Why MICP?

- Only pore throat experiment

Why not more MICP?

- Performed on plugs
- Inexpensive
- Lack of quick analytical tools to deal with the expanded workflow of more data

Solution – Thomeer-Swanson Spreadsheet Shareware – Lumping and Splitting

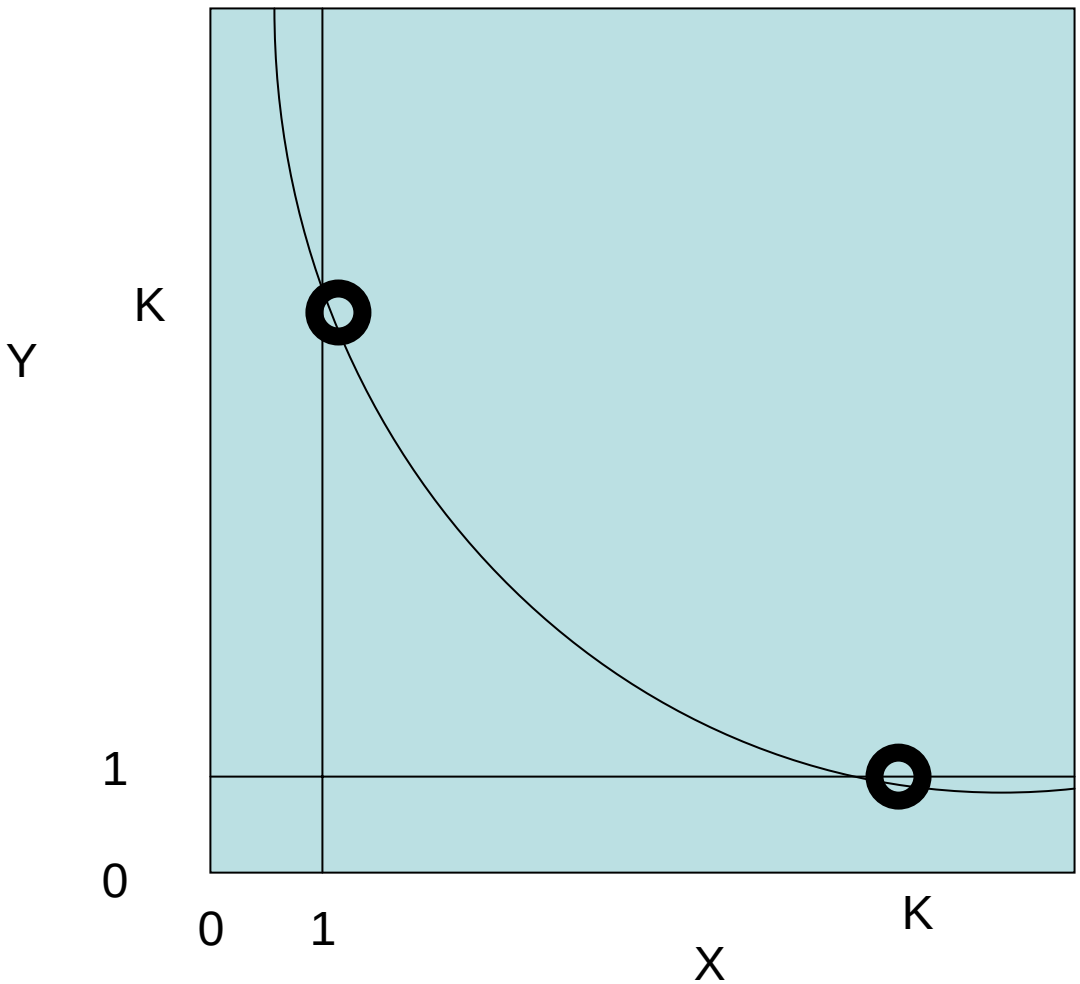
Using Hyperbolae for MICP Analysis
The Thomeer Swanson Spreadsheet

Hyperbola

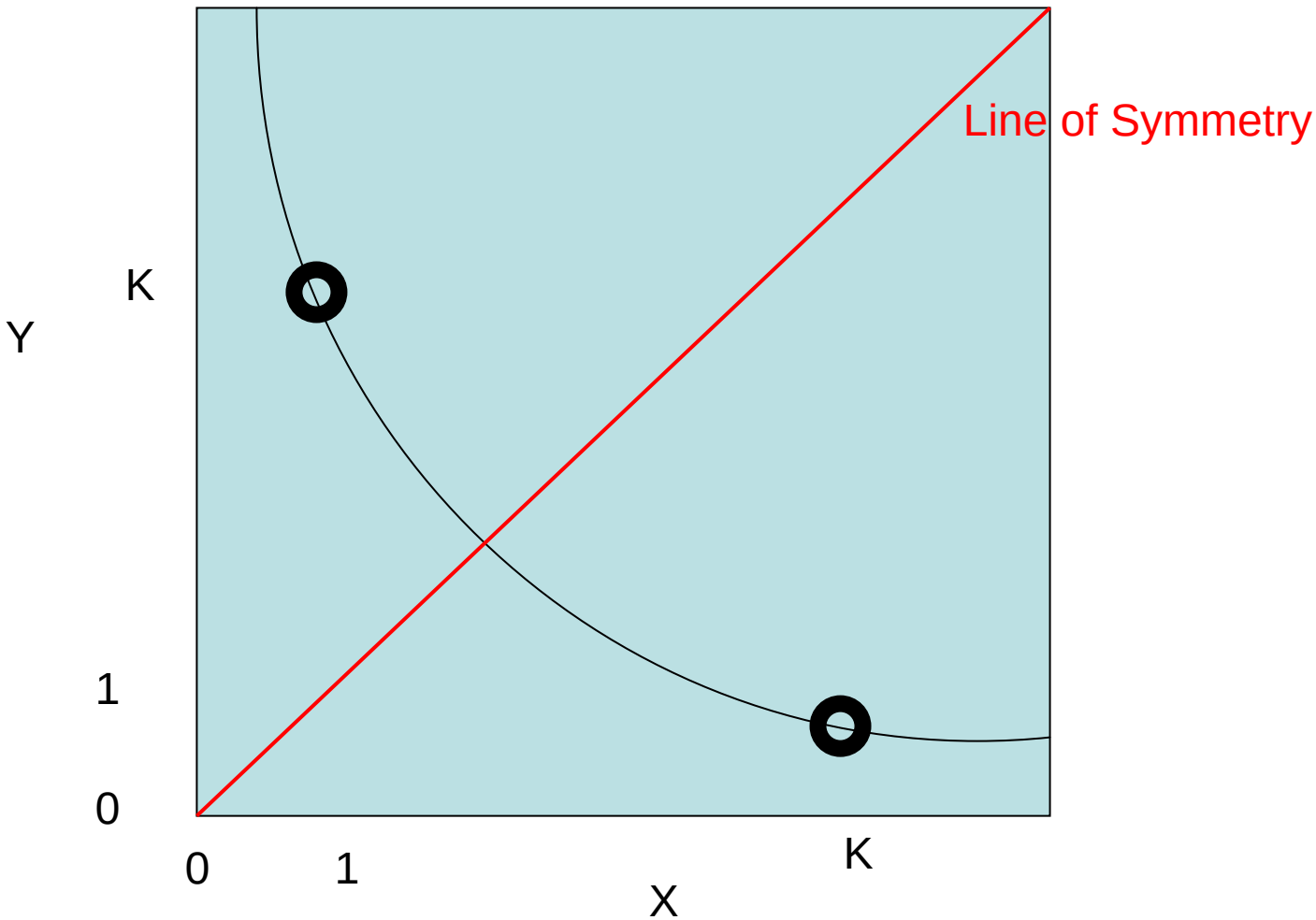
X * Y = constant, K

- Properties:
- When either X or Y are 1, then y or x are K, respectively
- As either X or Y approach 0, Y or X approach infinity

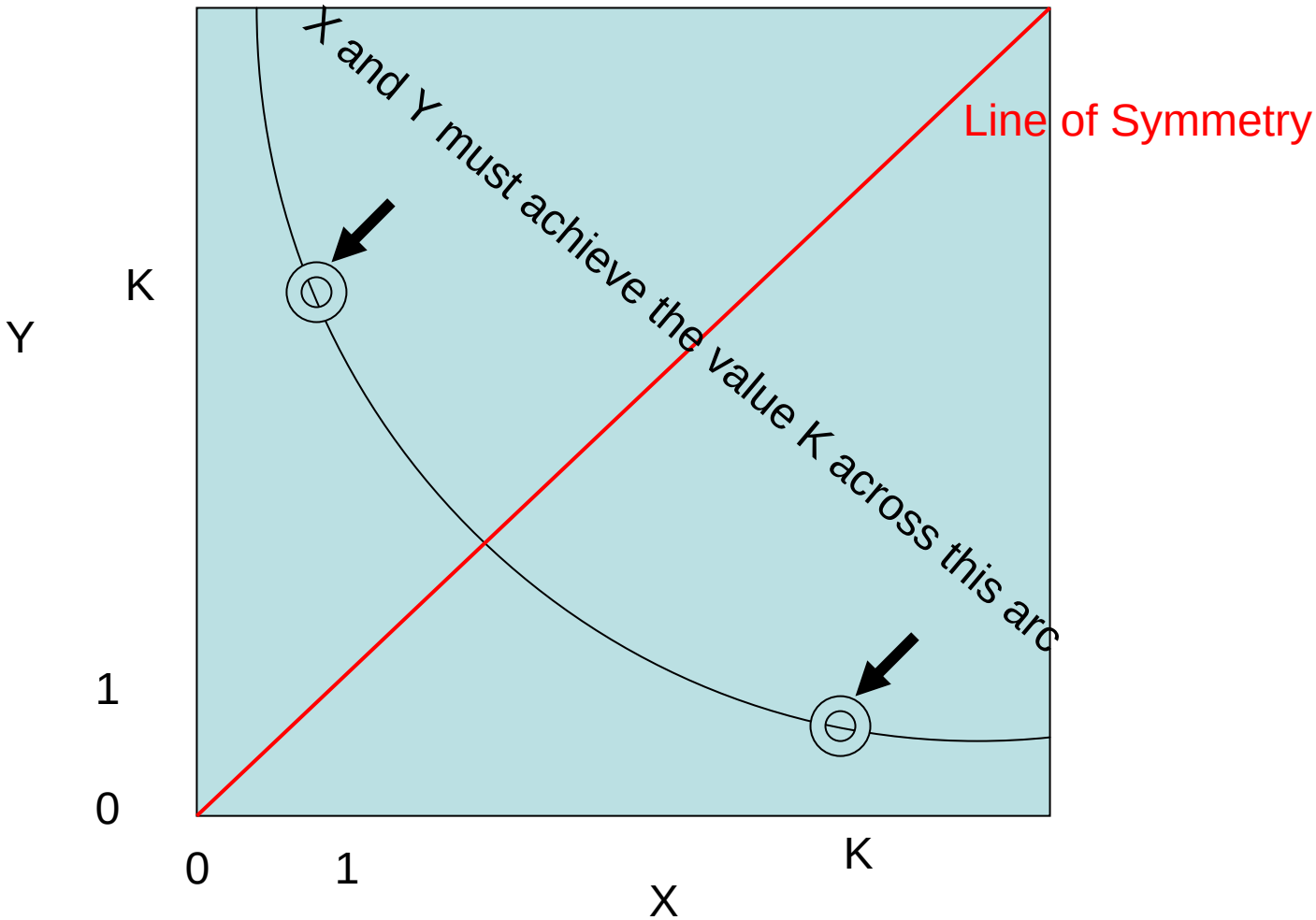
Graphical



Graphical

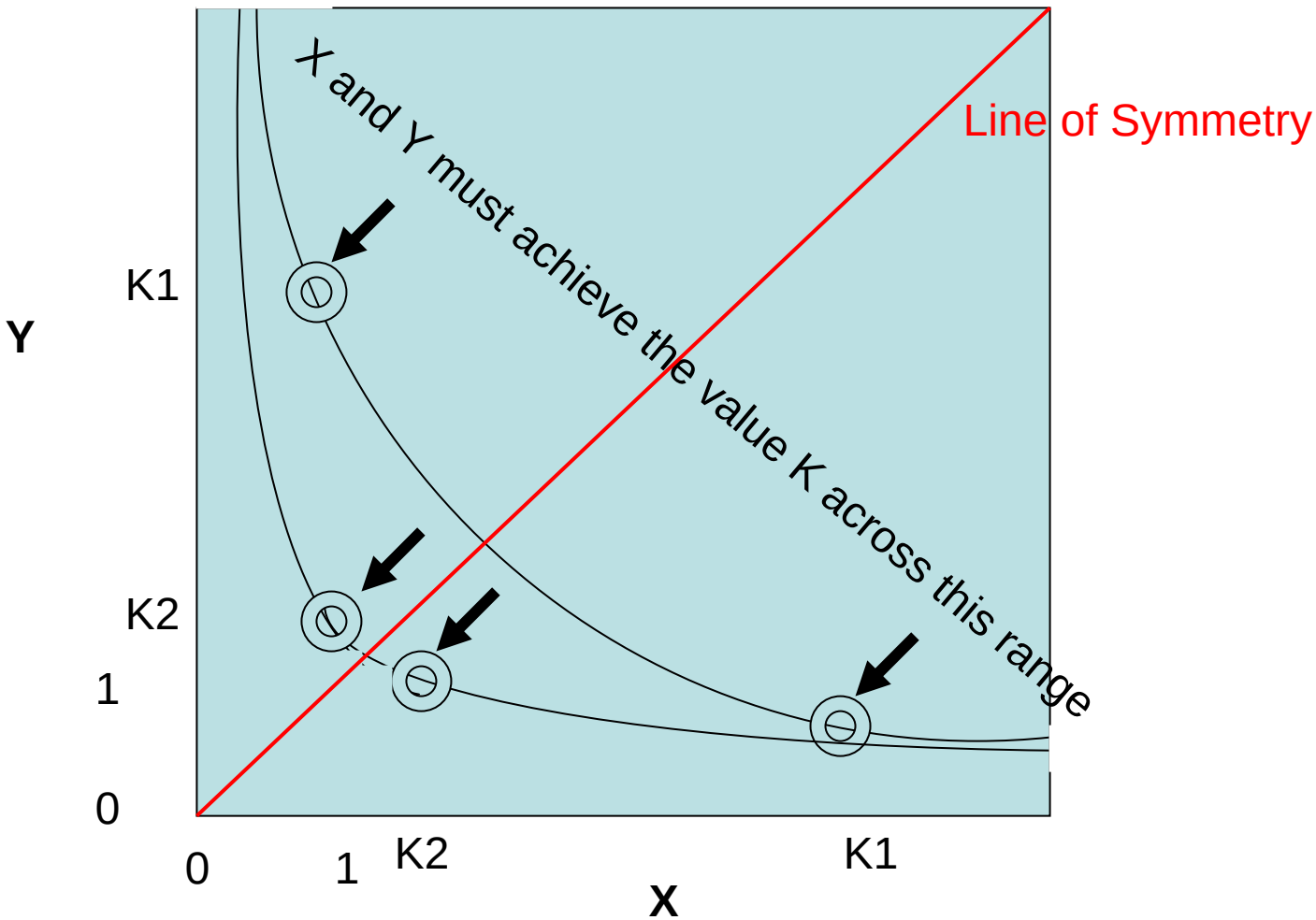


Graphical


X and Y must achieve the value K across this arc
Line of Symmetry
K
Y
1
0
0
1
K
X

Graphical

K is the Shape Factor, controlling the “sharpness” of the curvature



The Asymptotes

X * Y = constant, K

X = 0, Y = 0

X=0, Y ~Infinity

X~Infinity, Y=0

Saturation Height Models have this general hyperbolic shape but:

- Have nonzero asymptotes like

like $S_w = S_{w\ irr}$

Height = FWL

How can I make this work?

- Use a substitution to convert the zero asymptote value to 1
- i.e. X = Log(Q); Y = Log(R)
- Q = 1; X = 0
- R = 1; Y = 0

So Now we have asymptotes at value 1, still not what we need!!!

X * Y = constant, K

or

Log(Q) ***** Log(R) **= constant, K**

Has asymptotes

Q=1, Log(R) ~Infinity

Log(Q) ~Infinity, R=1

Another Substitution

- Let Q or R = $\frac{\text{input variable}}{\text{asymptotic value (a.v.)}}$

So when input variable = (a.v.) then Q, R = 1

Now we have our generalized hyperbola with any possible asymptotic value:

$$\text{Log}(q/q_{av}) * \text{Log}(r/q_{av}) = K$$

With shape constant K, and asymptotes

$q = q_{av}$ and $r = r_{av}$.

So we can *draw* any hyperbola by manipulating these three parameters: K, q_{av}, r_{av} **.**

Thomeer

$$[\log (\mathbf{Bv} / Bv_{inf},)] [\log (\mathbf{Pc} / P_d)] = K$$

This type of form could also be used

As

$$[\log (\mathbf{S_w} / Sw_{irr},)] [\log (\mathbf{Ht} / FWL)] = K$$

USEFUL EQUATIONS

$$d_{Throat}\ [microns] = \frac{46.9}{\Delta S_g\ h_{o/w}\ [ft]}$$

$$d_{Throat}\ [microns] = \frac{214}{Pc_{Mercury/Air}\ [psia]}$$

$$K_a = 3.8068\ G^{-1.3334}\ (S_{b\infty}/P_d)^2$$ Thomeer

$S_{b\infty}$ = Total Interconnected PV ~ ϕ

P_d = Hg/A Displacement Pressure [psia]

G = Pore Geometrical Factor

K_a = Air Permeability [md]

Analysis of Mercury Capillary Pressure Data

1. Look at it.
2. Scale them all by the square root of K/ϕ - Leverett J Function
3. Fit each individually to a hyperbola - Thomeer (1960)

Quantifying Capillary Pressure Data

Leverett J Function

$$J = \frac{0.217\, P_c}{\sigma \cos\theta}\sqrt{k/\phi}$$

scaled by:

k/ϕ

Thomeer Hyperbola

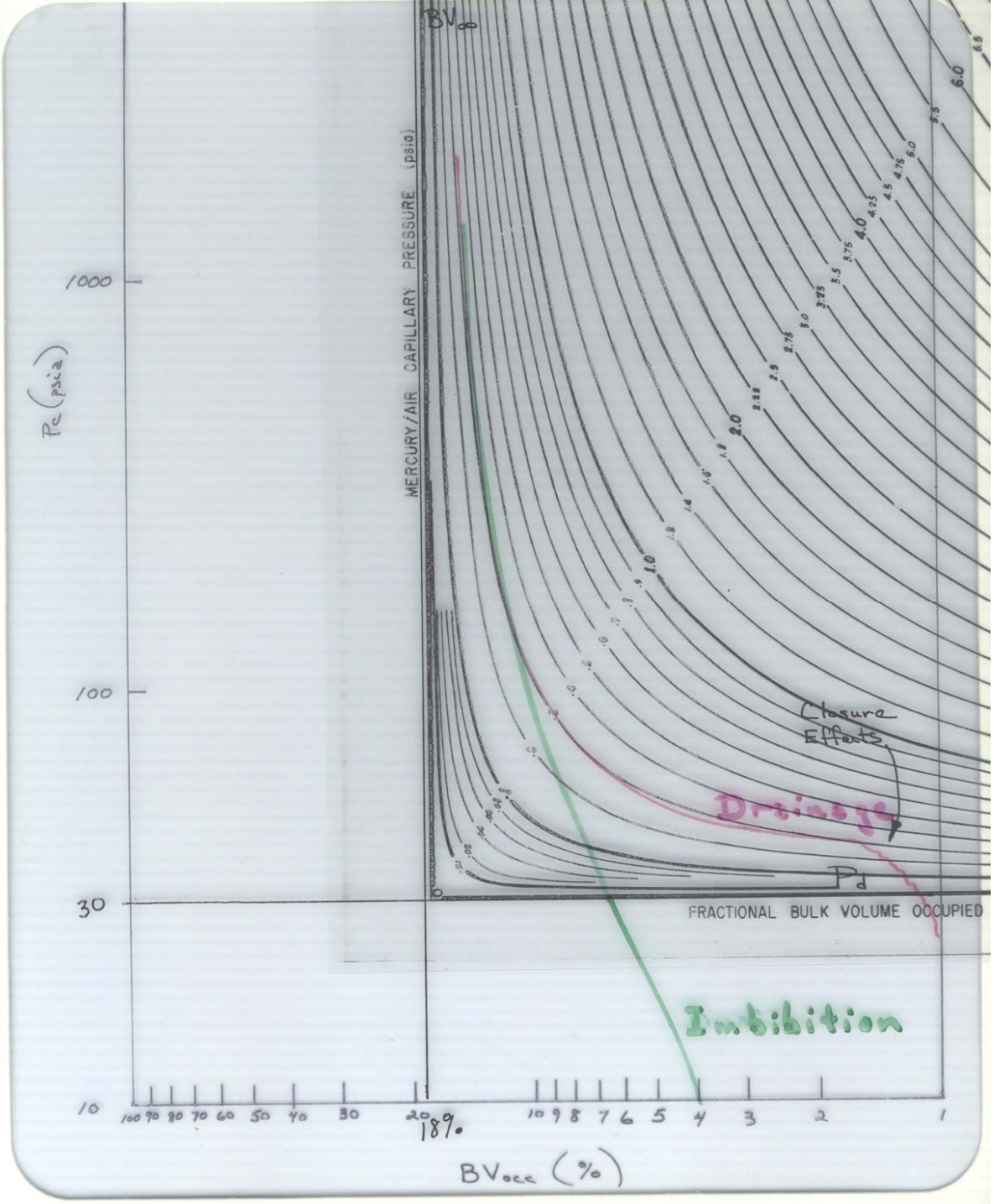
$$\log\left(P_c / P_d\right) \quad \log\left(BV / BV_\infty\right) = \log\left(e^{-G}\right)$$

scaled by:

P_d

BV_∞

G

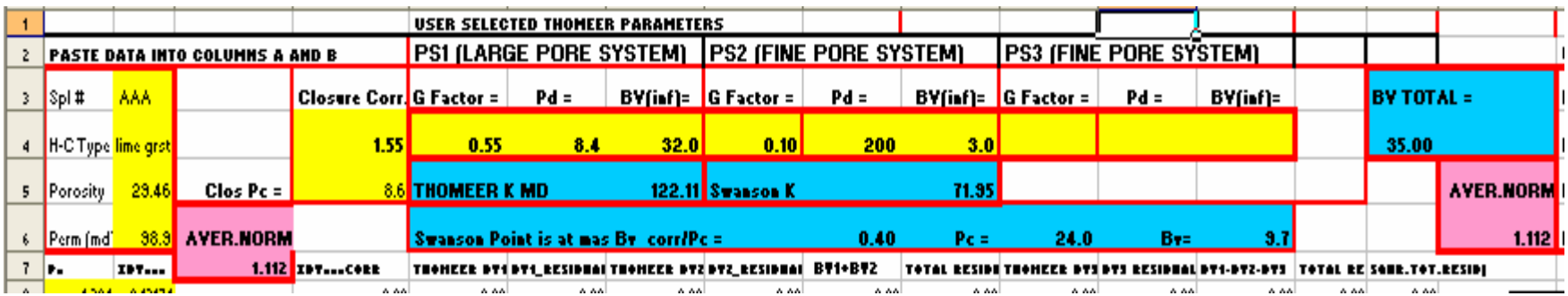

MERCURY/AIR CAPILLARY PRESSURE (psia)
Pc (psia)
1000
100
30
10
BV
FRACTIONAL BULK VOLUME OCCUPIED
Closure Effects
Drainage
Pd
Imbibition
100 90 80 70 60 50 40 30 20 10 9 8 7 6 5 4 3 2 1
18%
BVocc (%)

Thomeer Spreadsheet Philosophy

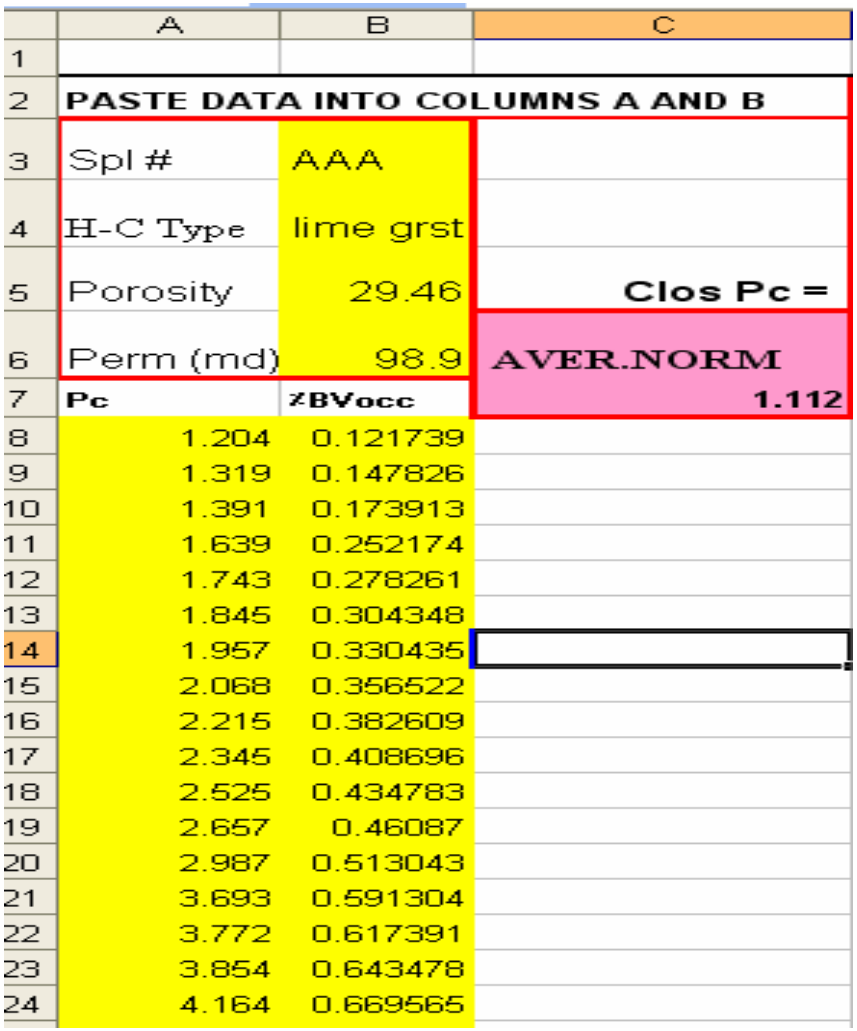
a. Bert Thomeer was right about the application of hyperbolae
b. Spreadsheet rapidly implements the fitting process
c. Closure Correction is a user defined “environmental correction” which must be supplied by the user
d. A good closure correction is one in which step (a) is made true

Truth

- Coherence measured – Average Norm
- The square root of the sum of the square of the difference between actual and predicted
- Cells C7 and P6
- Caveat: Average Norm uses equal weighting – all pressure steps equally important – however, this may not be your case – so you can modify it – manual or redefine norms



Spreadsheet Input Labels and Data



	A	B	C
1			
2	PASTE DATA INTO COLUMNS A AND B		
3	Spl #	AAA	
4	H-C Type	lime grst	
5	Porosity	29.46	Clos Pc =
6	Perm (md)	98.9	AVER.NORM 1.112
7	Pc	%BVocc	
8	1.204	0.121739	
9	1.319	0.147826	
10	1.391	0.173913	
11	1.639	0.252174	
12	1.743	0.278261	
13	1.845	0.304348	
14	1.957	0.330435	
15	2.068	0.356522	
16	2.215	0.382609	
17	2.345	0.408696	
18	2.525	0.434783	
19	2.657	0.46087	
20	2.987	0.513043	
21	3.693	0.591304	
22	3.772	0.617391	
23	3.854	0.643478	
24	4.164	0.669565	

- Sample ID
- Info
- He Porosity
- Permeability

Labels only not used in any computations

- MICP Data
- Pc and %BVocc

MICP Data Inputs

- Pc – the mercury- air pressure
- %BVocc – the percent of the bulk volume occupied by mercury at that Pc – incremental mercury porosity
  - Volume of mercury/Volume of sample
  - Maximum at Hg porosity (Pc = Pc max)

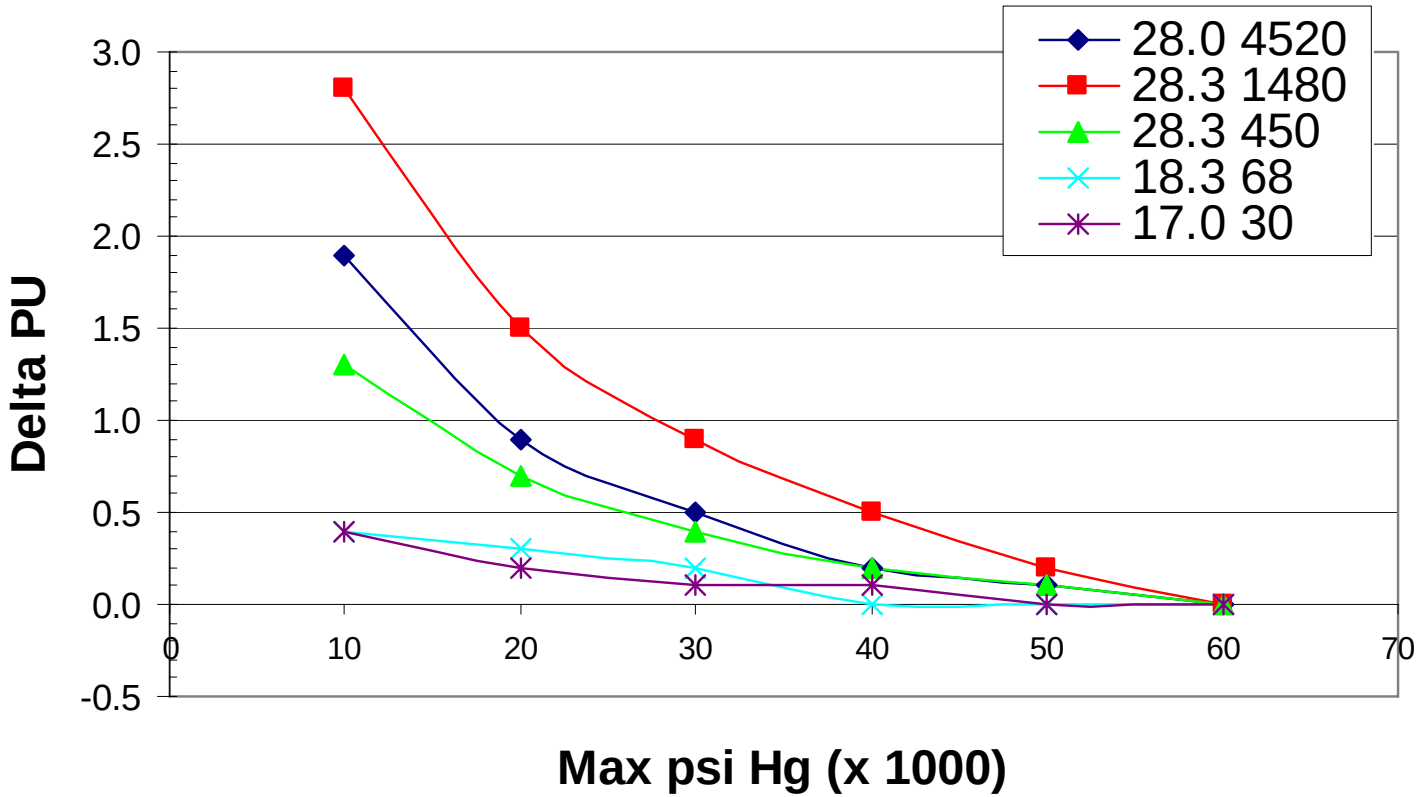
MICP Data Inputs

- Thomeer spreadsheet MICP available from many service providers:
  - Dr. John Neasham – PoroTech **
  - CoreLab
  - PTS
  - OmniLabs
- This removes data format troubles
- This aids in the client – service provider discussion in designing the pressure step protocol

MICP Input Considerations

- Spreadsheet is set up for a number of pressure steps – define this with service provider with concept of pore system, recommend ~200
- To use less than the available number of pressure steps – you cannot just throw away data points (derivative not preserved). It is necessary to spline fit the data and resample
- Maximum Pressure Considerations

Porosity Left to Observe vs Pressure on Five Carbonate Samples with Labelled Phi - Perm



Neasham and Clerke

Size and Scale Effects – 3R's

- MacDougall and Sorbie; SPE 25271, 1995,

"In a porous medium

Each pore element has three radii associated with it:

1. Volume governing radii
2. Conductance governing radii
3. Entry pressure governing radii "

- MICP analysis directly addresses 3 while considering constraints on 1 and 2

Size and Scale Effects

- Sample scale – one inch plug
- Lowest input pressure
  - 1.62 psia translates to ~150 micron pore throat diameter maximum
- For sure, the volume of mercury injected up to 1.62 psia or perhaps even higher has within it the volumes associated with plug surface vugs and pores and other surface irregularities (closure correction) of sizes greater than 150 micron

Size and Scale Effects

- Thomeer Spreadsheet Philosophy

Any low pressure volume that can not be incorporated into a Thomeer hyperbola of some volumetric significance (> 1.5 pu) is treated as a closure correction volume

That is, this is a volume that is either a surface irregularity or a piece of a larger pore system which is not properly investigated with a one inch core plug MICP experiment whose goal is to extract the Thomeer hyperbolic patterns

Plug Photographs

Whole Core MICP

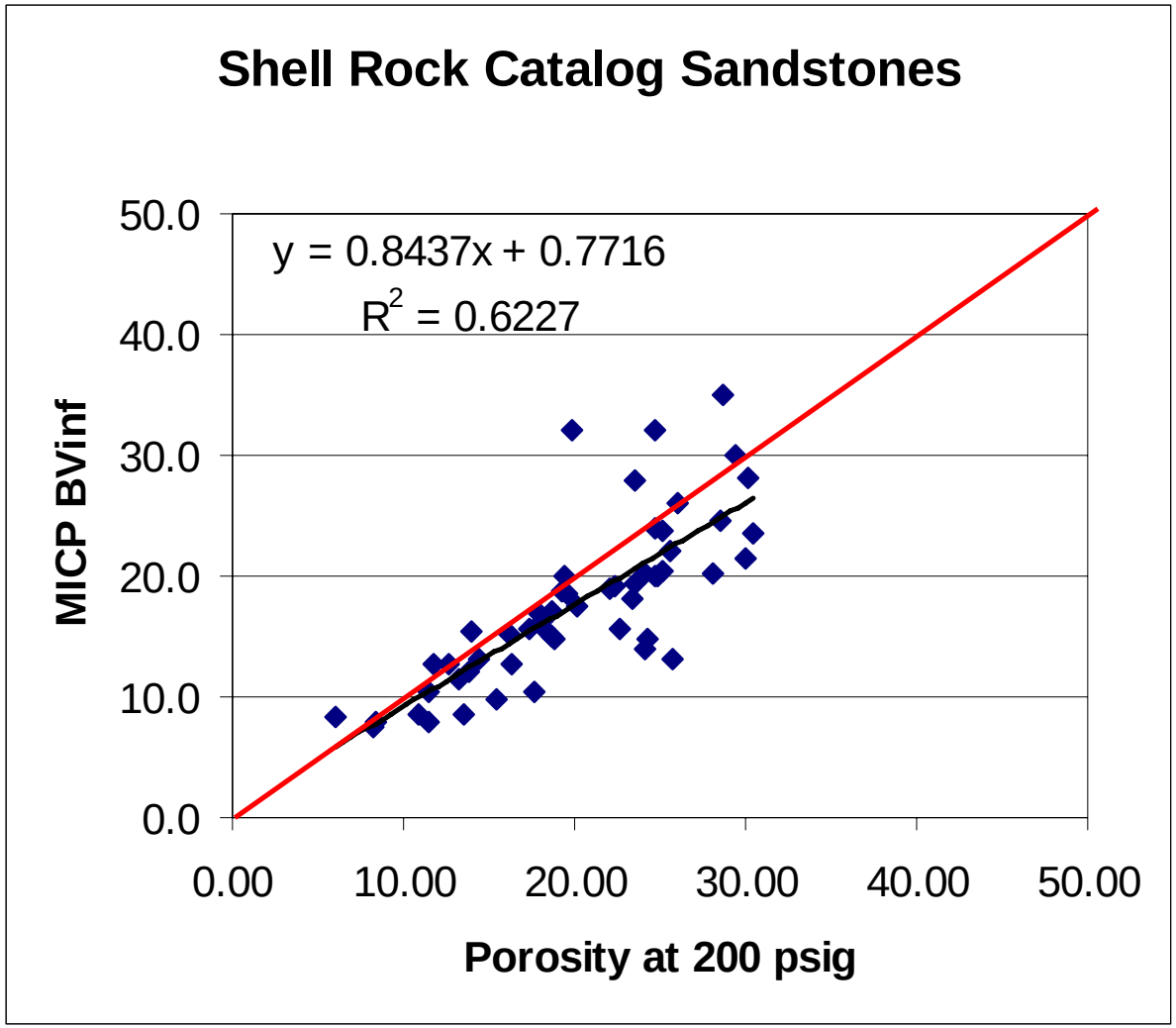
Plug to Whole Core Permeability Comparisons

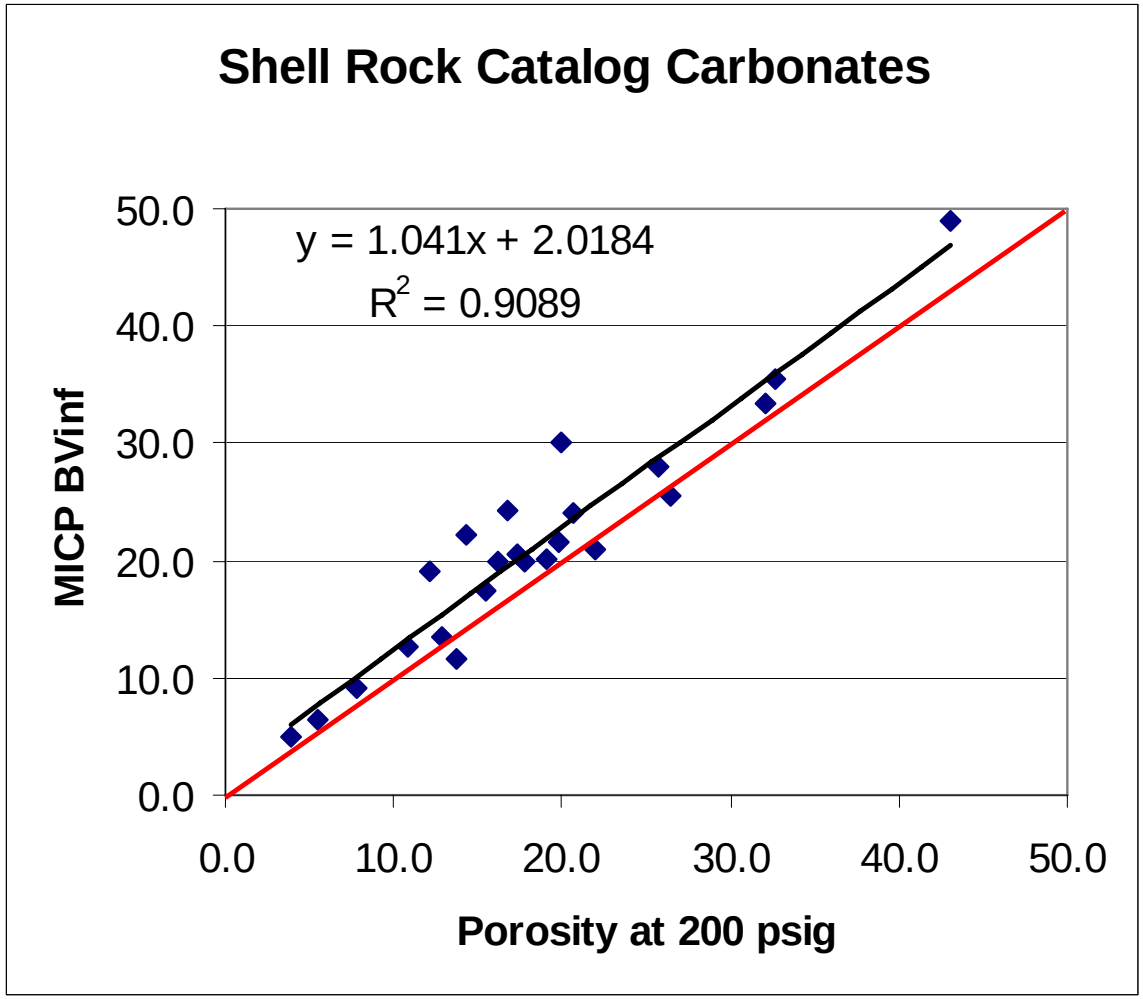
QC Tools

- 3R’s
- Recall that we are investigating one of the R’s – pore throat diameters with MICP
- All of the other information we have to QC the data is in the 2 other R’s
  - Volume
  - Conductance

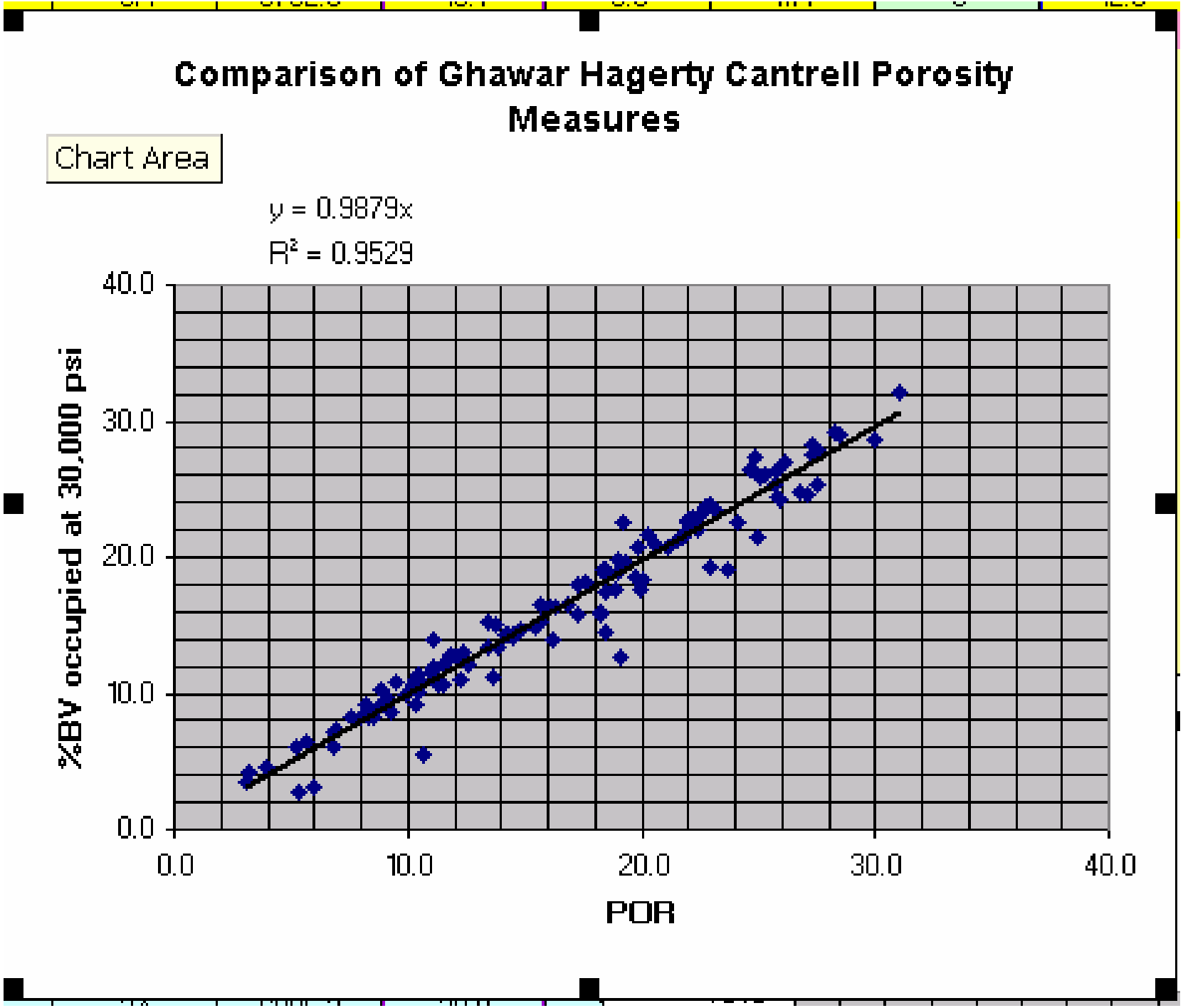
QC Tools

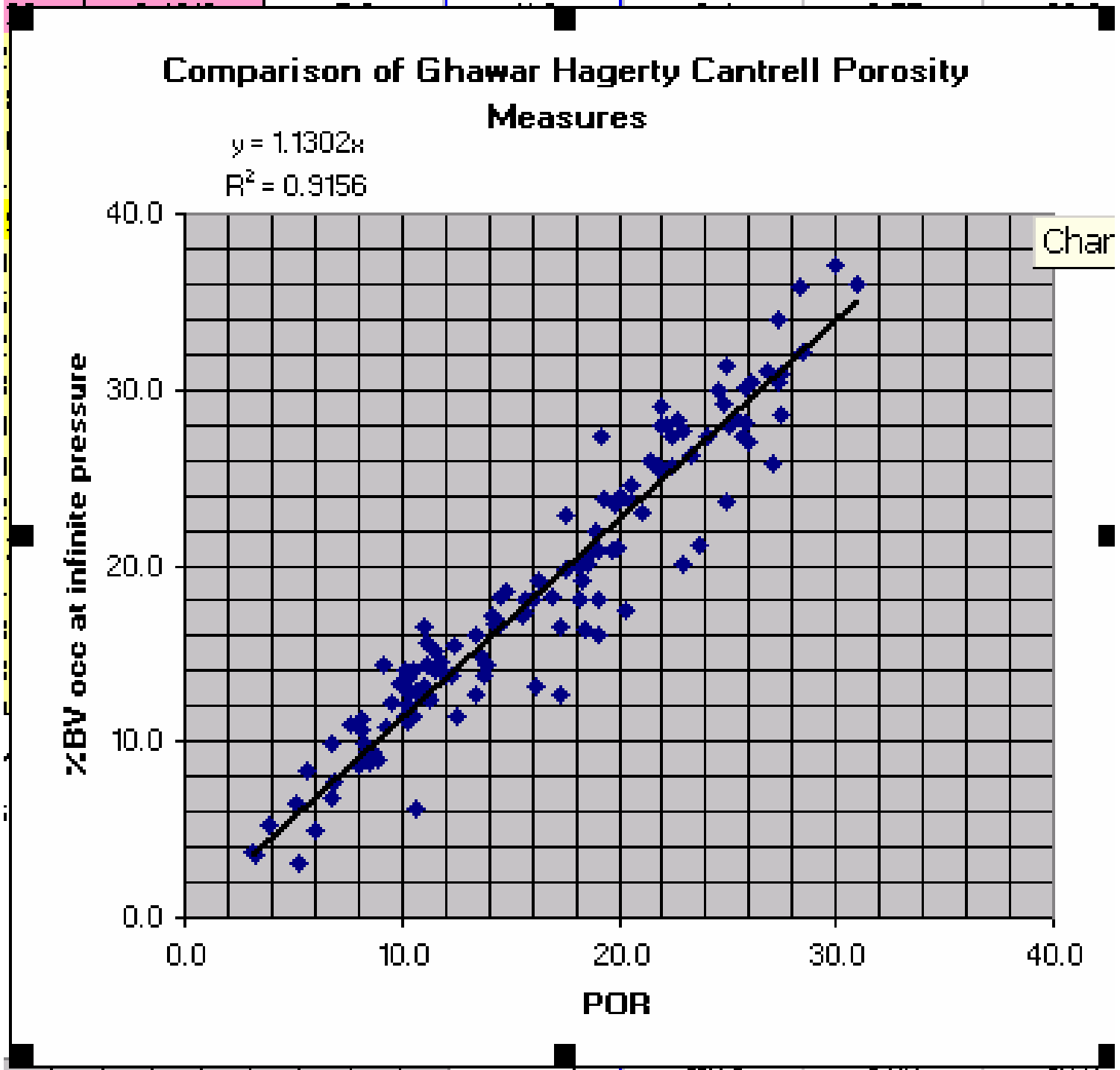
- Volume QC measures
  - He Por
  - Log porosity
  - %BV occ at Pc max – the integral of the injection process
  - Thomeer BV_{∞} - the asymptote of the Thomeer hyperbola

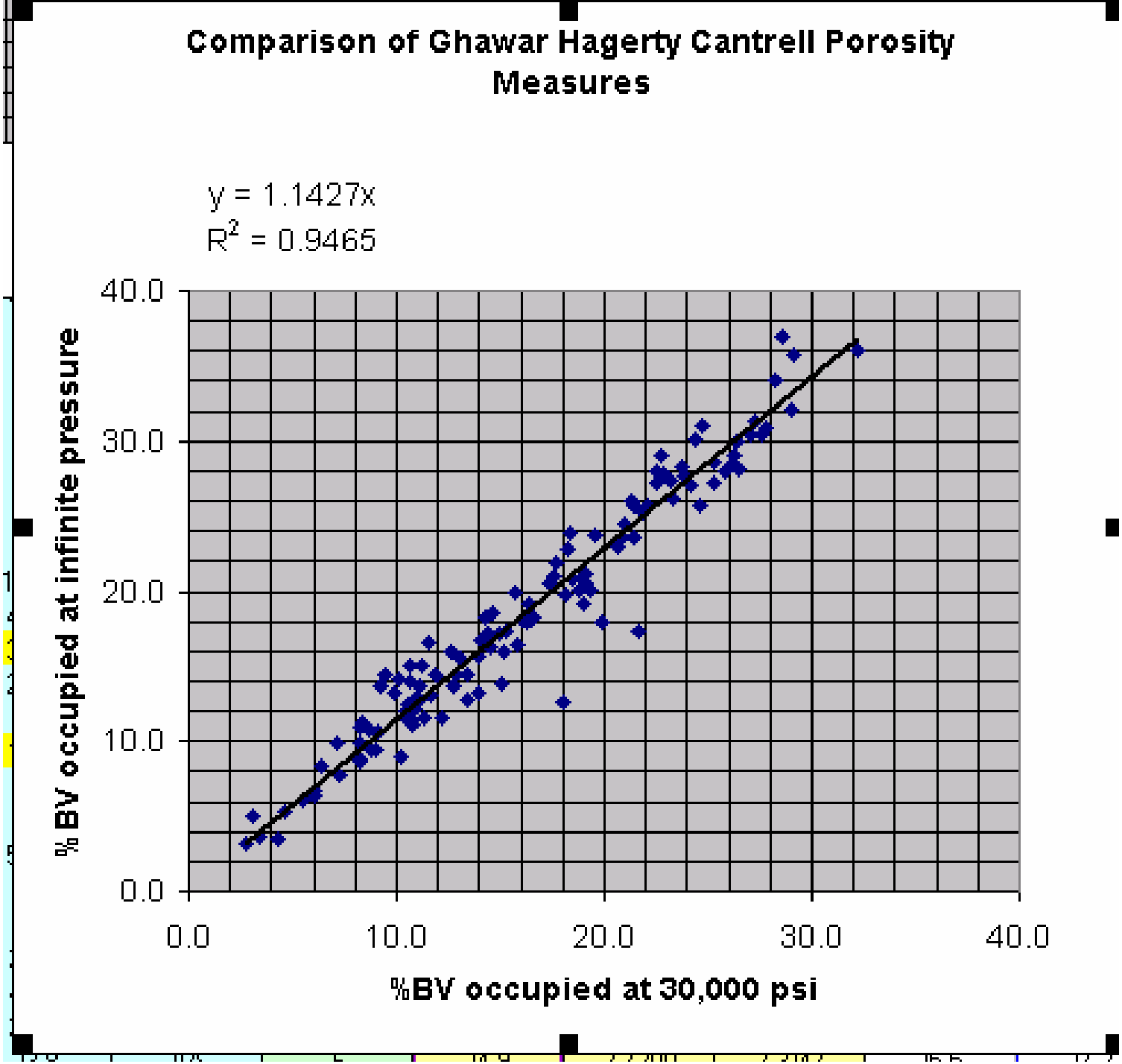

Shell Rock Catalog Sandstones
y = 0.8437x + 0.7716
R2 = 0.6227
MICP BVinf
Porosity at 200 psig
0.0
10.0
20.0
30.0
40.0
50.0
0.00
10.00
20.00
30.00
40.00
50.00


Shell Rock Catalog Carbonates
y = 1.041x + 2.0184
R2 = 0.9089
MICP BVinf
Porosity at 200 psig
0.0
10.0
20.0
30.0
40.0
50.0

Multiple Core Plug Porosity Measures on the Ghawar Arab D


Comparison of Ghawar Hagerty Cantrell Porosity Measures
Chart Area
y = 0.9879x
R² = 0.9529
%BV occupied at 30,000 psi
POR
0.0
10.0
20.0
30.0
40.0


Comparison of Ghawar Hagerty Cantrell Porosity Measures
y = 1.1302x
R² = 0.9156
%BV occ at infinite pressure
POR
0.0
10.0
20.0
30.0
40.0
Char


Comparison of Ghawar Hagerty Cantrell Porosity Measures
y = 1.1427x
R2 = 0.9466
40.0
30.0
20.0
10.0
0.0
% BV occupied at infinite pressure
0.0
10.0
20.0
30.0
40.0
%BV occupied at 30,000 psi

QC Tools

- Conductance QC measures
  - Air Permeability
  - Thomeer Permeability Correlation
  - Swanson Permeability Correlation

- Spreadsheet computes Thomeer permeability from only the first pore system PS1

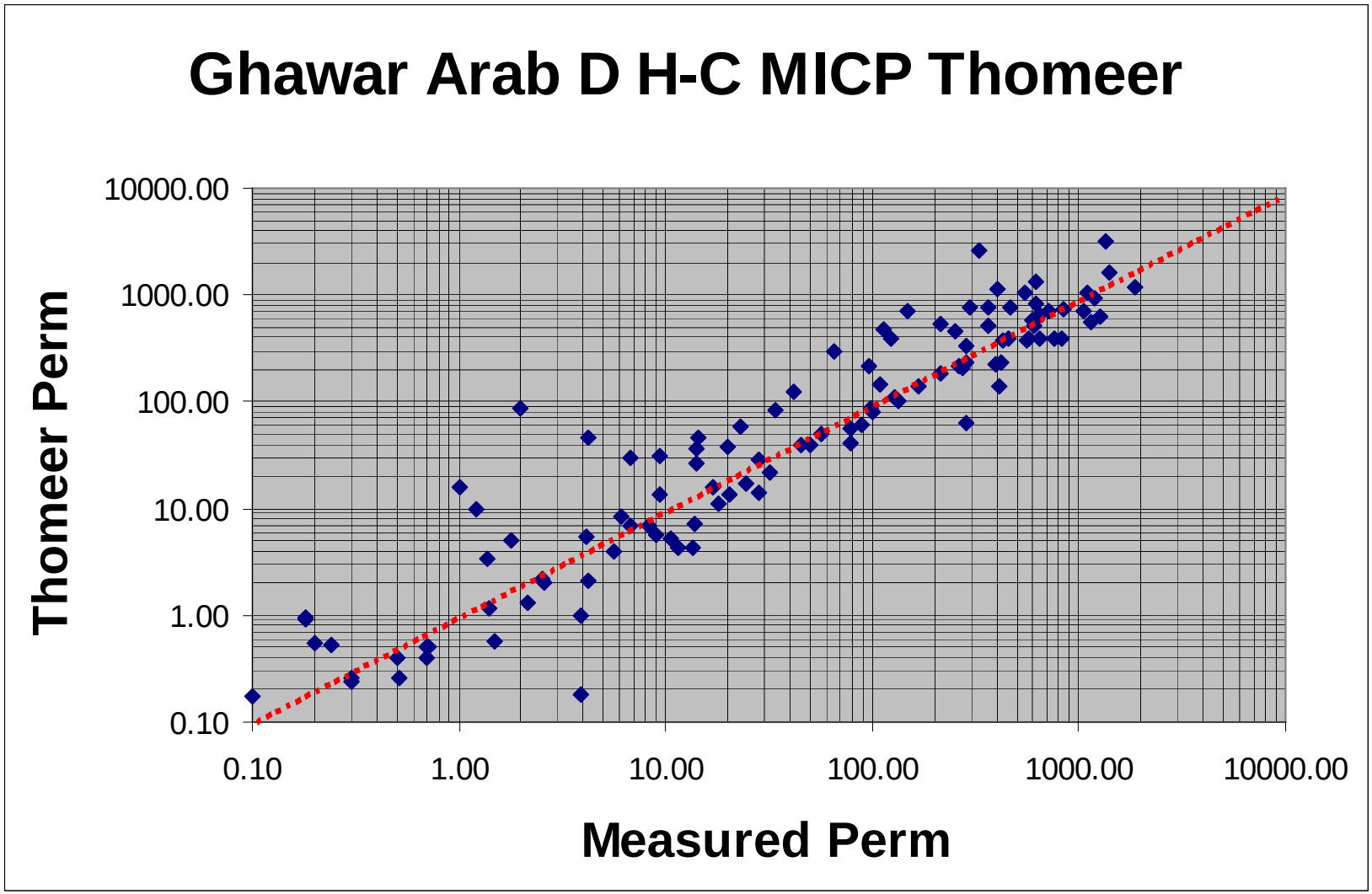
Thomeer Permeability

- Air permeability can be computed and predicted from the pore network parameters, P_d , $B_{v,inf}$, G , to within a multiplicative uncertainty of 1.8x, and this can be compared to a measured permeability.

$$K_a = 3.8068\ G^{-1.3334}\ (\ B_{v,inf,}\ /\ P_d\ )^2\ .$$

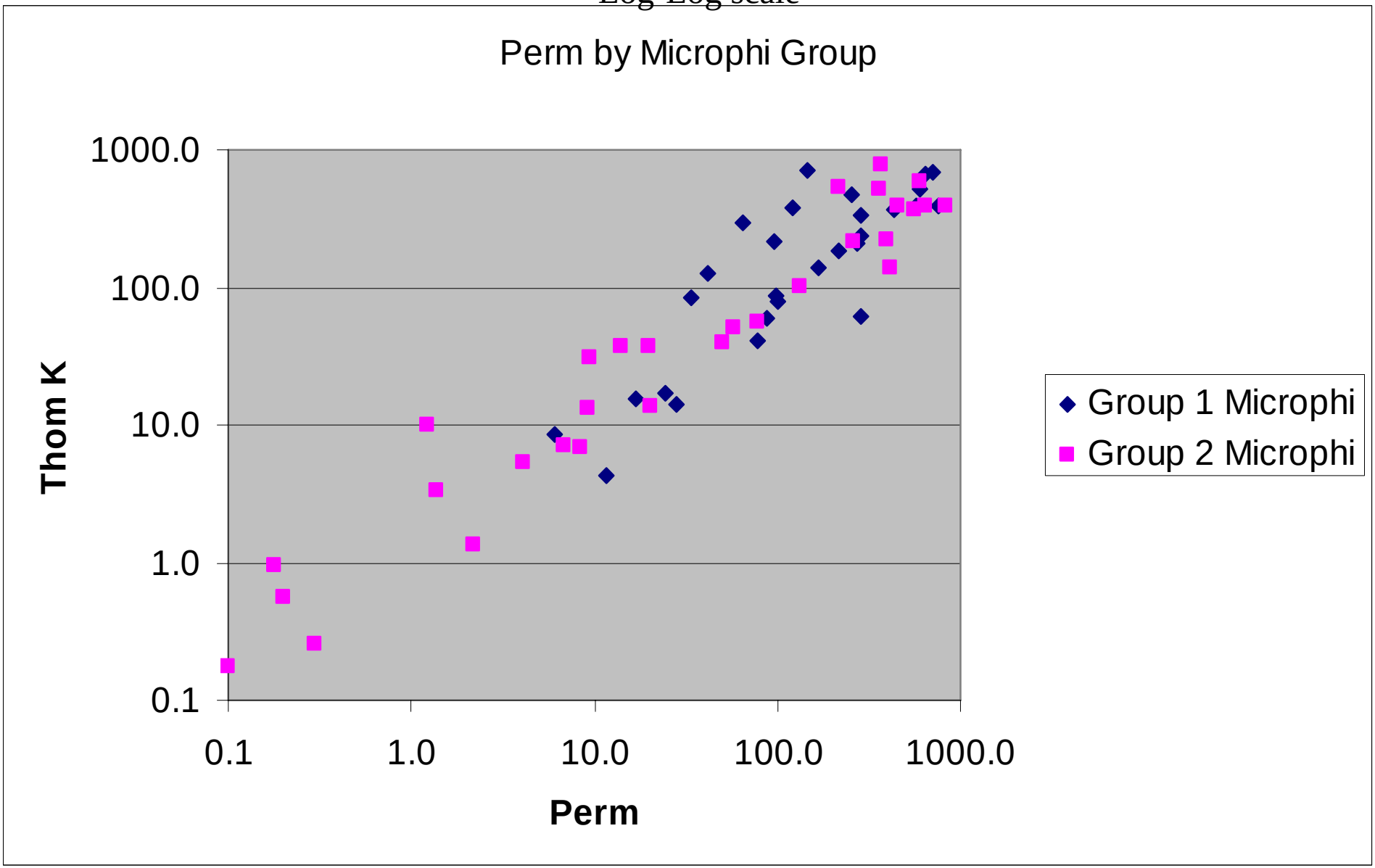
1983, Thomeer, J. H., Air Permeabilty as a Function of Three Pore-Network Parameters, Journal of Petroleum Technology, April, p 809-814.

Perm Prediction using only the *First* Pore System Looks Good over a wide range: 0.1 - 1000



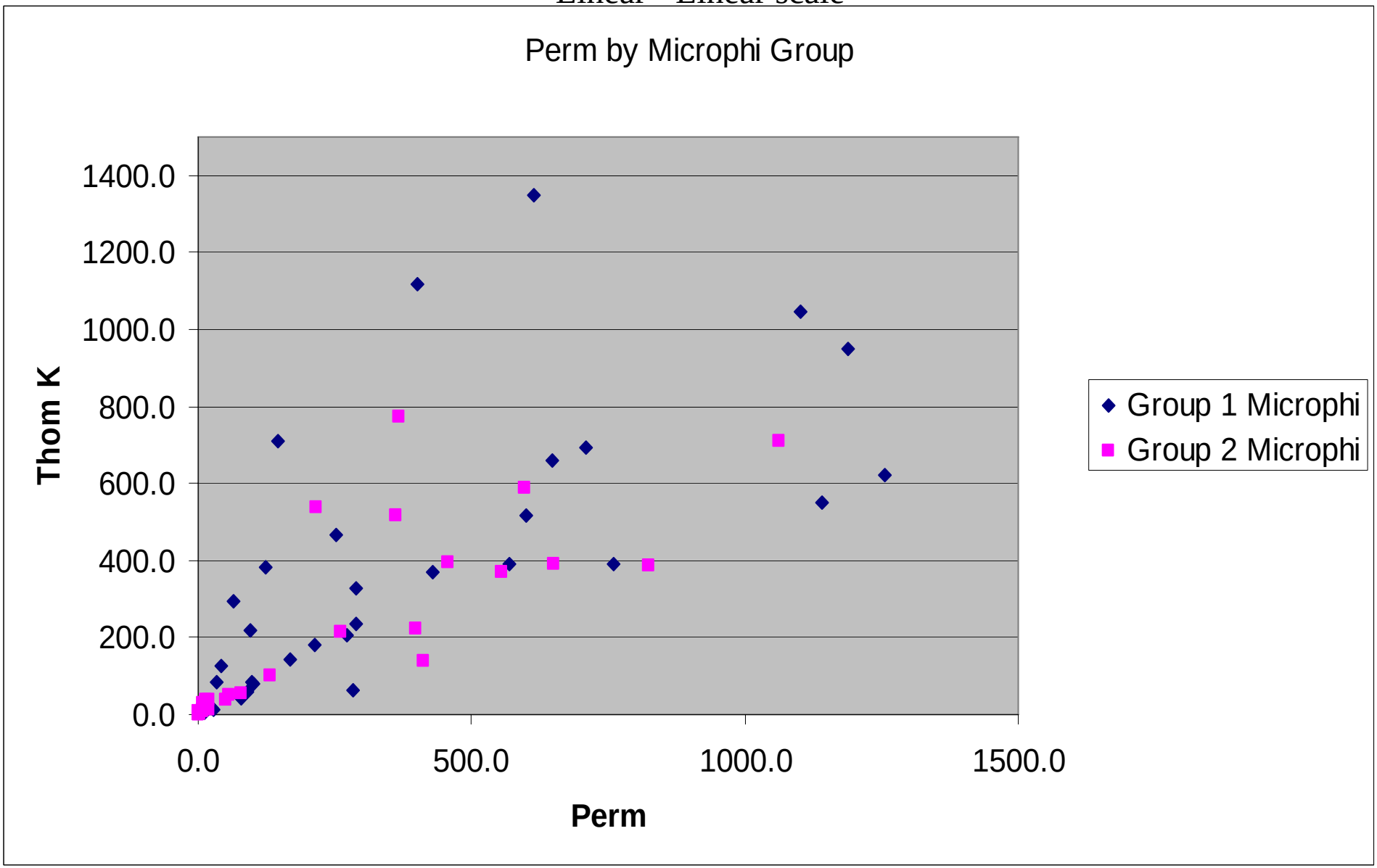
Thomeer Empirical Permeability vs Core Plug Permeability

Log-Log scale



Thomeer Empirical Permeability vs Core Plug Permeability

Linear - Linear scale



Swanson Permeability

- JPT Dec 1981, A Simple Correlation Between Permeabilities and Mercury Capillary Pressures, p 2498-2504.
- Find the perm controlling pore size (volume weighted radius = conductance radius) by finding Bv and Pc s.t. (Bv/Pc) is at a maximum
- In this spreadsheet the Swanson value is computed on the closure corrected data

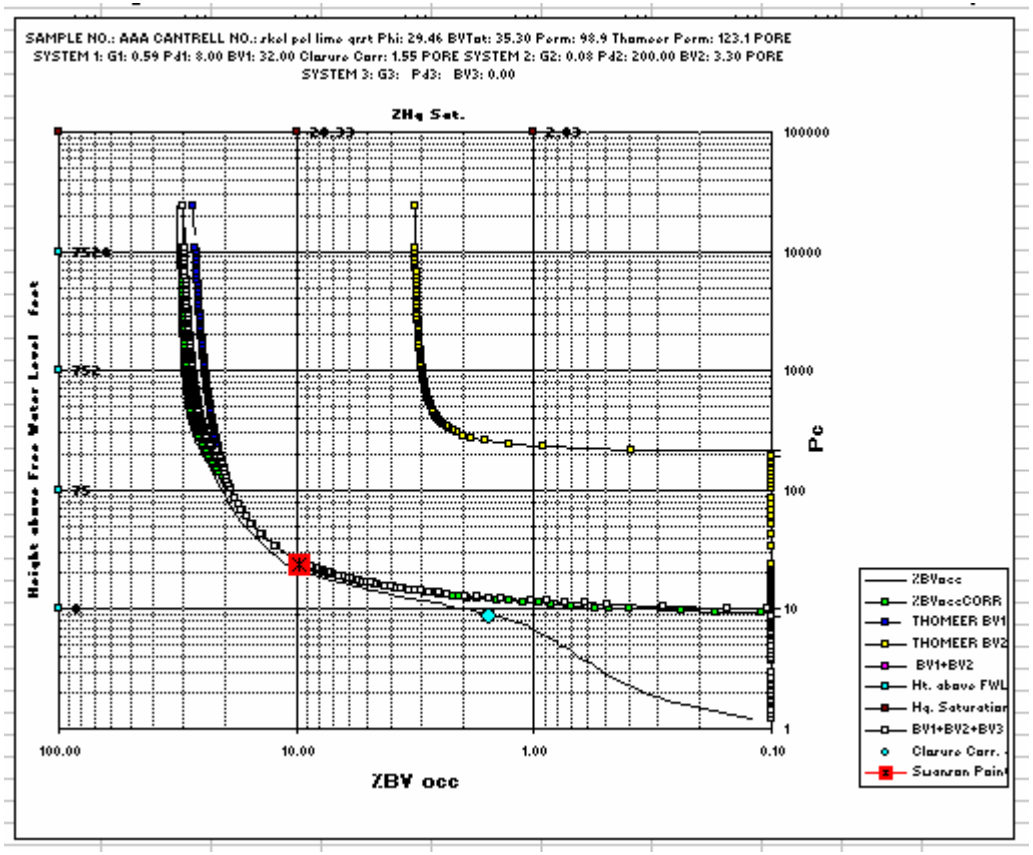
Then using that value compute air perm as

$$Ka = 399(Bv/P_c)^{1.69}$$ 1.96x uncertainty

Swanson Permeability

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1					USER SELECTED THOMEER PARAMETERS									
2	PASTE DATA INTO COLUMNS A AND B				PS1 (LARGE PORE SYSTEM)			PS2 (FINE PORE SYSTEM)			PS3 (FINE PORE SYSTEM)			
3	Spl #	AAA		Closure Corr.	G Factor =	Pd =	BV(inf)=	G Factor =	Pd =	BV(inf)=	G Factor =	Pd =	BV(inf)=	
4	H-C Type	lime grst		1.55	0.55	8.4	32.0	0.10	200	3.0				
5	Porosity	29.46	Clos Pc =	8.6	THOMEER K MD		122.11	Swanson K		71.95				
6	Perm (md)	98.9	AVER.NORM		Swanson Point is at mas Bv corr/Pc =				0.40	Pc =	24.0	Bv=	9.7	
7	Pc	ΔBV...	1.112	ΔBV...CORR	THOMEER BV1	BV1_RESIDUAL	THOMEER BV2	BV2_RESIDUAL	BV1+BV2	TOTAL RESIDU	THOMEER BV3	BV3 RESIDUAL	BV1-BV2-BV3	TOTAL RE
8	1.204	0.12174		0.00	0.00	0.00								

Swanson Point Indicator



Measure Perm = 99
Thomeer Perm = 123
Swanson Perm = 72

Microporosity

- Ben Swanson gave one microporosity definition:
-
- " We define micropores in reservoir rocks as pores whose dimensions are significantly smaller than those contributing to the rock's permeability."

Type Curve Matching Heuristics

- Do with the fewest possible number of pore systems – sequential process
- Put as much porosity BV1 in PS1 as you can before turning on a PS2
- Let the derivative data force you into adding PS2
- PS2 is negligible unless > 1 pu

Thomeer Spreadsheet Fits

- First guess:

  Closure correction is 0.5 pu – cell D4

  Read Pc of 0.5 pu off of data table – cell D5

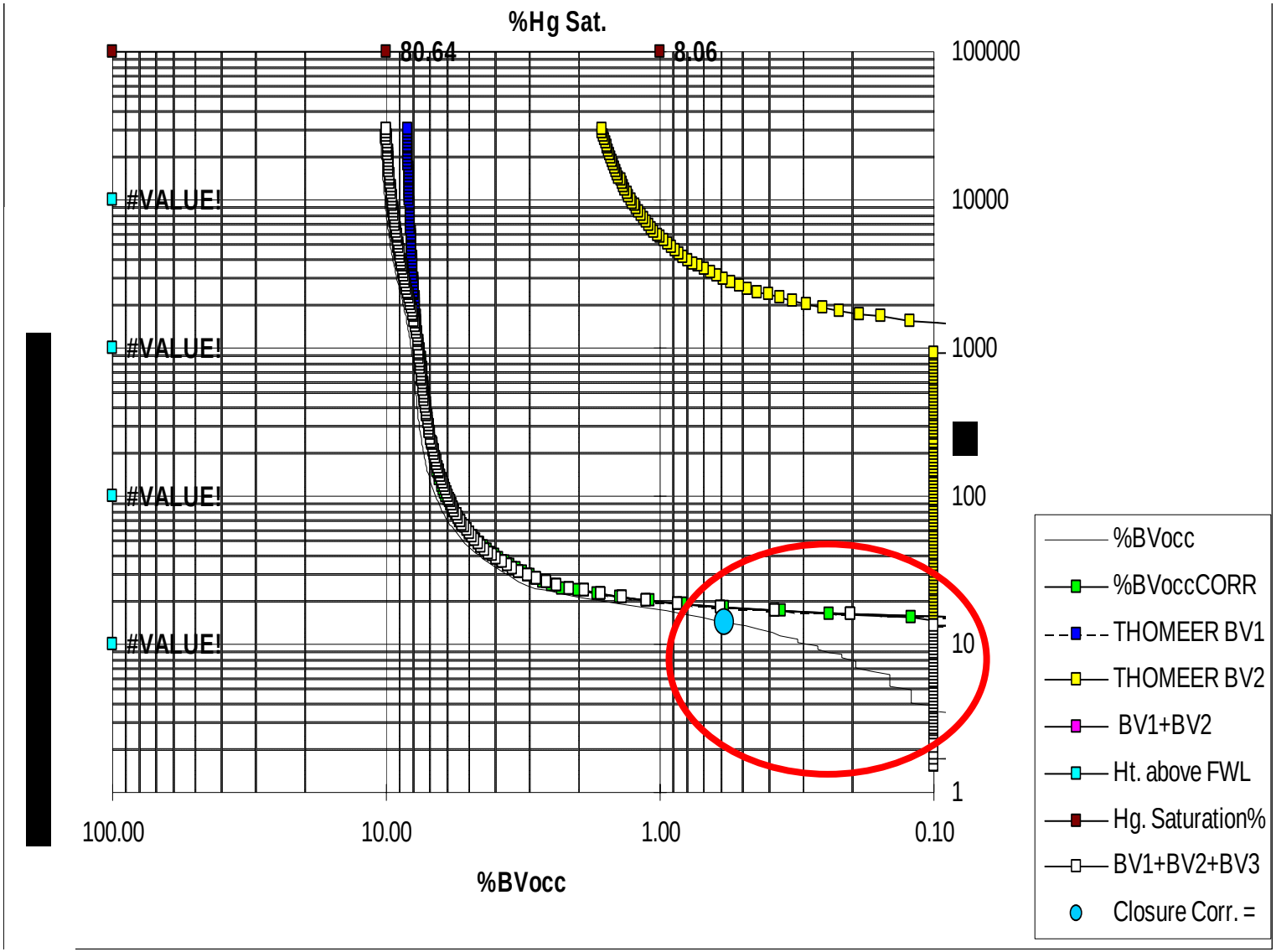
  BV1 is near Por – cell G4

  G1~0.5 – cell E4

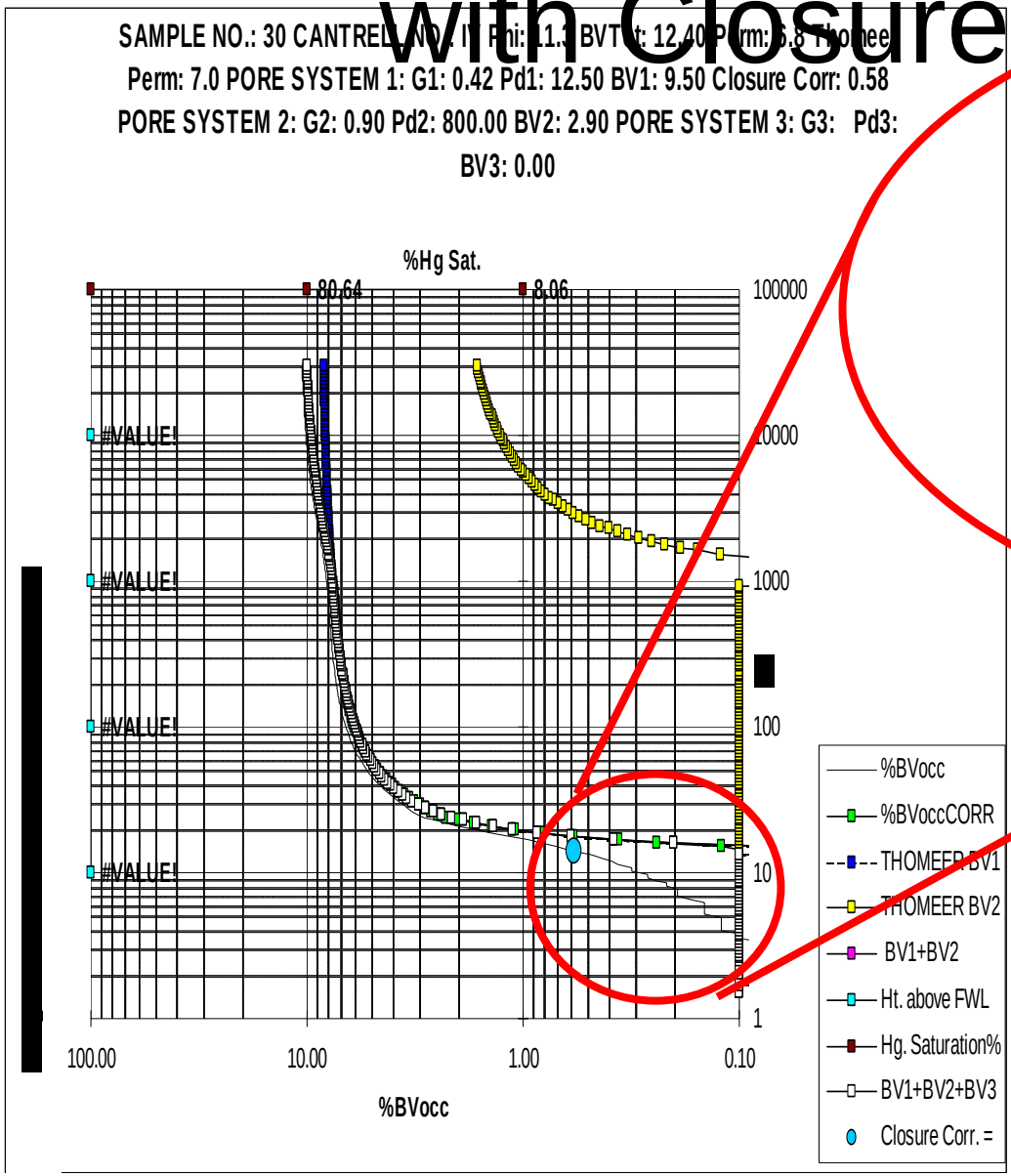
  Pd1~right intercept of closure corrected data – cell F4

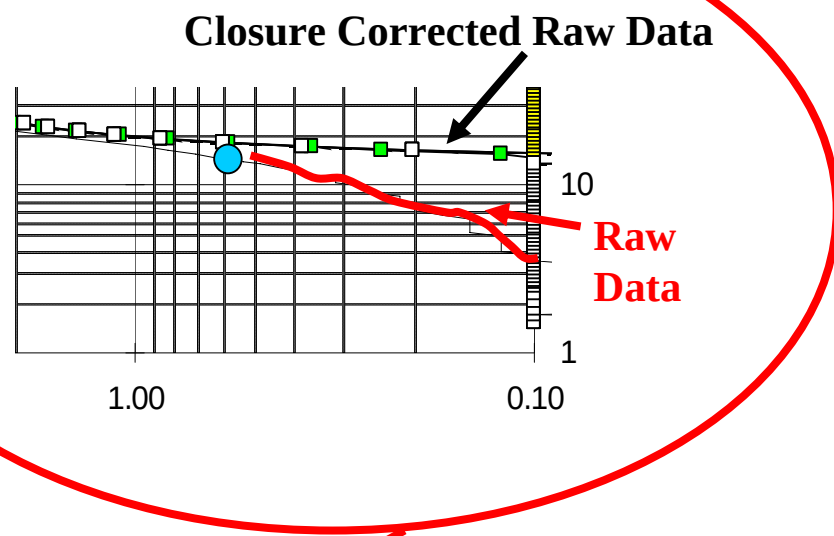
  - Drive manual watching Average Norm and graphs
  - Drive automatic – Solver Add In
  - Stop when you are satisfied – not on low average norm

Arab Capillary Pressure Data with Closure Artifact



Arab Capillary Pressure Data with Closure Artifact

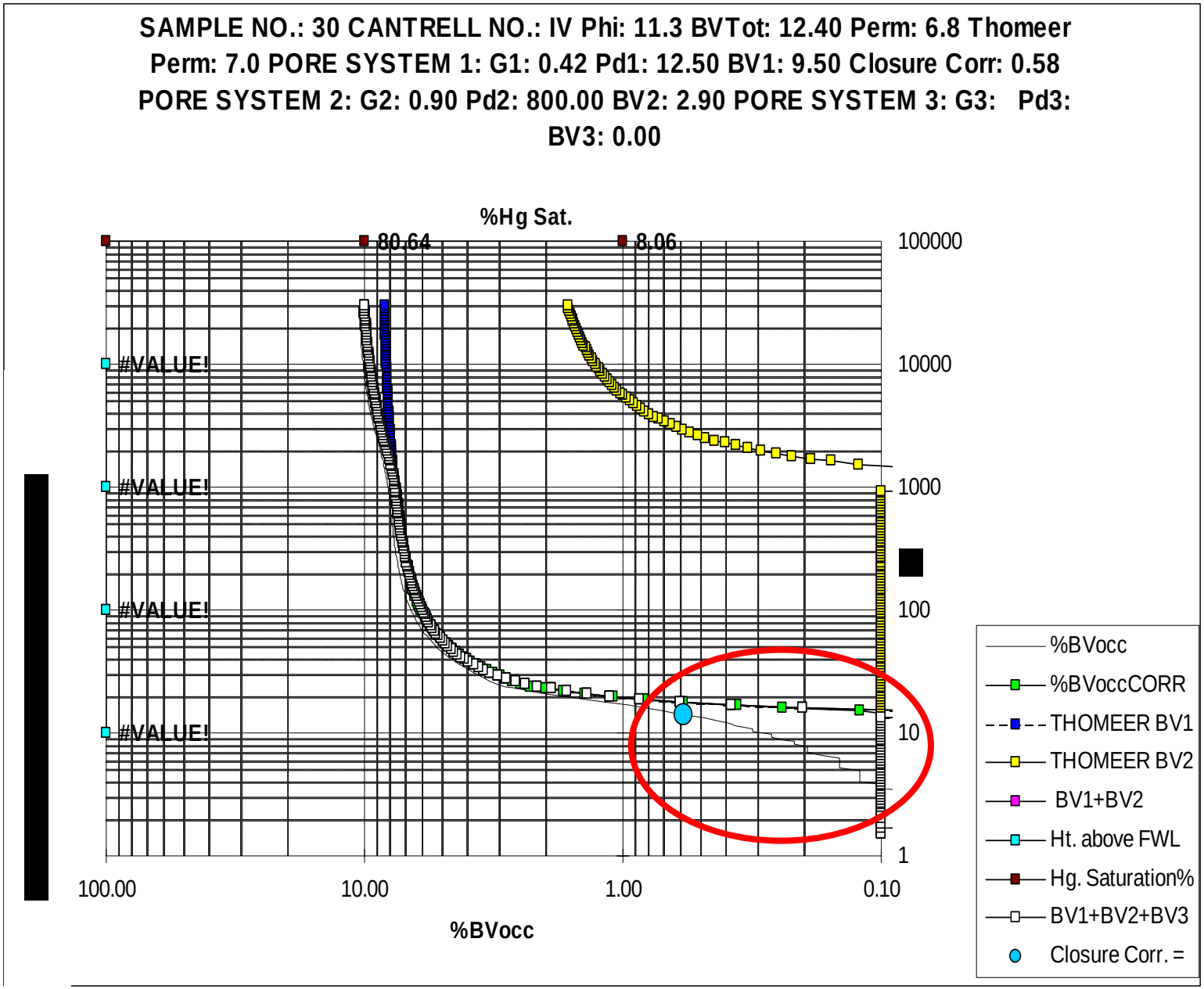




Solver Settings

- Minimize cell C7 or P6
- By changing values in cells:
  - E4, F4, G4 with constraint >=0
  - Assume nonnegative
  - Use Automatic scaling

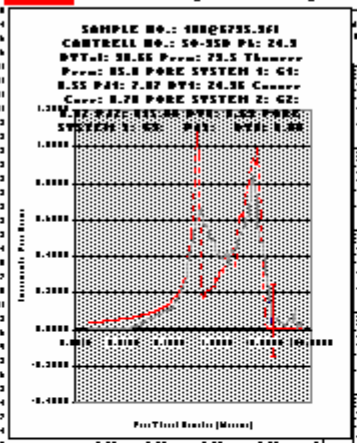
When to add a PS2

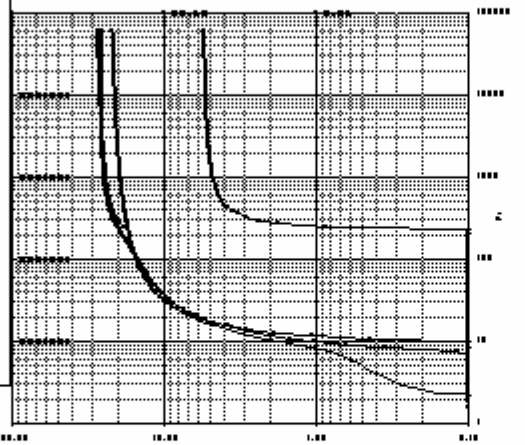


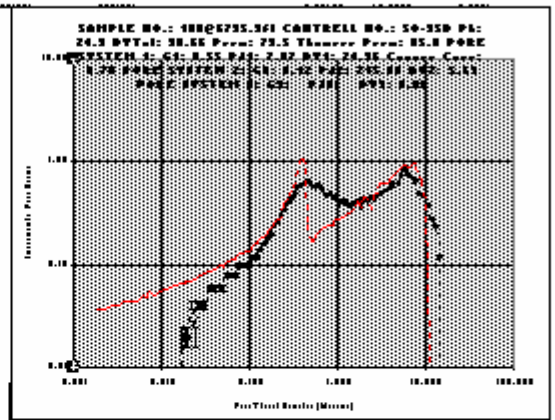
Other Help

- FAQ file on CD
- Perm matching is not the objective – core plug perm may be wrong
- Geology, thin sections, …

Value (Y) axis



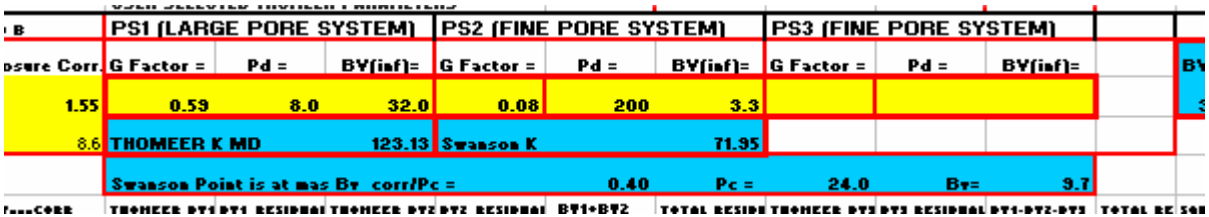




SAMPLE NO.:
188@6735.36I
CANTRELL NO.:
50-35D
Pk:
24.3
DYT.w:
38.55
Perm:
79.5
Thomeer Perm:
85.8
PORE SYSTEM 1:
G1:
8.55
Pd1:
7.87
DY1:
24.36
Connec Curv:
8.78
PORE SYSTEM 2:
G2:
8.42
Pd2:
DY2:
5.63
PORE SYSTEM 3:
G3:
Pd3:
DY3:
8.88

Spreadsheet Idiosyncrasies

- Once you turn on a second pore system by putting in values

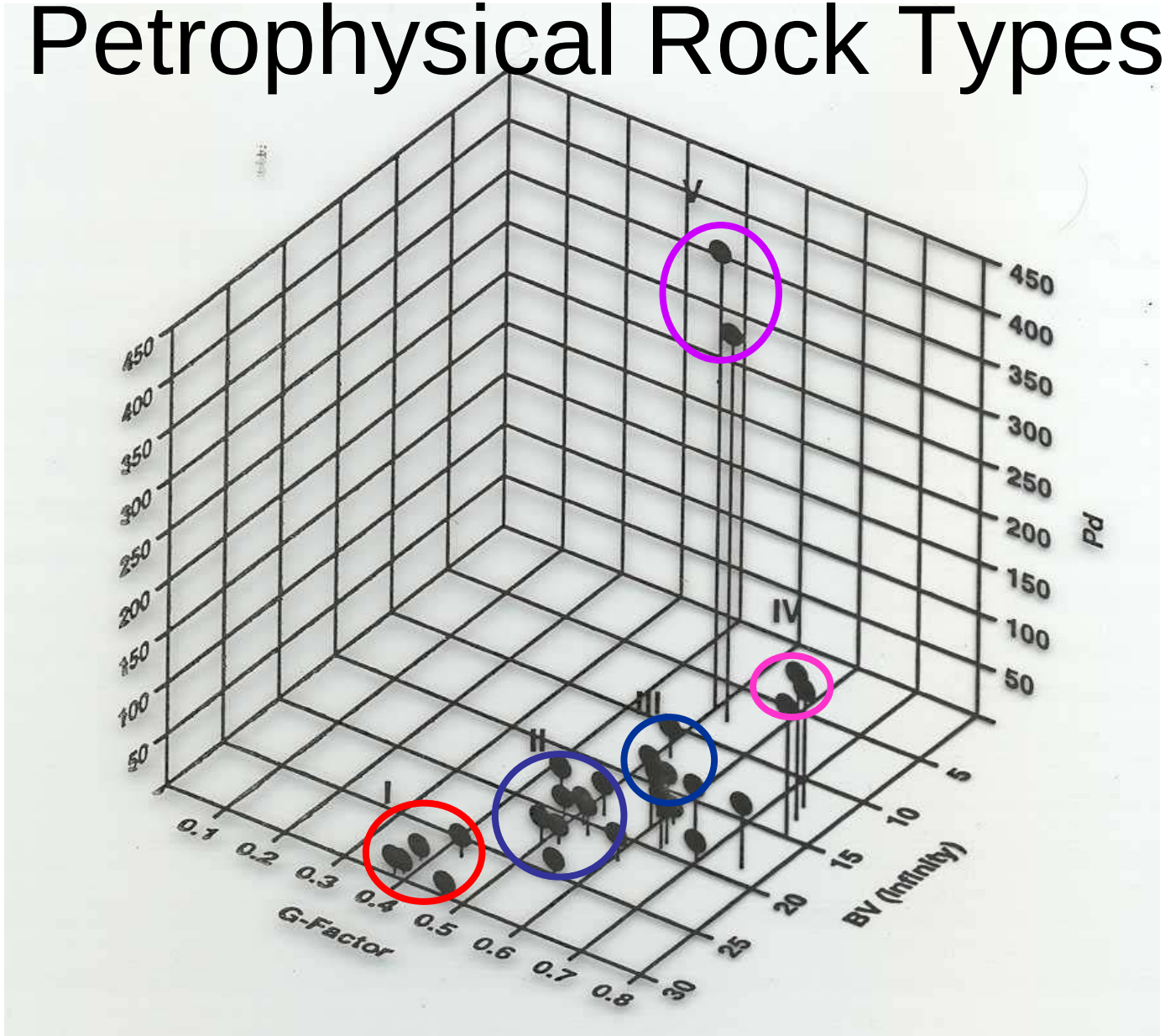


	PS1 (LARGE PORE SYSTEM)			PS2 (FINE PORE SYSTEM)			PS3 (FINE PORE SYSTEM)			
osure Corr.	G Factor =	Pd =	BV(inf)=	G Factor =	Pd =	BV(inf)=	G Factor =	Pd =	BV(inf)=	BV
1.55	0.59	8.0	32.0	0.08	200	3.3				
8.6	THOMEER K MD		123.13	Swanson K		71.95				
	Swanson Point is at mas Bv corr/Pc =				0.40	Pc =	24.0	Bv=	9.7	

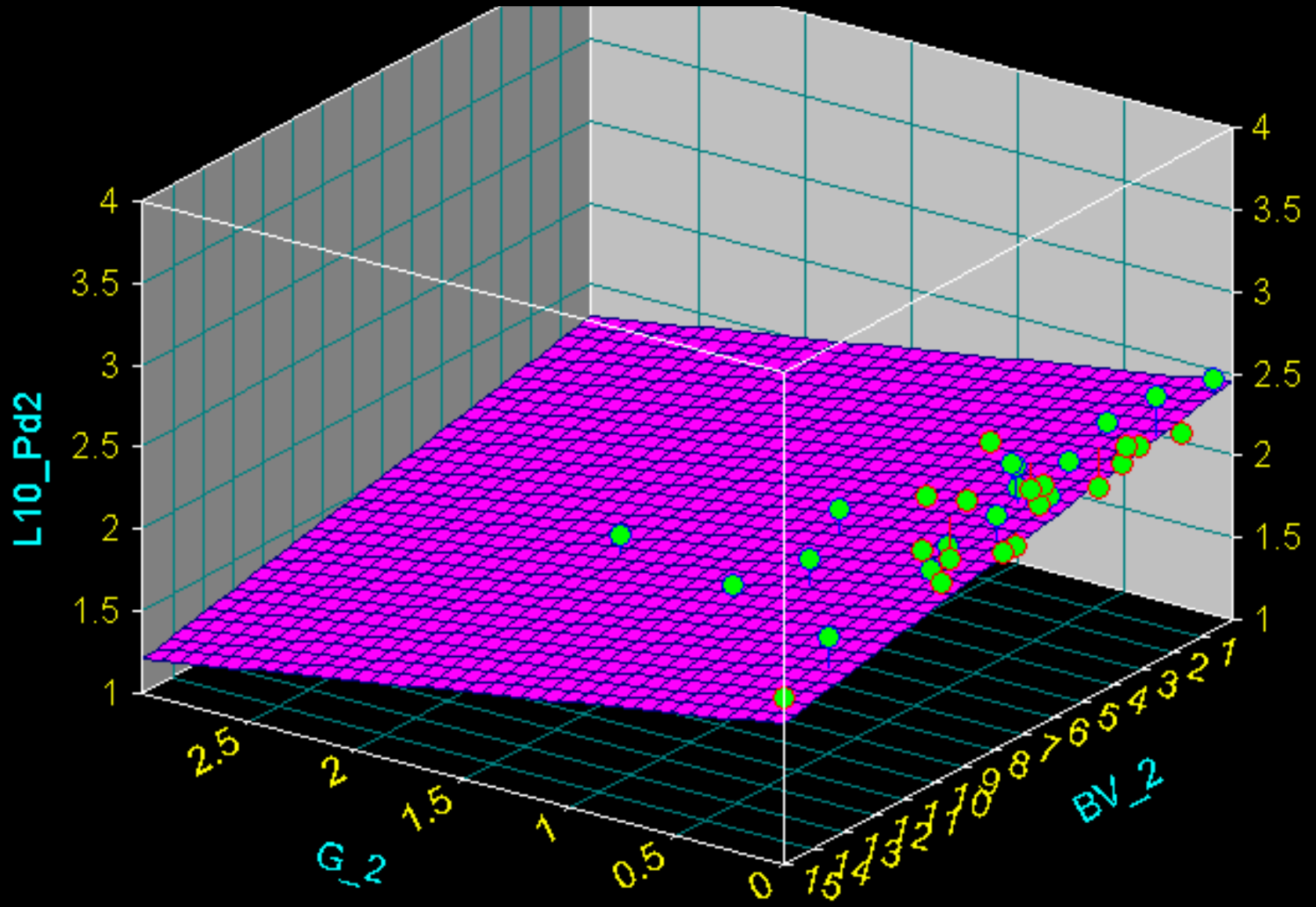
- You can only turn them back off by setting the volume assignment to 0.0001 – not by clearing the cells

Visualizing Thomeer Parameters

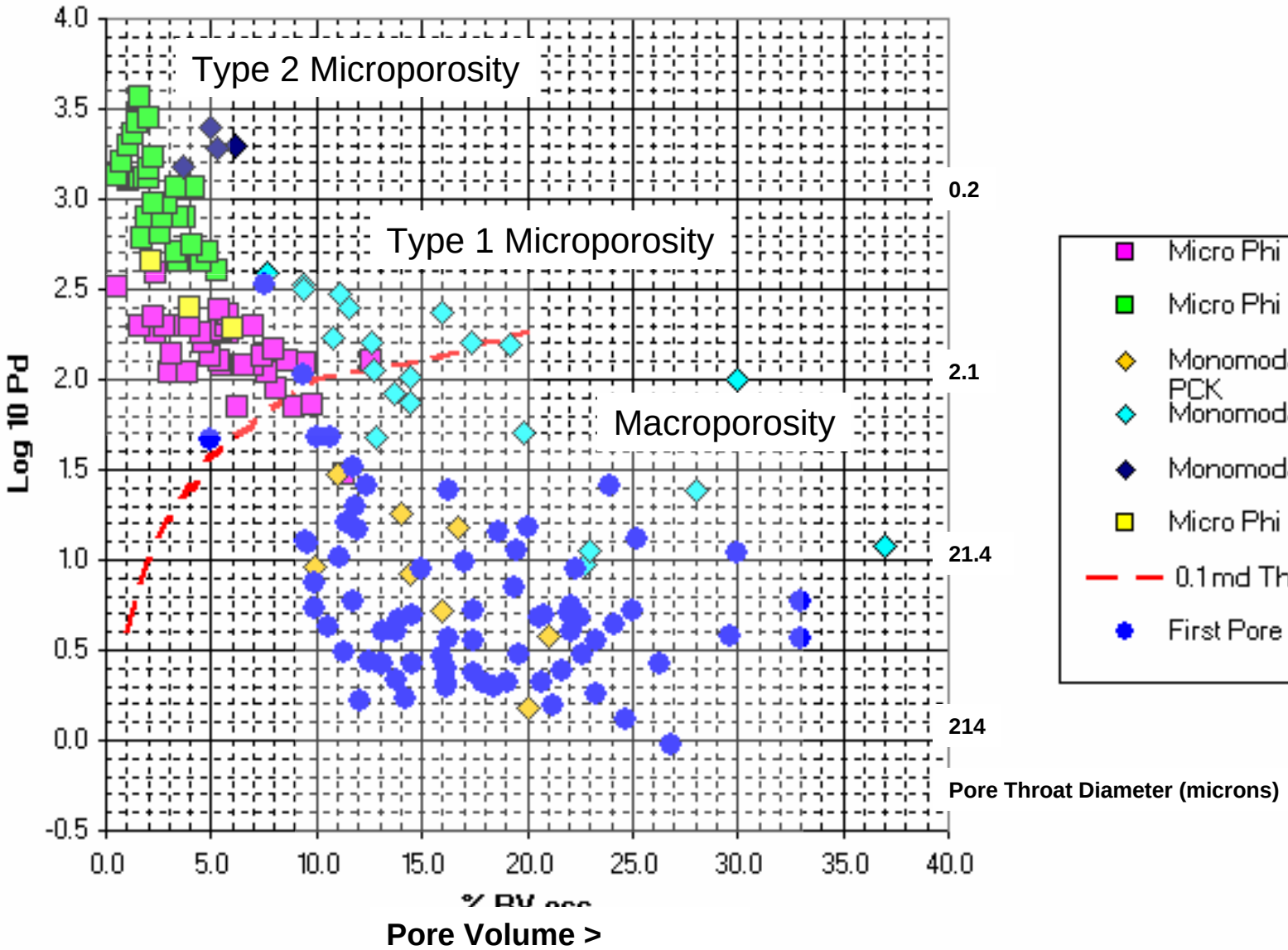
Thomeer Clusters for Petrophysical Rock Types

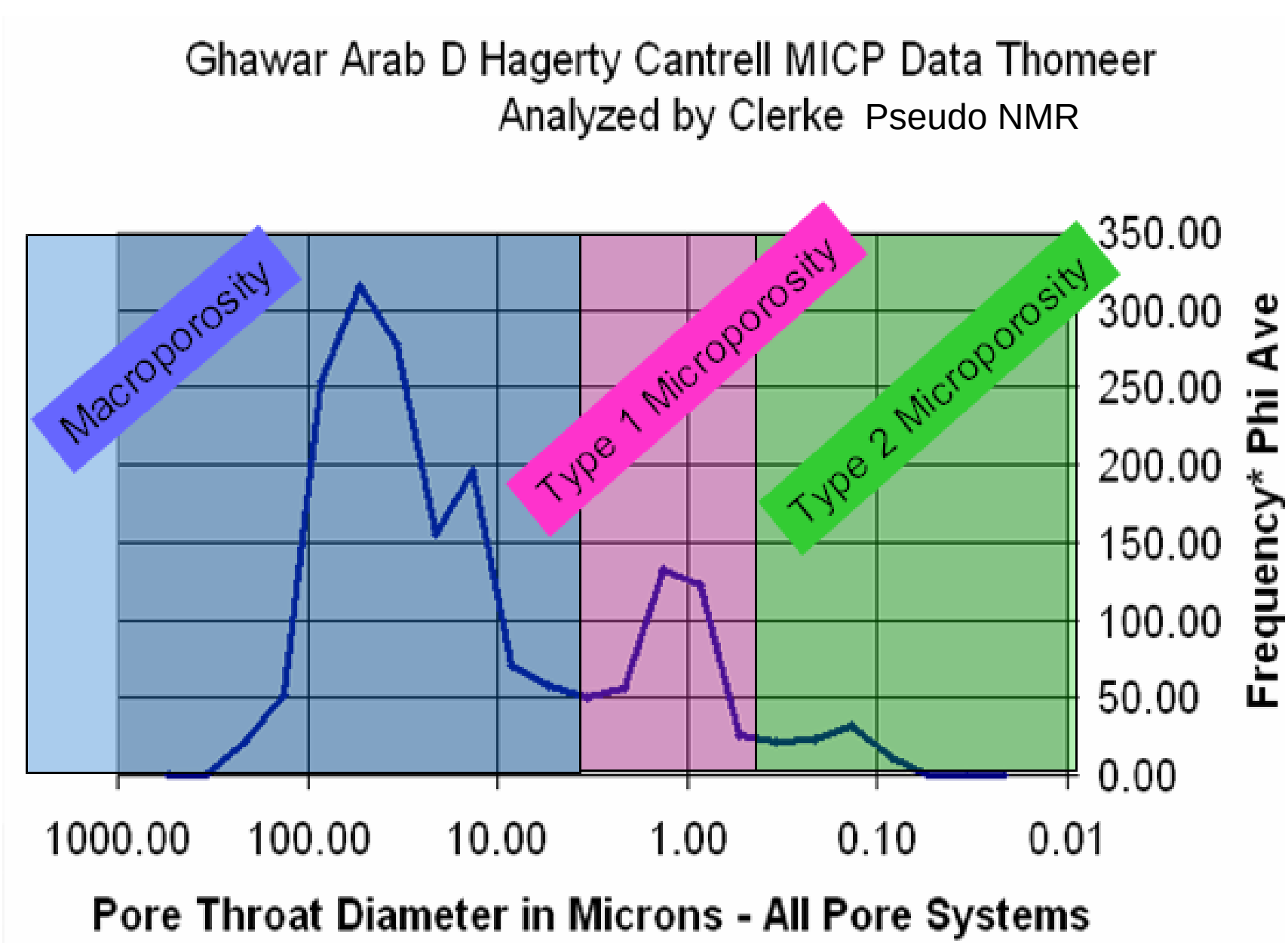


Type 1 Microporosity



Ghawar Arab D Limestones
2D Projection




Ghawar Arab D Hagerty Cantrell MICP Data Thomeer
Analyzed by Clerke Pseudo NMR
Macroporosity
Type 1 Microporosity
Type 2 Microporosity
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
Frequency* Phi Ave
1000.00
100.00
10.00
1.00
0.10
0.01
Pore Throat Diameter in Microns - All Pore Systems

Thomeer Petrophysical Rock Type Process