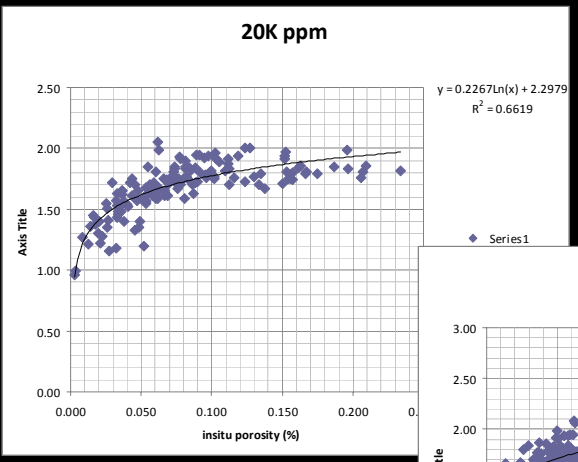


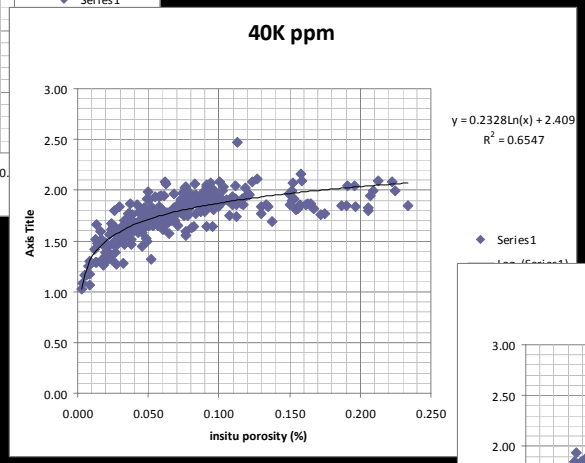


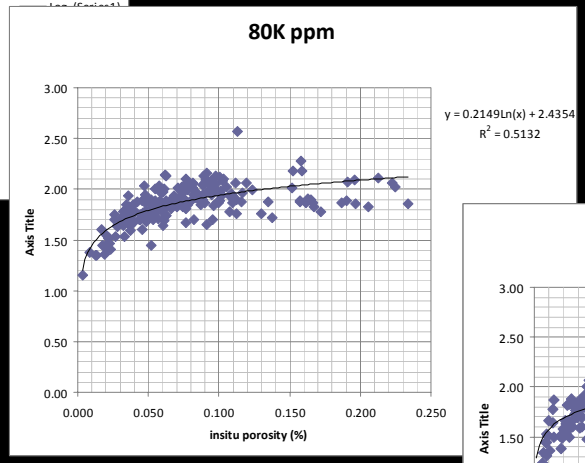
All data, all salinities

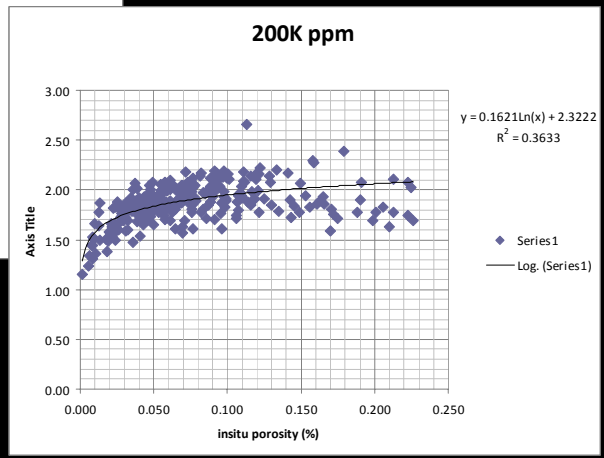


Salinity dependence of “m”







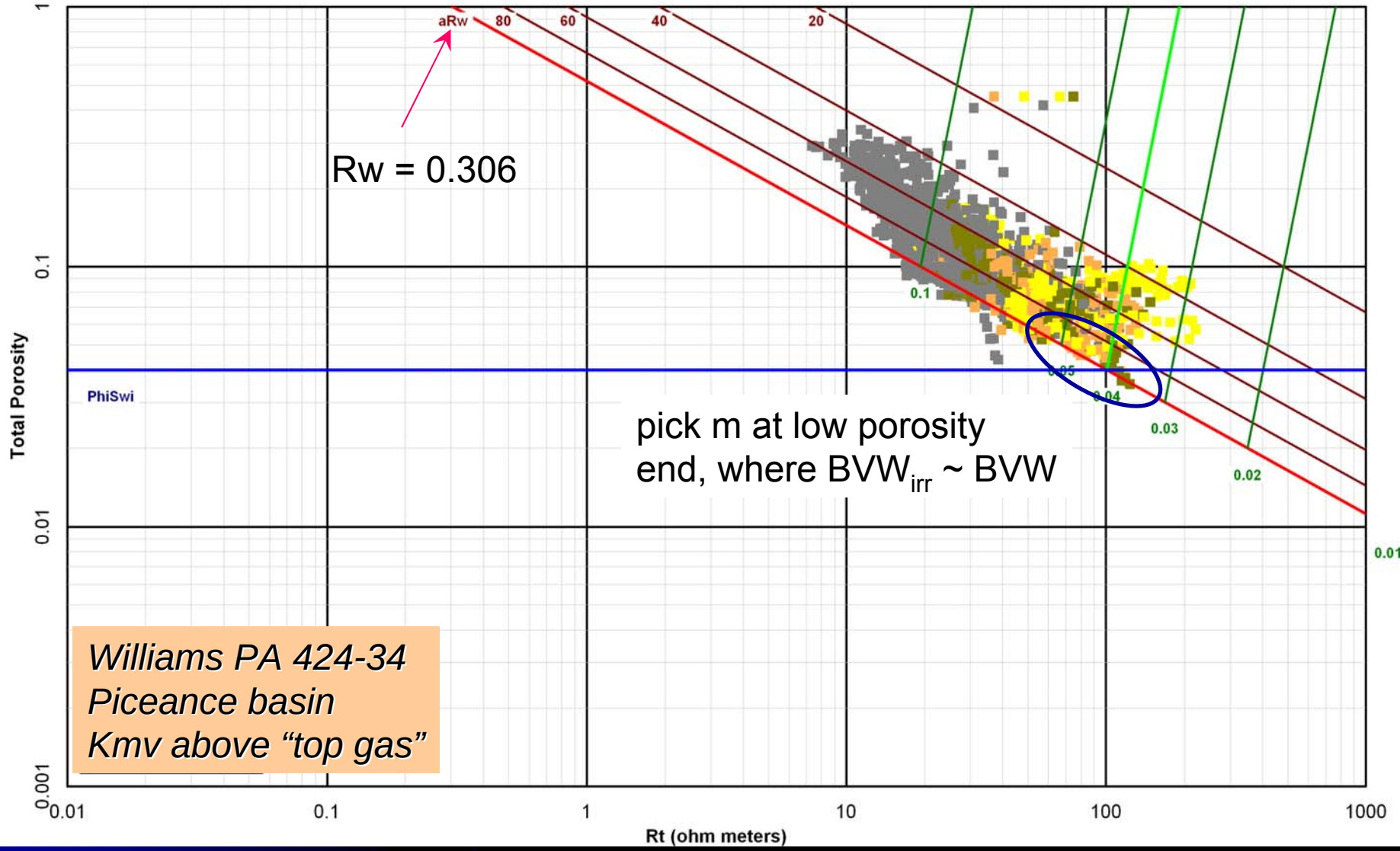


- $m = a \log \phi + b$
- intercept b drops with decreasing salinity
- slope is ~ constant

Simple procedure to compute Sw

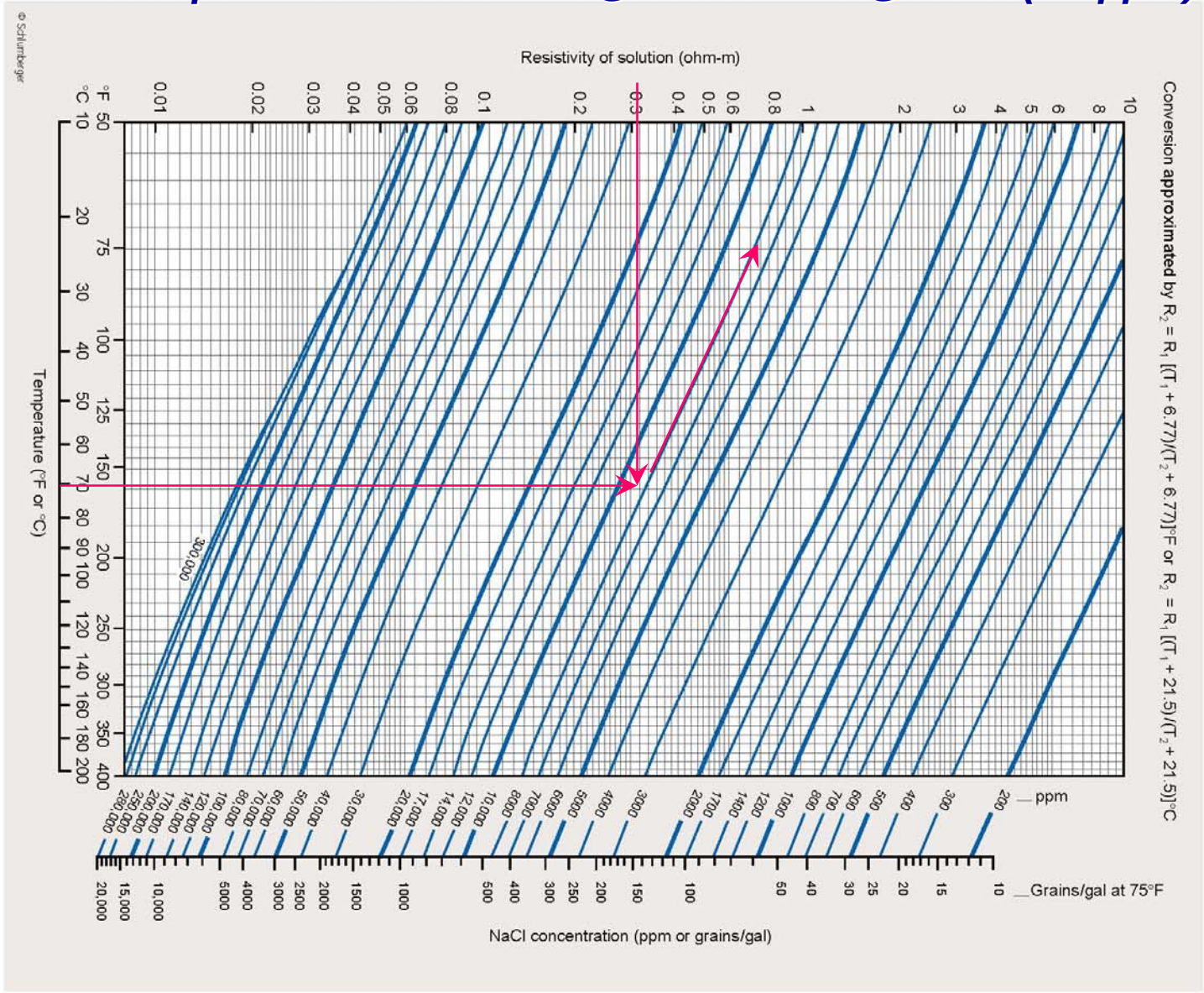
- determine Rw @ Tf conventionally
  - Pickett plots – focus on the lower porosity, wetter sandstones
  - produced waters
  - your best guess.....
- convert Rw to 75°F by chart lookup or Arps equation

Pickett Plot example



Williams PA 424-34
Piceance basin
Kmv above "top gas"

Pickett plot Rw 0.306 ohmm @ 160°F = 0.7 @ 75°F (9K ppm)



Our new procedure

- compute m at 40K ppm from RMA regression:

  $m40k = 0.676 \log \phi + 1.22$

  e.g. for 10% ϕ : $m = 0.676 + 1.22 = 1.896$
- correct m for salinity effect by

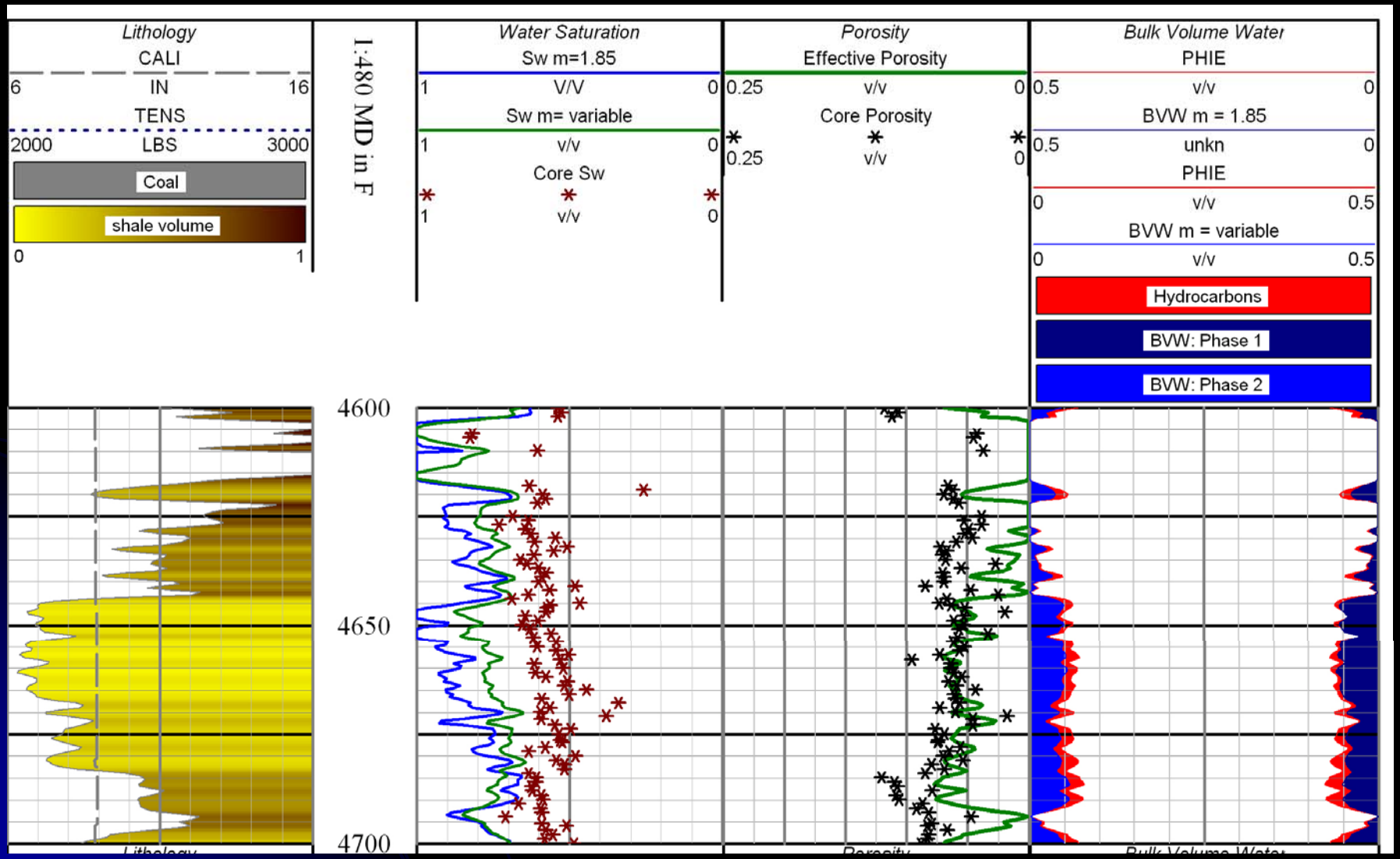
  $m = m40k + ((0.0118\ \phi - 0.355) * (\log Rw + 0.758))$
- e.g. for 10% ϕ, Rw = 0.7 @ 75°F
  - $m = 1.896 + ((0.0118 * 10 - 0.355) * (\log 0.7 + 0.758))$

    $m = 1.896 + (-0.237 * 0.603) = 1.753$
- cap m at 1.95 (~12% porosity)

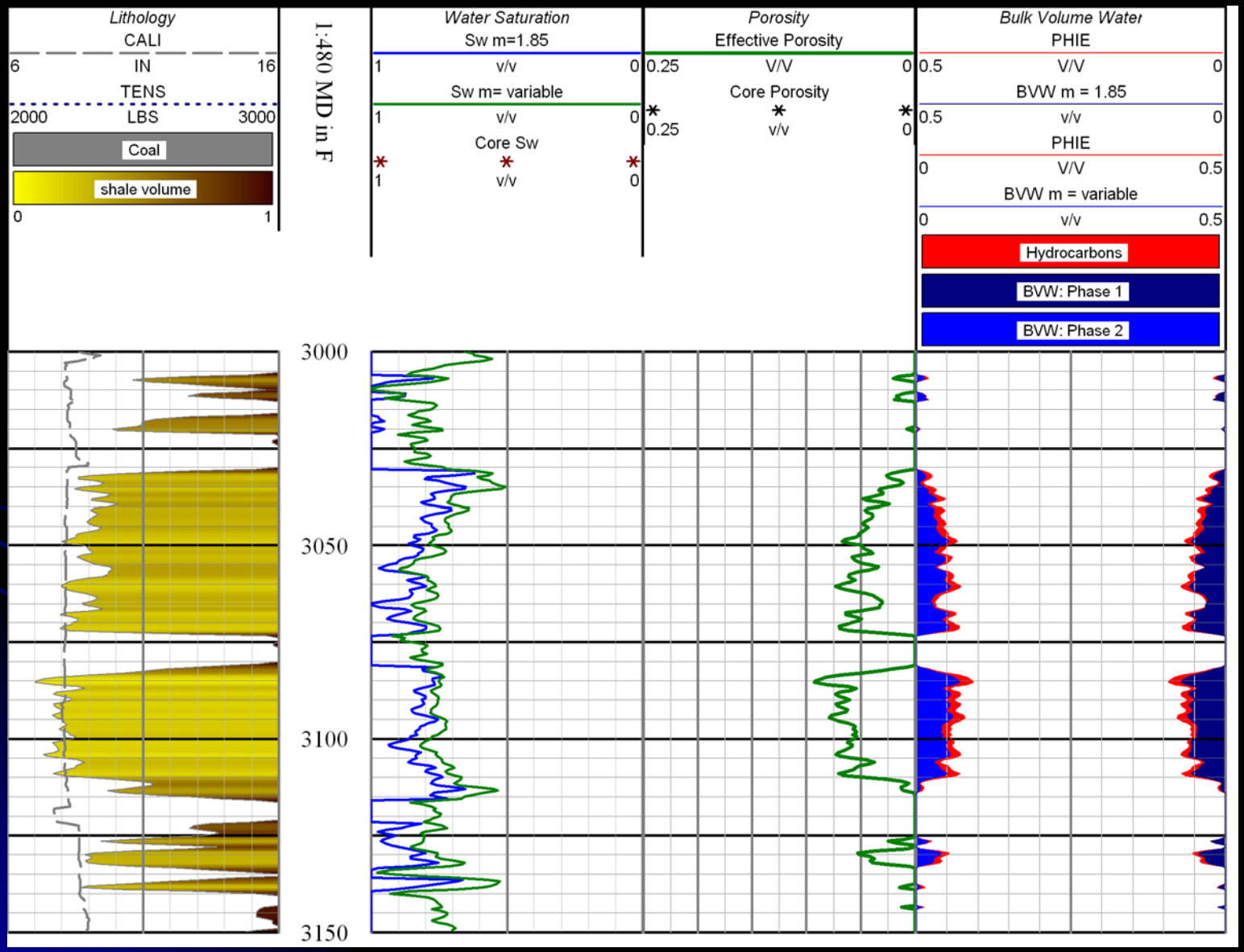
Practical impact

- 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 Sw's
- Therefore, there is more gas in the tight rocks than we thought.
- Above 10% porosity there is very little difference

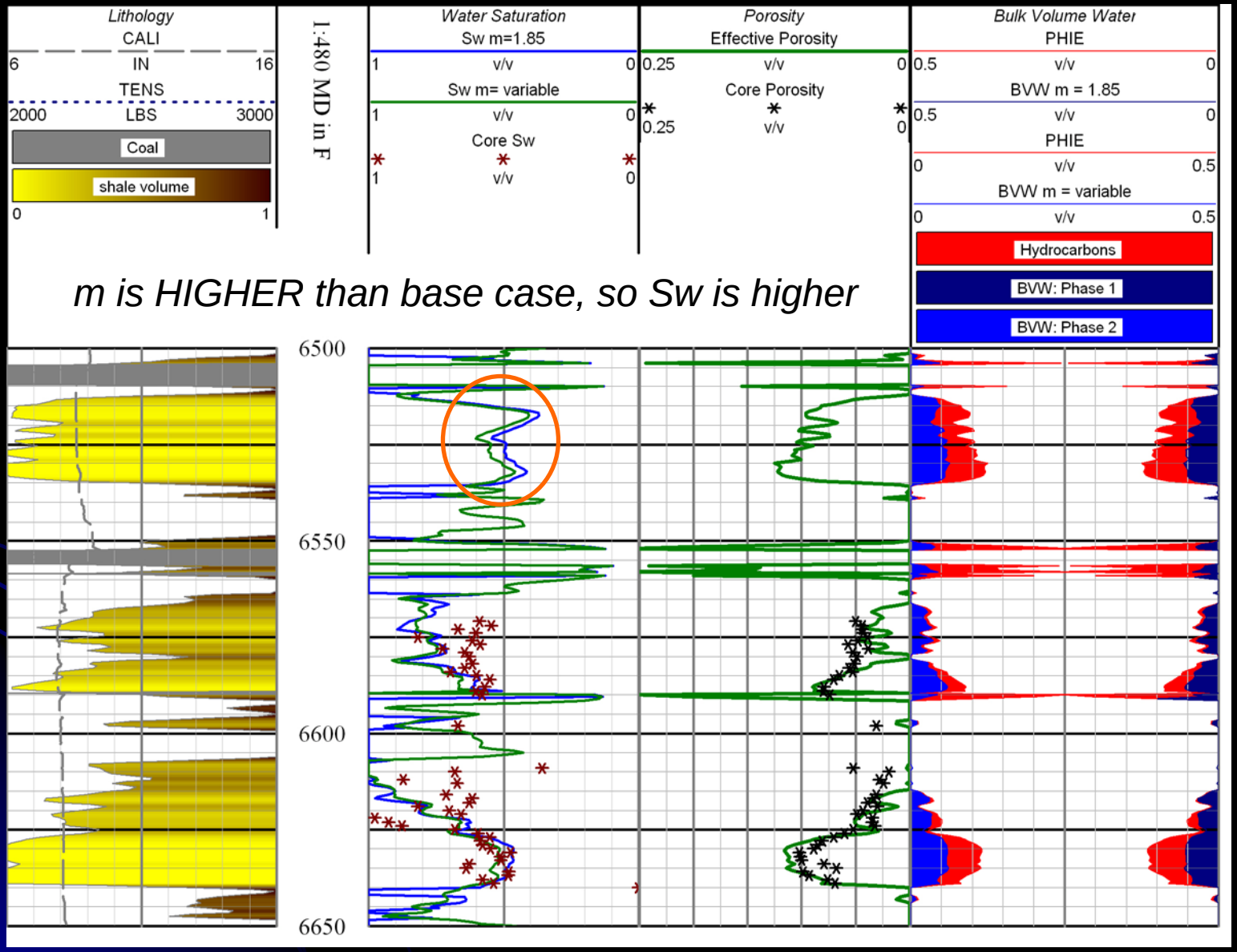
Example: Low porosity, wet zone



Moderate porosity, wet

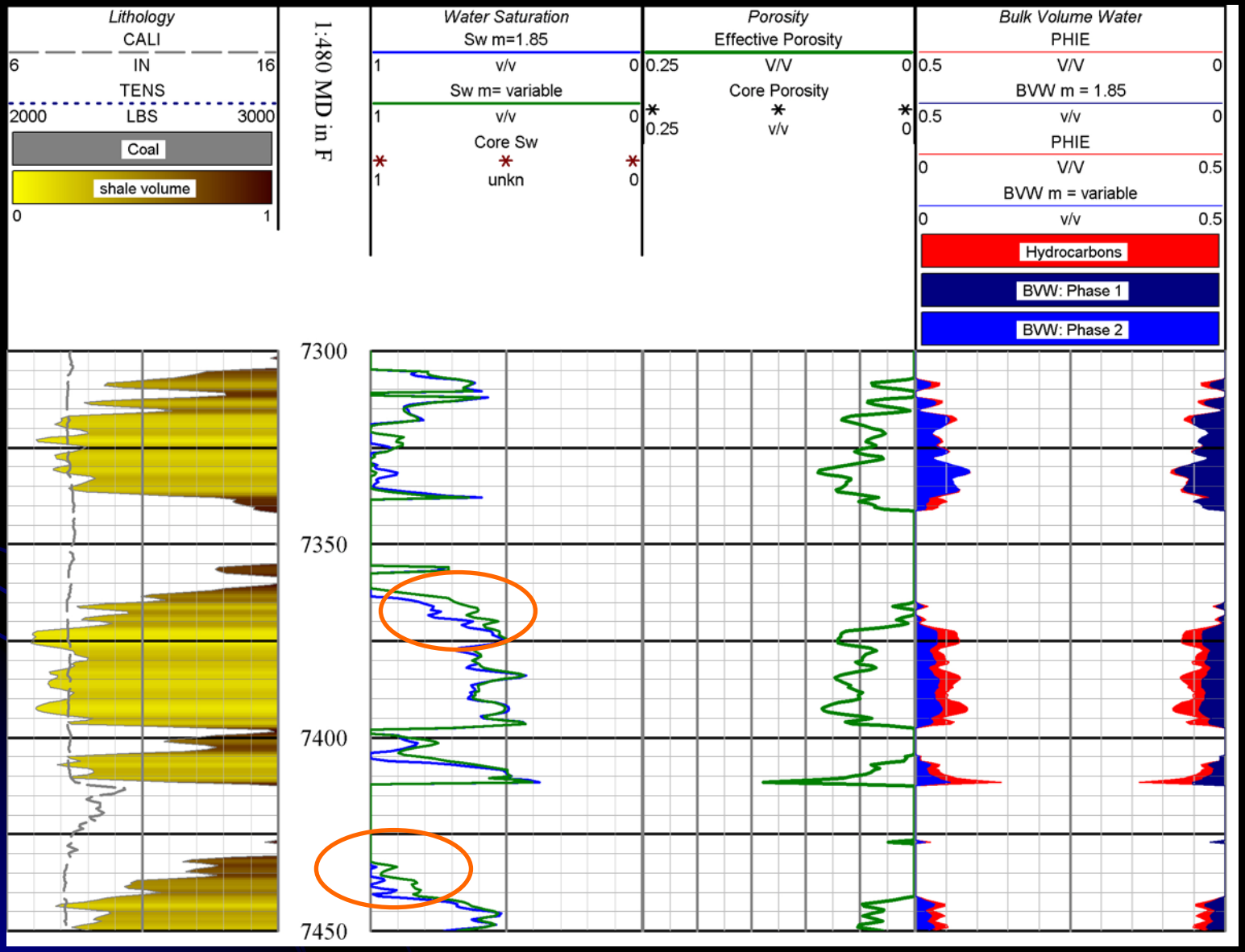


“High” porosity gas zone

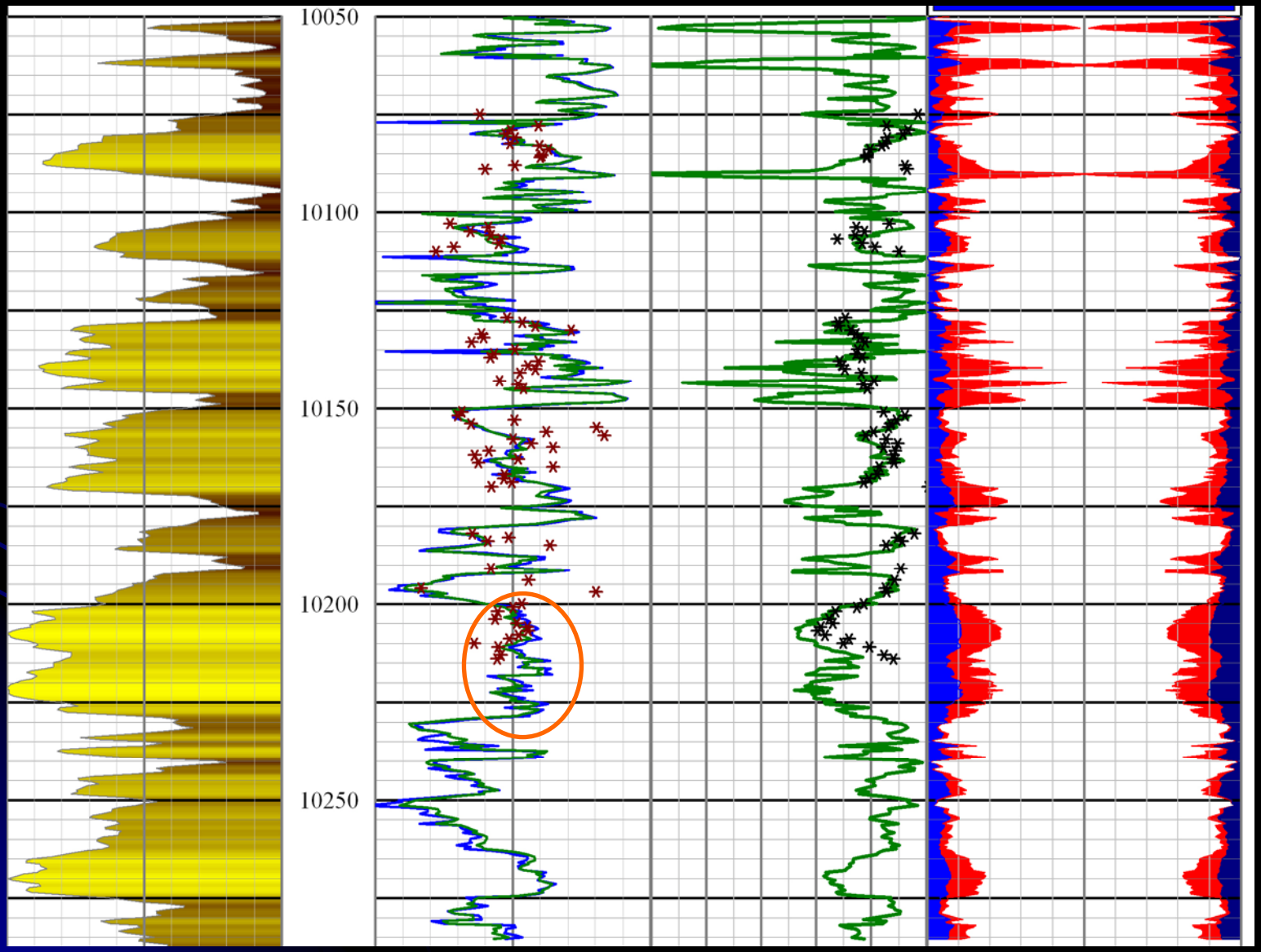


m is HIGHER than base case, so Sw is higher

20Kppm example, Natural Buttes



30K ppm example, Wamsutter



Summary & Conclusions

- 335 Kmv samples run at multiple salinities
- Archie porosity exponent m varies with
  - *porosity* m ↓ as porosity ↓
  - *salinity* m ↓ as salinity ↓
- 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% ϕ increases GIP
- see no impact below ~5% porosity
  - BVW_{irr} is typically 3-5%
  - no longer calculate Sw's >> 1
  - Sw = 1 at low ϕ validates Rw

Visit our project website

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

Questions?

The Discovery Group, Inc.