Multiple Discrete Pore Systems in Arab D Limestone*

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Abstract

The pore systems of the Arab D limestone, a formation that holds a large proportion of the world's oil reserves, show abundant microporosity. Prior petrographic studies are continued here with an extensive mercury injection capillary pressure study. The MICP study demonstrates that the pore volume of the micropores (~25% of pore space) is volumetrically significant. Using Thomeer type curve analysis to fit the MICP data of our very large MICP data set, the pore systems' volumes and entry pressures are quantified. The micropores are shown to be oil-charged and do not contribute measurably to permeability.

The MICP entry pressure data show four distinct entry pressure modes or "porositons," three of which represent forms of microporosity. The Arab D limestone matrix pore system, therefore, requires a multimodal matrix storage model and a monomodal matrix permeability model.

Having determined the nature of the embedded carbonate pore system modes, the petrophysical model is rebuilt for the relationship of the entry pressure modes to the depositional geology, spectral porosity log response, hydrocarbon storage, permeability and multiphase transport ,and microscopic displacement efficiency. The conventional experimental data must be analyzed using new multimodal methods and algorithms.

Permeability is shown to be controlled by the properties of the mode containing the largest of the maximum pore throat diameters. The Type 1 microporosity is shown to shift the imbibition cycle oil relative permeability curve to the right and hence affect the determination of the microscopic displacement efficiency in the presence of macro and micropores.

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Multiple Discrete Pore Systems in Arab D Limestone

Spectral Analysis of the Arab D Limestone Pore Geometries

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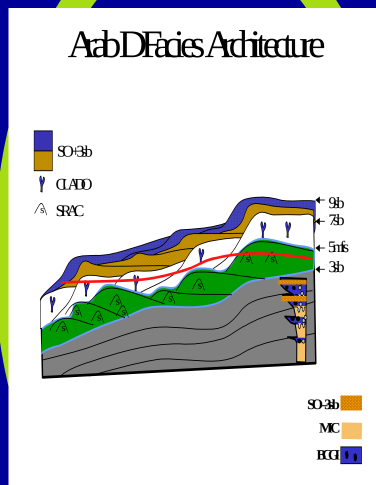
Rosetta Stone



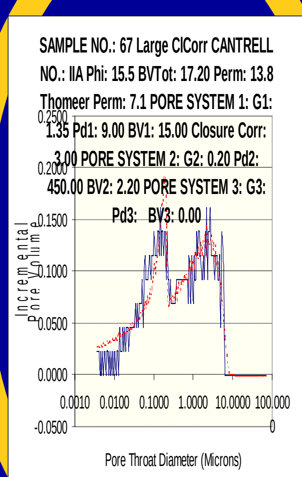
Mile Scale

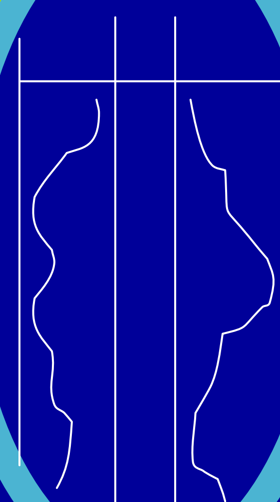
Depositional Rock Types

Micron Scale

Pore System Parameters

- Permeability
- Relative Perm





Centimeter Scale

Wireline Log Responses

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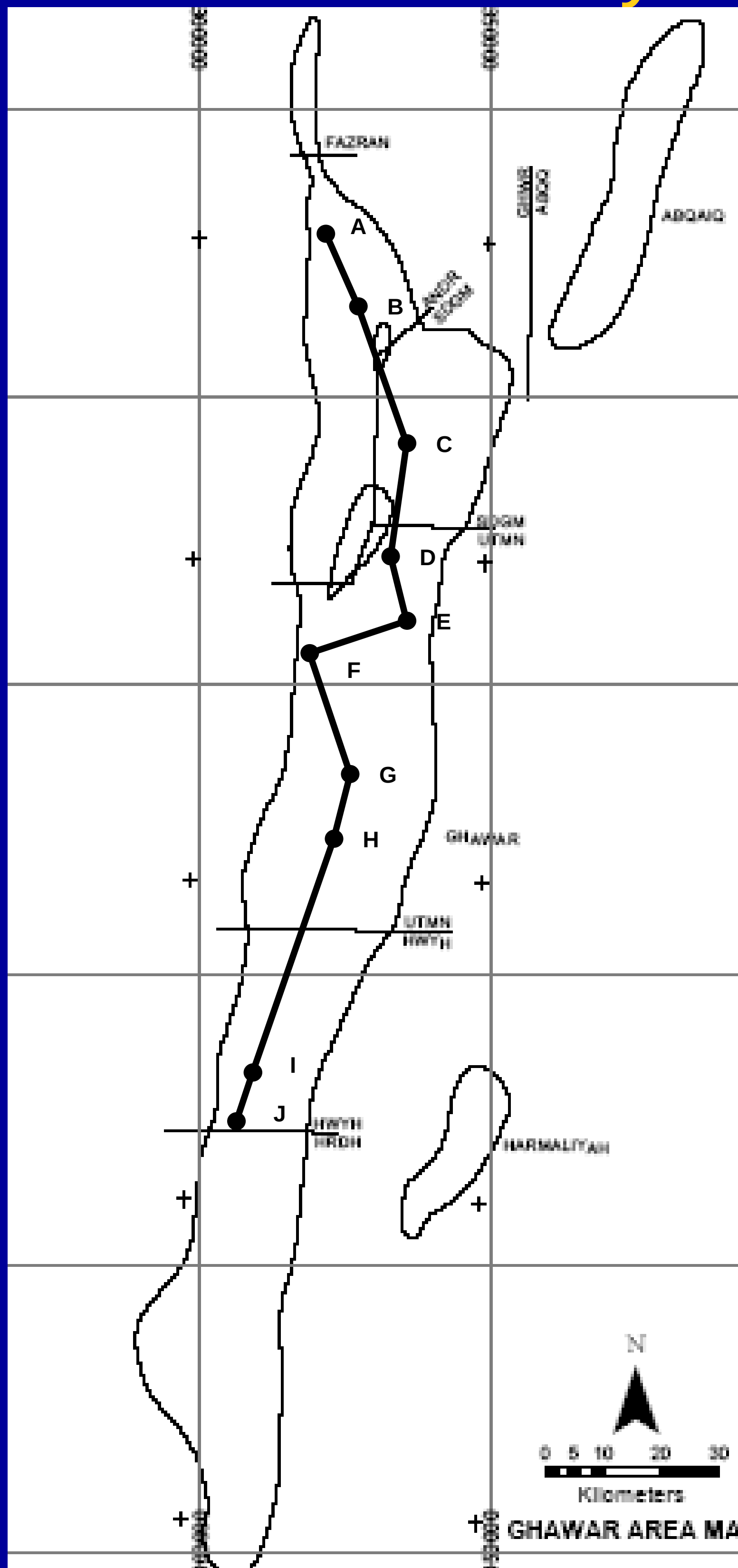
Rosetta Stone Project

- **480 new mercury injection capillary pressure curves taken by HWM-C facies using random processes within the facies from 10 wells on a N-S transect through Ghawar**
- **All 480 MICP curves have been fit with Thomeer type curves**
- **860 Thomeer Hyperbolae**

Rosetta Stone Key Wells



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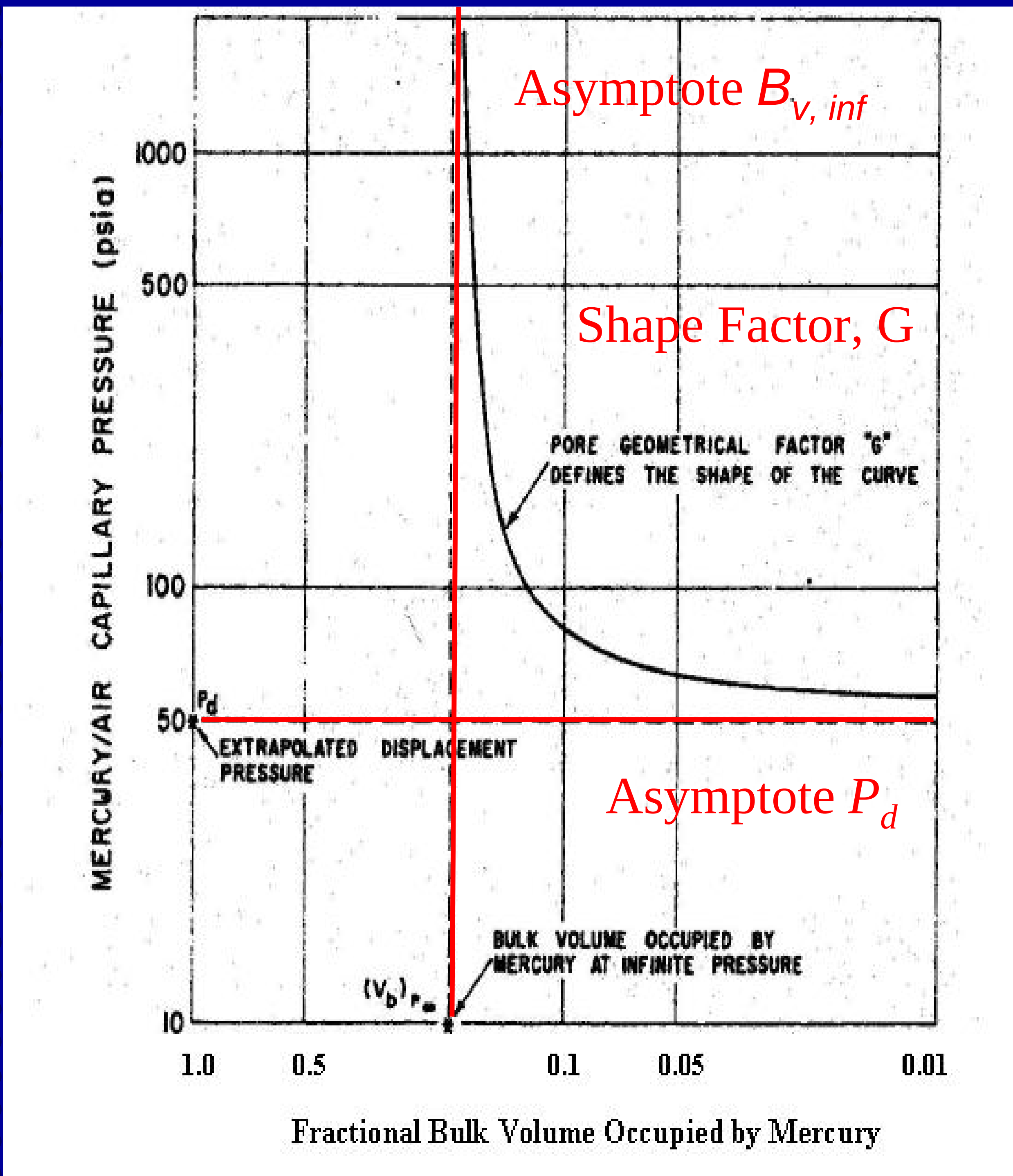
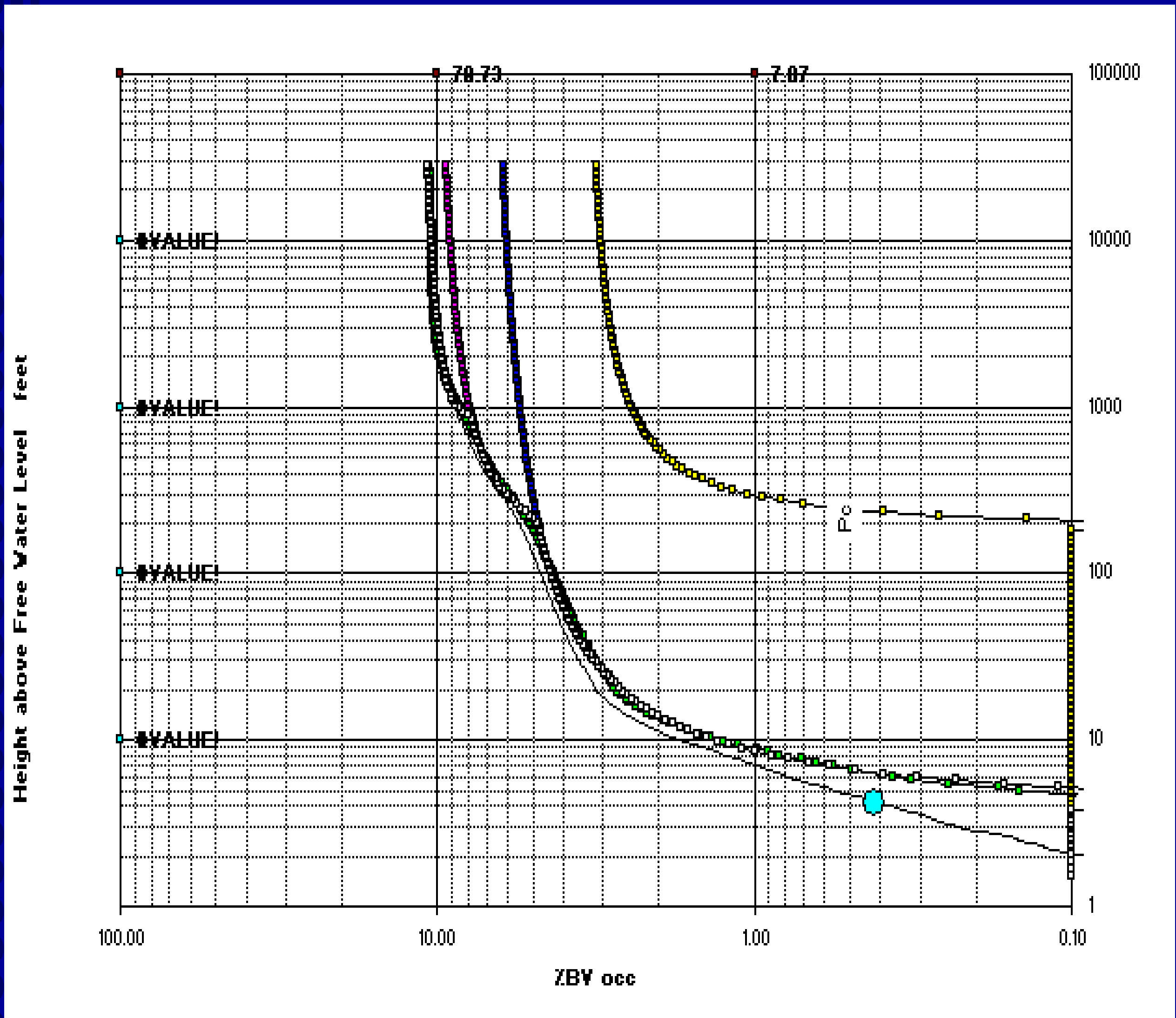
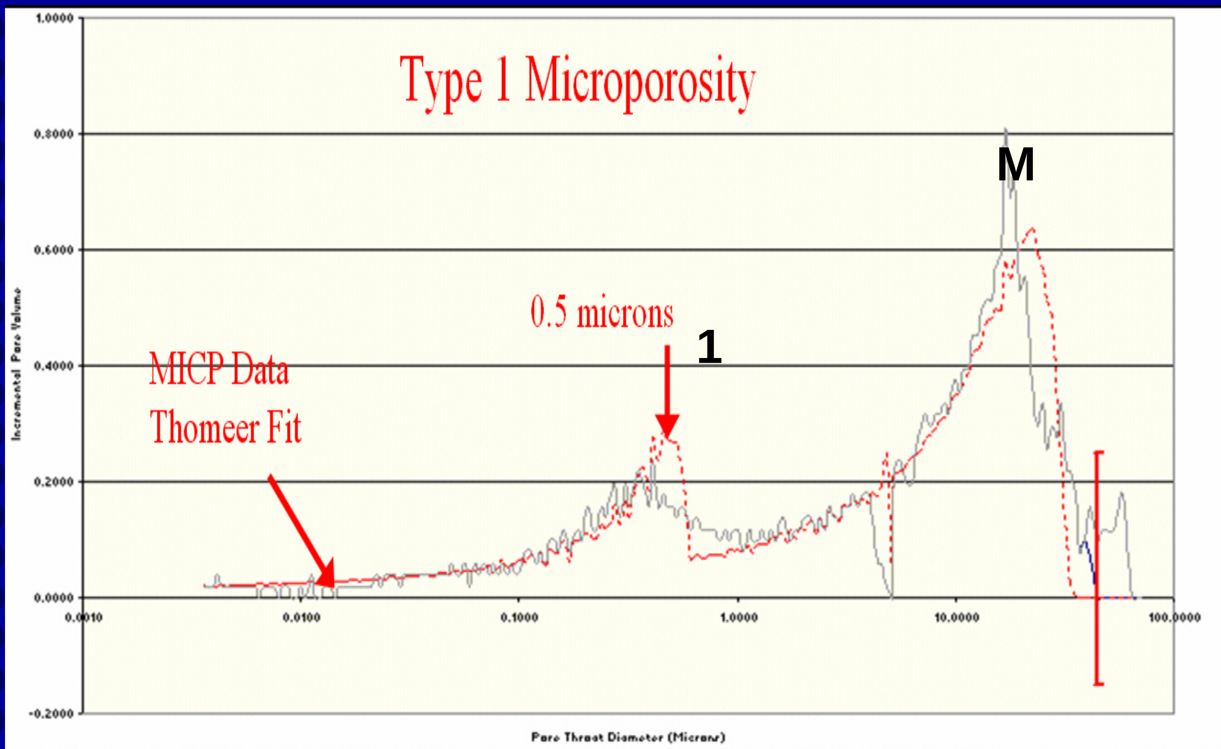
Thomeer Hyperbola = A Single Pore 'System'

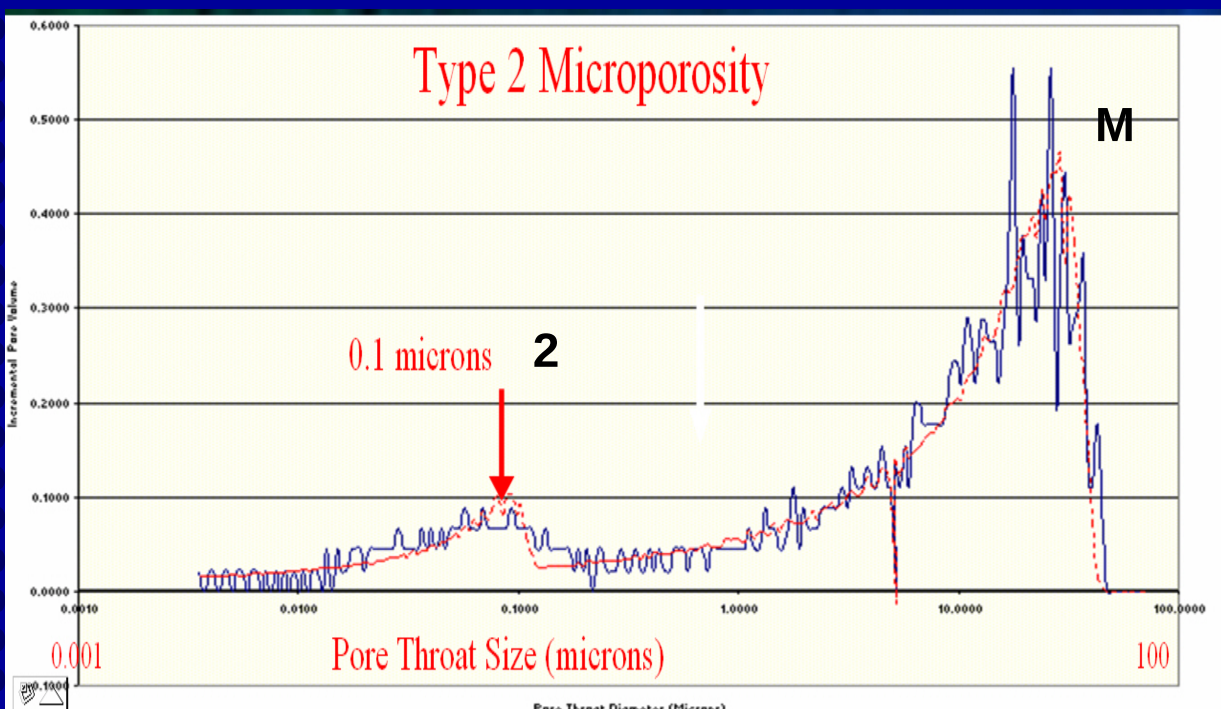


Superposition of Hyperbolas to Model and Quantify Complex Arab D Pore Systems

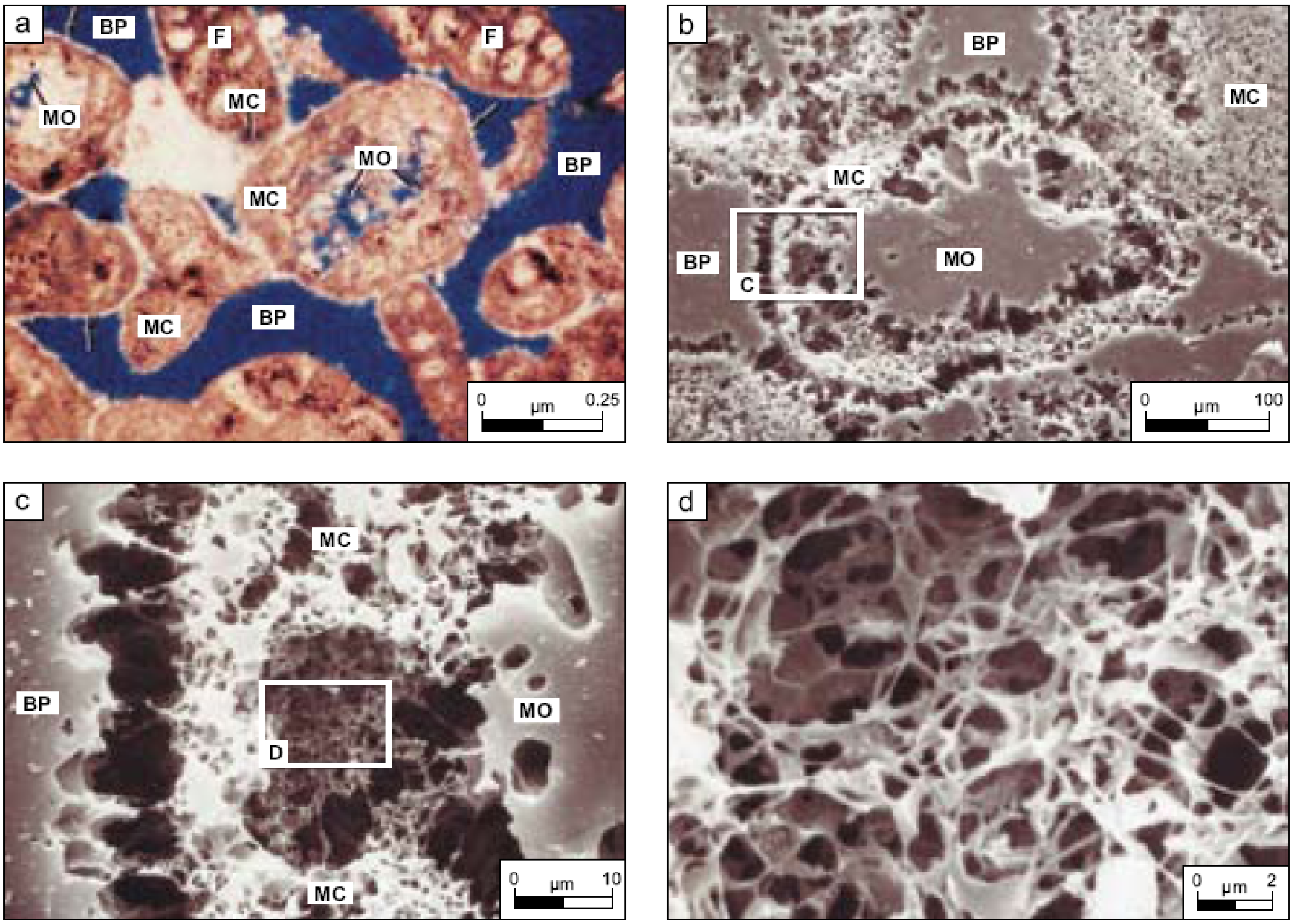


Bimodals are very common
Two of the three Porositons are present in many samples as intraparticle porosity





M_1



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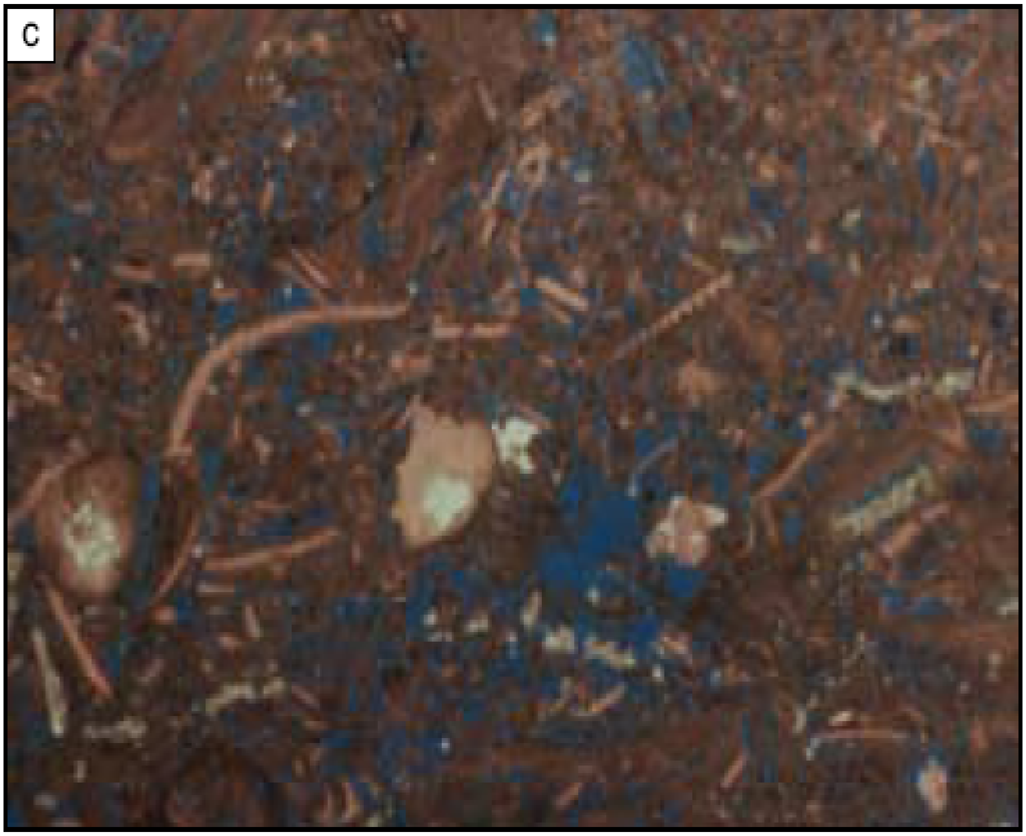
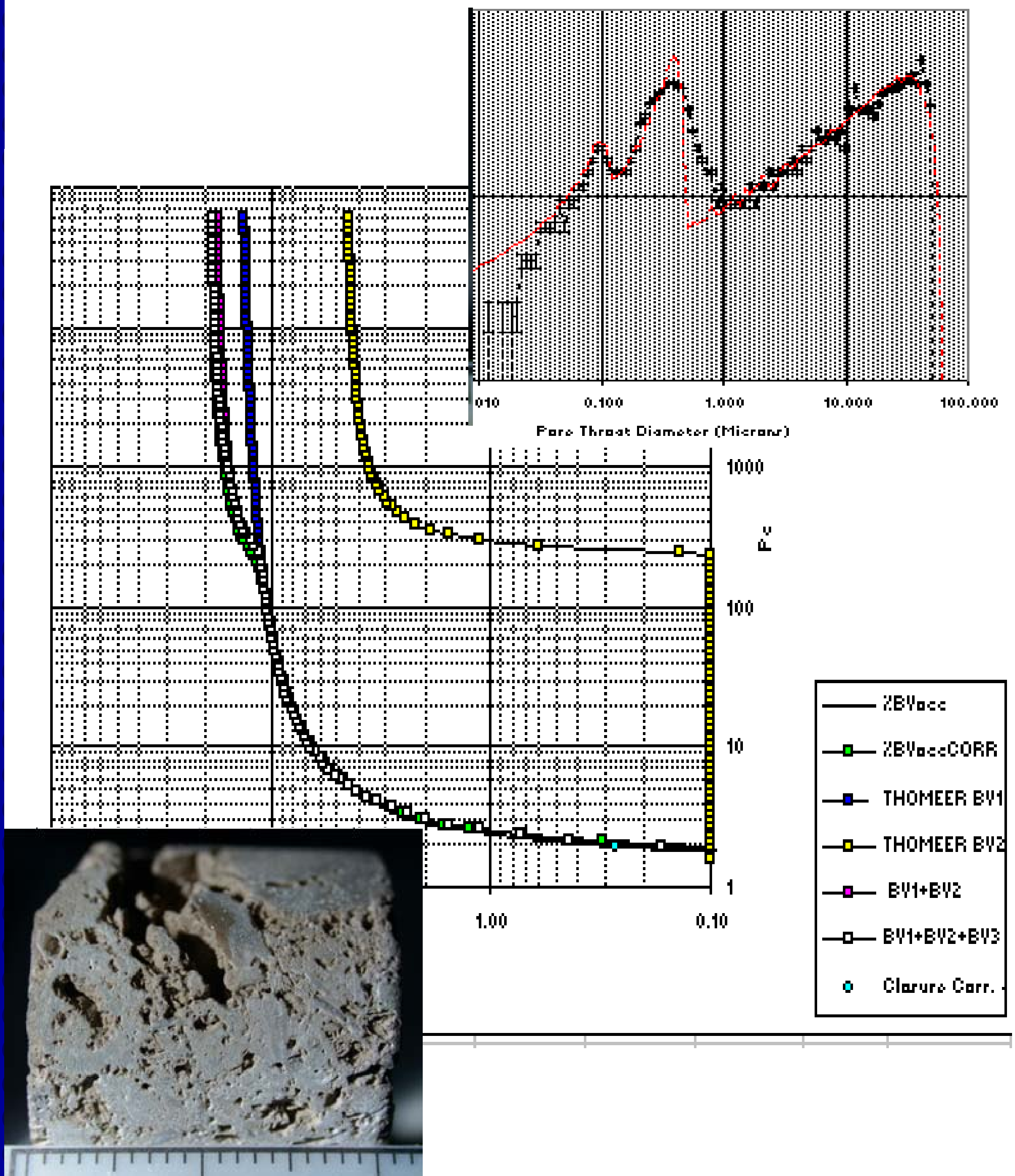
M_2

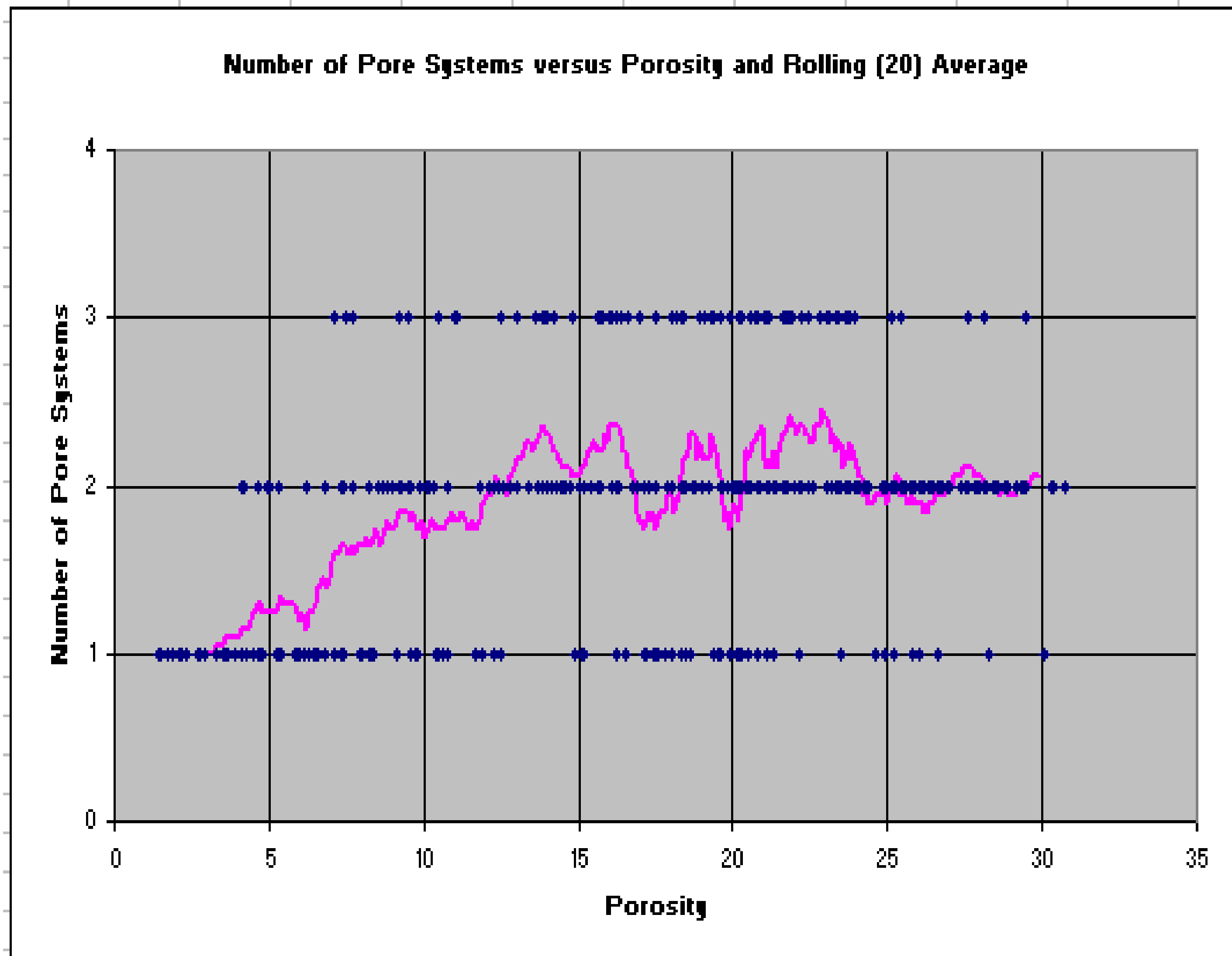


SRAC M_1_2 Trimodal from UTMN 1049



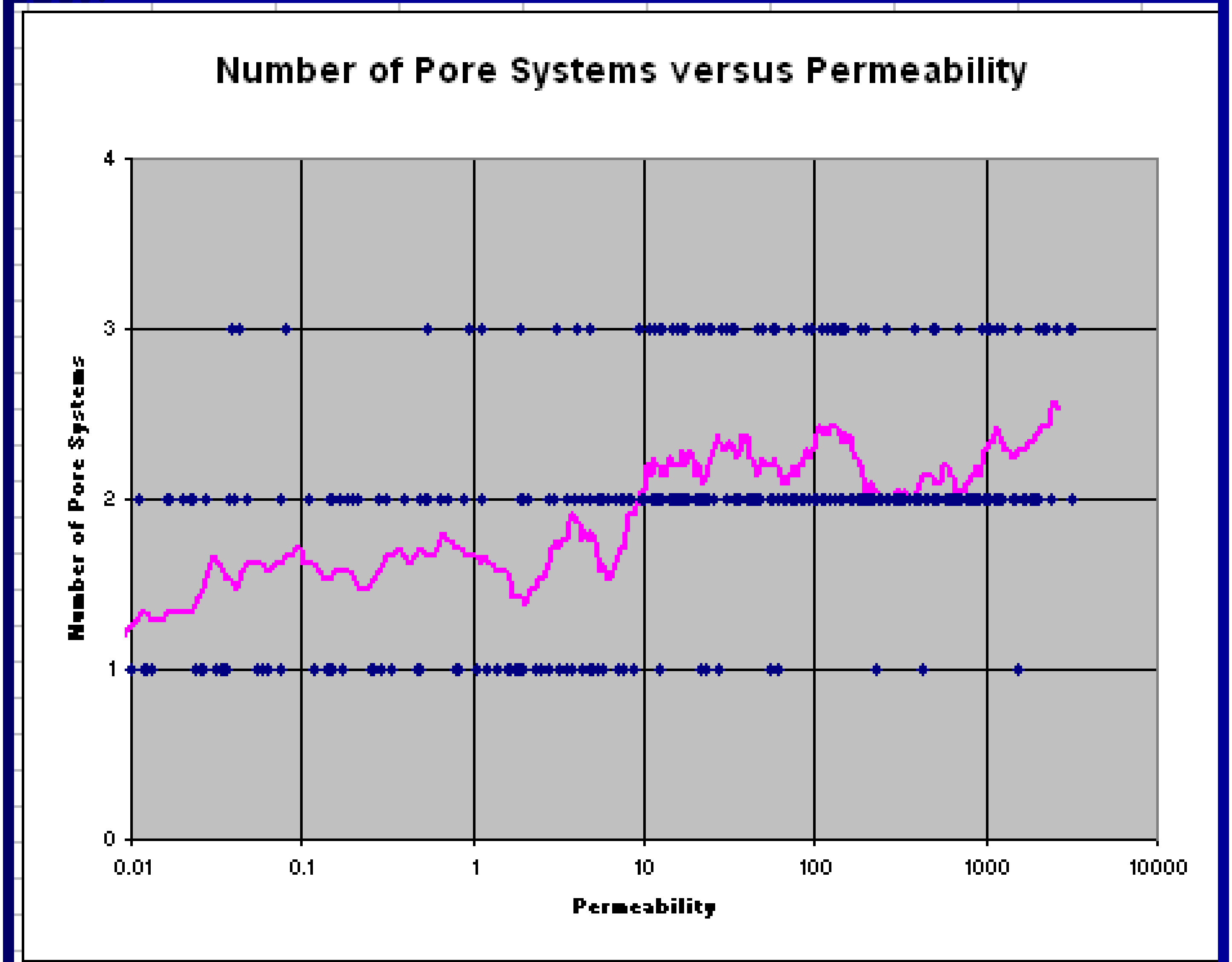
Selected Results

Bimodality common in porous reservoir rock



Selected Results

Bimodality common in permeable and porous reservoir rock



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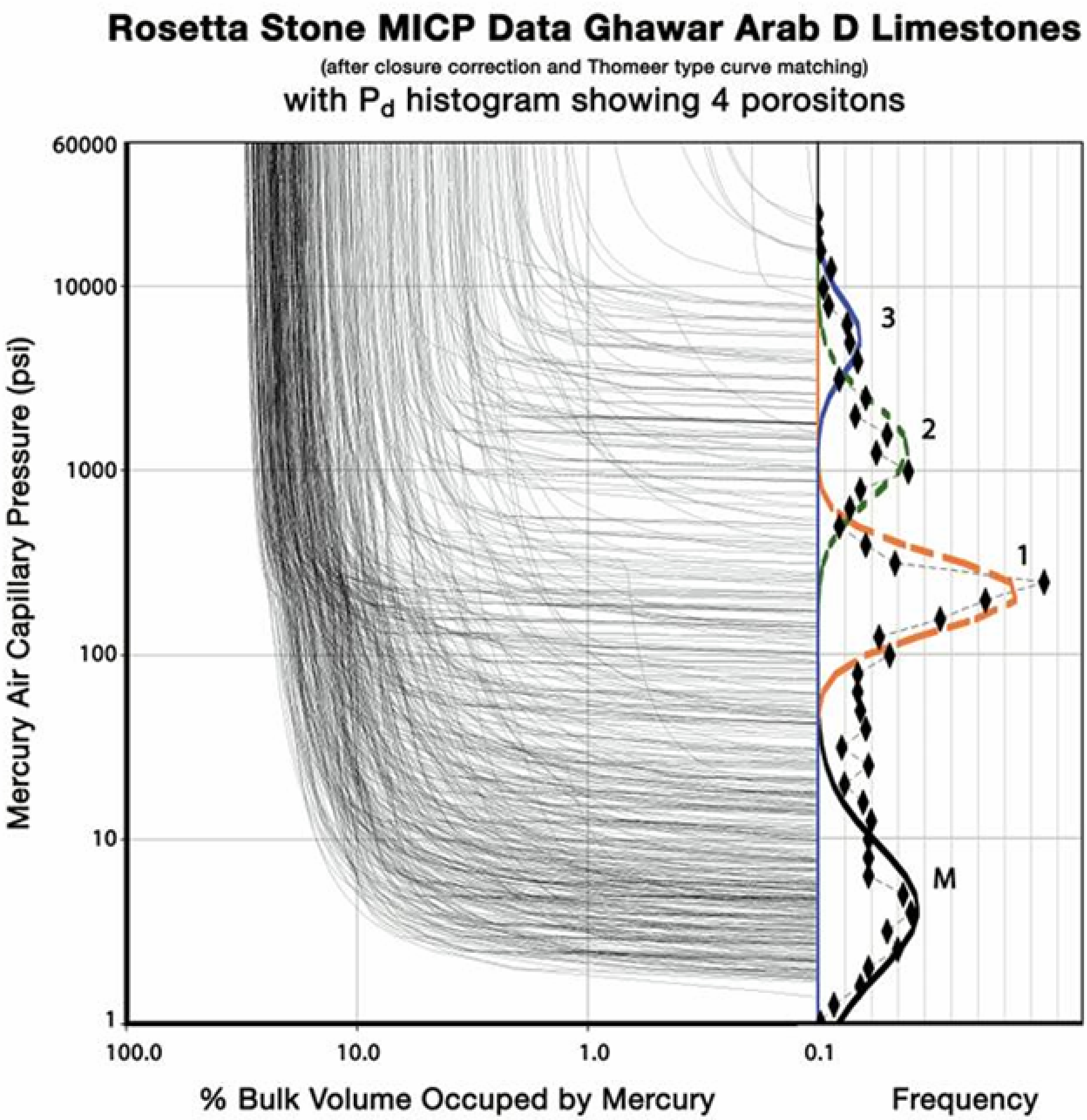
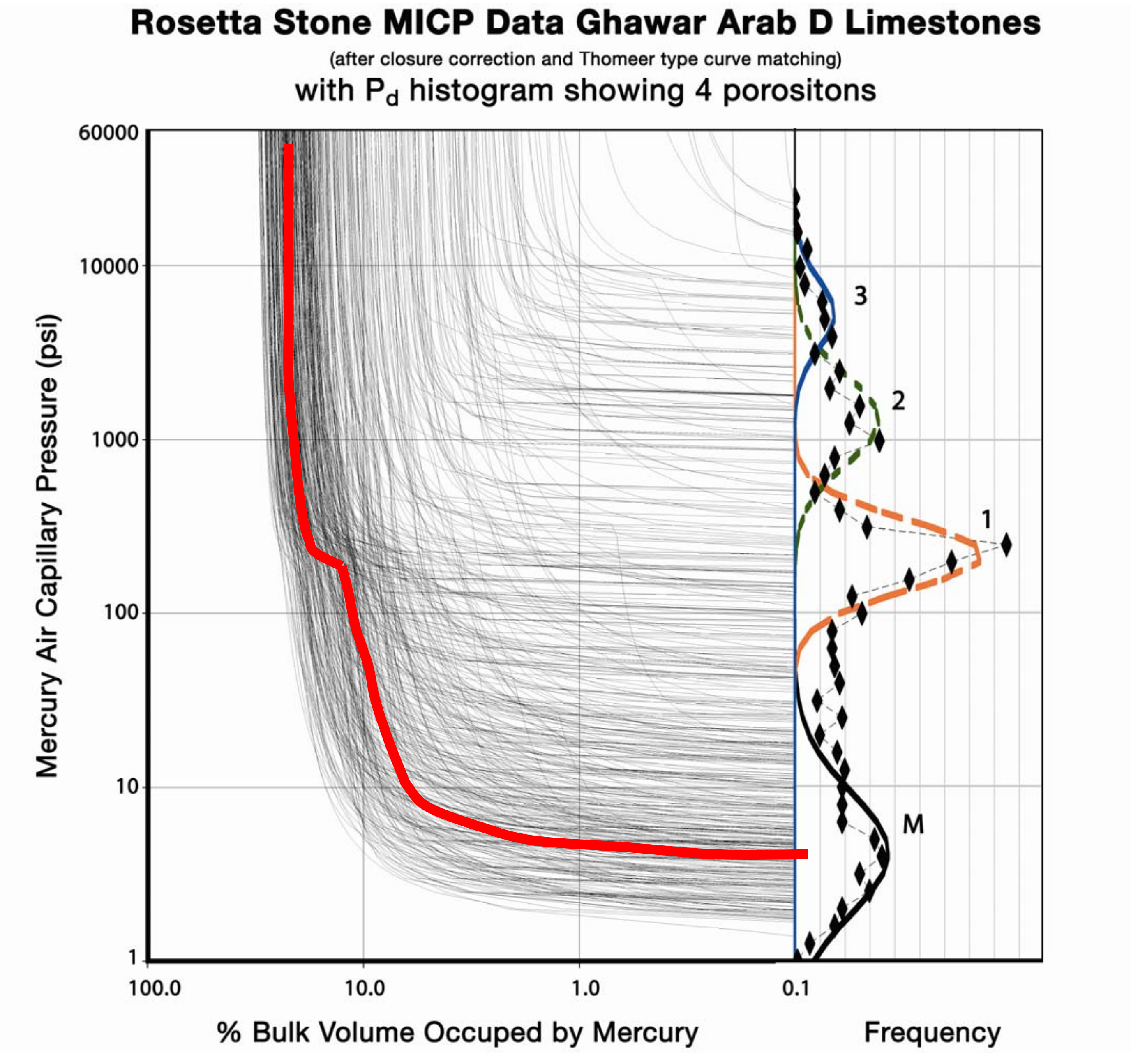
Porositons



Rosetta Stone MICP Data Ghawar Arab D Limestones
(after closure correction and Thomeer type curve matching)
with P_d histogram showing 4 porositons
60000
10000
1000
100
10
1
Mercury Air Capillary Pressure (psi)
100.0
10.0
1.0
0.1
% Bulk Volume Occuped by Mercury
Frequency
3
2
1
M

M_1 Emphasis



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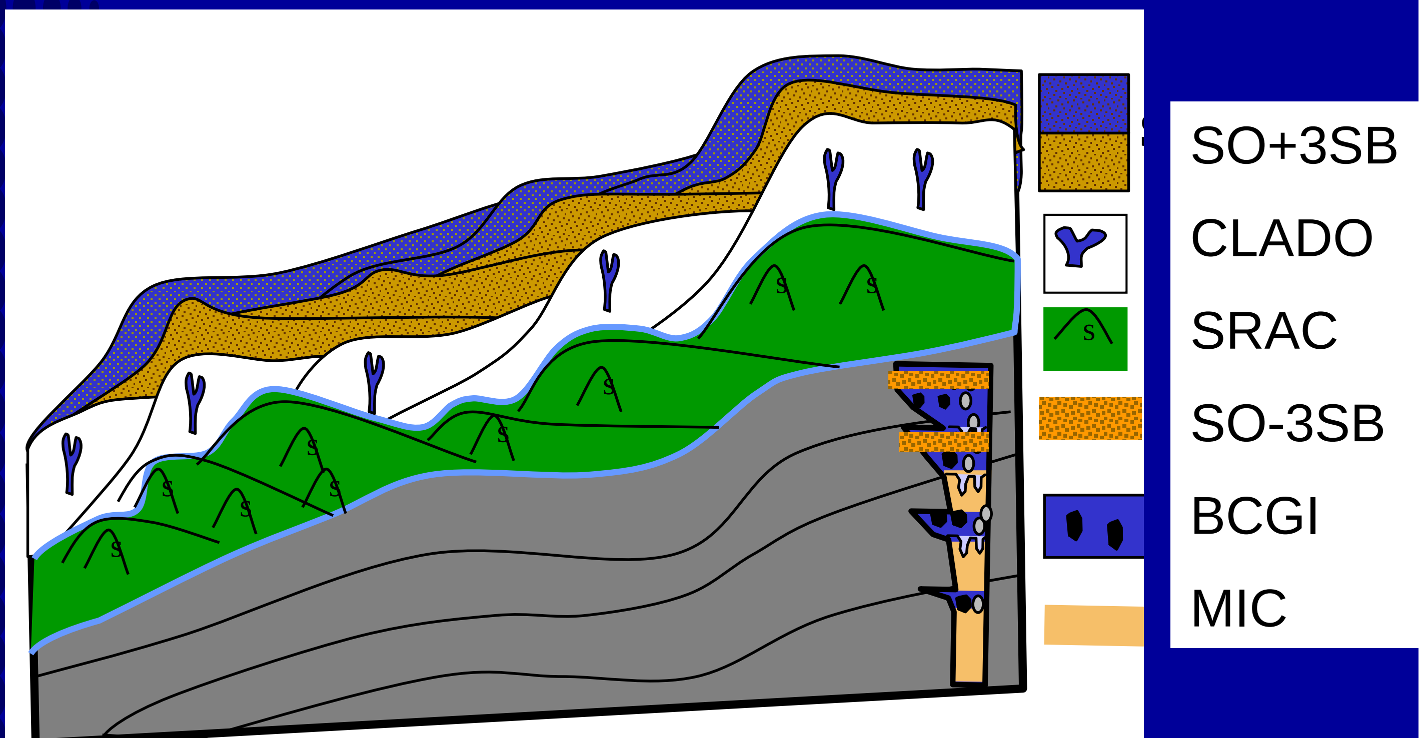
HWM-C Facies and Stacking Patterns



SO+3SB: Skeletal Oolitic above the 3rd Sequence Boundary

CLADO: Cladocoropsis

SRAC: Stromatoporoid, Red-Algae, Coral

SO-3SB: Skeletal Oolitic below the 3rd Sequence Boundary

BCGI: Bivalve, Coated Grain, Intraclast

MIC: Micrite – not burrowed

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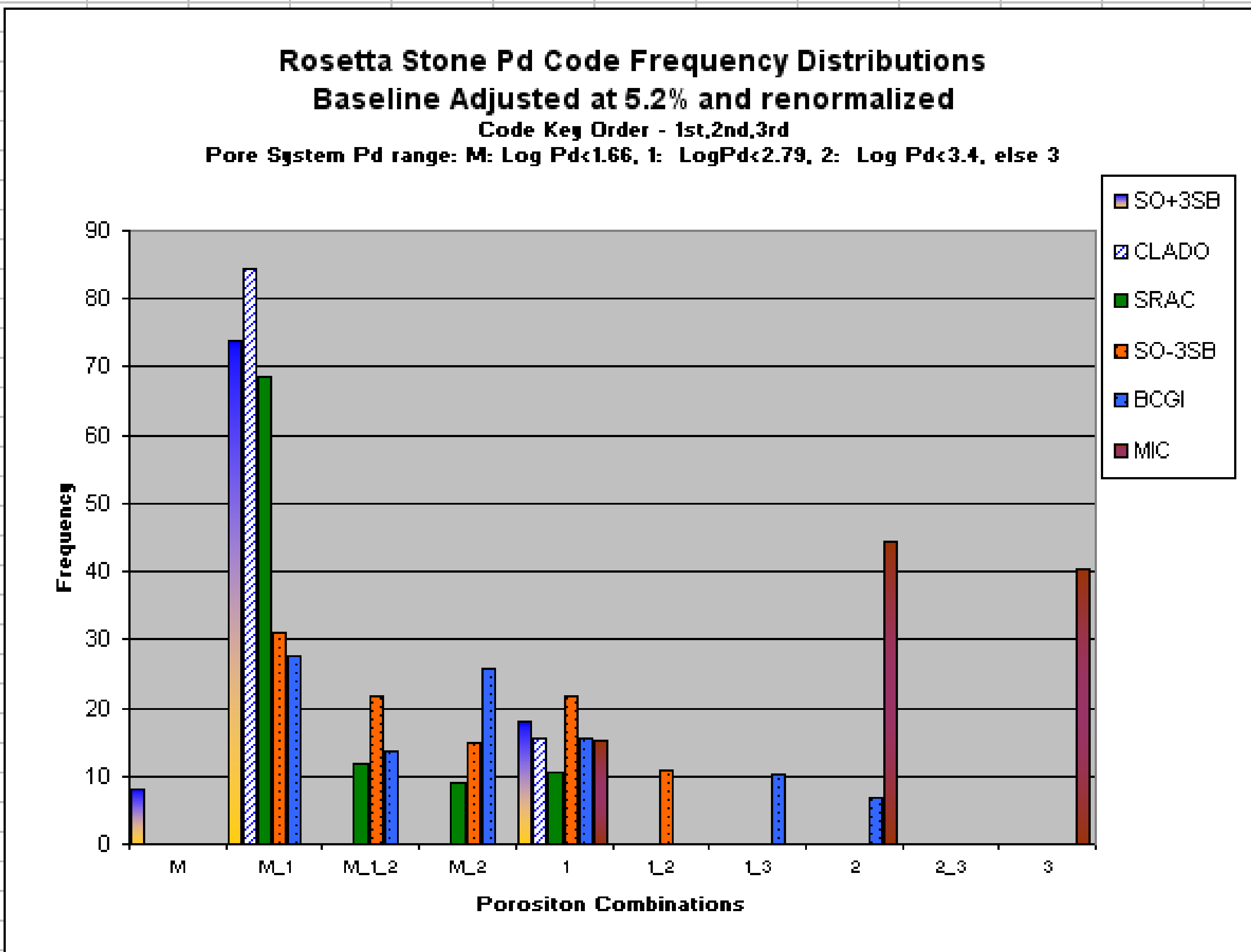
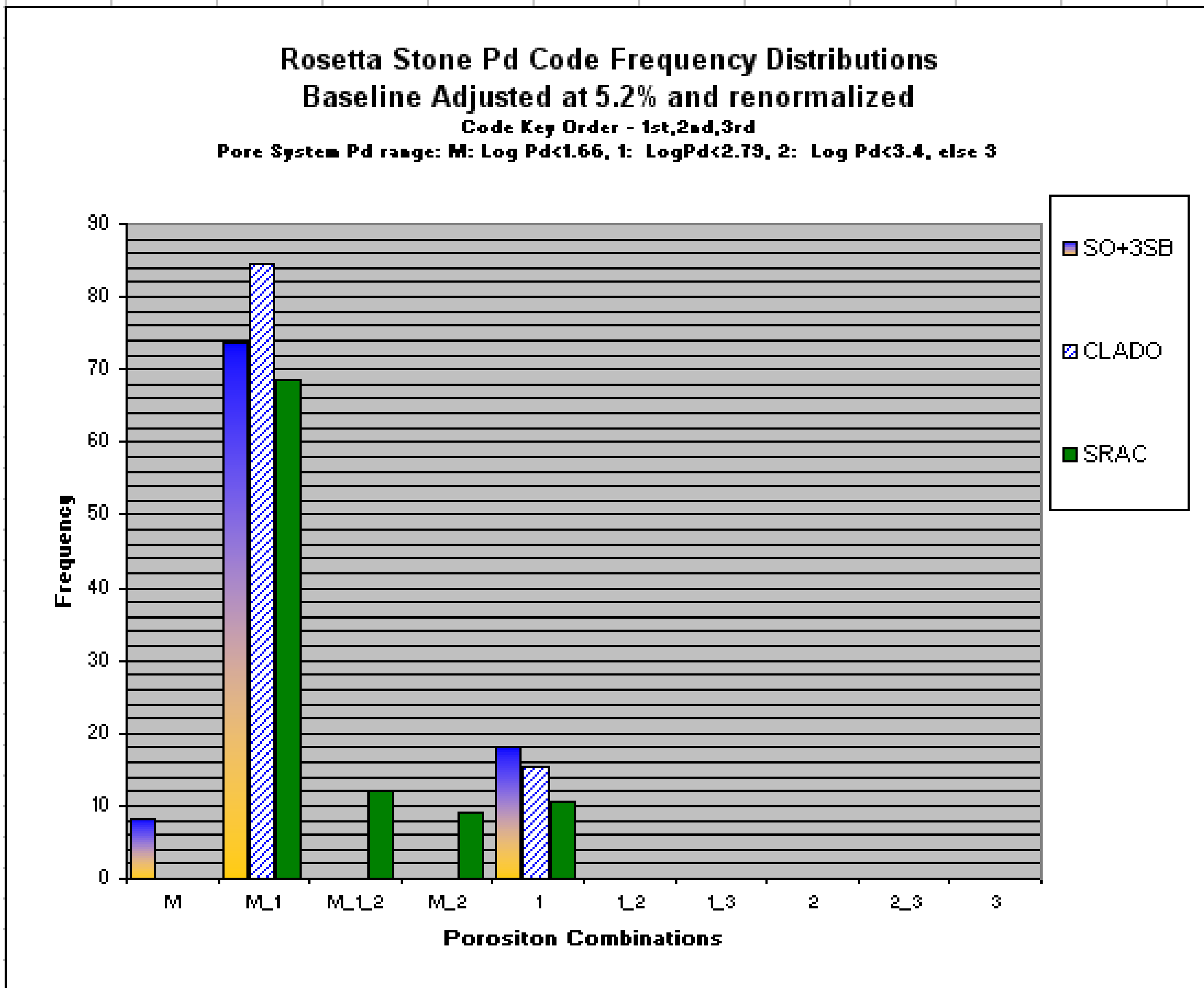
HWM-C Facies in terms of Porositon Classified Pore Systems



SO+3SB, CLADO, SRAC are dominantly M_1



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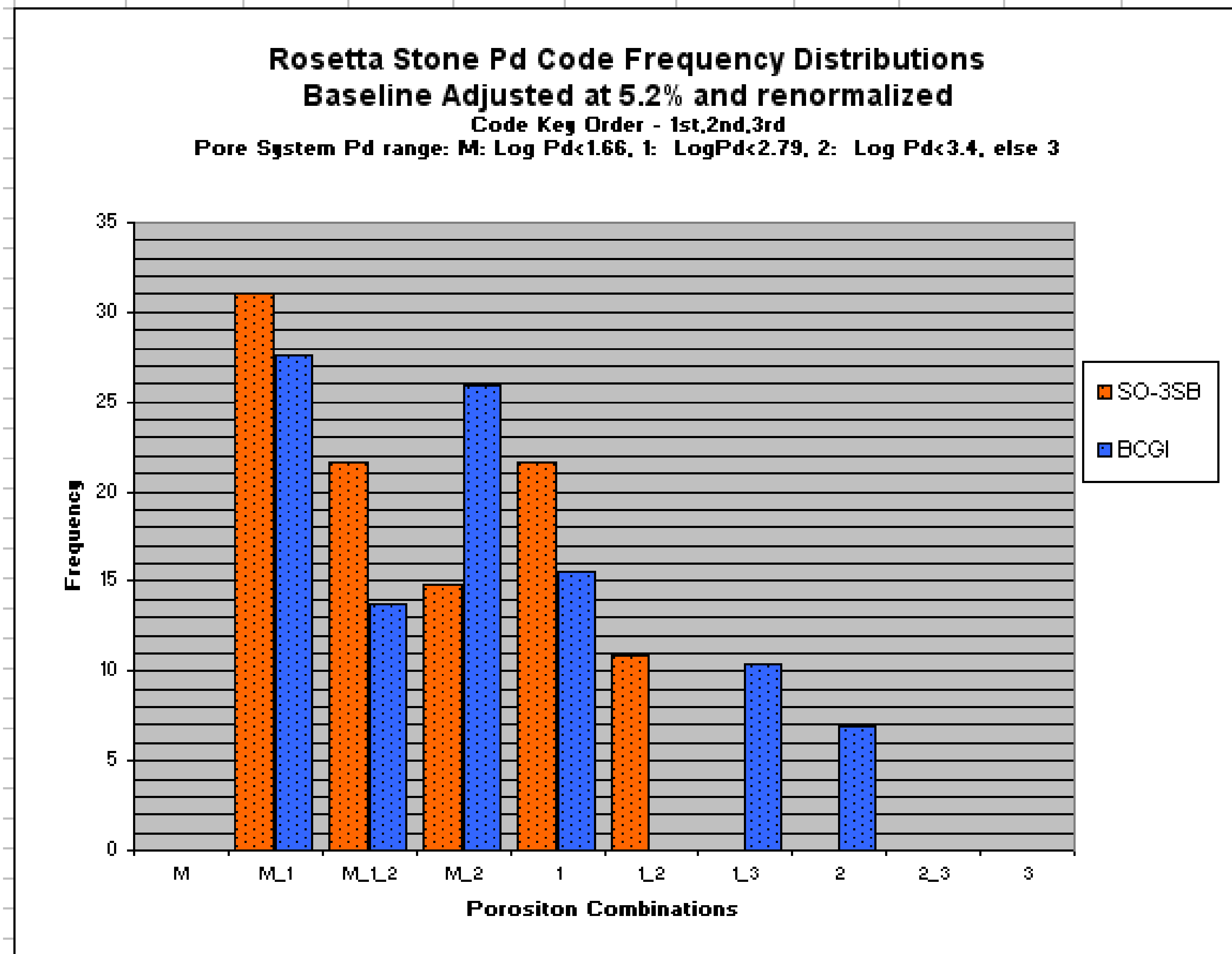
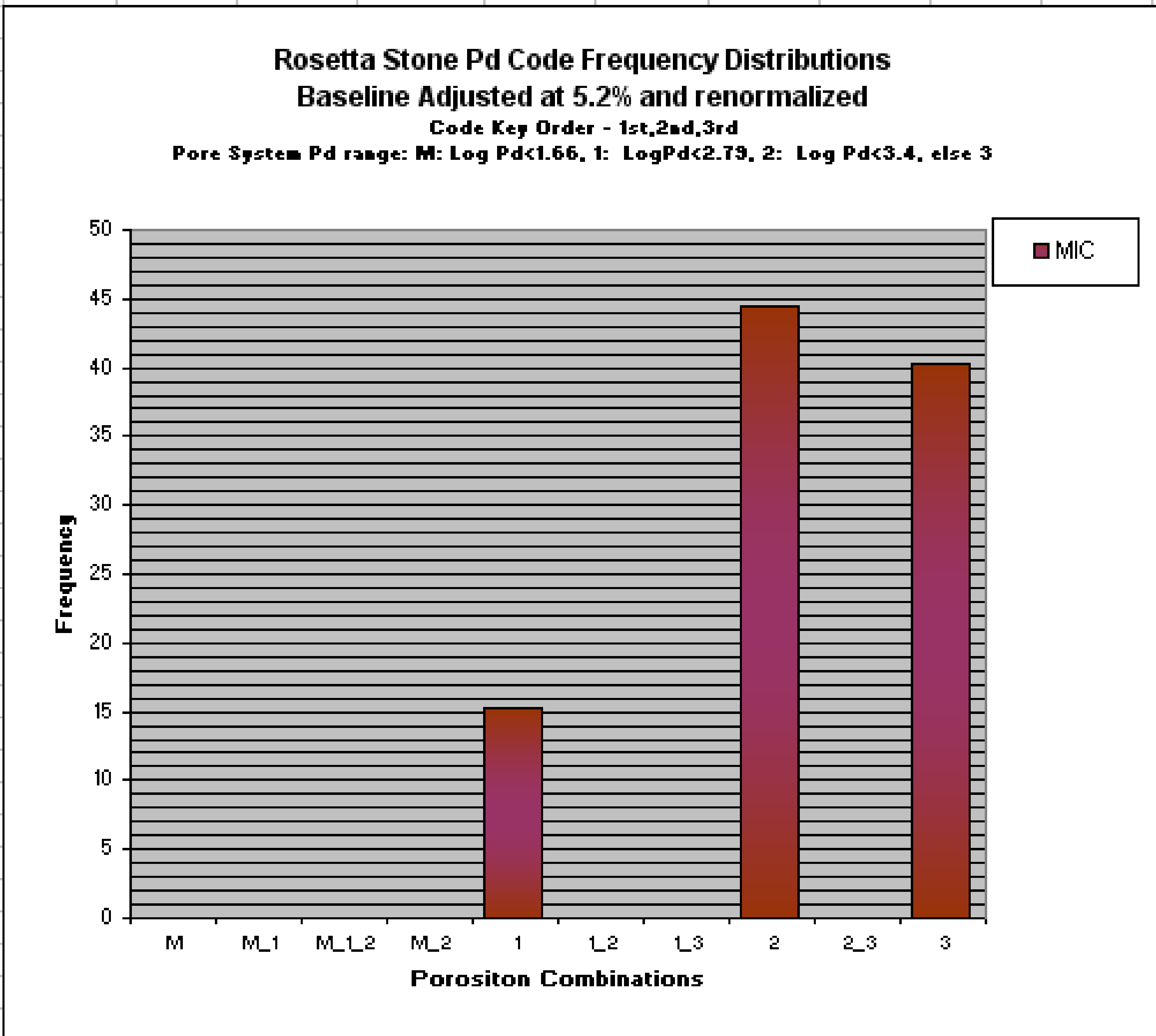
SO-3SB is similar to BCGI and different from SO+3SB

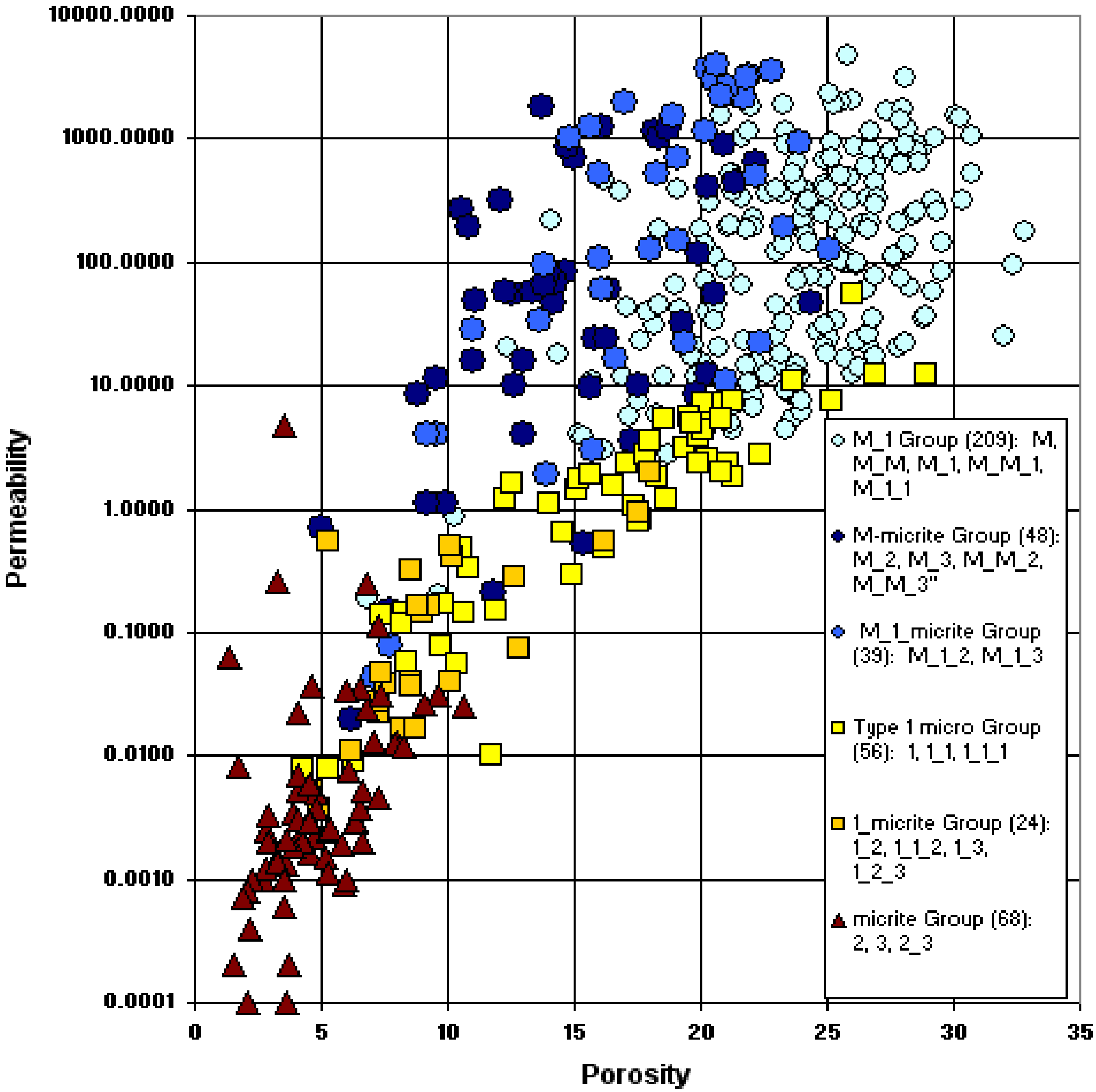
These facies are mixes of 7 porositon combinations



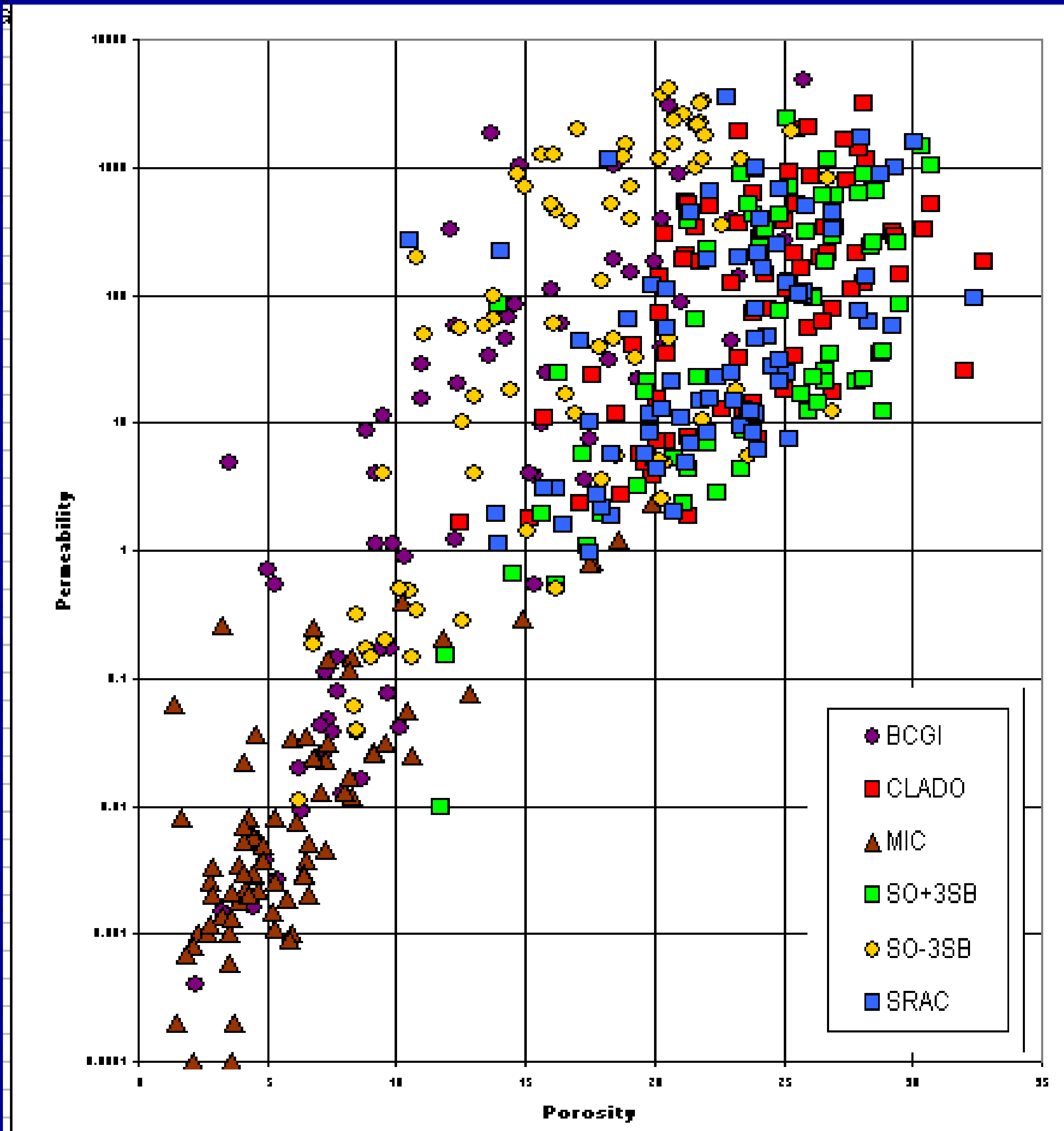
Micrite (unburrowed) is a mix of the three microporositons



Main Porositon Combinations in terms of Poro-Perm



HWM-C Facies in terms of Poro-Perm



Dynamic Reservor Properties to Pore System Connections

Permeability in multimodal pore systems

- **Permeability can be modelled using data from the *<u>First Pore System Only</u>*, usually the M porositon**

- **First porositon, M, carries the useful permeability**

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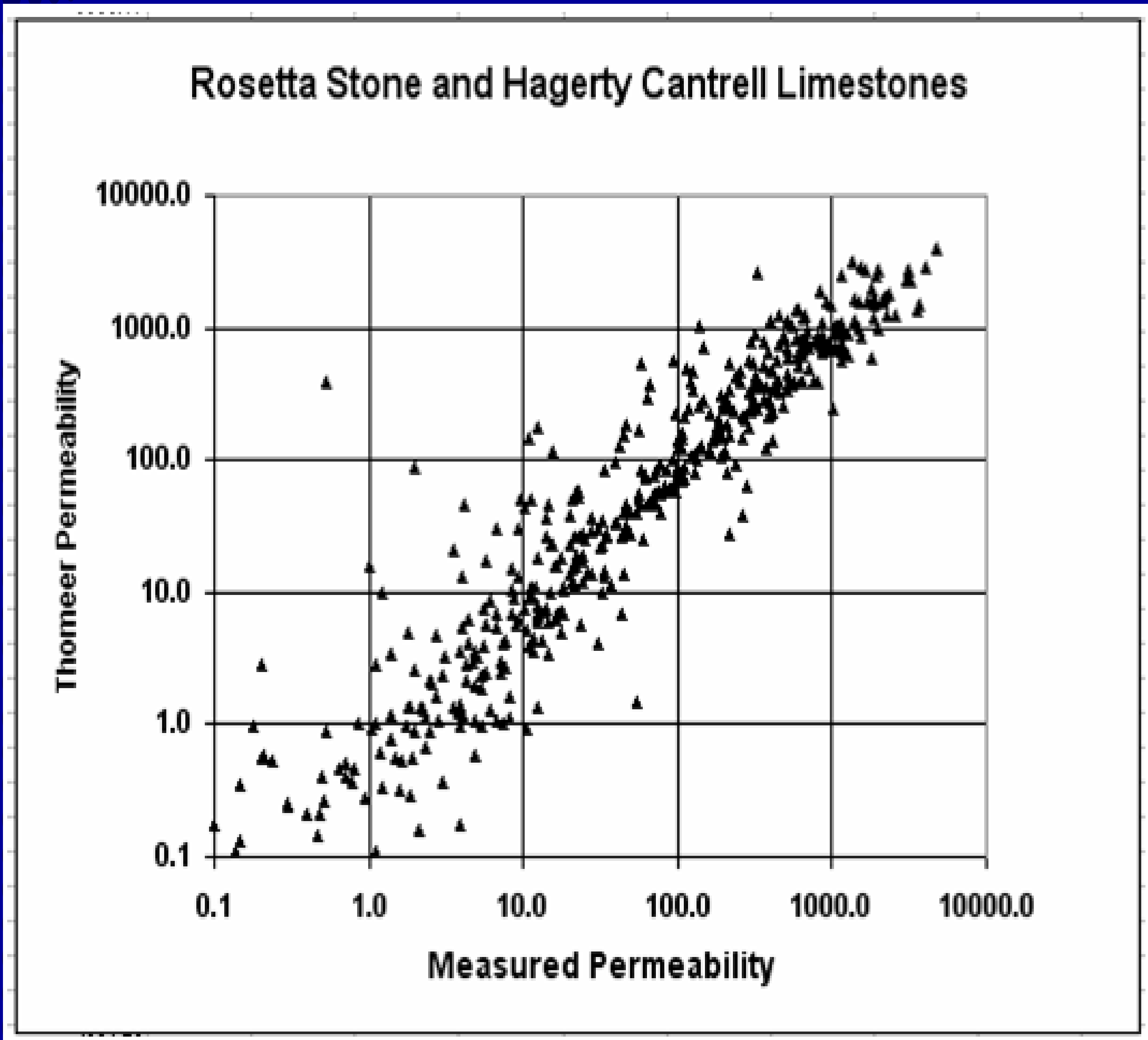
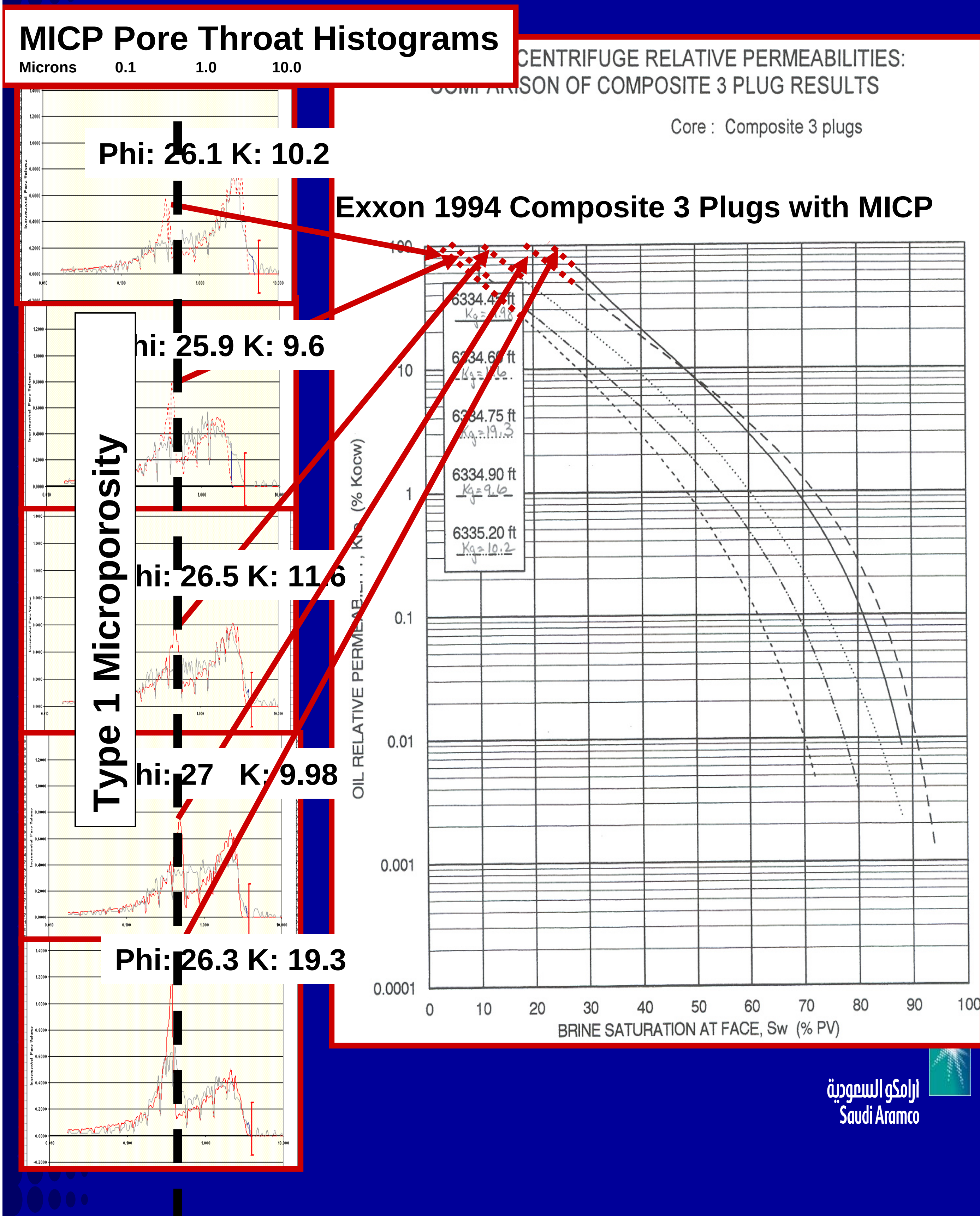


Rosetta Stone and Hagerty Cantrell Limestones
10000.0
1000.0
100.0
10.0
1.0
0.1
Thomeer Permeability
0.1
1.0
10.0
100.0
1000.0
10000.0
Measured Permeability

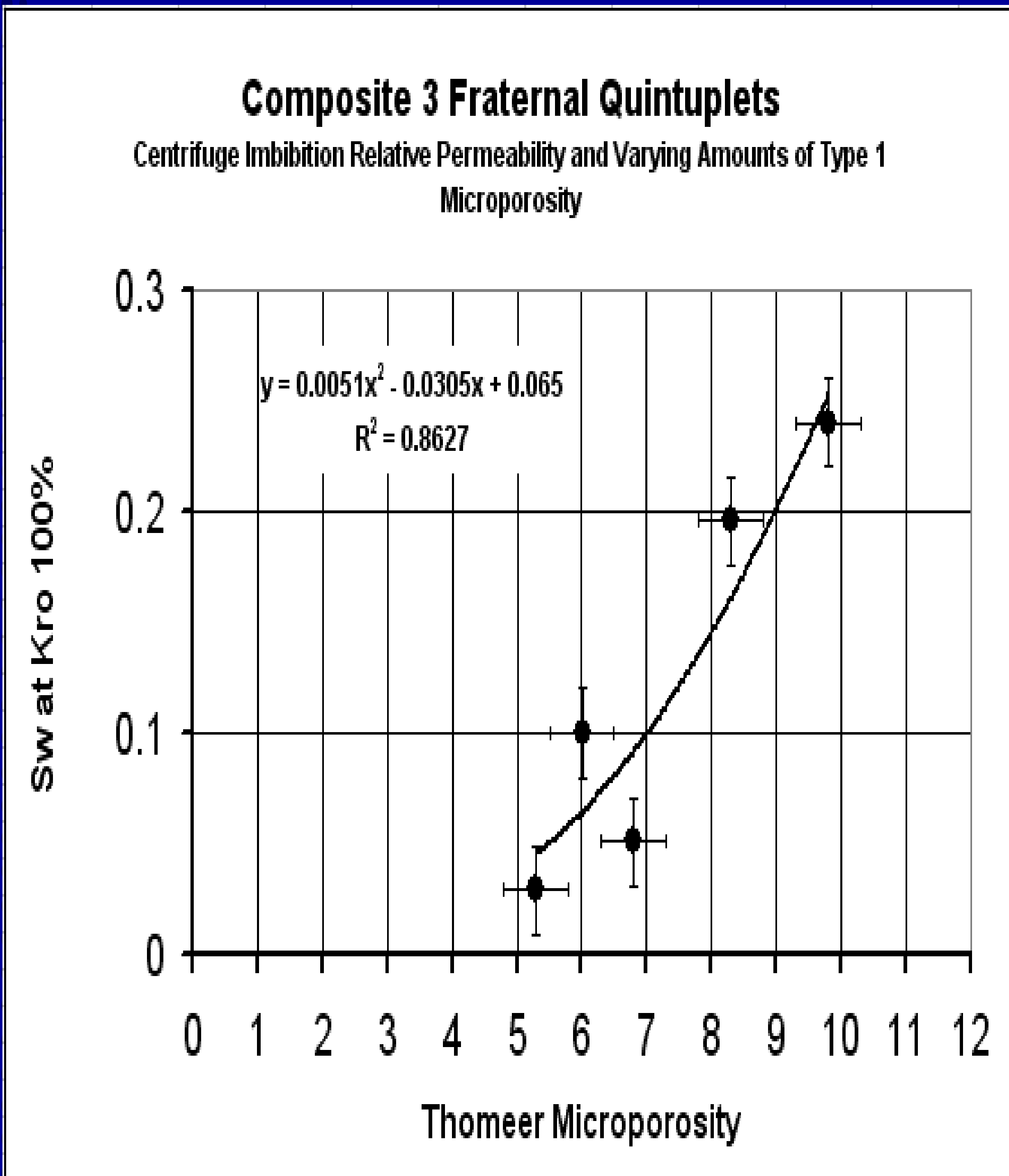
Separability by Porositon also applies to Relative Permeability

Clerke SPE 105259

Centrifuge Relative Permeability – Core Plugs



$S_{w,offset}$ to K_{ro} is directly related to the amount of Type 1 Microporosity



Conclusions

Using a porositon combination approach, we can:

- *connect the geological, petrophysical and reservoir engineering properties*
- *Focus permeability modelling on the front end of the M porositon*
- *Understand that imbibition relative permeability requires knowledge of the M macroporositon and of the Type 1 microporositon*
- *Recognize that shifts of the imbibition Kro to the right result from the presence of varying amounts of microporosity not just wettability*
- *SPE 105259*
- *GeoArabia – in press*

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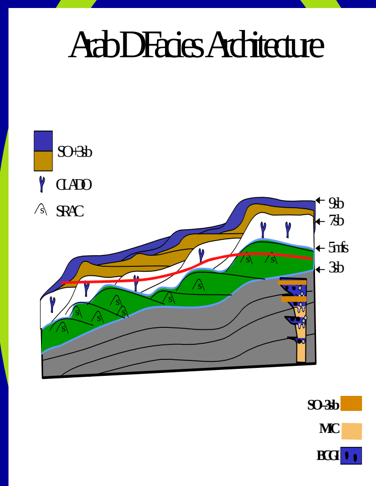
Rosetta Stone



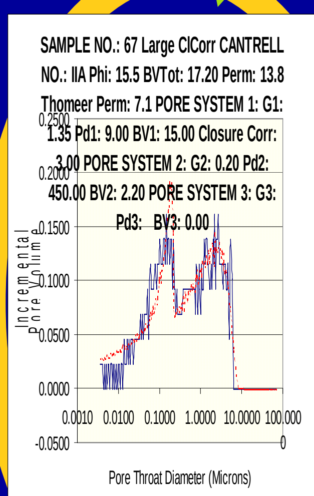
Mile Scale

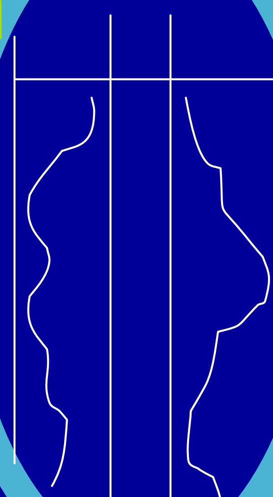
Depositional Rock Types

Micron Scale

Pore System Parameters

- Permeability
- Rel Perm





Centimeter Scale

Wireline Log Responses

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Dynamic modelling with porositons - separability

Permeability is controlled by the first pore system in multimodal Arab D Limestones:

M_1

M_1_2

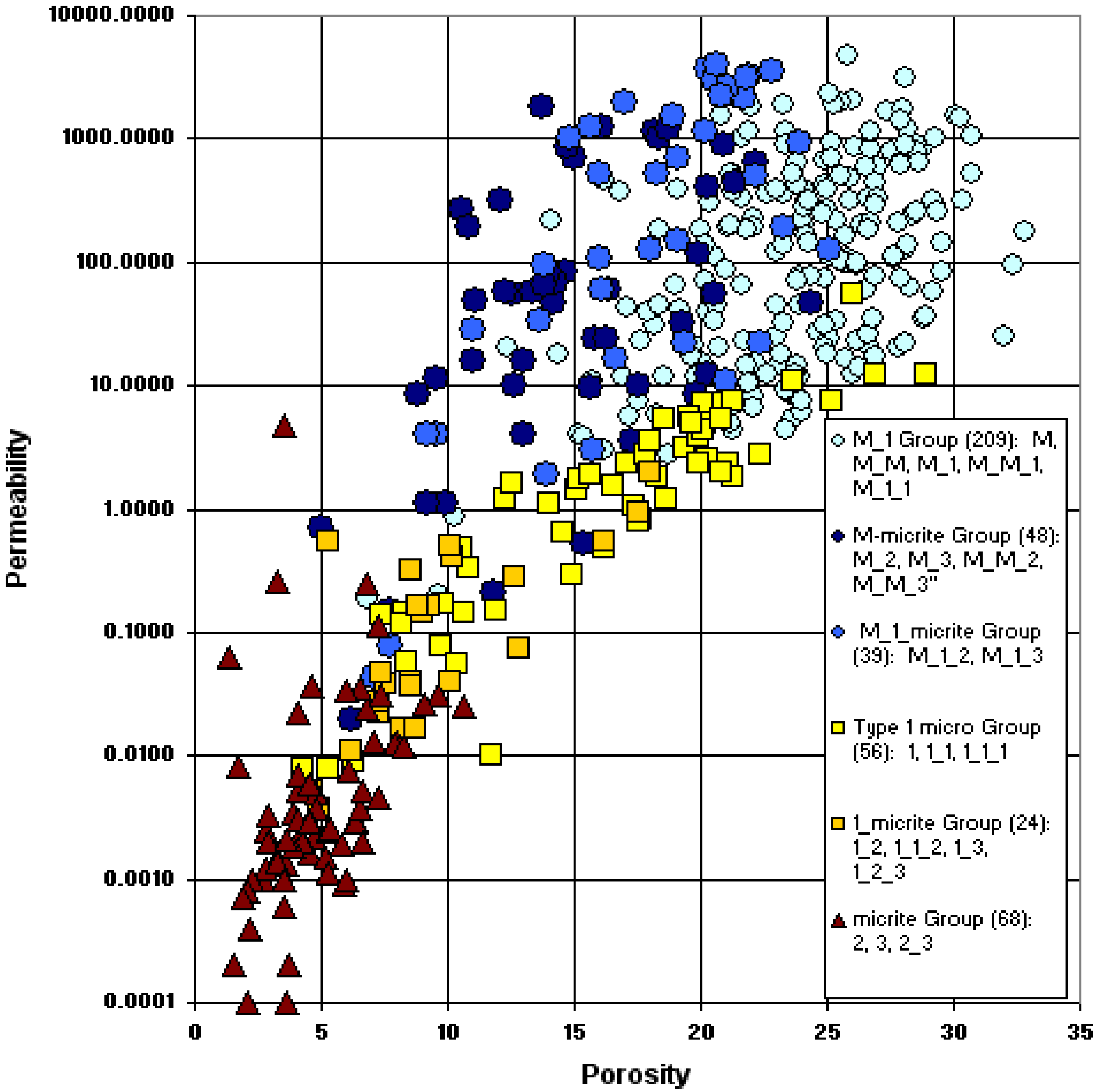
M_2

1_2

1_2_3

2_3

Main Porositon Combinations in terms of Poro-Perm



Within the first ranking Porositon – usually M

- Most important attribute is the *maximum* pore throat diameter

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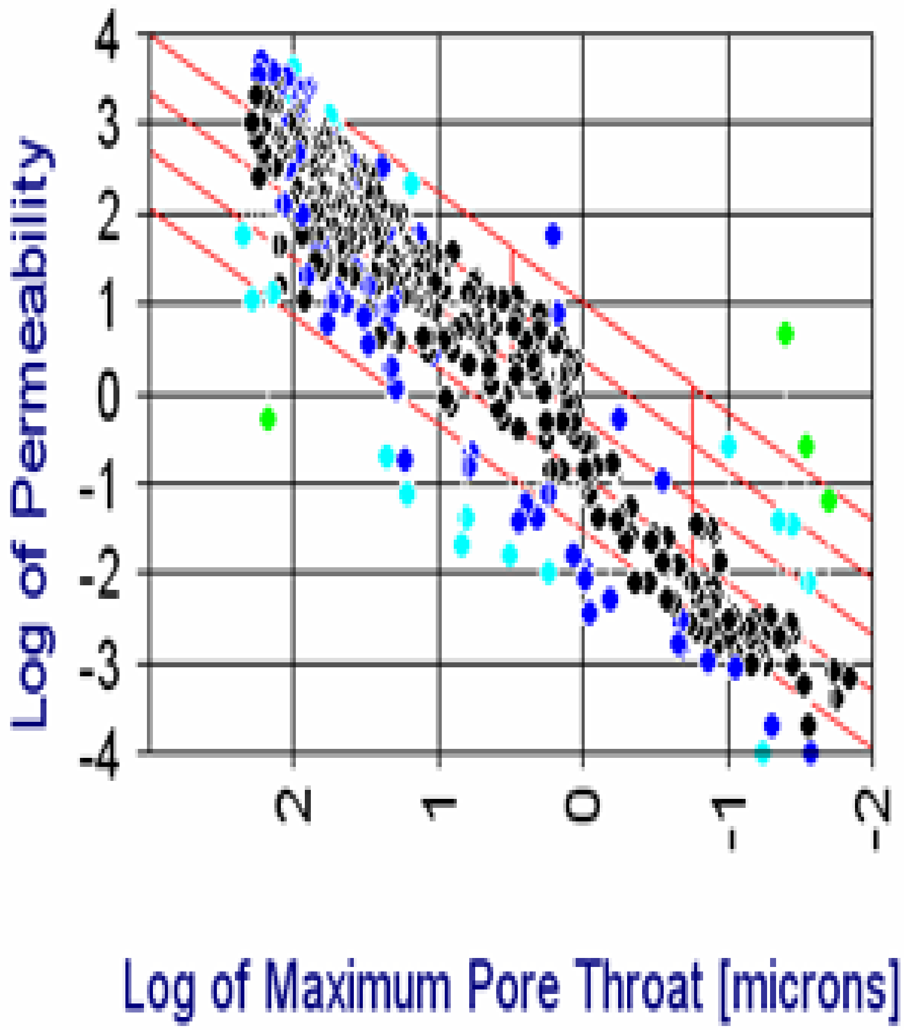
Permeability is 65% correlated to the diameter of the largest pore throat



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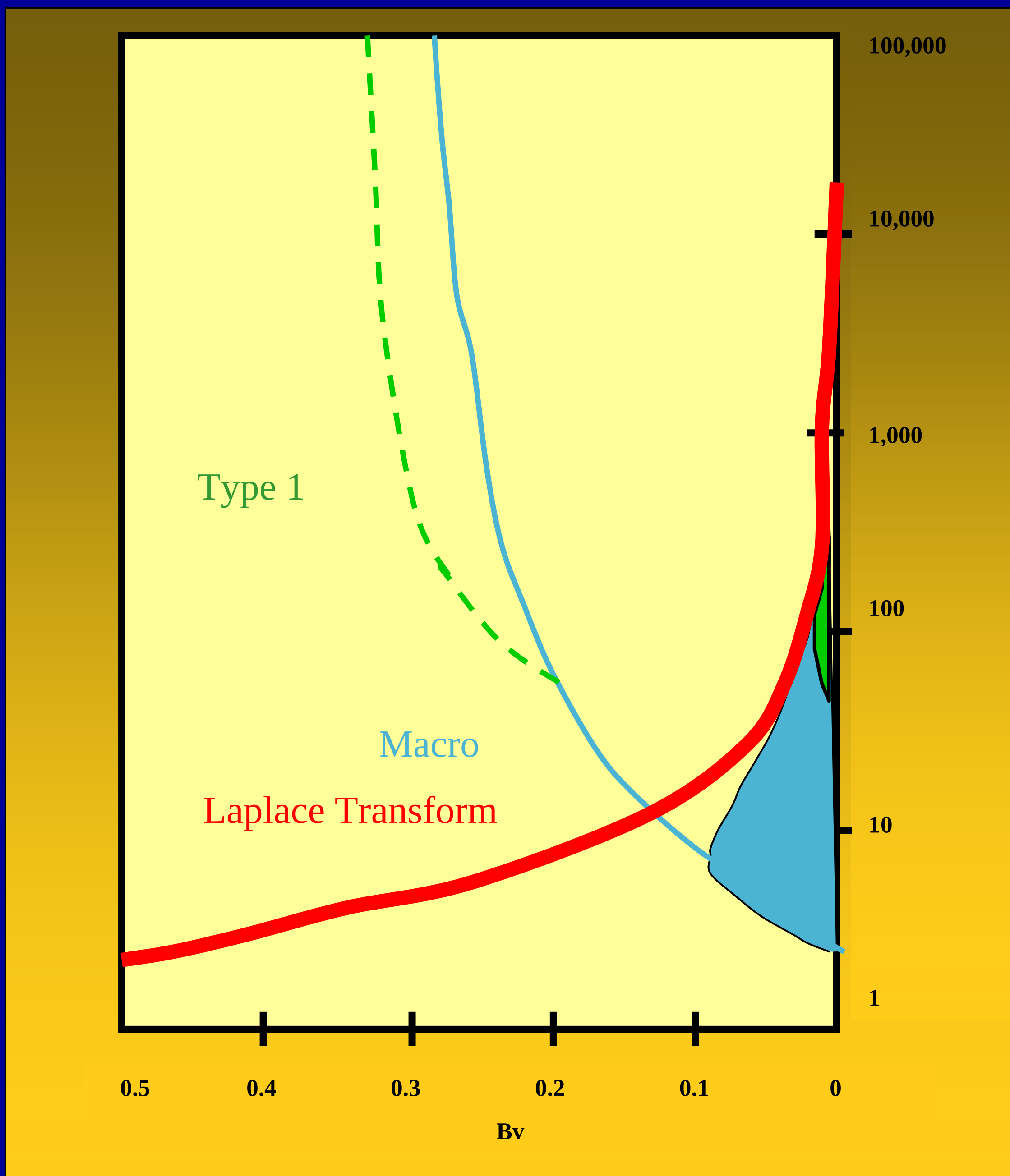
Buiting – Clerke Permeablity Model – M_1

Permeability is > 98% determined by the parameters of the Macro pore system in the M_1 bimodal pore system



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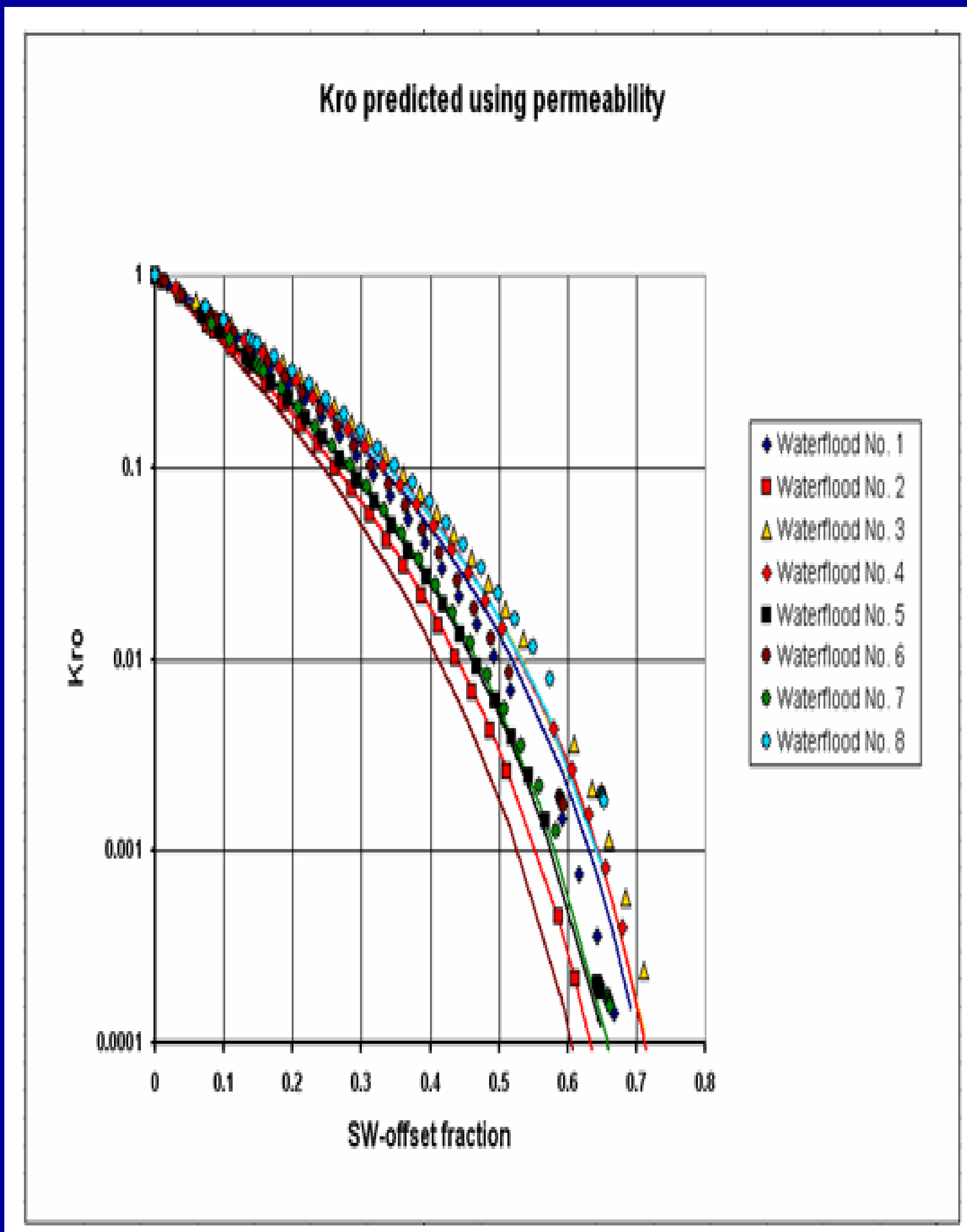
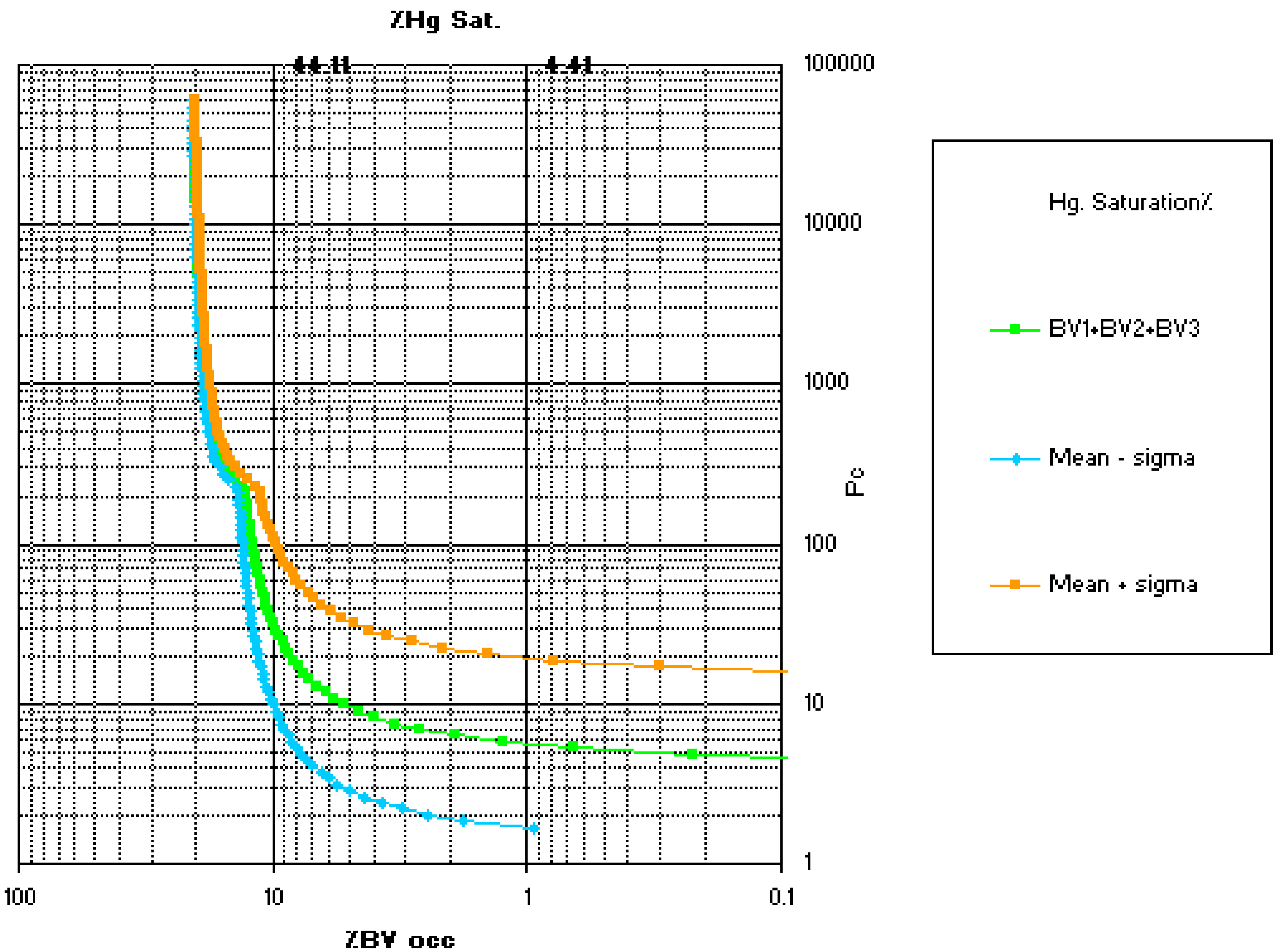
M_1 K_{ro} offset “curve” matched only by using permeability from the M porositon



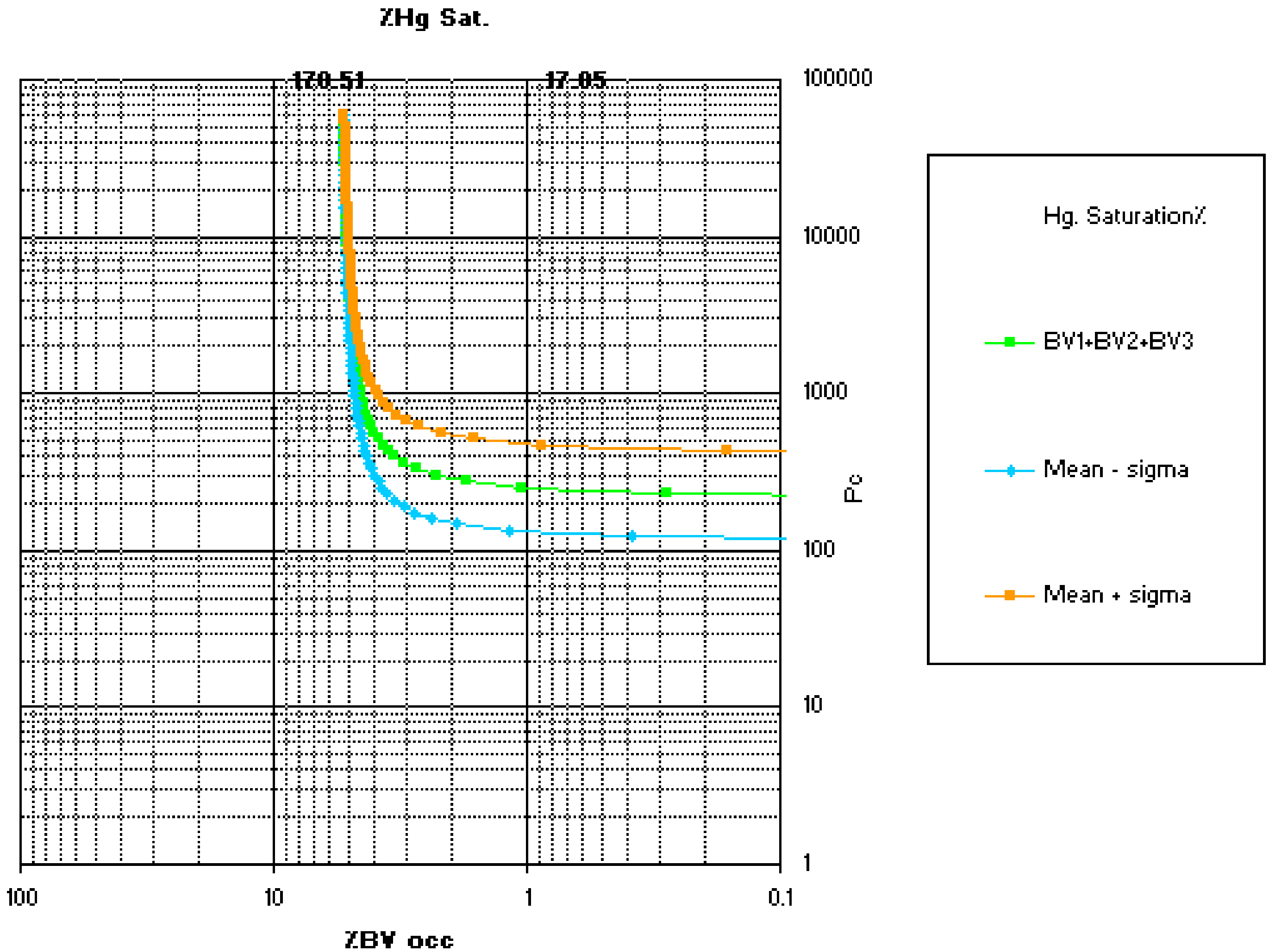
M_1

SAMPLE NO.: M_1 Mean Thomeer Phi: 0 BVTot: 22.67 Perm: 0 Thomeer Perm: 199.6 PORE SYSTEM 1: G1: 0.51 Pd1: 3.70 BV1: 17.10 PORE SYSTEM 2: G2: 0.15 Pd2: 204.00 BV2: 5.57 PORE SYSTEM 3: G3: 0.00 Pd3: 0.00 BV3: 0.00



1

SAMPLE NO.: Type 1 Microphi Mean Thomeer Phi: 0 BVTot: 5.60 Perm: 0 Thomeer Perm: 0.036
PORE SYSTEM 1: G1: 0.15 Pd1: 204.00 BV1: 5.60 PORE SYSTEM 2: G2: 0.50 Pd2: 2000.00 BV2: 0.00 PORE SYSTEM 3: G3: 0.00 Pd3: 0.00 BV3: 0.00



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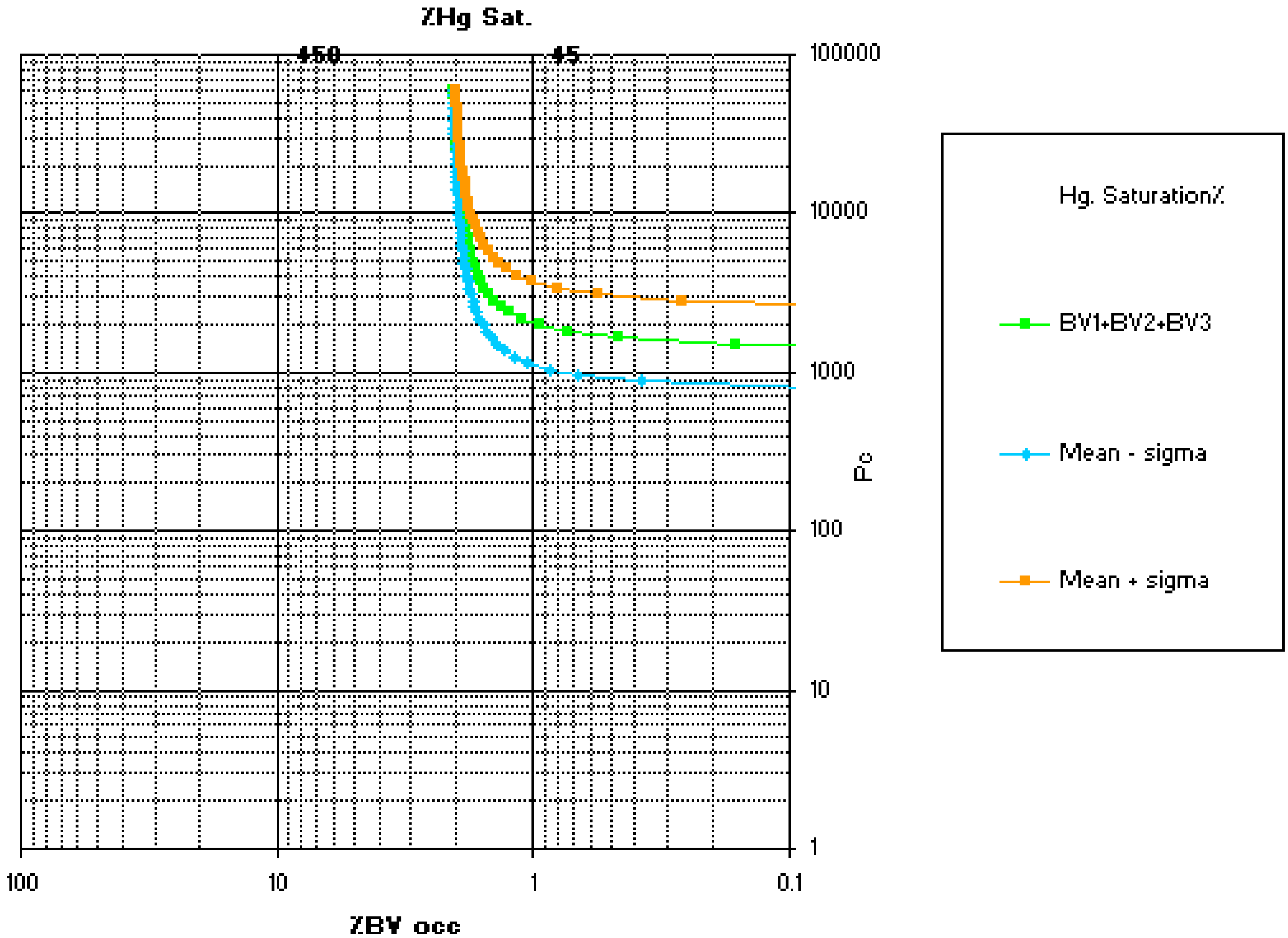
2

SAMPLE NO.: Type 2 Microphi Mean Thomeer Phi: 0 BVTot: 2.22 Perm: 0 Thomeer Perm: 0.0001 PORE SYSTEM 1: G1: 0.15 Pd1: 1318.00 BV1: 2.22 PORE SYSTEM 2: G2: 0.50 Pd2: 2000.00 BV2: 0.00 PORE SYSTEM 3: G3: 0.00 Pd3: 0.00 BV3: 0.00



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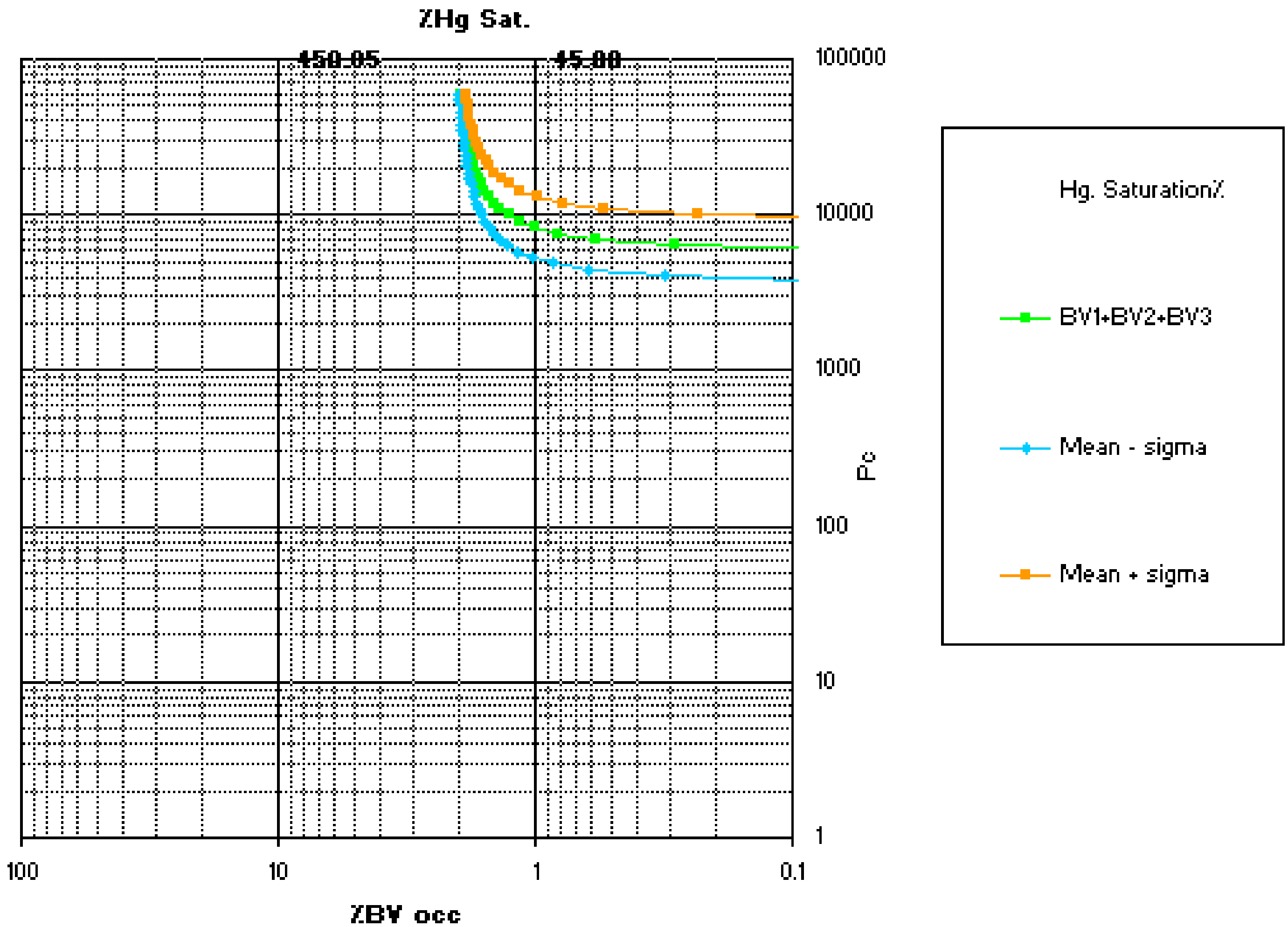
3

SAMPLE NO.: Type 3 Microphi Mean Thomeer Phi: 0 BVTot: 2.22 Perm: 0 Thomeer Perm: 0.00001 PORE SYSTEM 1: G1: 0.15 Pd1: 5370.00 BV1: 2.22 PORE SYSTEM 2: G2: 0.50 Pd2: 2000.00 BV2: 0.00 PORE SYSTEM 3: G3: 0.00 Pd3: 0.00 BV3: 0.00



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Clerke, E.A., 2007, Permeability and microscopic displacement efficiency of M_1 biomodal systems in Arab-D limestone: SPE Middle East Oil and Gas Show and Converence, 11-14 March, 2007, Kingdom of Bahrain, SPE Paper 105259-MS, doi:10.2118/105259-MS.

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Clerke, E.A., 2007, The Rosetta Stone project – II; spectral analysis of pore geometries and their relationships to reservoir properties for the Arab D limestones: GeoArabia, v. 12/1, p. 157.