Regional petrophysical properties of Mesaverde low-permeability sandstones

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

US DOE # DE-FC26-05NT42660

US DOE Project Summary

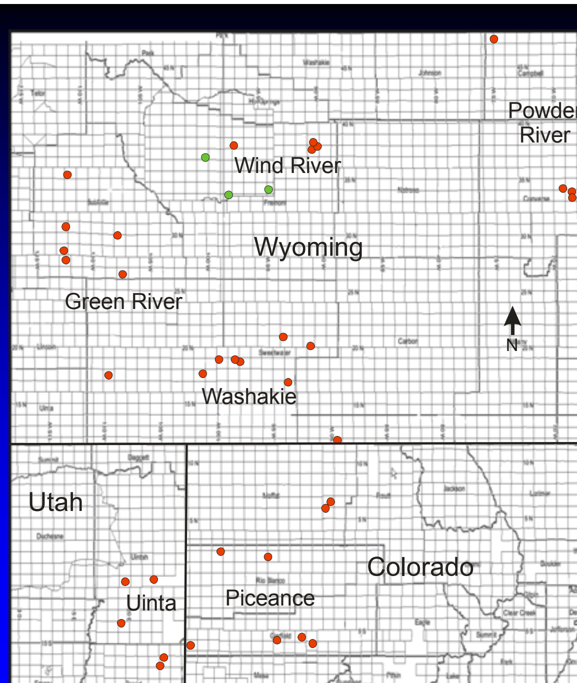
- Solicitation DE-PS26-04NT42072-0
  - subtopic area 1: Understanding Tight Gas Resources
  - Award Date: October 1, 2005
  - Completion Date: June 30, 2008
  - Contract # DE-FC26-05NT42660
- Organization: University of Kansas, Kansas Geological Survey
- Principal Investigator: Alan P. Byrnes, KGS
-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

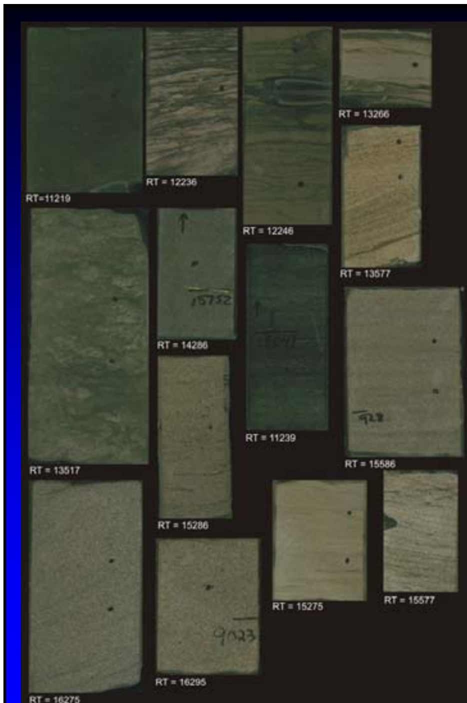
Objectives

- The project will provide petrophysical tools that address:
  - 1) minimum gas flow, critical and residual gas saturation, Sgc=f(lithofacies, Pc, architecture)
  - 2) capillary pressure, Pc=f(P), Pc=f(lithofacies, k, ϕ, architecture)
  - 3) electrical properties, m* & n*
  - 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 sample
- 150-300 advanced properties samples



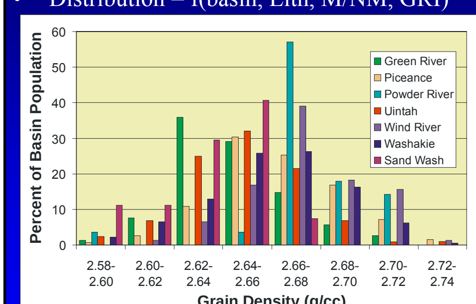


Digital Core Description

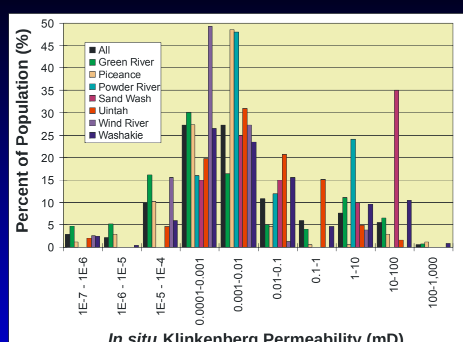
- Sampling designed to sample across all lithofacies
- To provide lithologic input to equations and predict lithology from log s used 5 digit system
  - basic type (Ss, Ls, coal)
  - grain size/sorting/texture
  - consolidation
  - sedimentary structure
  - cement mineralogy
- Property continuum not mnemonic

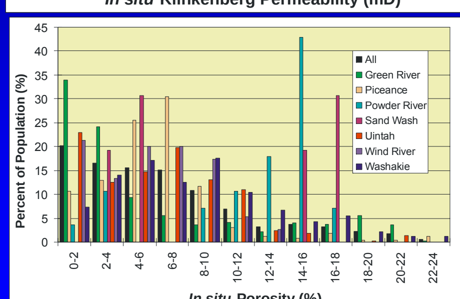
Basic Properties Distributions

- Sampling QA
- Distribution is sampling dependent but interesting
- Distribution = f(basin, Lith, M/NM, GRI)

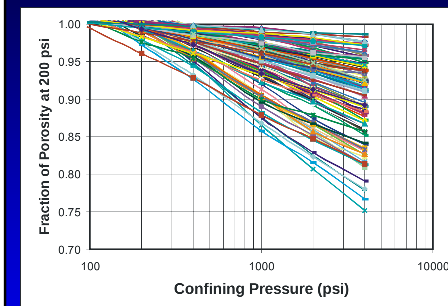


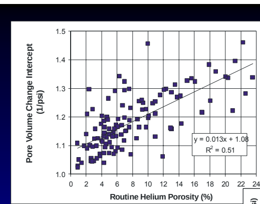
	mean	median	stdev	Δϕ - 2.65
All	2.654	2.652	0.033	0.2
Green River	2.645	2.641	0.028	-0.2
Piceance	2.663	2.662	0.035	0.7
Powder River	2.679	2.674	0.026	1.5
Sand Wash	2.633	2.639	0.020	-0.9
Uintah	2.646	2.648	0.031	-0.2
Washakie	2.662	2.661	0.034	0.6
Wind River	2.672	2.673	0.029	1.1

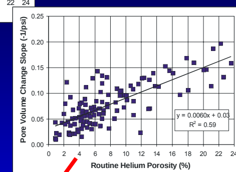


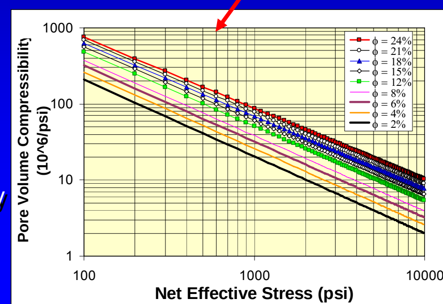


Pore Volume Compressibility



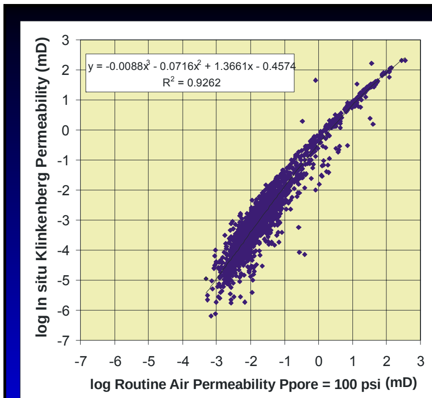




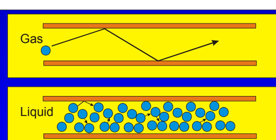


- $\phi_{insitu} = \phi_{routine} - 0.8$ (%)
- 113 Samples
- Log-linear pore volume change characteristic of fractures/sheet-pores
- Slope and intercept change with porosity
- $\beta = 10$^[(0.000031ϕ^2+0.00275ϕ-1.016)*logP +(0.000034ϕ^3-0.00223ϕ^2+0.056ϕ+4.238)]

In situ Klinkenberg Permeability

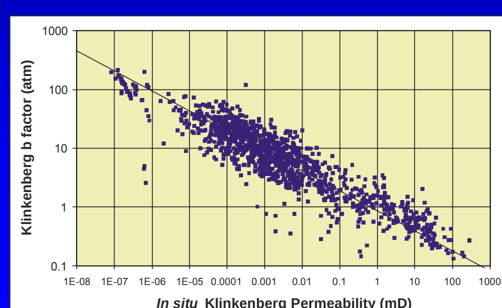


- Generalized = f(P_{pore}, Lith)
- $k_{ik} = 10$^[0.0088 ($logk_{air}$)^3 - 0.072 ($logk_{air}$)^2+ 1.37 $logk_{air}$ +0.46]
- $k_{ik} = 10$^[1.34 ($logk_{air}$) - 0.6] (Byrnes, 1997)
- Statistically similar except for k > 1 mD



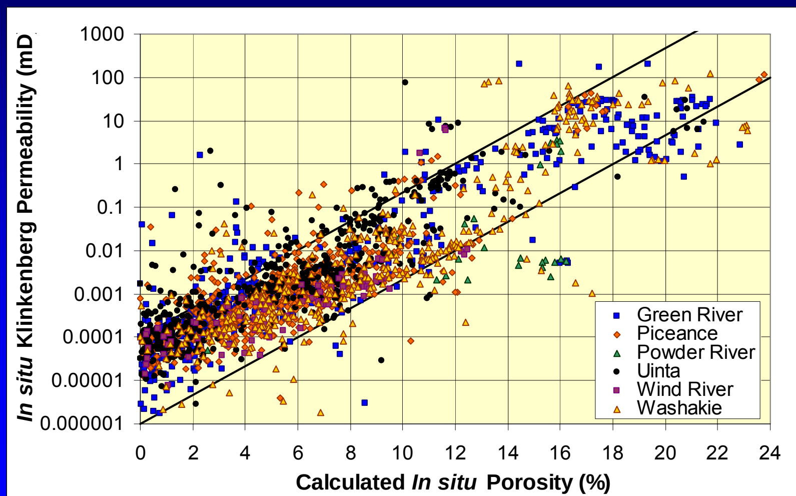
$k_{gas} = (1+b/P)$

- $b = 0.851\ k_{ik}^{-0.34}$ (Present Study)
- $b = 0.867\ k_{liq}^{-0.33}$ (Jones & Owens)
- $b = 0.777\ k_{liq}^{-0.39}$ (Heid)

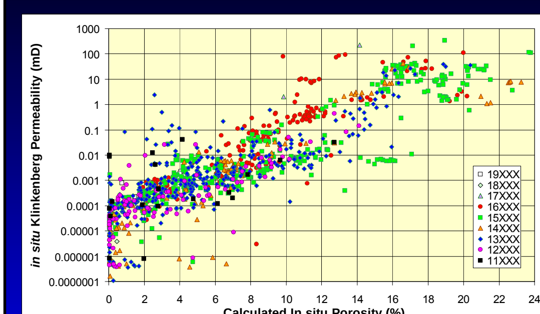


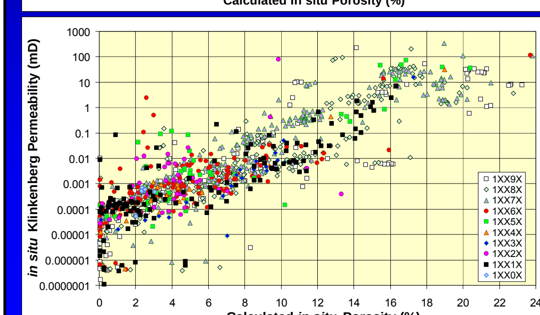
Permeability vs Porosity

- Generalized trend $k_{ik} = 10^{[0.333\phi i-5]}$ with 10X error
- Different k-ϕ trends among basins due to lithologic variation
- Beyond common k↑ with grain size↑, lithologic influence changes with porosity - nonlinear

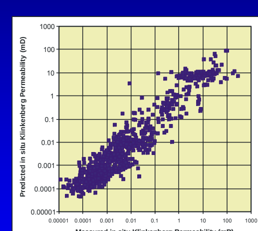


Permeability vs Porosity





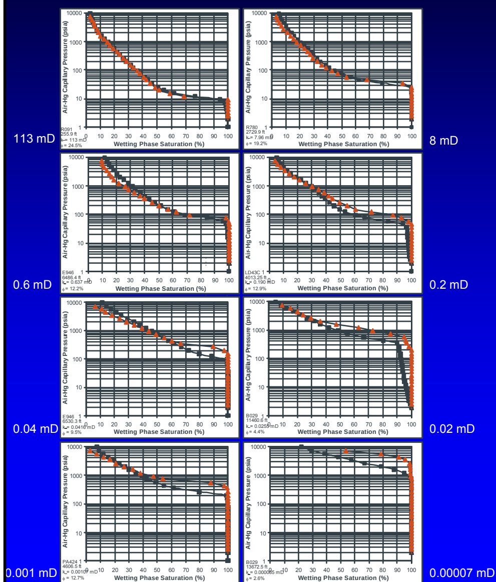
- $\log k_{ik} = 0.282\phi_i + 0.18RC_2 - 5.13$ (±4.5X MLRA)
- $\log k_{ik} = 0.034\phi_i^2 - 0.00109\phi_i^3 + 0.0032RC_2 - 4.13$ (±4.1X MNLRA)
- Artificial Neural Network ±3.3X

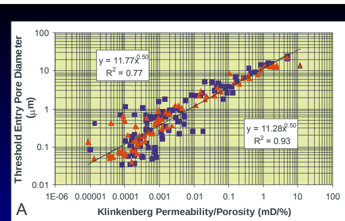


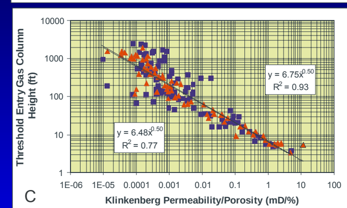
hidden layer: 1
Hidden layer nodes: 10

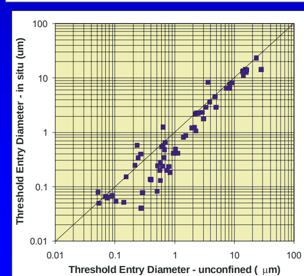
Node	Constant	Phii	RC2	RC4	hidden layer-to-output weights
	Mean>	8.239	4.280	6.294	
	Std Dev>	5.260	1.335	2.527	
	Input-to-hidden layer weights				
Constant					-0.388
1	-0.760	2.946	-2.027	-6.438	-0.885
2	-2.155	4.637	1.279	0.895	2.323
3	-4.999	7.901	0.957	3.167	-2.583
4	-1.484	-0.307	-1.695	6.175	-0.154
5	-4.597	4.582	1.568	0.730	4.022
6	-2.609	0.320	-2.201	-2.257	-2.495
7	-1.765	-1.843	-1.122	0.145	-3.859
8	2.839	-3.146	-9.237	0.264	0.789
9	-1.566	1.029	-1.588	-3.390	2.400
10	2.951	0.778	3.316	0.179	-2.136

Capillary Pressure under Pressure





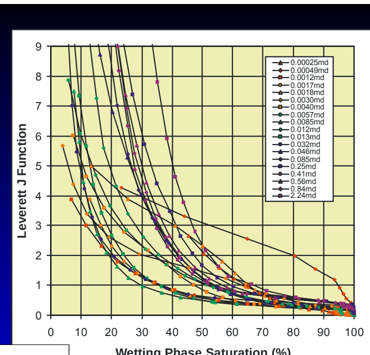


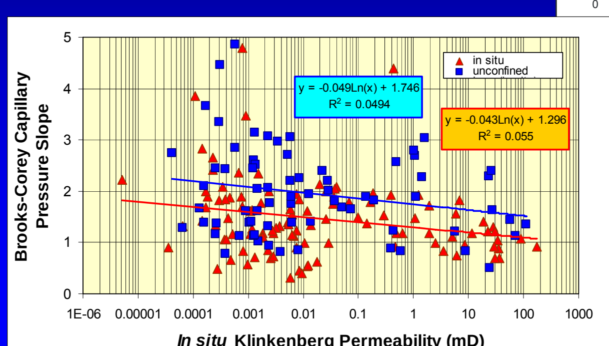


Capillary Pressure

Pore Size Distribution (PSD)

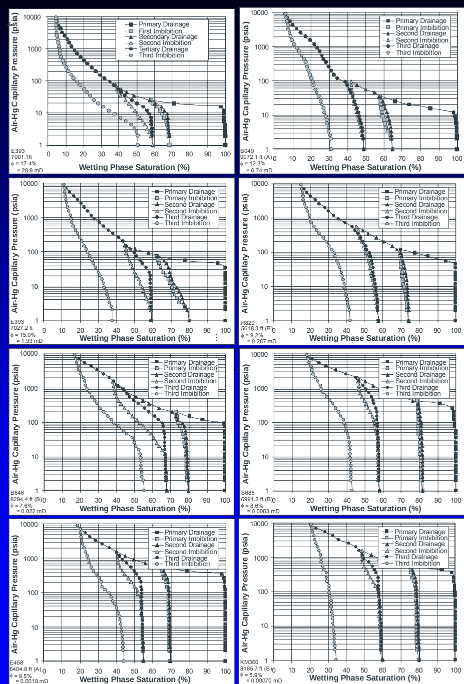
- PSD expressed by Pc_{slope}
- $Pc_{slope} = f(k)$
- $Pc_{slope} \downarrow$ with P $\uparrow$





Leverett J(Sw) = Pc $(k/\phi)^{0.5}/\tau\cos\theta$

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

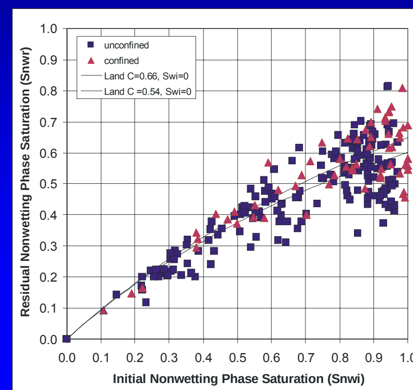


Residual Gas Saturation

$$C = 1/S_{nwr} - 1/S_{nwi}$$

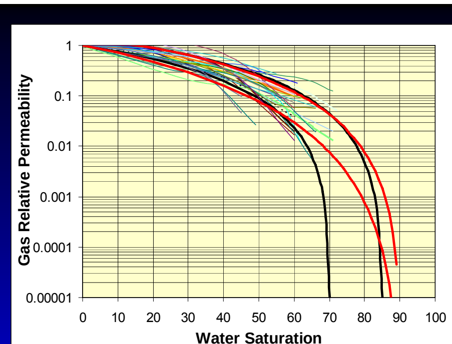
$$S_{nwr} = 1/[C + 1/S_{nwi}]$$

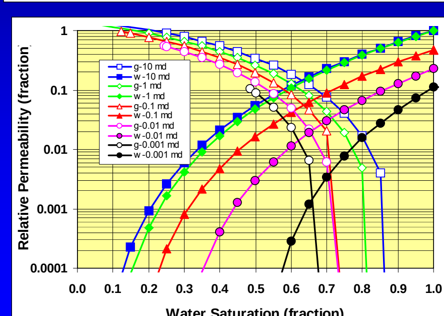
$$C = 0.55 \ (\min \varepsilon)$$



Critical Gas Saturation

- Experimental work indicates Sgc < 10% often < 5% but krg curves extrapolate to 35% < Sgc < 0%
- Issues
  - little krg data at Sw > 65%

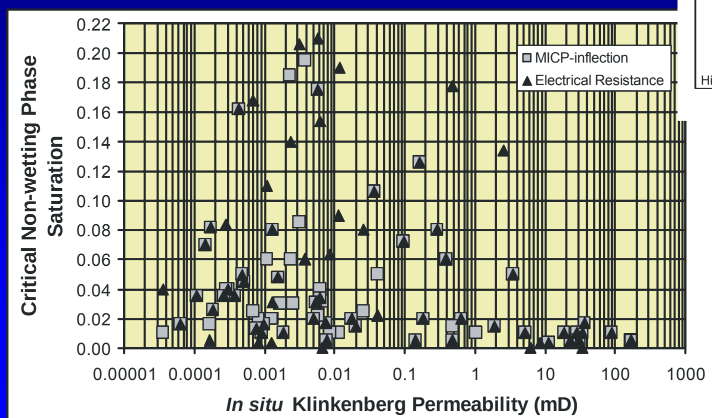


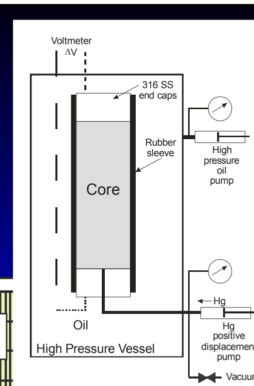


← S_{gc}?

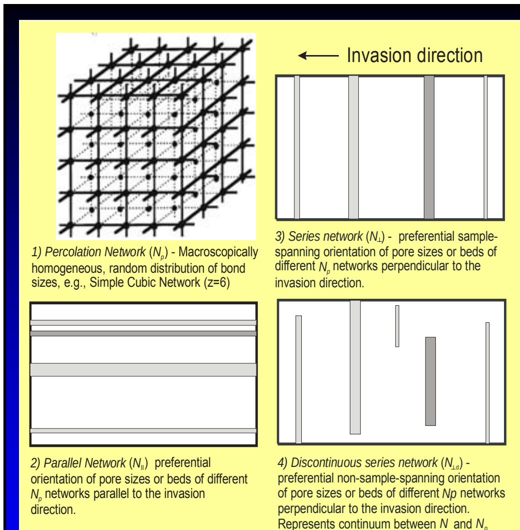
Critical Nonwetting Phase Saturation

- Electrical conductivity and Pc inflection indicate 0% < Sgc < 22%
- Higher Sgc in complex bedding lithofacies





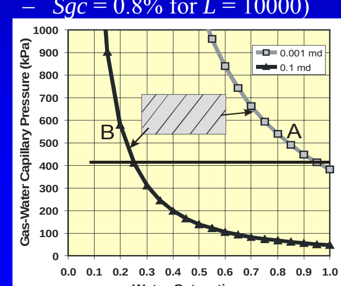
Sgc and Percolation



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

- $Sgc(L) = A\,L^{D-E}$

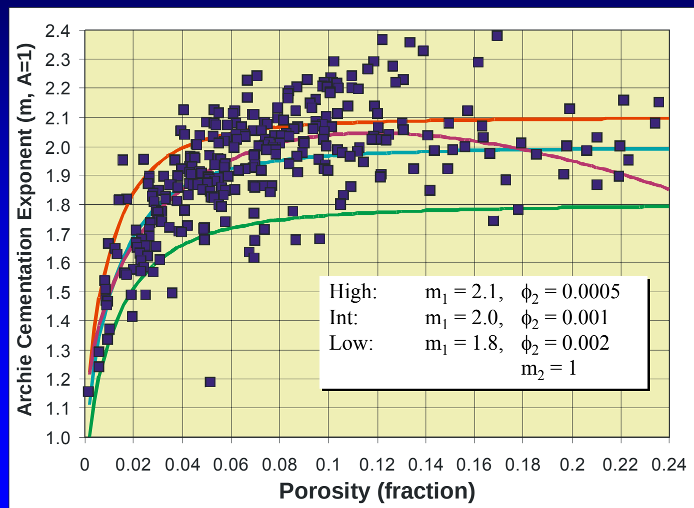
  (Wilkinson and Willemsen, 1983)
  - L is network dimension
  - A is a numerical constant (for simple cubic network A = 0.65)
  - *D* is the mass fractal dimension of the percolation cluster
  - E is the Euclidean dimension
- As $L \to \infty$ $\quad Sgc \to 0$
  - *Sgc* = 21.5% for *L* = 10
  - *Sgc* = 2.4% for *L* = 1000
  - *Sgc* = 0.8% for *L* = 10000)



Archie Cementation Exponent

- Empirical: $m = 0.95 - 9.2\phi + 6.35\phi^{0.5}$
- Dual porosity: $m = \log[(\phi-\phi_2)^{m1} + \phi_2^{m2}]/\log\phi$

- ϕ = bulk porosity
- ϕ_2 = fracture or touching vug porosity
- m_1 = matrix cementation exponent
- m_2 = fracture or touching vug cementation exponent



Conclusions

- Grain density for 2200 samples averages 2.654+0.033 g/cc (+1sd) but grain density distributions differ slightly among basins, lithofacies.
- $\log k_{ik} = 0.282\ \phi_i + 0.18\ RC2 - 5.13$ ($\pm$4.5X,1 sd)
- ANN analysis provides prediction within ($\pm$3.3X)
- Capillary pressure (Pc) exhibits an log-log threshold entry pressure (Pte) versus k_{ik}/ϕ_i trend and variable Brooks-Corey slopes.
- Snwr ↑ with Snwi ↑ Land-type relation: 1/Snwr-1/Snwi = 0.55
- Critical nonwetting-phase (e.g., gas) saturation is low (Sgc < 0.05) in massive and parallel bedded lithologies but may increase in rocks with more complex bedding - Percolation theory provides a tool for predicting limits.
- Archie cementation exponent (m) decreases with decreasing porosity below approximately 6% - empirical or by a dual- porosity model
- These relationships are still being investigated.
- Mesaverde Project website is http://www.kgs.ku.edu/mesaverde
- Poster presentation