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

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2008 AAPG Annual Convention presentation, San Antonio

US DOE Project Summary

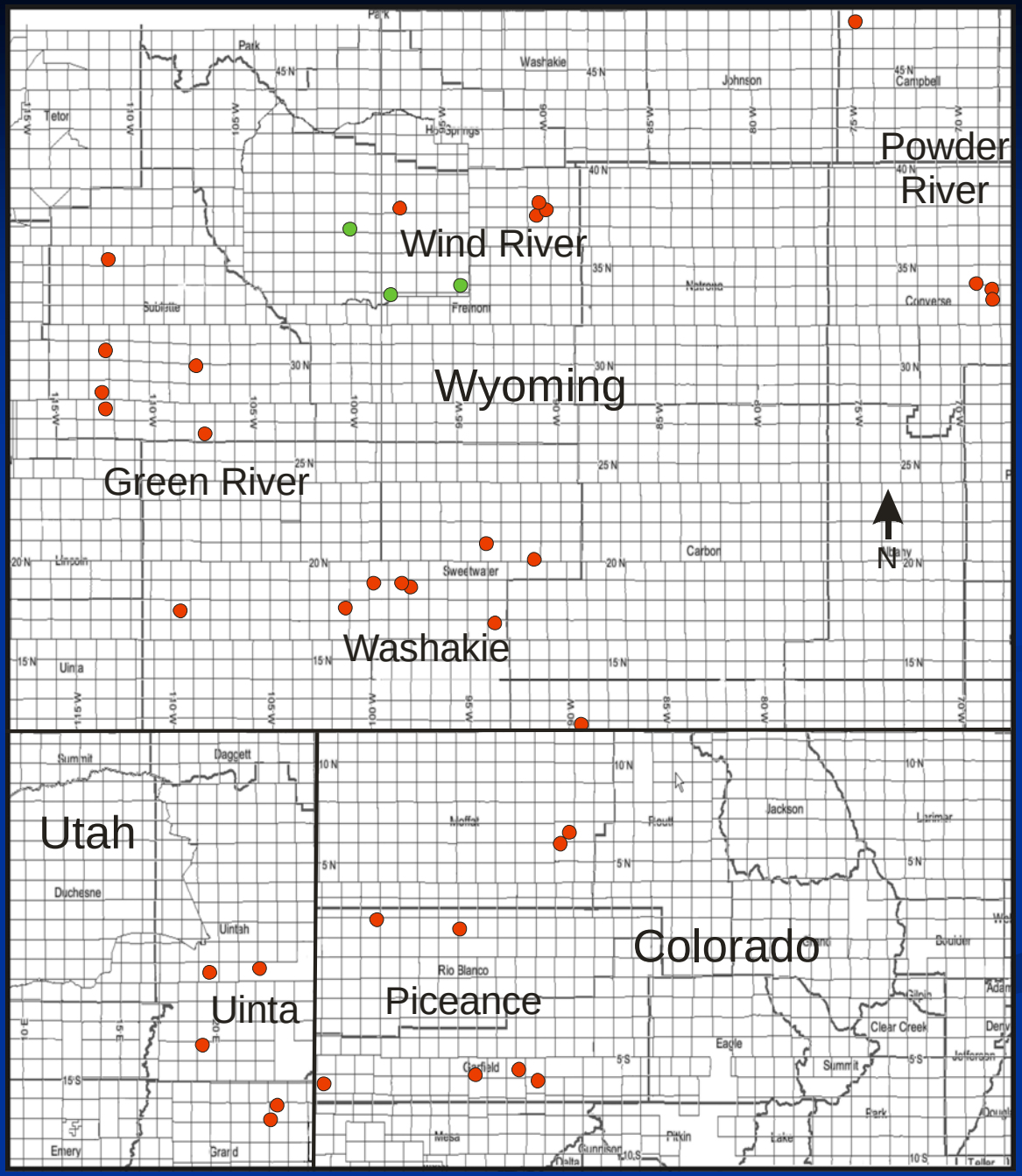
- DOE Contract # DE-FC26-05NT42660
  - completion date 30 June 2008
- Organizations
  - University of Kansas Center for Research, Inc.
  - Kansas Geological Survey, Lawrence, KS
  - The Discovery Group Inc., Denver, CO
- Principal Investigator: Alan P. Byrnes, KGS
- project website is http://www.kgs.ku.edu/mesaverde

Project objectives

- investigate minimum gas flow, critical and residual gas saturation, Sgc=*f* (lithofacies, Pc, architecture)
- investigate capillary pressure, Pc=*f* (P), Pc=*f* (lithofacies, k, ϕ, architecture)
- investigate electrical properties, m = *f* (ϕ, 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

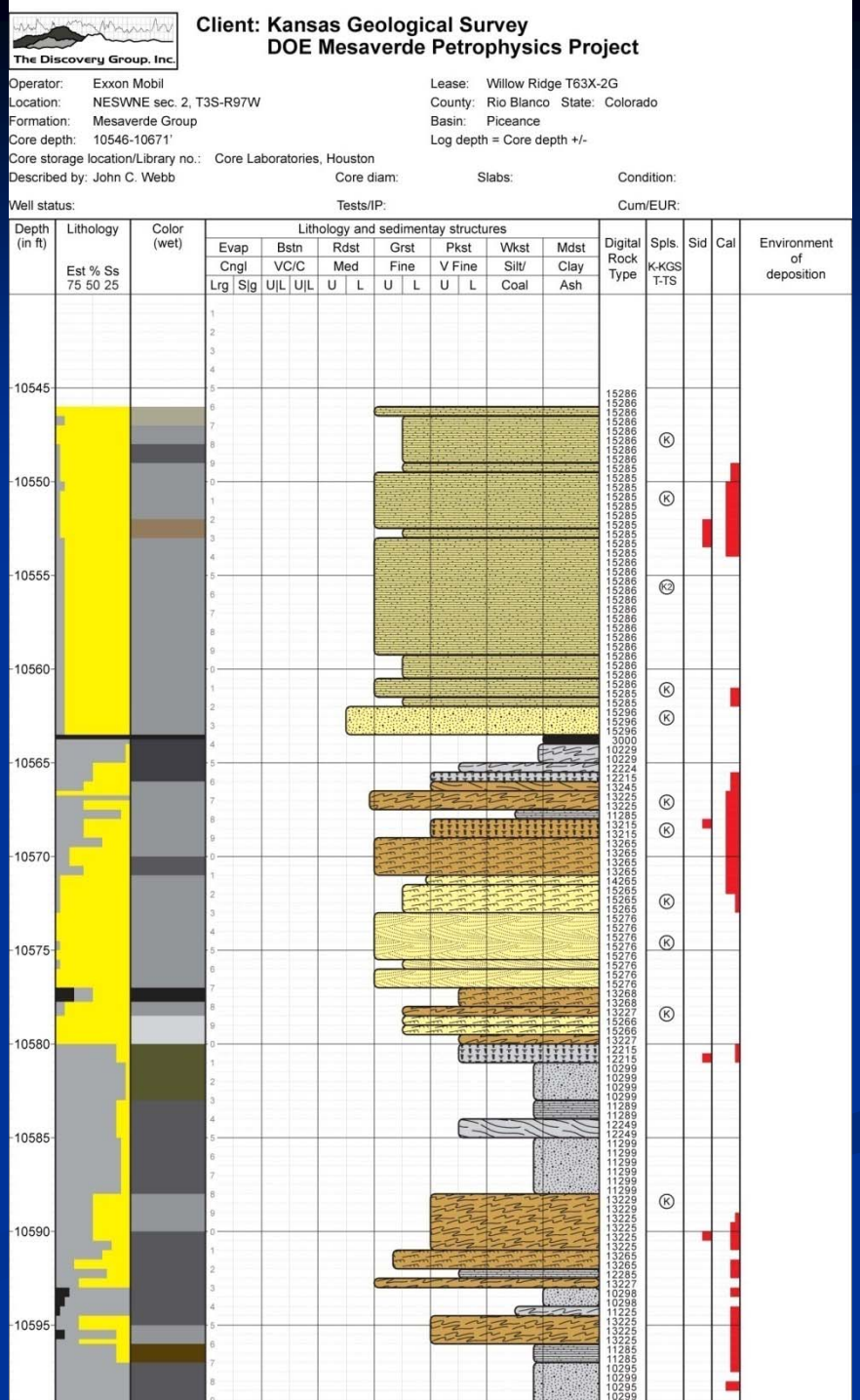


Digital Core Description

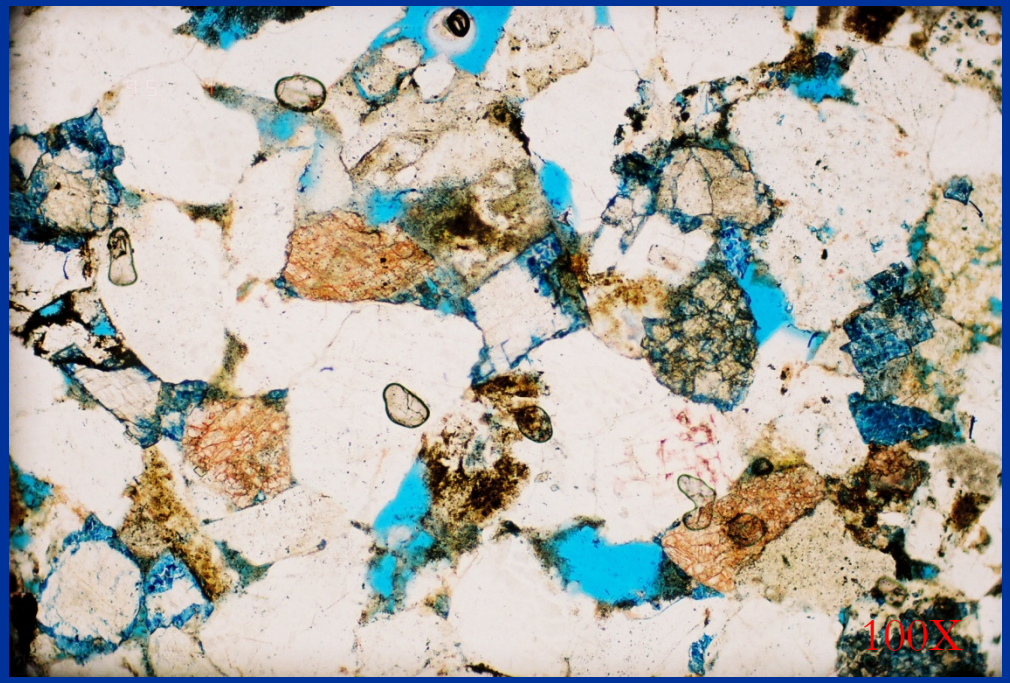
- To provide lithologic input to equations and predict lithology from logs used 5 digit system
  - 1 basic type (Ss, Ls, coal)
  - 2 grain size/sorting/texture
  - 3 consolidation
  - 4 sedimentary structure
  - 5 cement mineralogy
- Property continuum - not mnemonic or substitution cipher
- Similar 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.



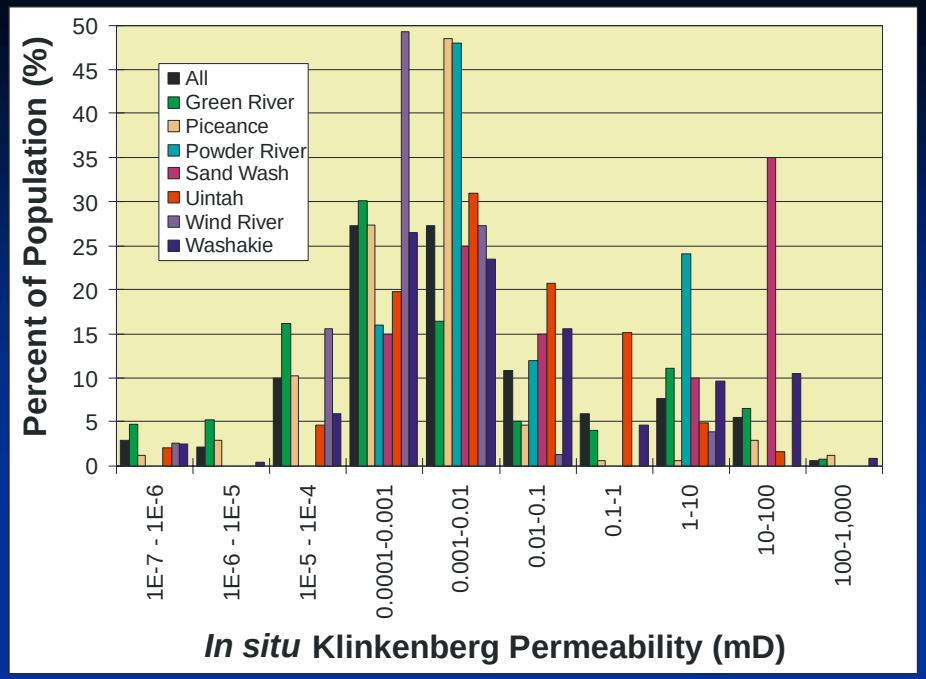
Williams PA 424, 6148.8’ 15276
9.9% 2.66 g/cc Ka=0.0237 mD

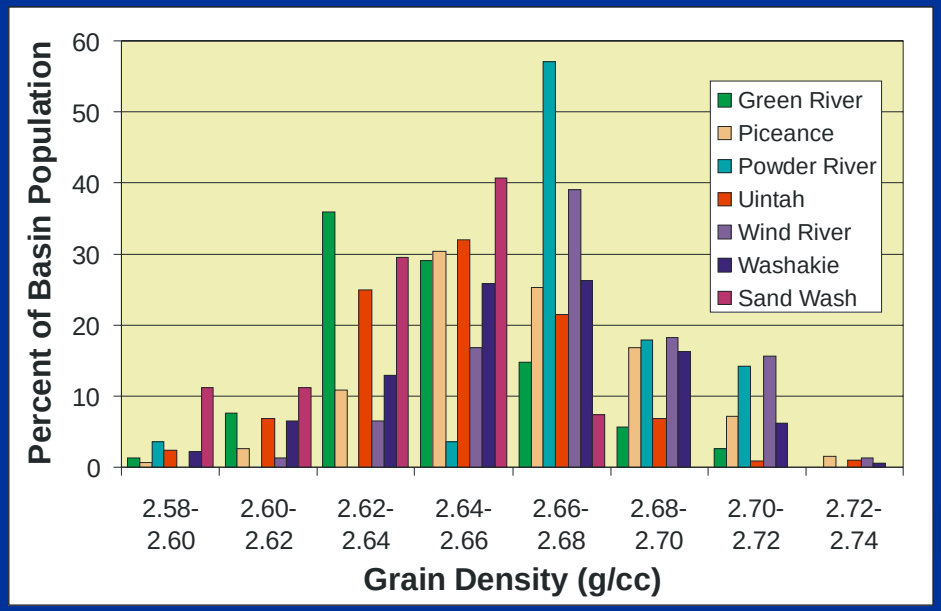
Porosity consists almost entirely of sparse, poorly connected, clay-filled intergranular microporosity.
Quartz cement is prominent, ferroan calcite is sparse.
Pore-filling clay cement causes elevated Swi and reduced relative permeability.

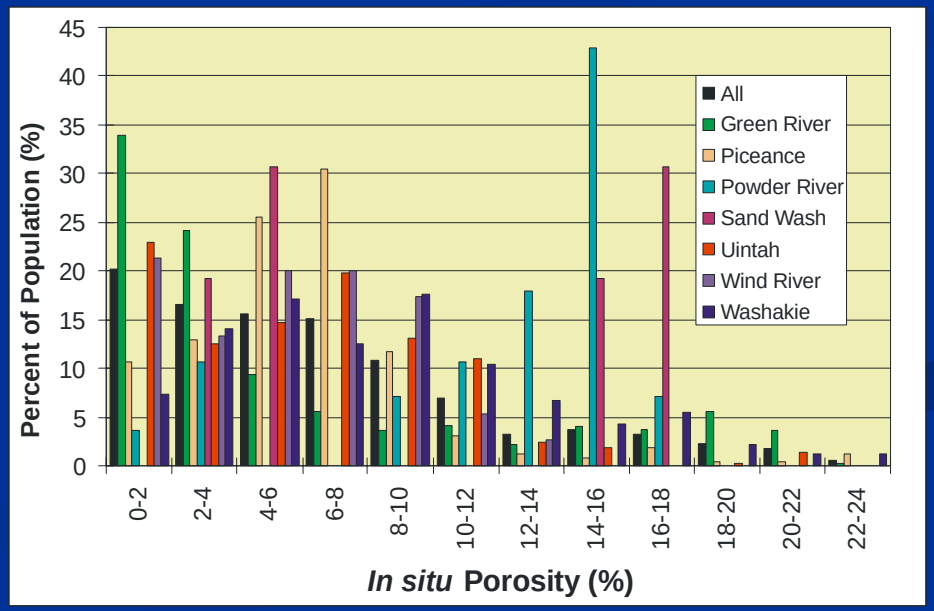
Williams PA 424, 4686.4’ 15286
7.9% 2.65 g/cc Ka=0.211 mD

Sample QA & distributions

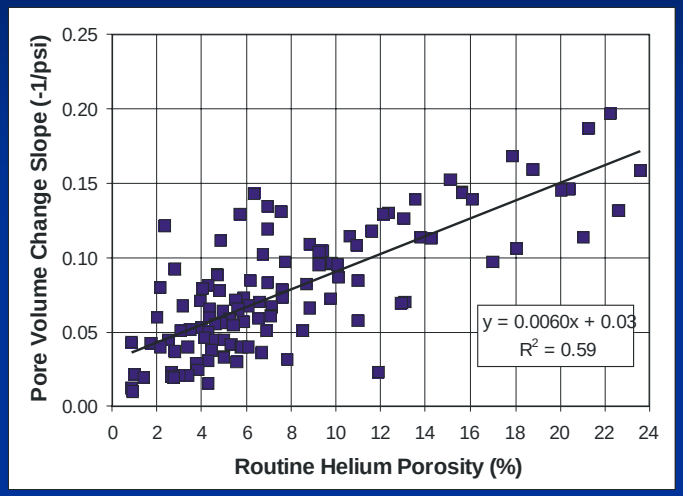
- Petrophysical property distributions are generally normal or log-normal
- Sub-distributions = *f* (basin, lithofacies, marine/non-marine, etc.)

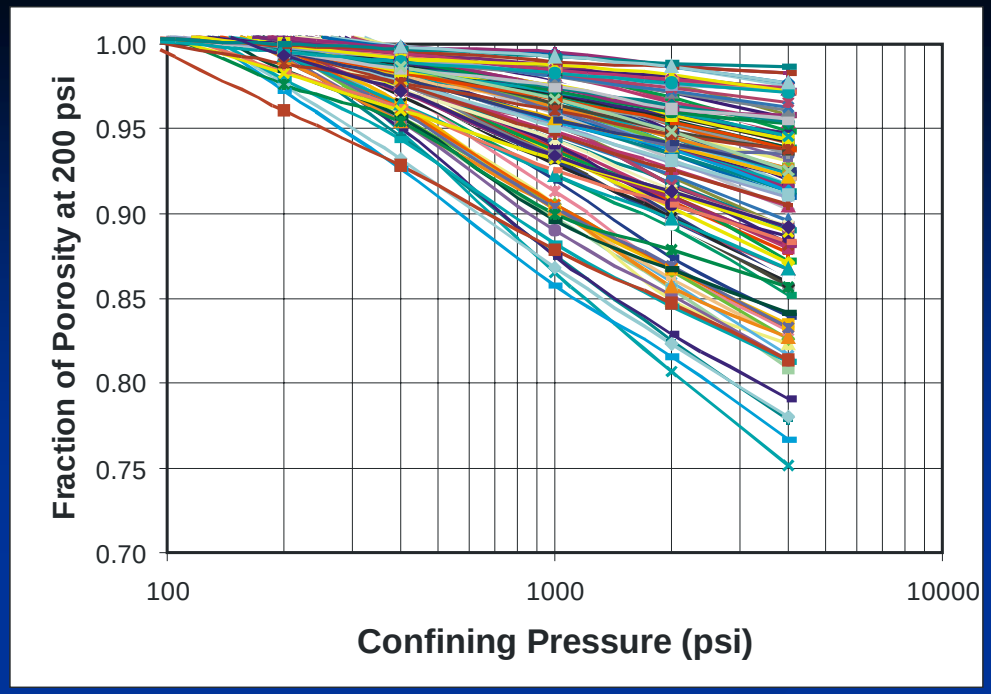


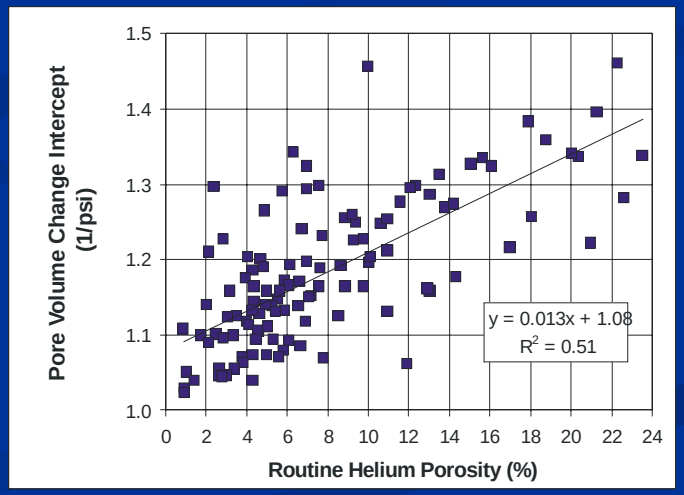




Pore Volume Compressibility

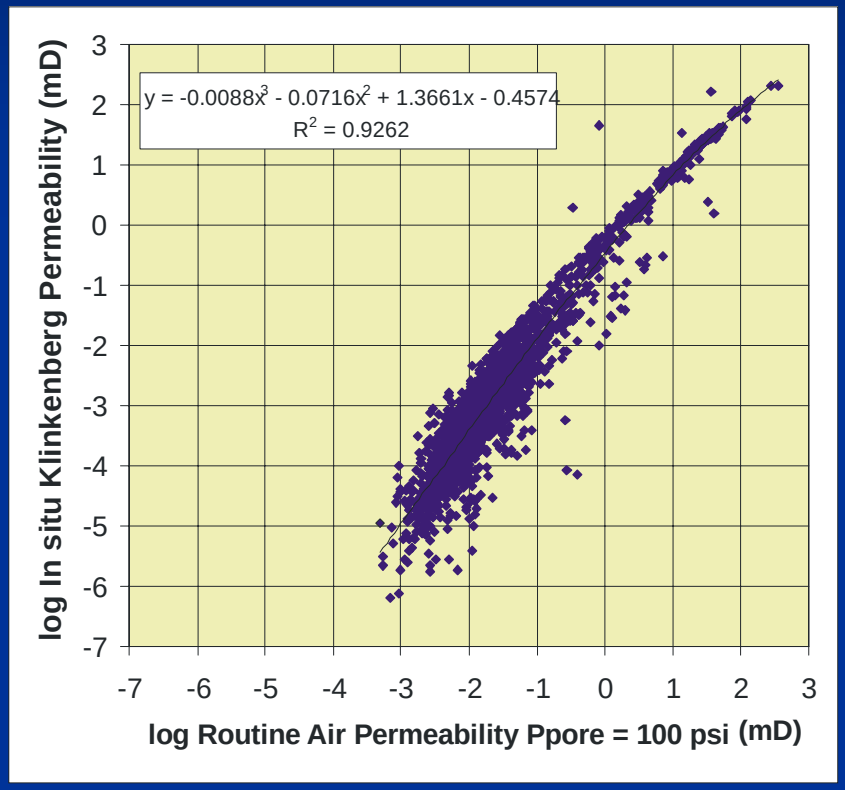






- Previously documented in literature
- no large datasets in public domain
- 113 Samples
- Log-linear pore volume change seen in EVERY sample, avg. $R^2 = 0.99$
- characteristic of cracks/sheet-pores
- Slope and intercept increase with increasing porosity

Stress dependence of permeability



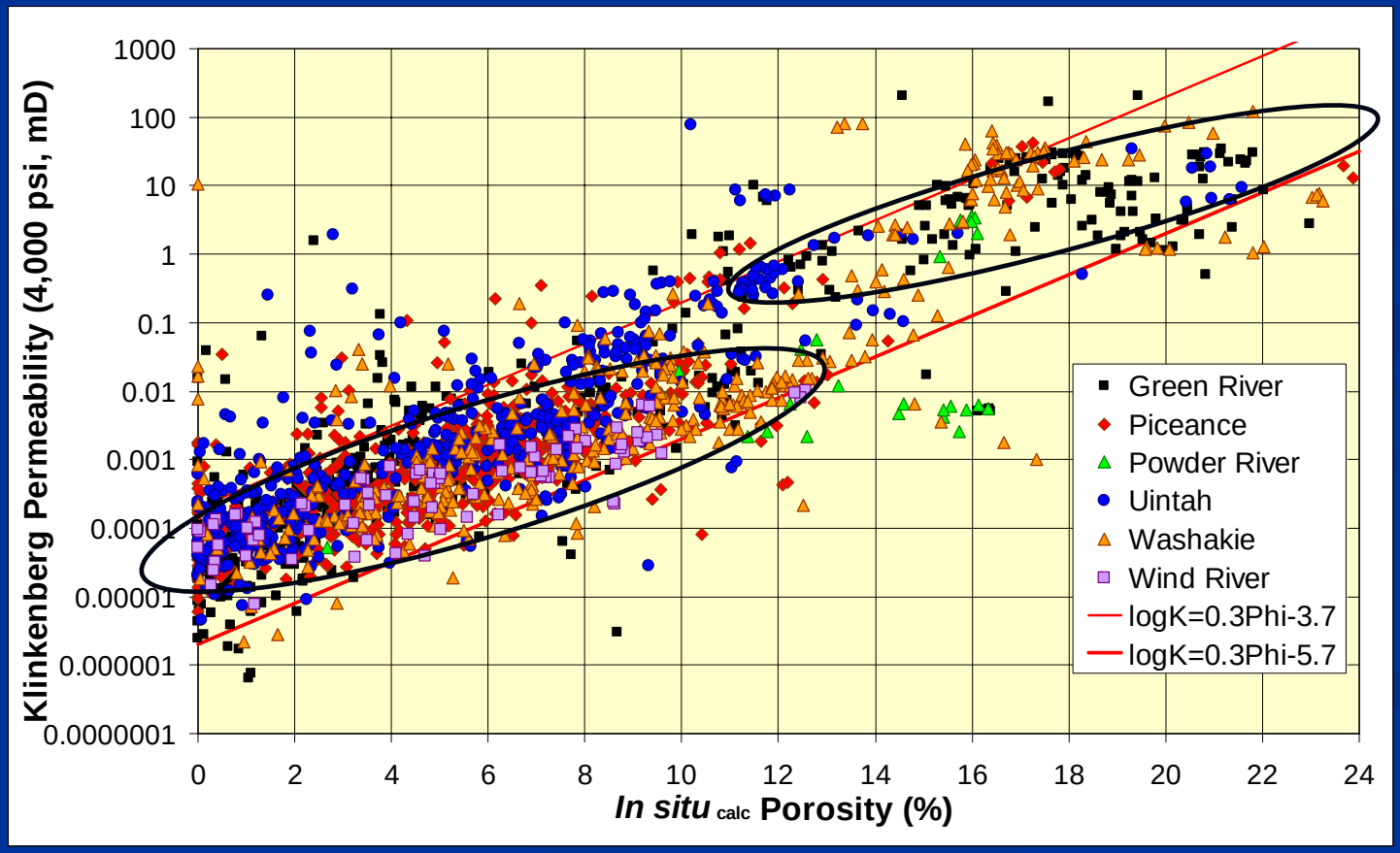
- Known for many years that low-K sandstones are stress sensitive
- Generalized = f (P_{pore}, Lith)
- 1997 Byrnes equation:

  k_{ik} = 10^[1.34 ($\log k_{air}$) - 0.6]
- This study:

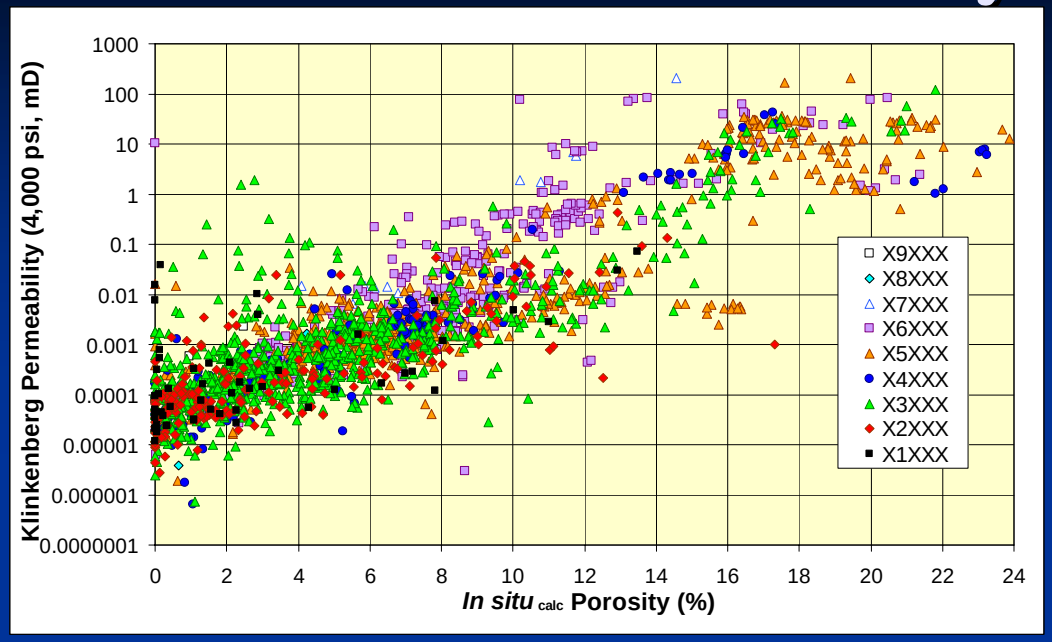
  k_{ik} = 10^[0.0088 $(\log k_{air})^3$ - 0.072 $(\log k_{air})^2$+ 1.37 $\log k_{air}$ +0.46]
- Statistically similar except for k > 1 mD
- no meaningful stress dependence over 10 mD

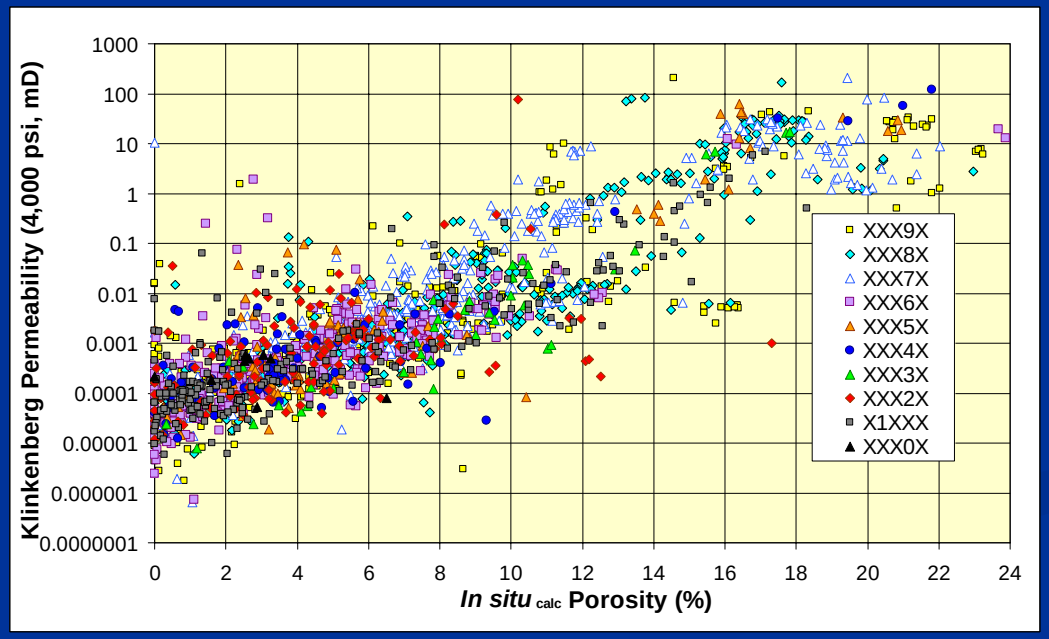
Permeability vs Porosity

- Overall trend allows prediction of Kik from porosity with 10X error
- Breaking into two subtrends at ϕ~12% improves to 5X error
- Different k-ϕ trends among basins
- Beyond common k↑ with grain size↑, lithologic influence changes are complex and nonlinear

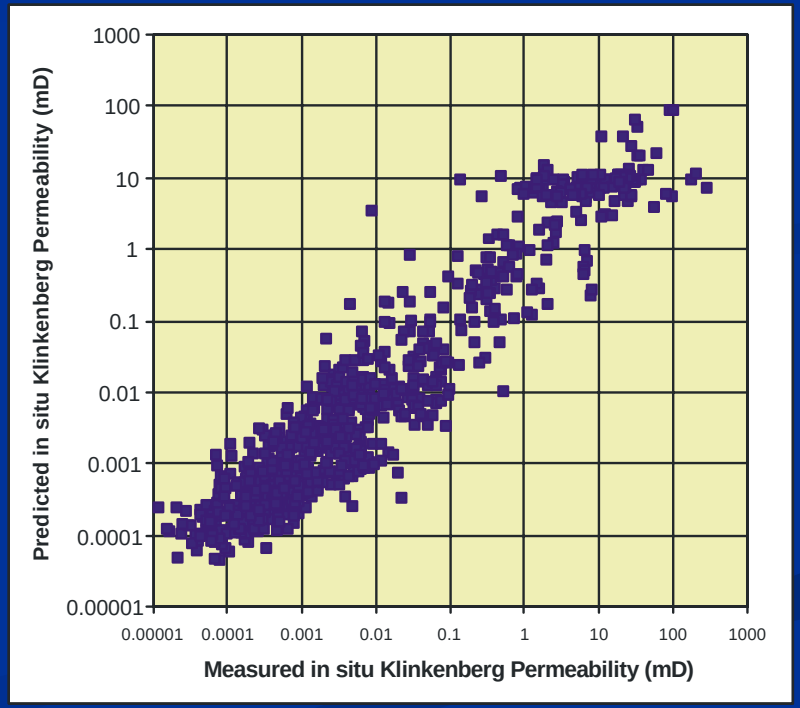


Permeability vs Porosity





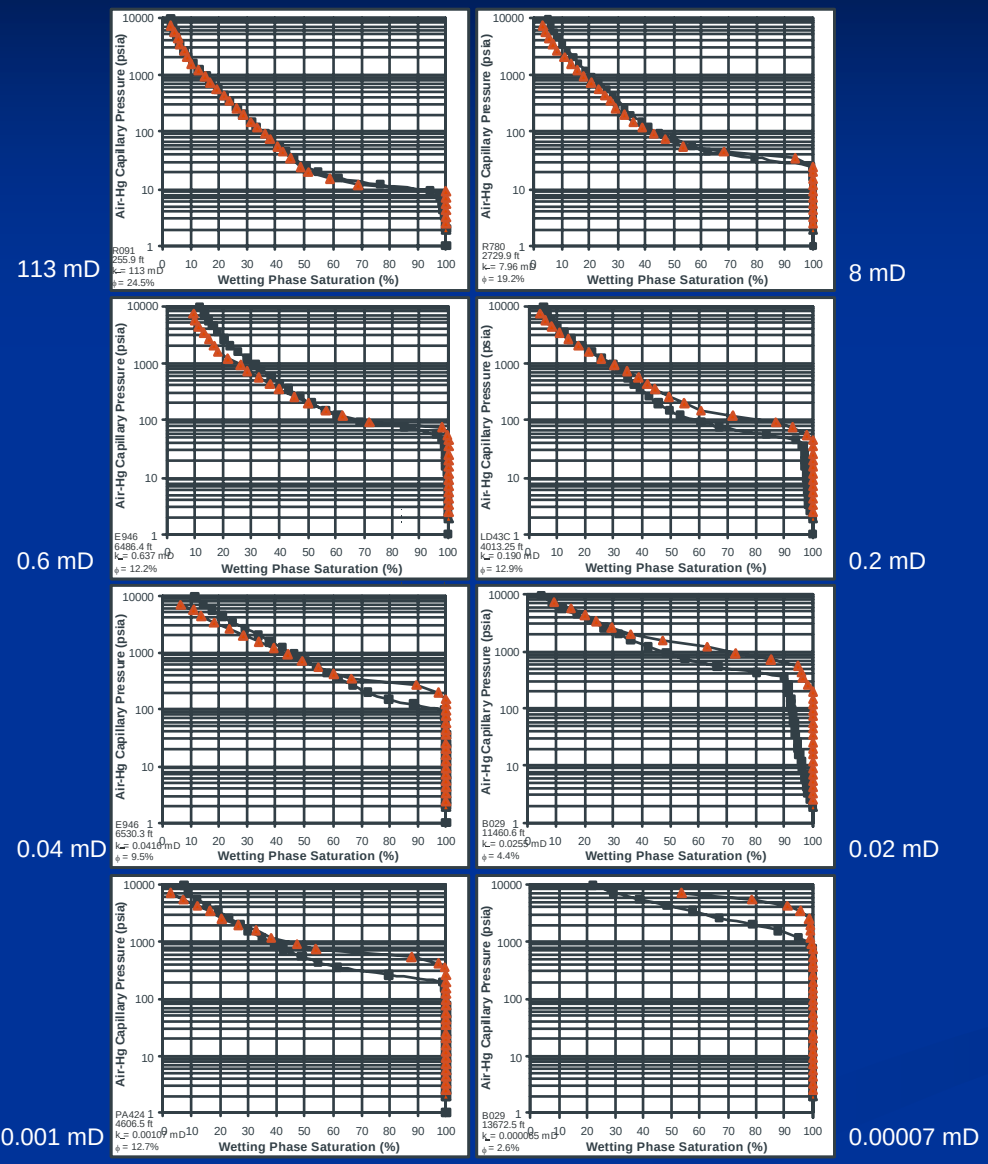
- $\log k_{ik} = 0.234\phi_i + 0.12RC_2 - 4.71$ ($\pm$4X; ϕ<12%)
- $\log k_{ik} = 0.265\phi_i + 0.11RC_2 - 4.80$ ($\pm$5X; 0<ϕ<24%)
- Artificial Neural Network $\pm$3.3X

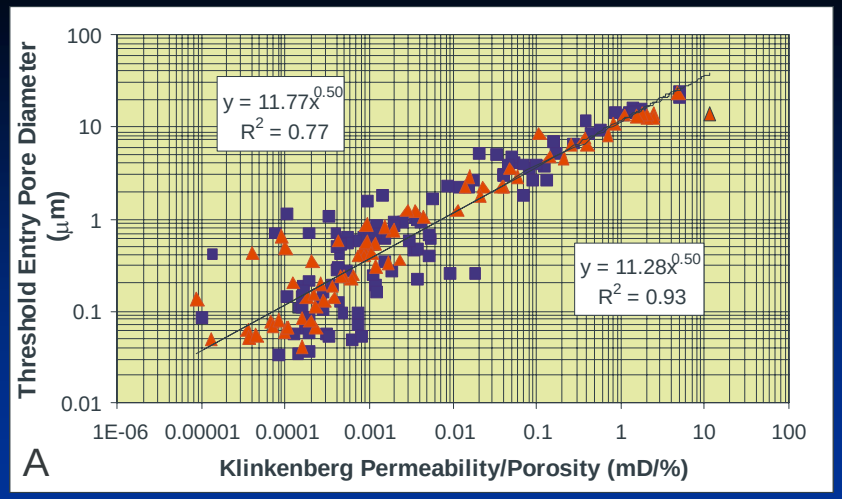


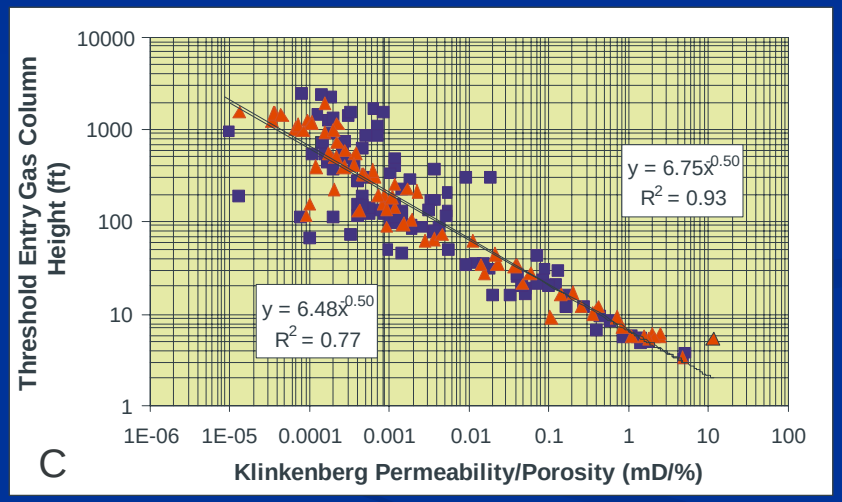
Capillary pressure

- investigating Pc as *f* (lithology, ϕ, K)
  - 120 high-low pairs
  - sampled across basins, permeability range, & lithology
- stress sensitivity of Pc
  - most MICP curves are run under laboratory conditions, but given stress dependence of permeability we expect Pc 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



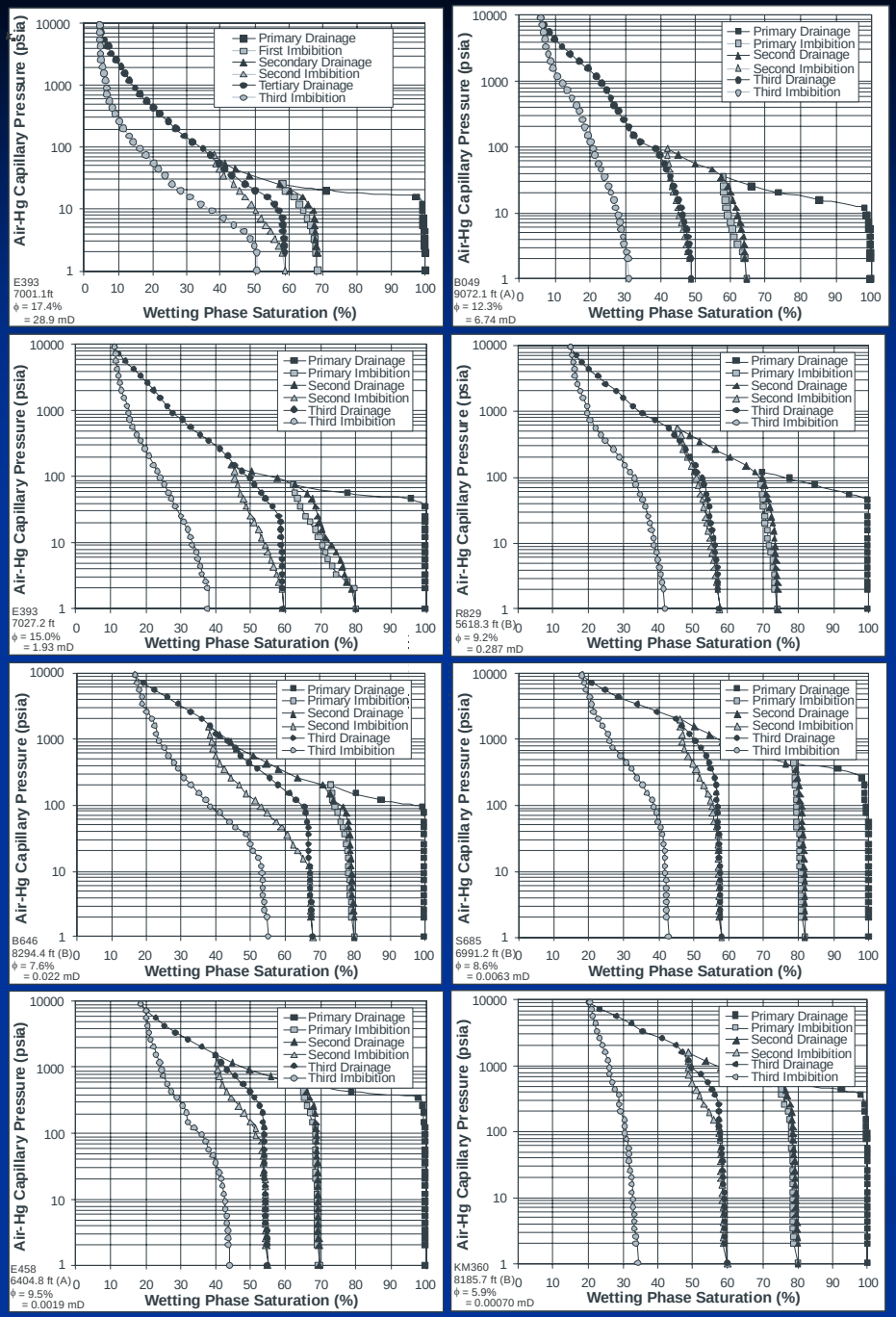


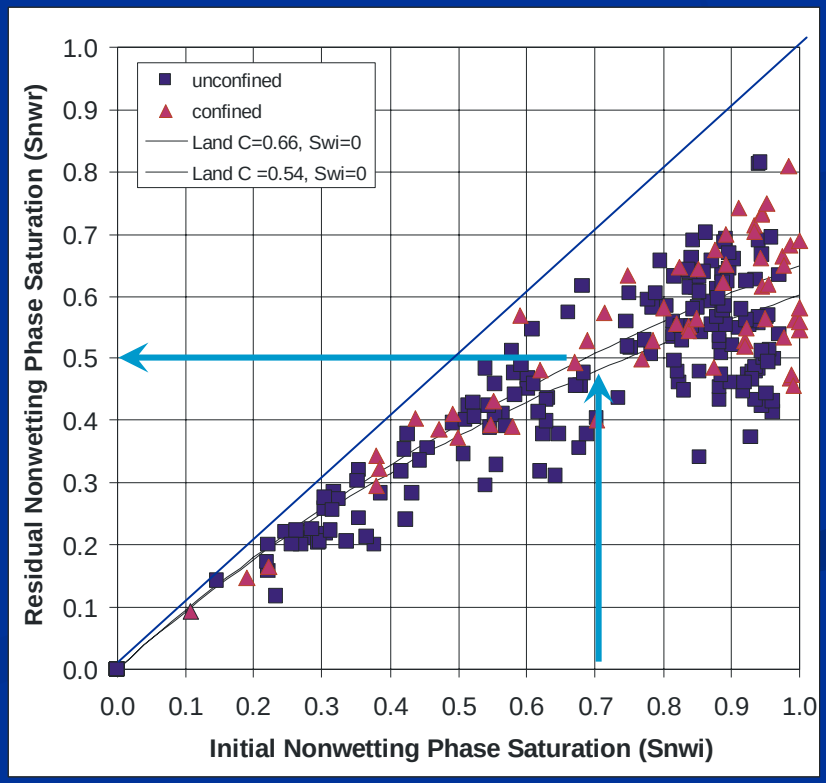


- threshold entry pressure is entirely predictable from $\sqrt{K/\phi}$ ratio at any P

Residual Gas Saturation

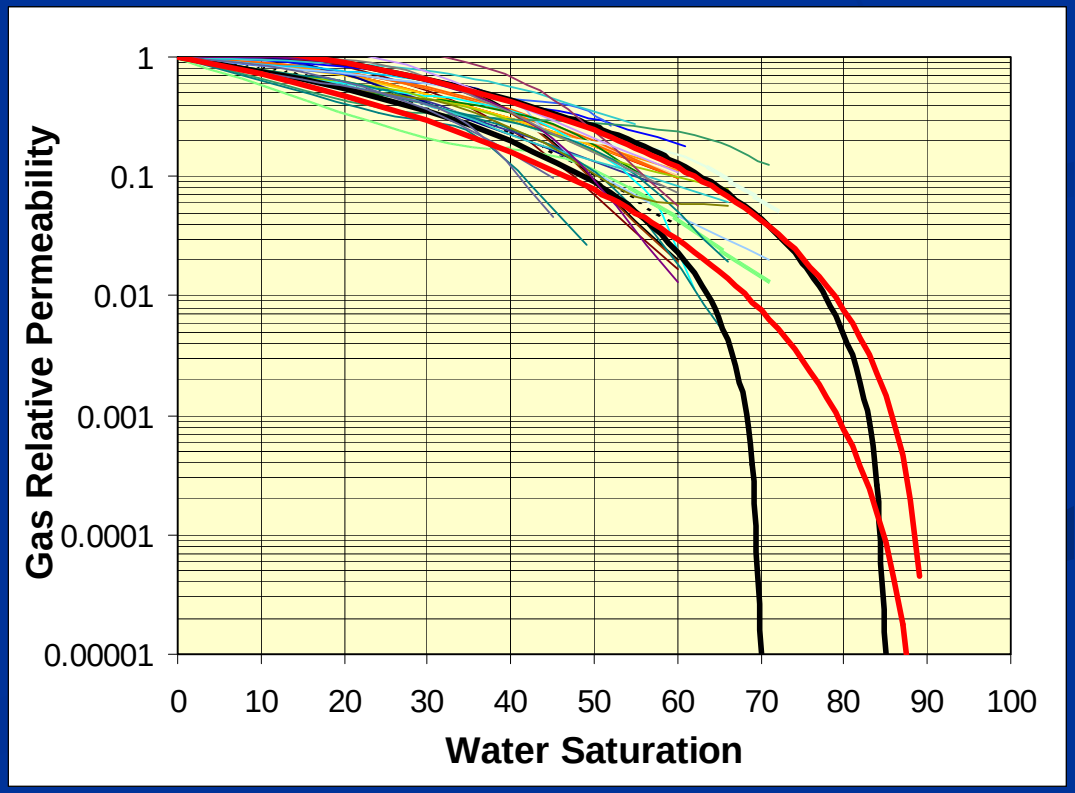
- Snwi and Snwr are ~ = for Sw > 80%
- e.g., for Swi of 30%, Swr is ~50%





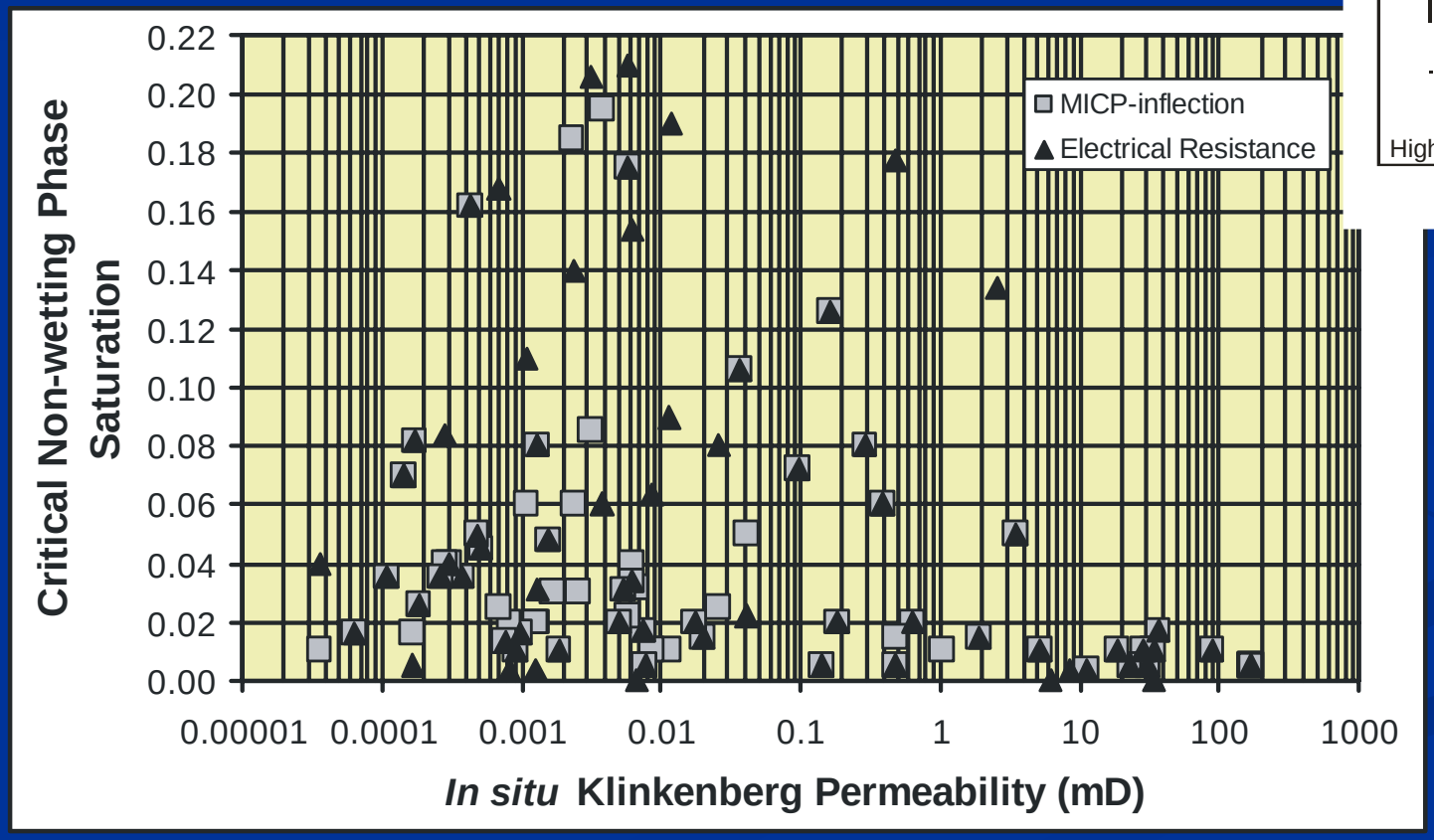
Critical Gas Saturation

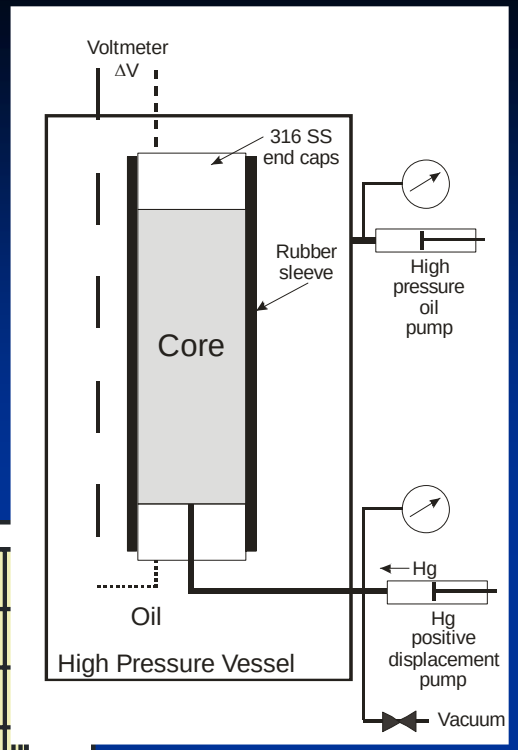
- Experimental work indicates Sgc < 10% often < 5%
- <u>but</u> krg curves extrapolate to 35% < Sgc < 0%
- <u>Issues</u>
  - little krg data at Sw > 65%
  - two different ways to model the data, which is better?



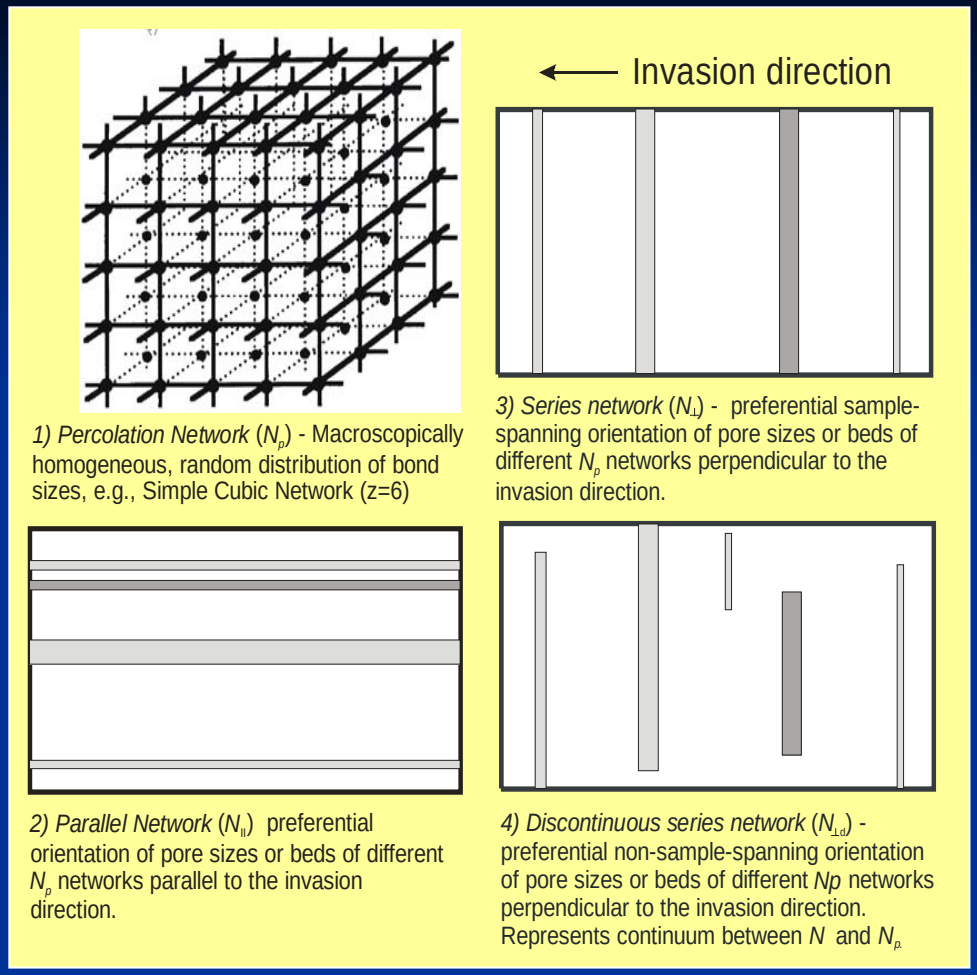
Critical Nonwetting Phase Saturation

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

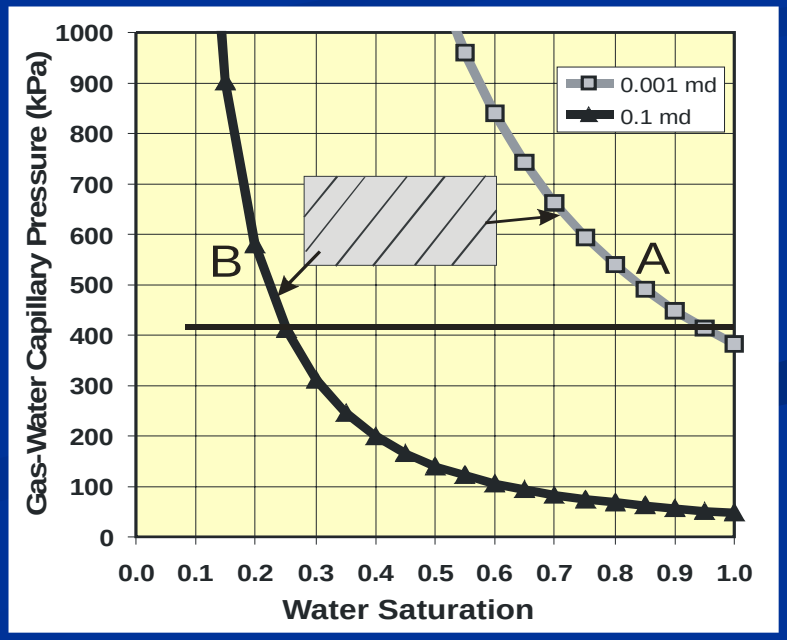




Sgc and percolation theory



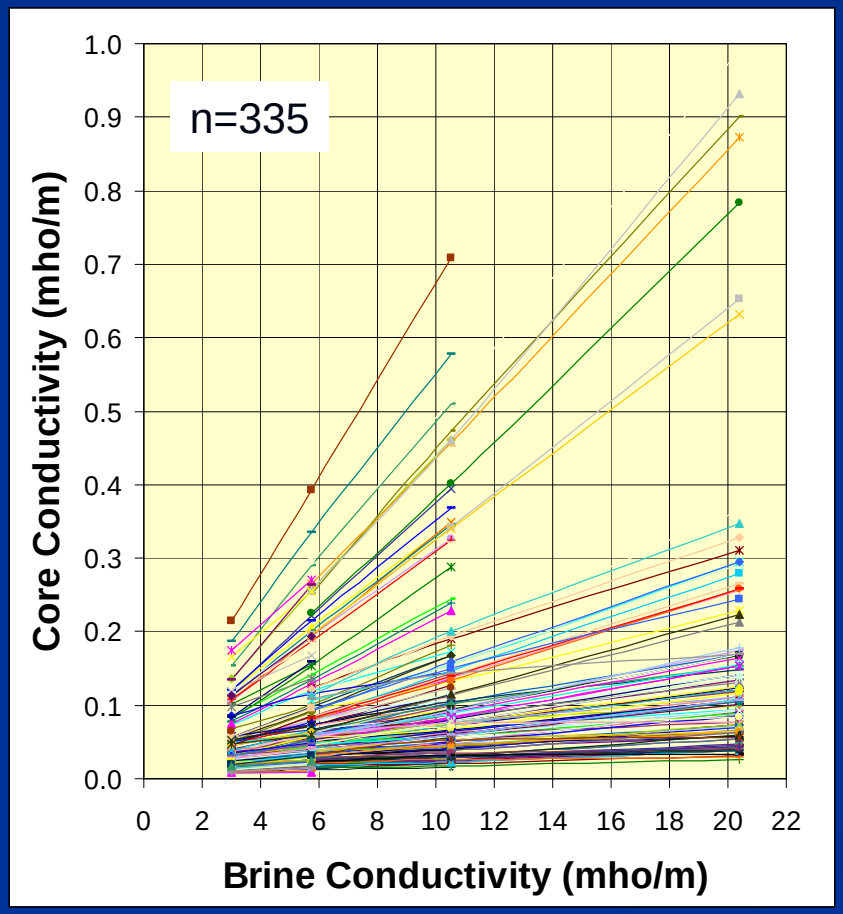
- critical gas saturation strongly controlled by sedimentary structures/rock fabric
- <u>any</u> bedding parallel laminations result in low Sgc

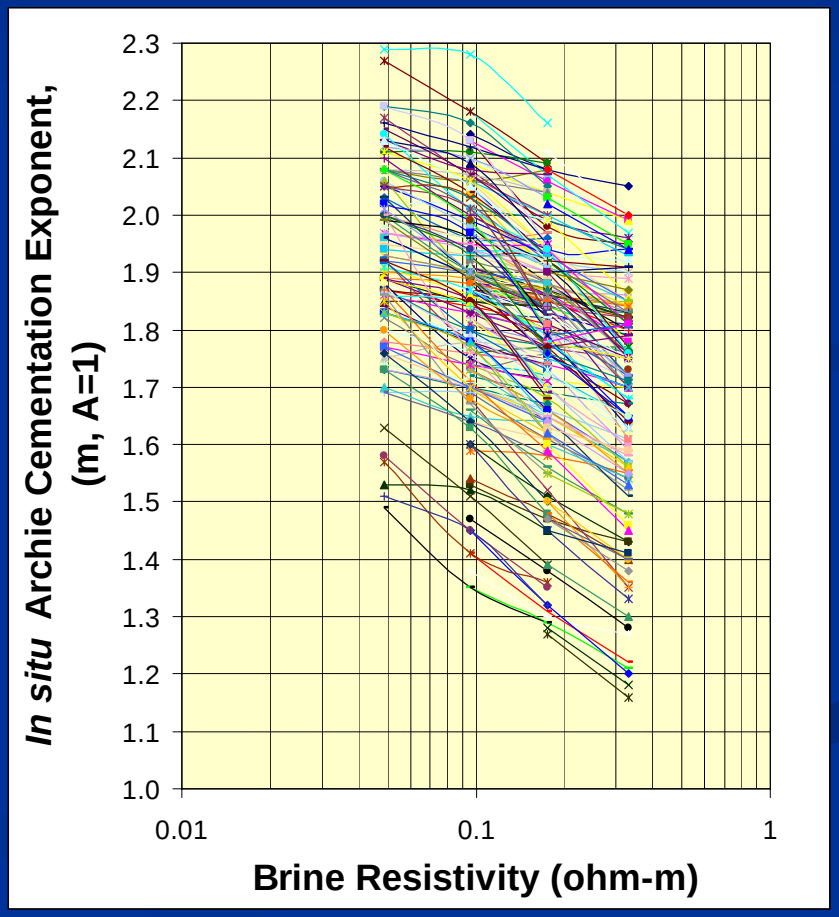


- experimental results can be explained using four - pore network architecture models

Archie porosity (cementation) exponent

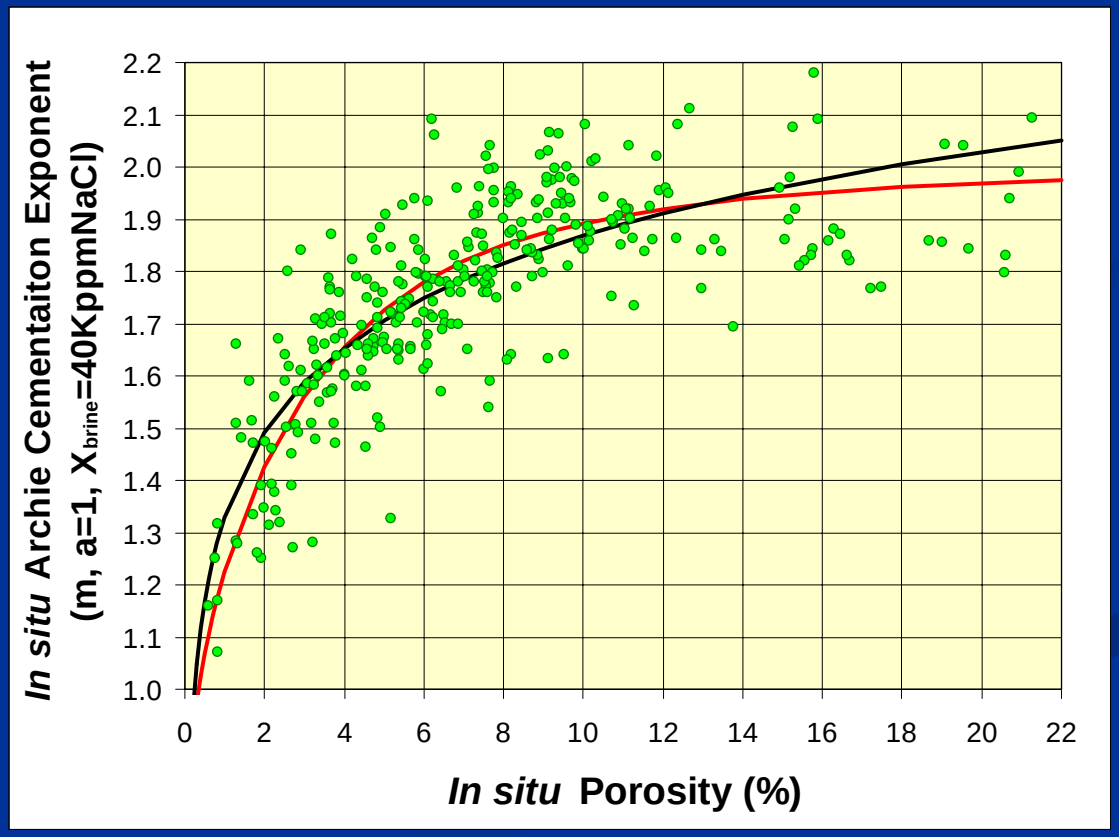
- Nearly all cores exhibit some salinity dependence
- tested plugs with 20K, 40K, 80K, and 200K ppm brines





Porosity dependence of "m"

- Empirical: $m = 0.234 \ln \phi + 1.33$
- Dual porosity: $m = \log[(\phi-\phi_2)^{m1} + \phi_2^{m2}]/\log \phi$
  - $\phi_2 = 0.35\%$ $m_1=2$, $m_2=1$; SE both = 0.11
  - rock behaves like a mixture of matrix porosity and cracks or fractures
- both models fit data



ϕ = bulk porosity

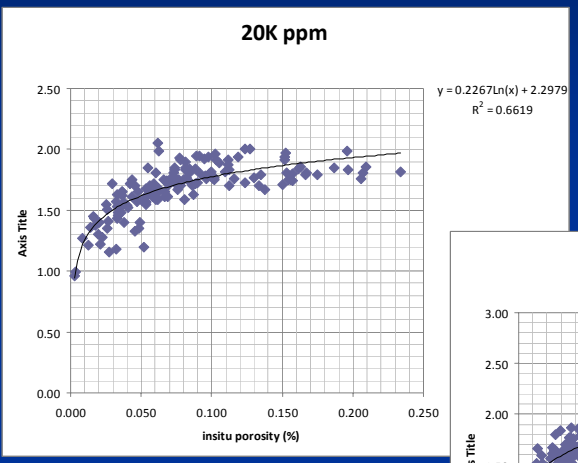
ϕ_2 = fracture porosity

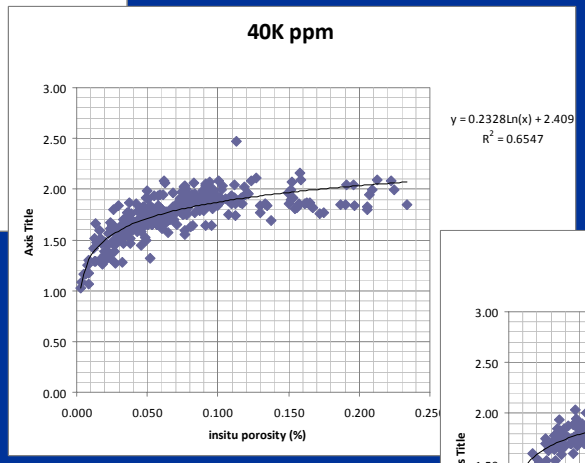
m_1 = matrix cementation exponent

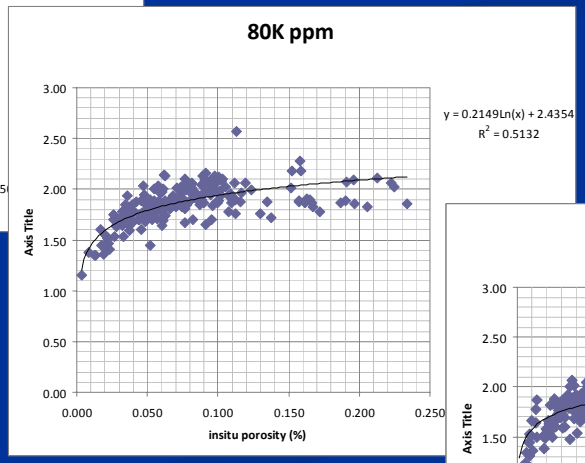
m_2 = fracture cementation exponent

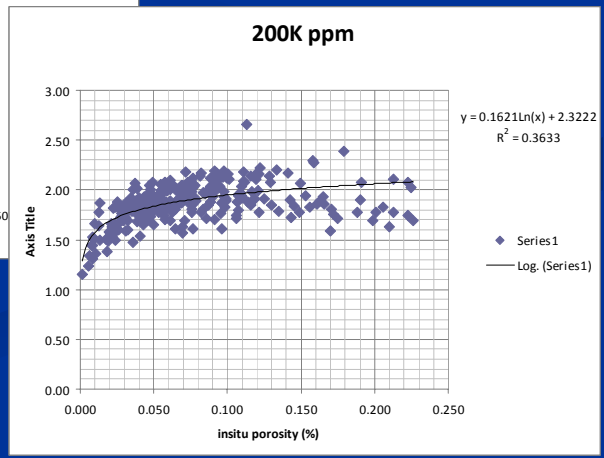
Salinity dependence of "m"

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



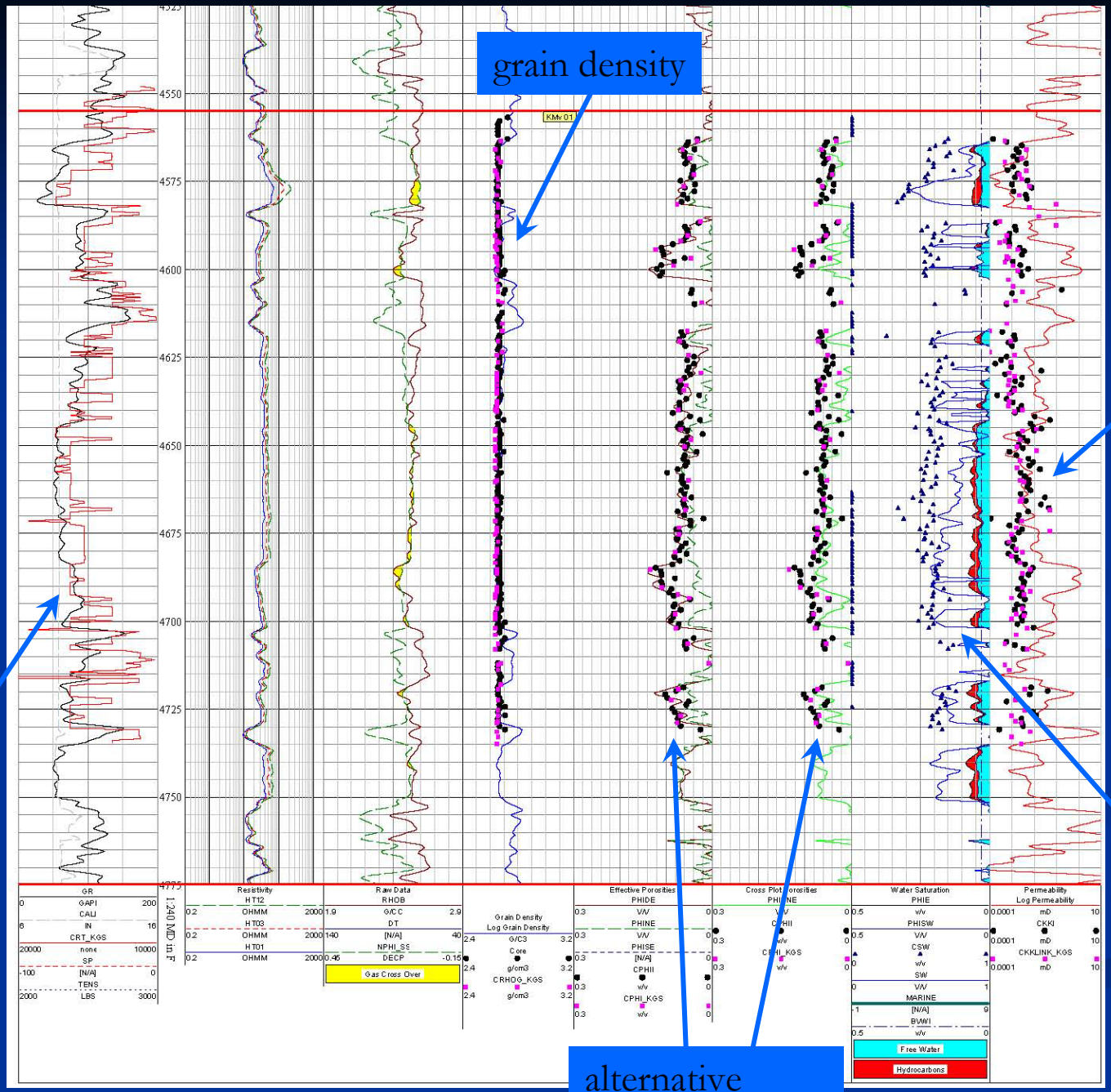






Log modeling

- 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


grain density
Kabs
core rock number vs. GR
Sw model
alternative porosity models
KMv 01
4550
4575
4600
4625
4650
4675
4700
4725
4750
4775
1:240 MD in F
GR
GAPI
CALI
IN
CRT_KGS
SP
TENS
LBS
Resistivity
HT12
HT03
HT01
OHMM
Raw Data
RHOB
G/C C
DT
NPHI_SS
DECP
Gas Cross Over
Grain Density
Log Grain Density
G/C3
Core
g/cm3
CRHOG_KGS
Effective Porosities
PHIDE
PHINE
PHISE
CPHII
CPHI_KGS
Cross Plot Porosities
Water Saturation
PHIE
PHISW
CSW
SW
MARINE
BVWI
Free Water
Hydrocarbons
Permeability
Log Permeability
CKKI
CKKLINK_KGS

Advanced log modeling

- variable grain density model as *f* (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 (Pc) 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: $(1/Snwr)-(1/Snwi) = 0.55$
- Critical gas saturation is low ($Sgc < 0.05$) 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?

The Discovery Group, Inc.