Carbonate Petrophysics in Wells Drilled with Oil Base Mud

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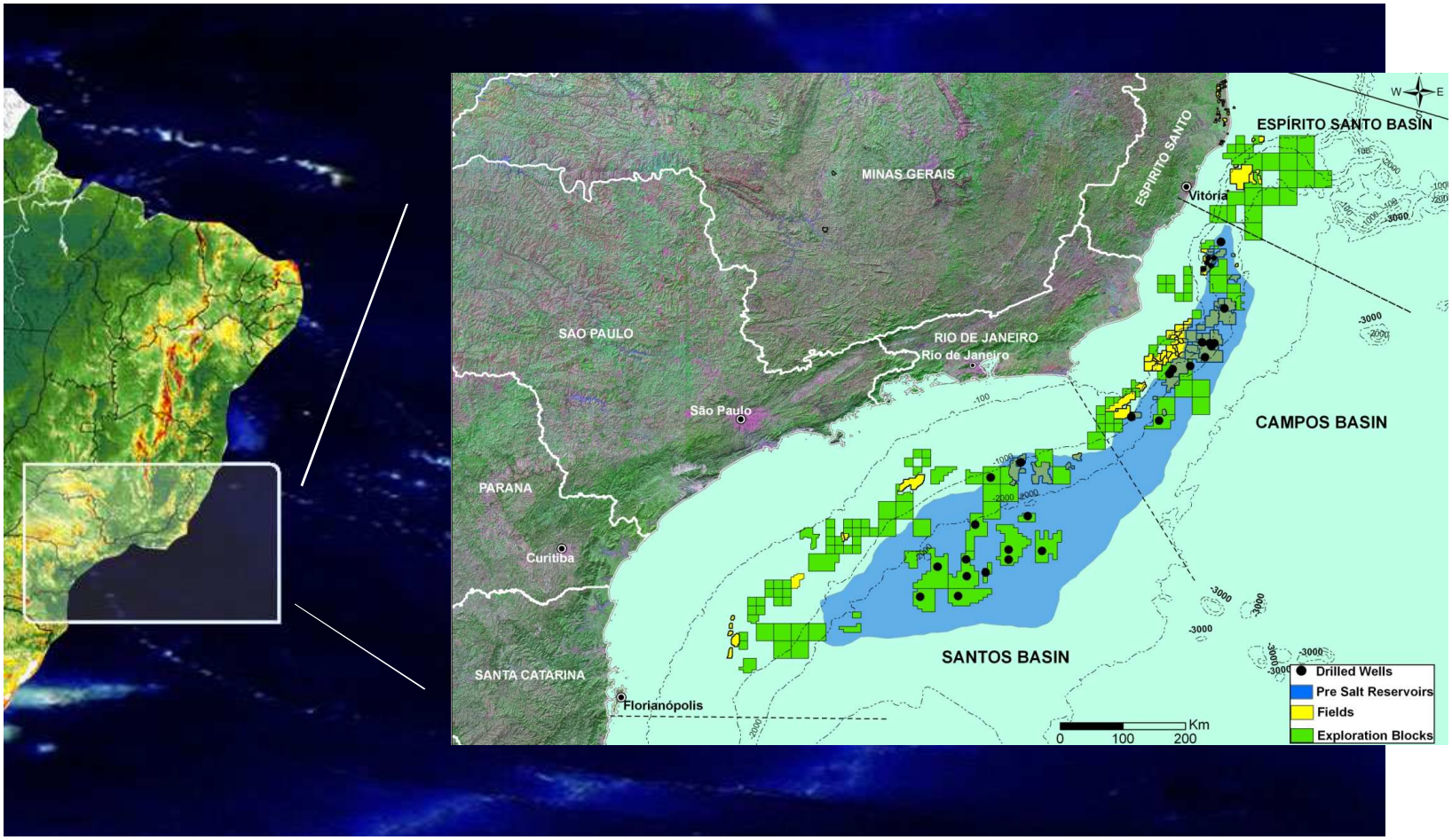
Brazilian Pre-Salt Carbonates



2 Km Water Depth, 2 Km Salt : (Oil Base Mud)
200 Km Offshore
Pre-Salt Carbonates : 18,000 ft TVD
Oil 28-30 Api, GOR 1350 scf/brl

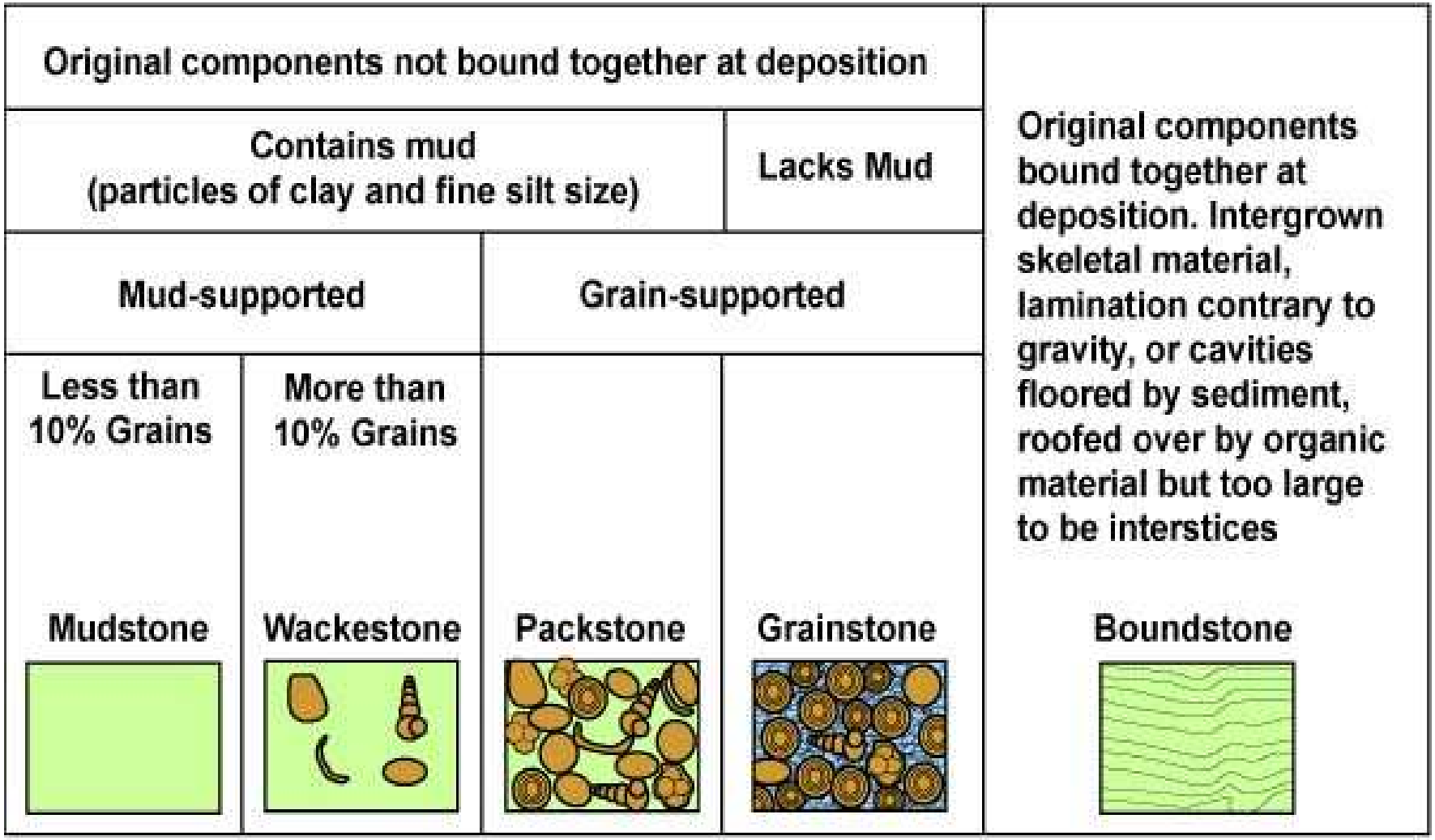
Formigli, 2007

Pre-Salt Carbonates

- Microbial, Stromatalites
- Complex Lithology
  - Calcite, Dolomite, Quartz
  - NMR Porosity - PHIT
- Variable Permeability
  - 4 decade range
- Oil Wet
  - Very High Resistivity
  - Sw?
  - Swirr from NMR Bound Fluid

Formigli, 2007

Dunham Classification for Carbonates



C. G. St. C. Kendall, 2005 (after Dunham, 1962, AAPG Memoir 1)

Carbonate Classifications by Pore Size and/or Grain Size

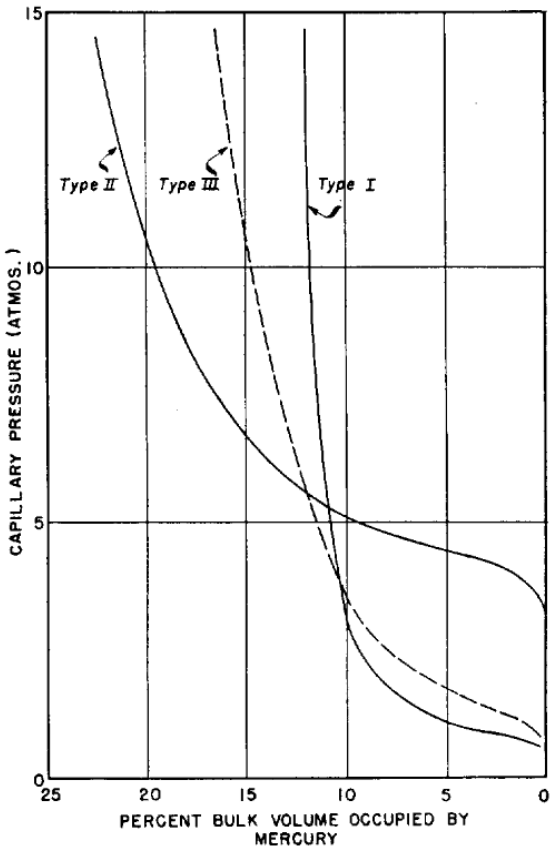
- Archie-1952 (grain size / cuttings)
- Choquette and Pray 1970 (micro-meso-mega)
- Pittman 1971 (micro-macro)
- Marzouk 1995 (micro-meso-macro)
- Lucia 1967, 1983, 1995 (grain size & vugs)
- Ramakrishnan 1997-2001 (micro-macro-vugs)
- Cantrell & Hagerty 1999 (micro-macro)
- Clerke 2007 (micro I, II, III & macro)

Archie 1952

- Matrix Type
  - I (Crystalline)
  - II (Chalky)
  - III (Granular / Sucrosic)
- Grain Size (mm)
  - V.Fine (0.05), Fine (0.1),
  - Med. (0.2), Coarse (0.4)
- Visible Pore Size (x10 microscope)

Primary
  - Class A (less than 0.01mm, not visible)
  - Class B (0.01-0.1mm)

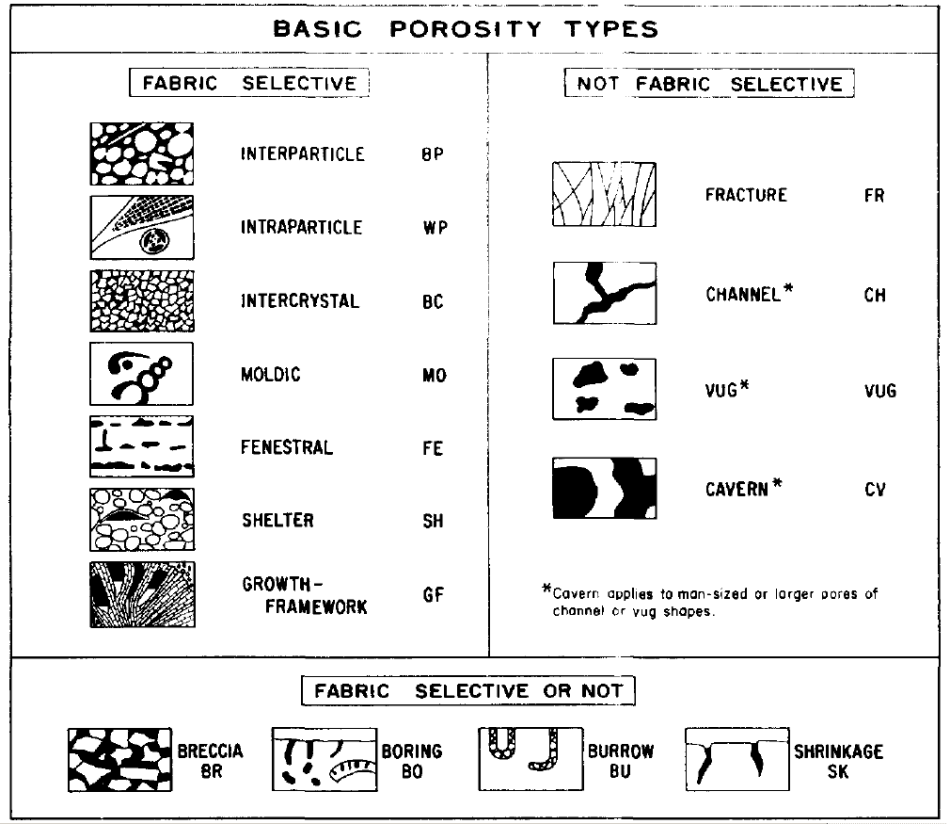
Secondary
  - Class C (greater than 0.1mm but less than grain size)
  - Class D (greater than grain size – vug)



Designed for field geologist looking at cuttings. Made initial correlation between rock-type and Swirr.

Choquette and Pray, 1970

- Micropores <1/16mm
- Mesopores 1/16-4mm
  - Small
  - Large
- Megapores 4-256mm
  - Small
  - Large

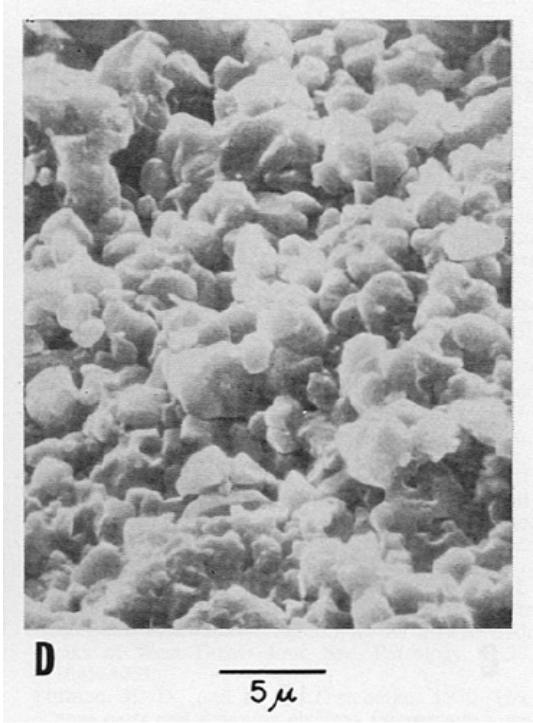


15 Porosity Types

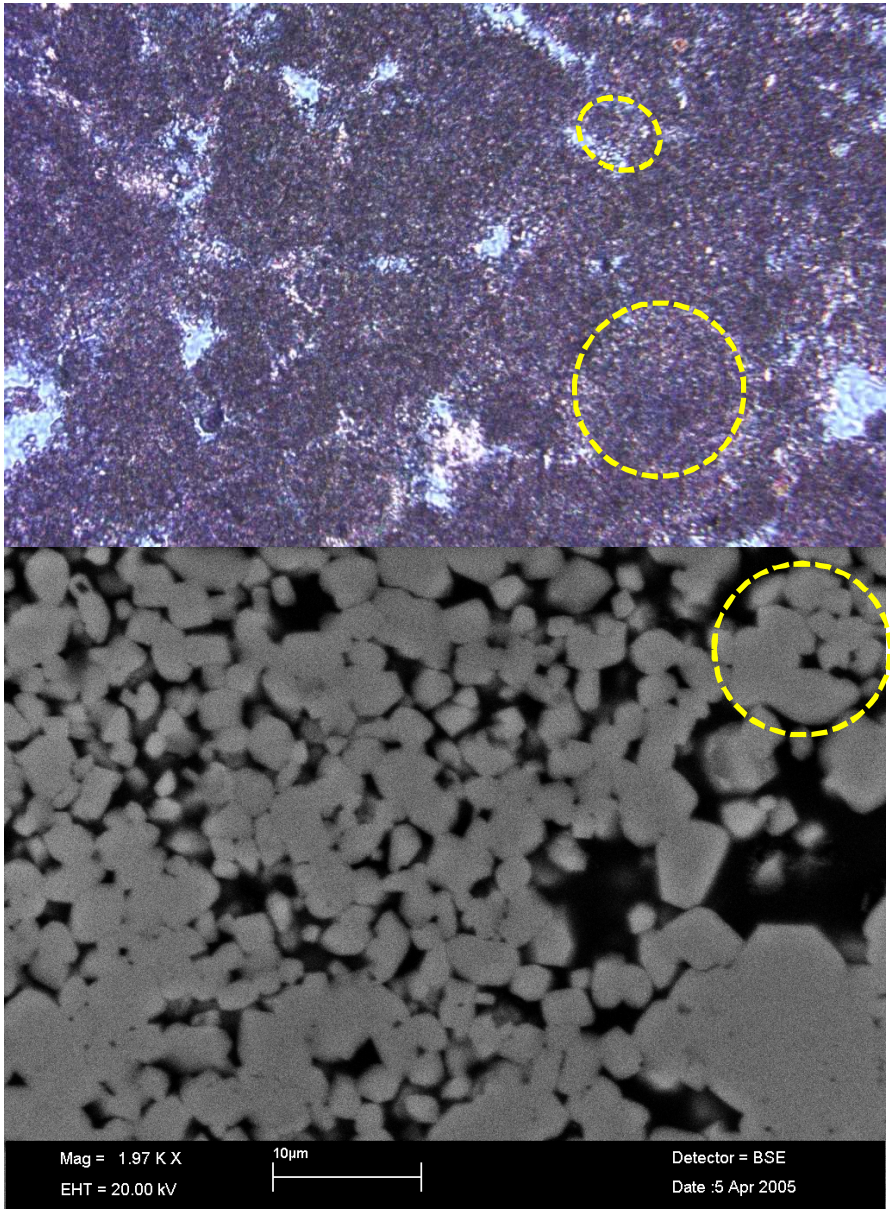
Core & Outcrop Description

Pittman 1971

- Micropores
  - occur between calcite crystals
  - Less than 1 micron diameter
  - Visible with SEM
  - Impact on high SWIRR
- Macropores
  - Visible in thin sections
  - Greater than 30 microns
  - Can be inter-granular or intra-granular

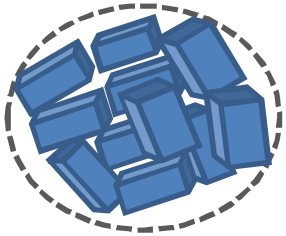


Marzouk 1995: micro-meso-macro pores

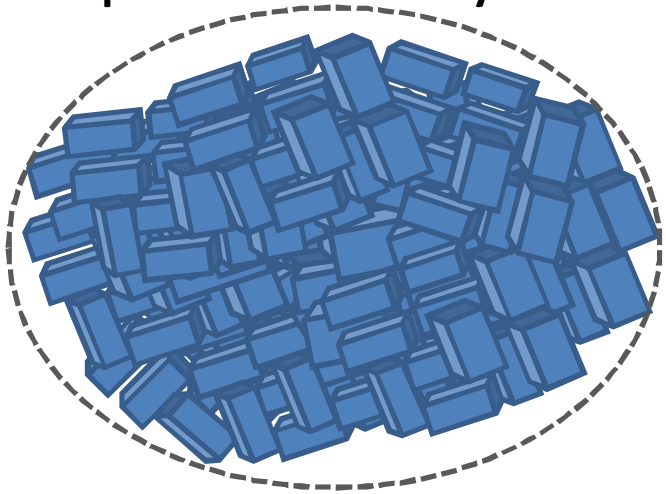


Micrite (Calcite Crystal)
1-2 um in length

Micrite Particle, clump of calcite crystals, 10-20 um in diameter



Carbonate Grain, > 200 um, composed of micrite crystals

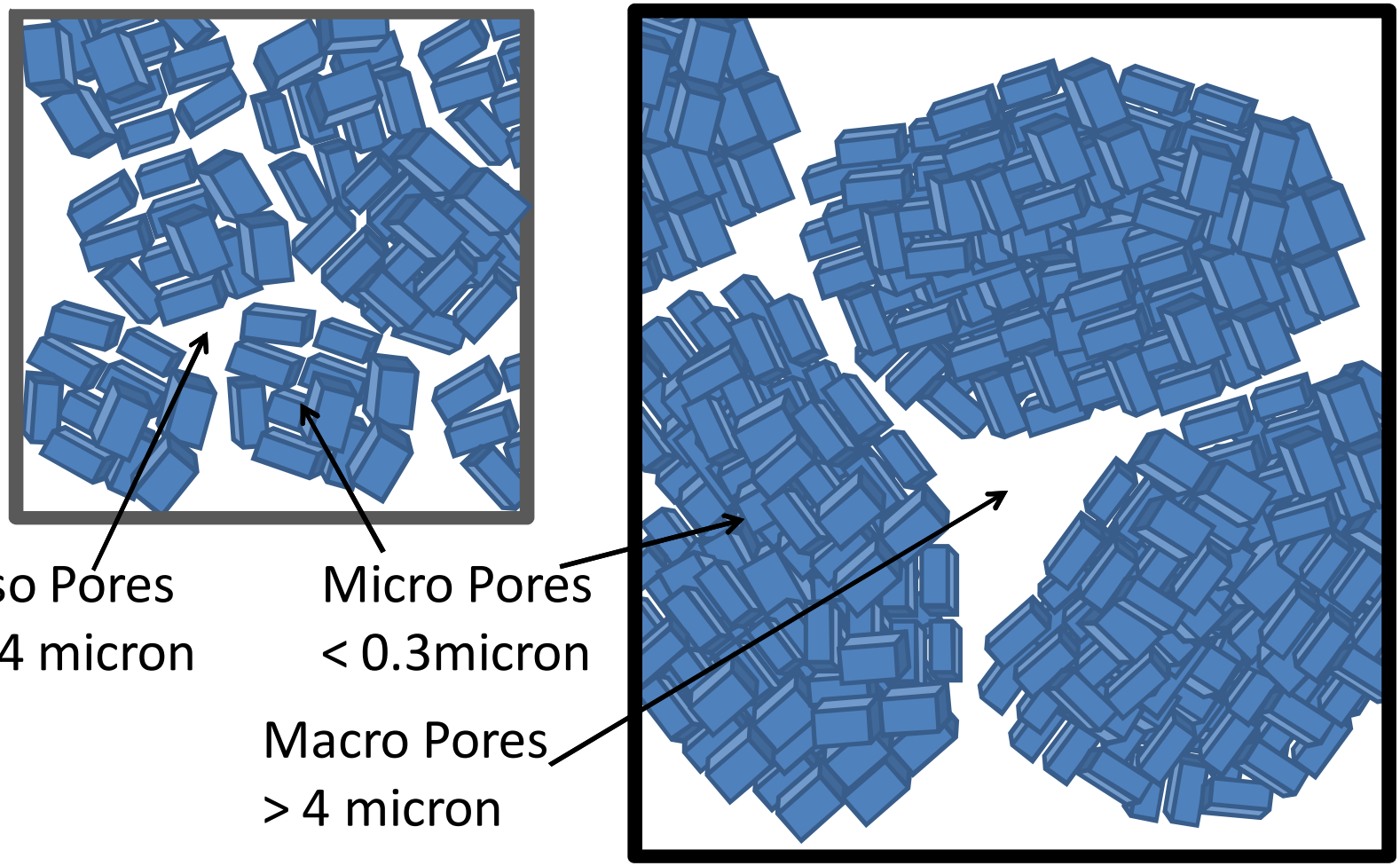


Marzouk et al SPE 49475

Micritic Carbonate Porosity

Micrite Particles 10-20um

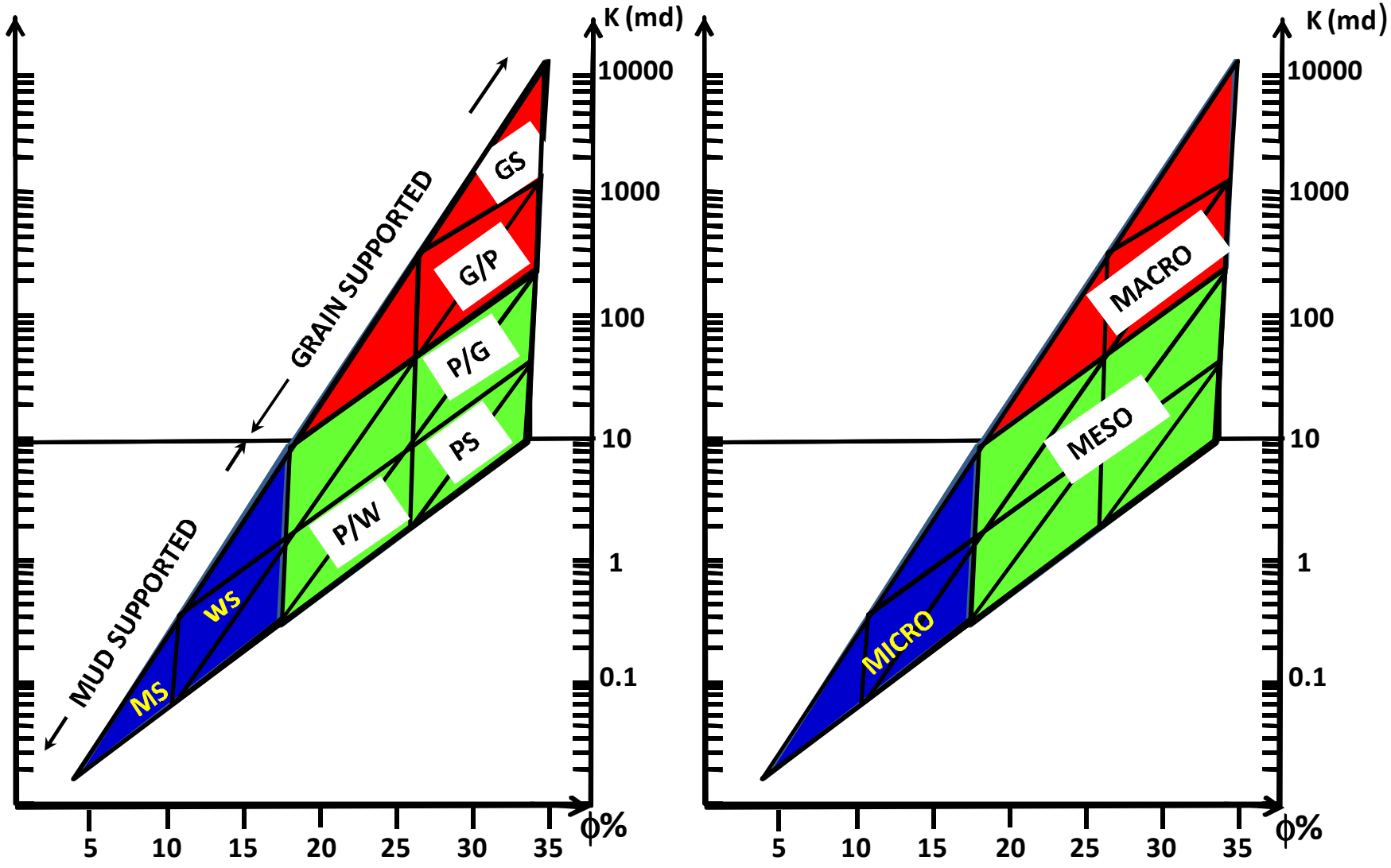
Micrite Grains > 200um



Based on Pore Throat Radius
from Mercury Porosimetery

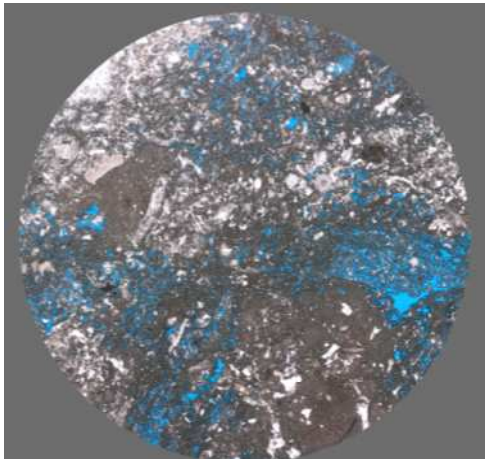
Marzouk et al SPE 49475

Porosity Partitioning & Dunham

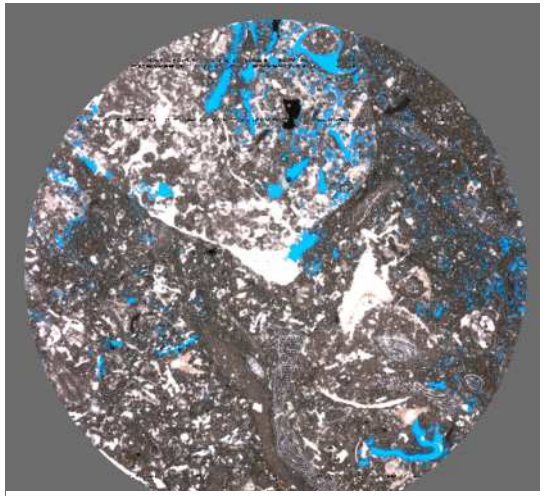


Marzouk et al SPE 49475

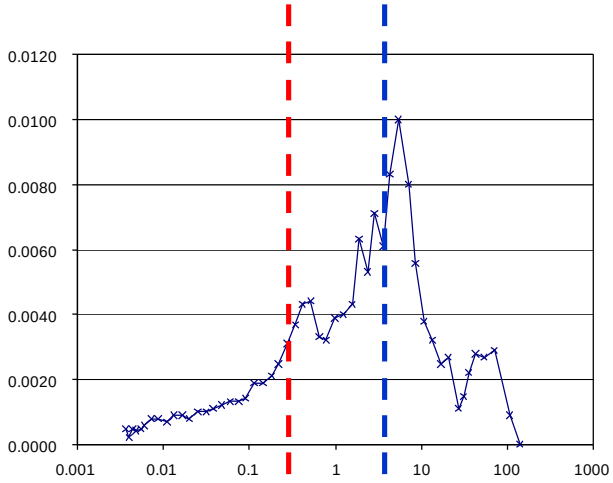
NMR T2 & Mercury Porosimetry

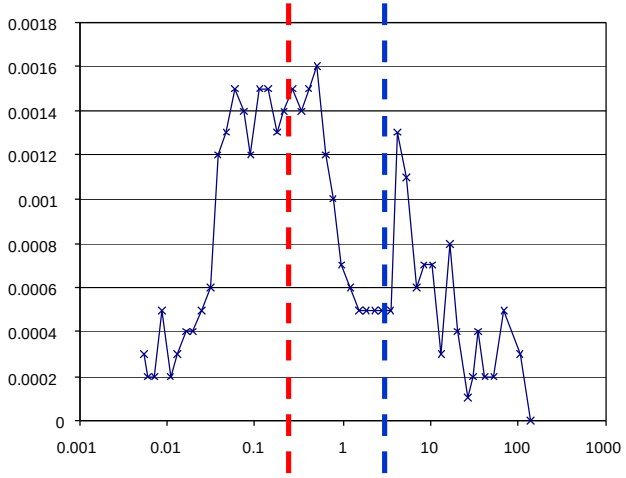


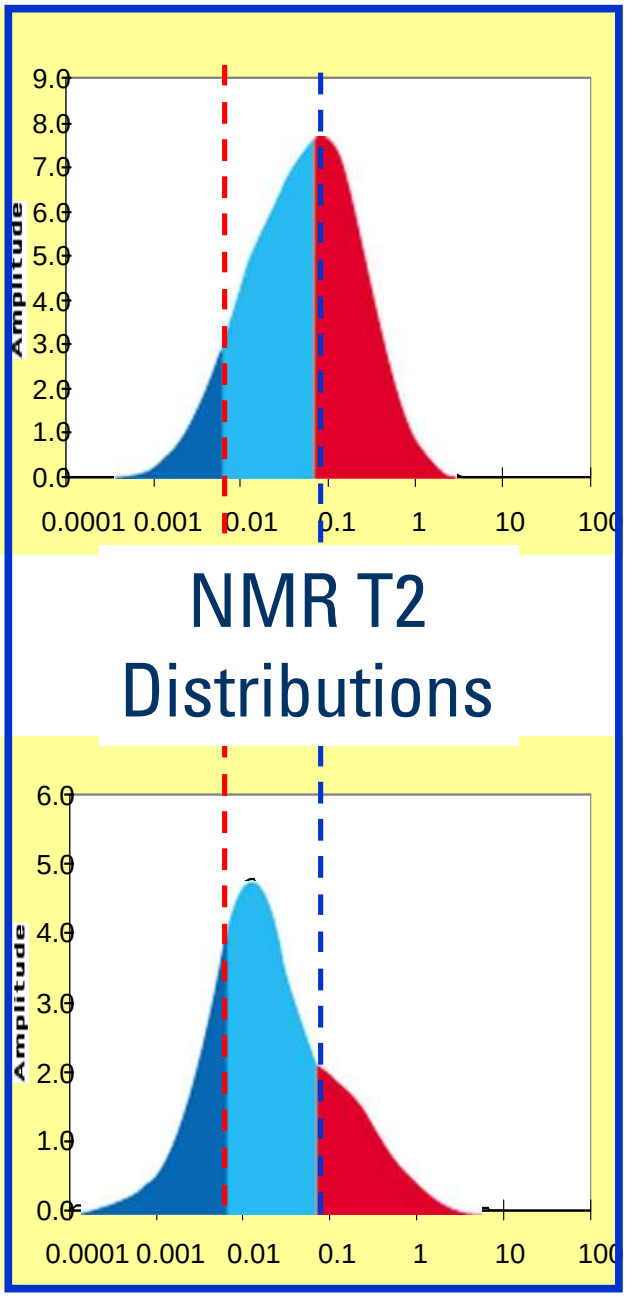
Sample 1 30 p.u. 97 md.



Sample 2 18 p.u. 2 md.







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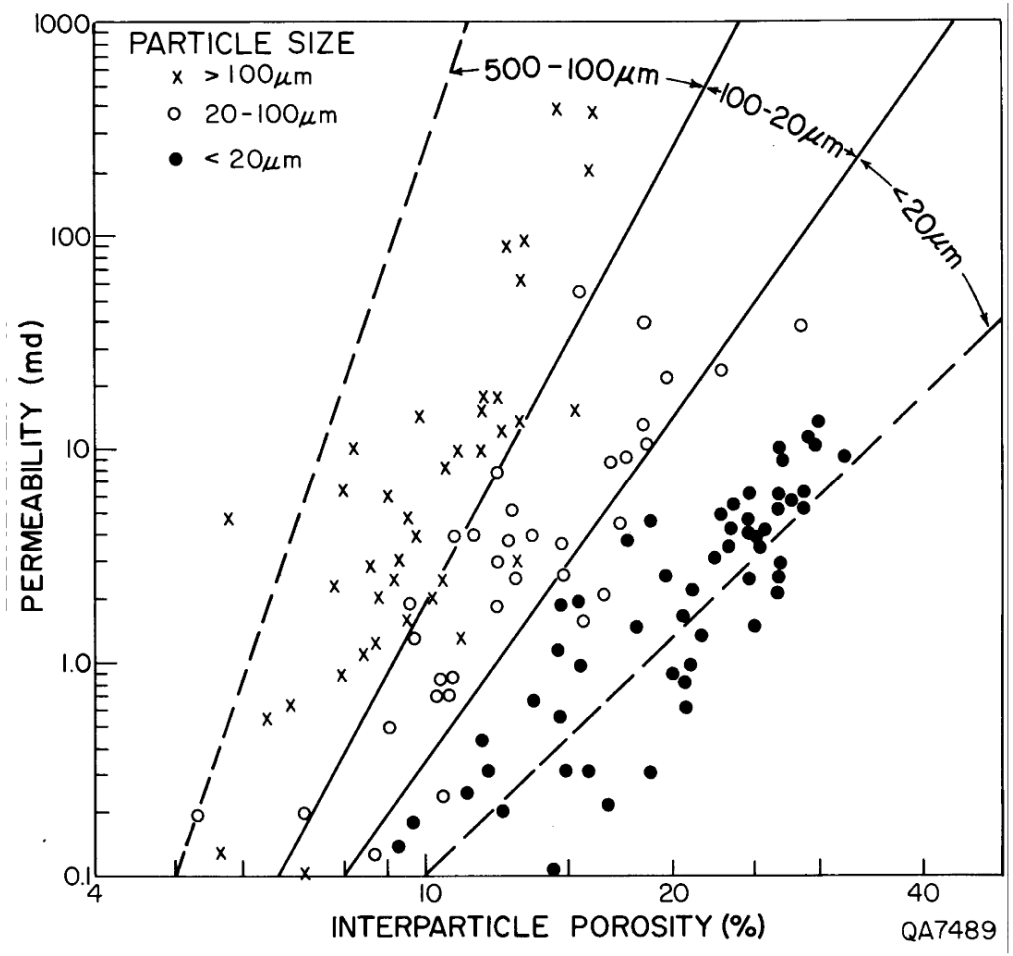
- Lucia 1967, 1983, 1995 (grain size & vugs)
- Ramakrishnan 1997-2001 (micro-macro-vugs)
- Cantrell & Hagerty 1999 (micro-macro)
- Clerke 2007 (micro-macro)

Lucia 1967,1983,1995

- Interparticle
  - Fine/Class 3
    - (< 20um, Pd > 70psi)
  - Medium/Class 2
    - (20-100um, Pd 15-70psi)
  - Large/Class 1
    - (> 100um, Pd<15psi)
- Vuggy
  - Separate Vugs
  - Touching Vugs

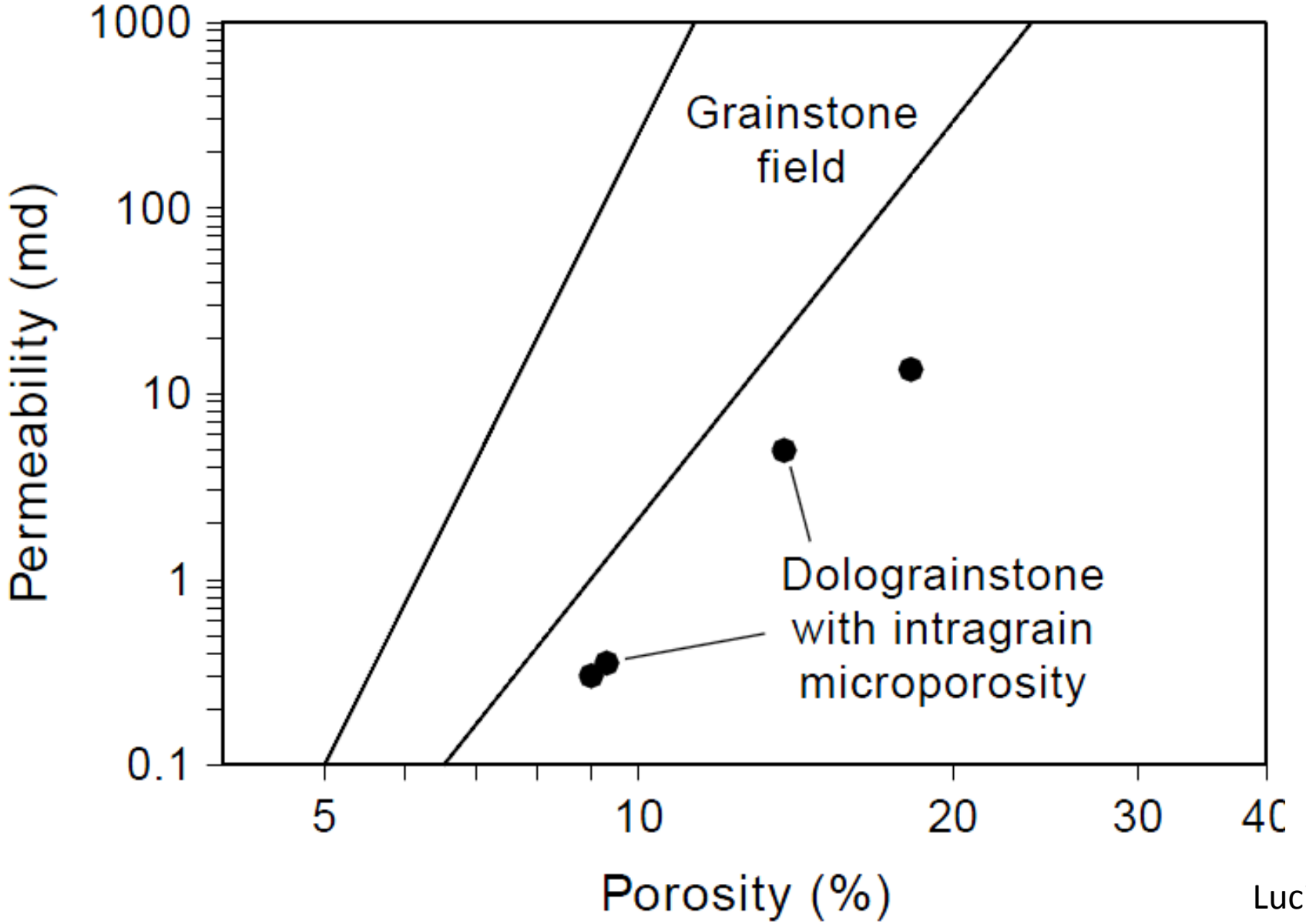


Grain Size & Permeability Prediction

(No distinction between intercrsytal & interparticle)

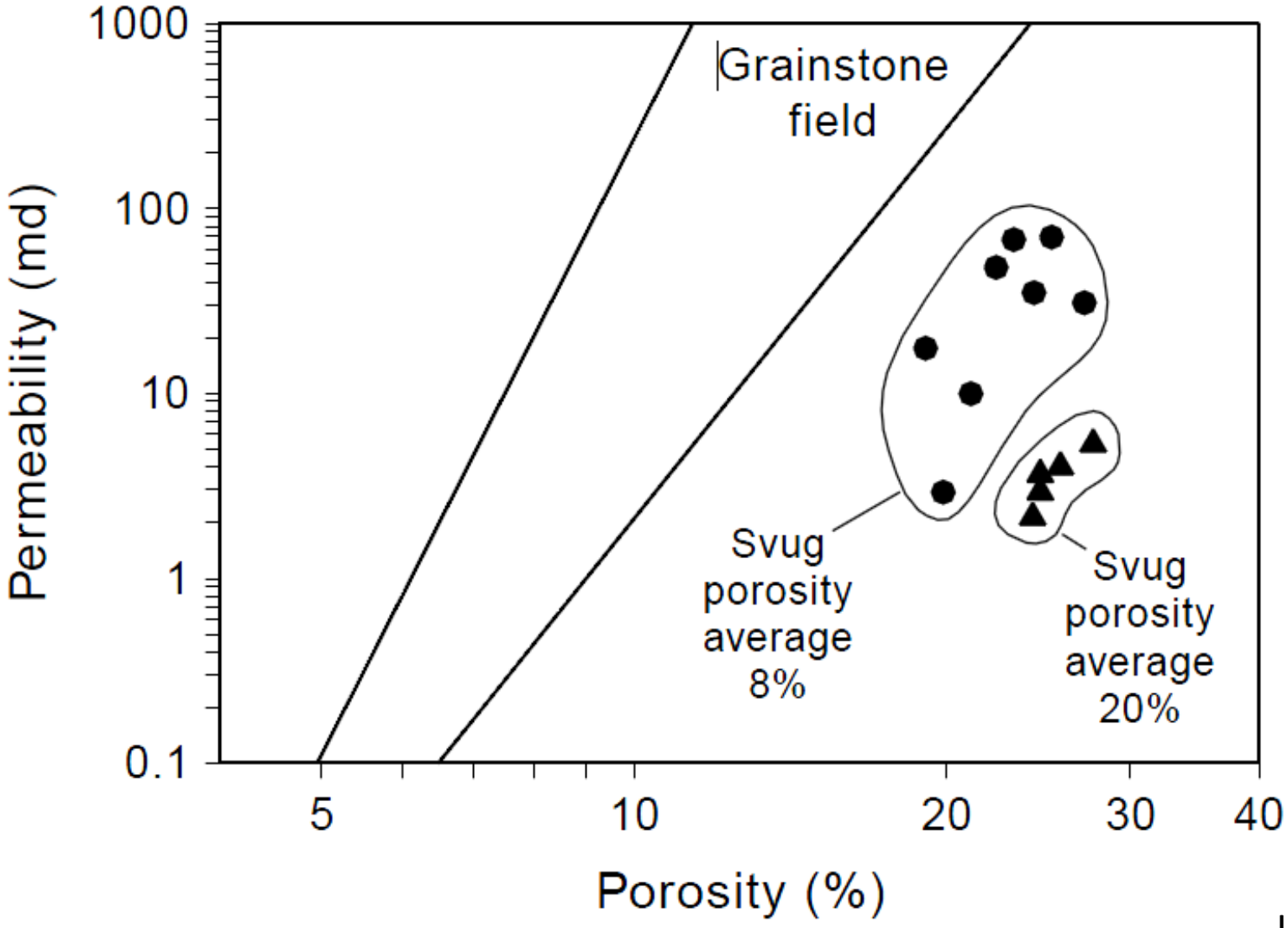
Lucia 1995

Intragranular Microporosity



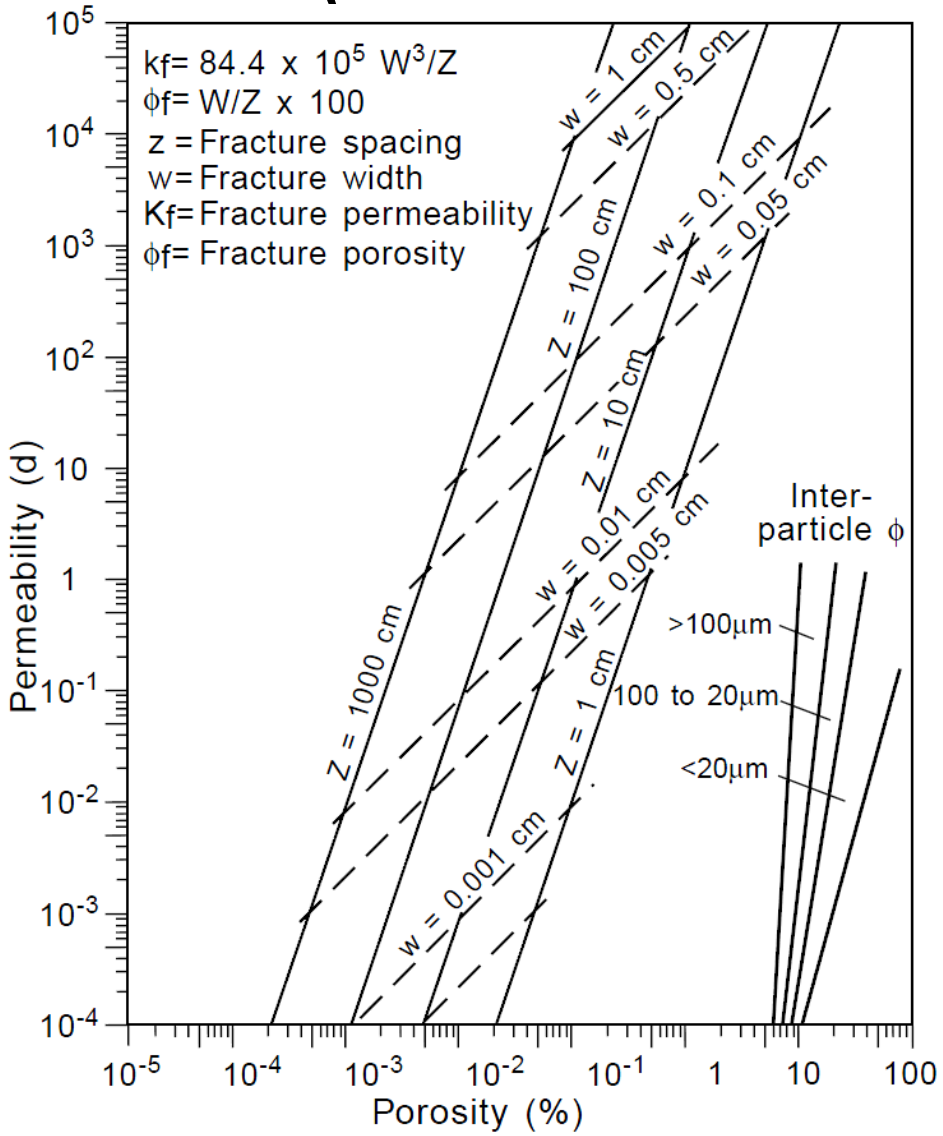
Lucia 1995

Separate Vugs Effect



Lucia 1995

Touching Vug Trend (similar to fractures)



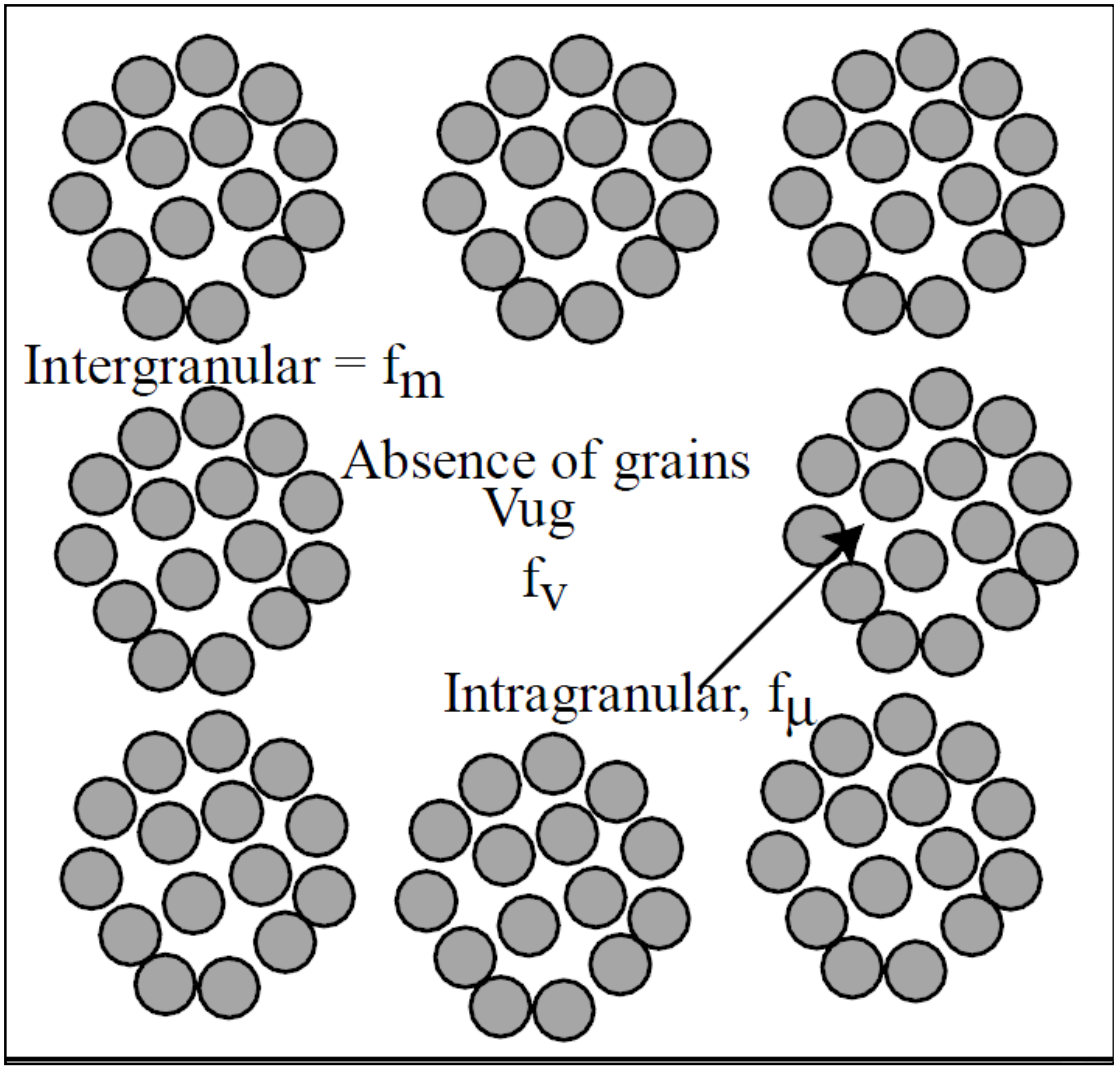
Lucia 1995

Ramakrishnan

- Micro
  - Intragranular
- Macro
  - Intergranular
- Vugs
  - Absent grain

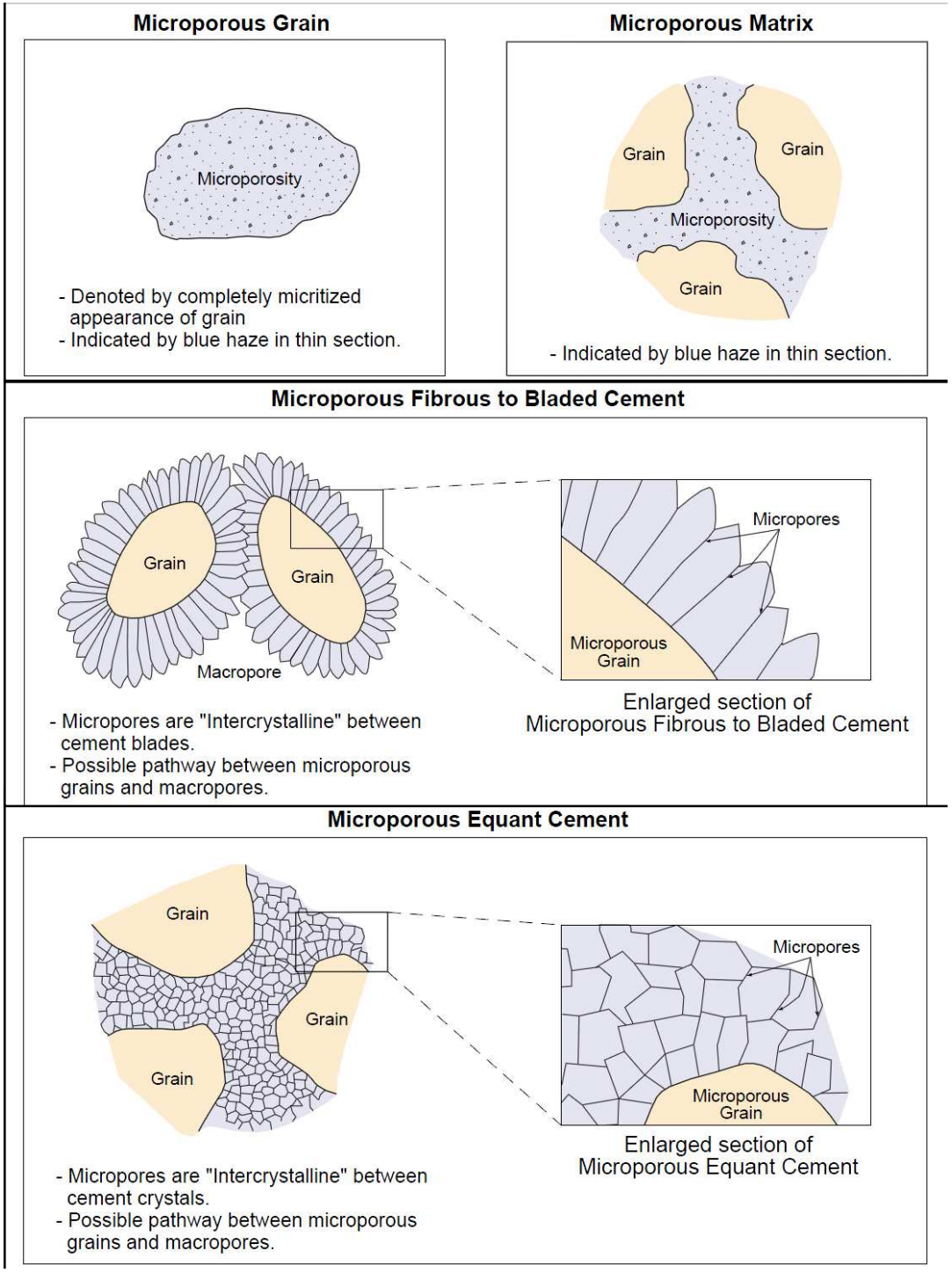
$$Bruggeman.....k_{eff} = \frac{k_{matrix}}{1-3f_v}$$

(assumes $k_{vug} = \infty$)



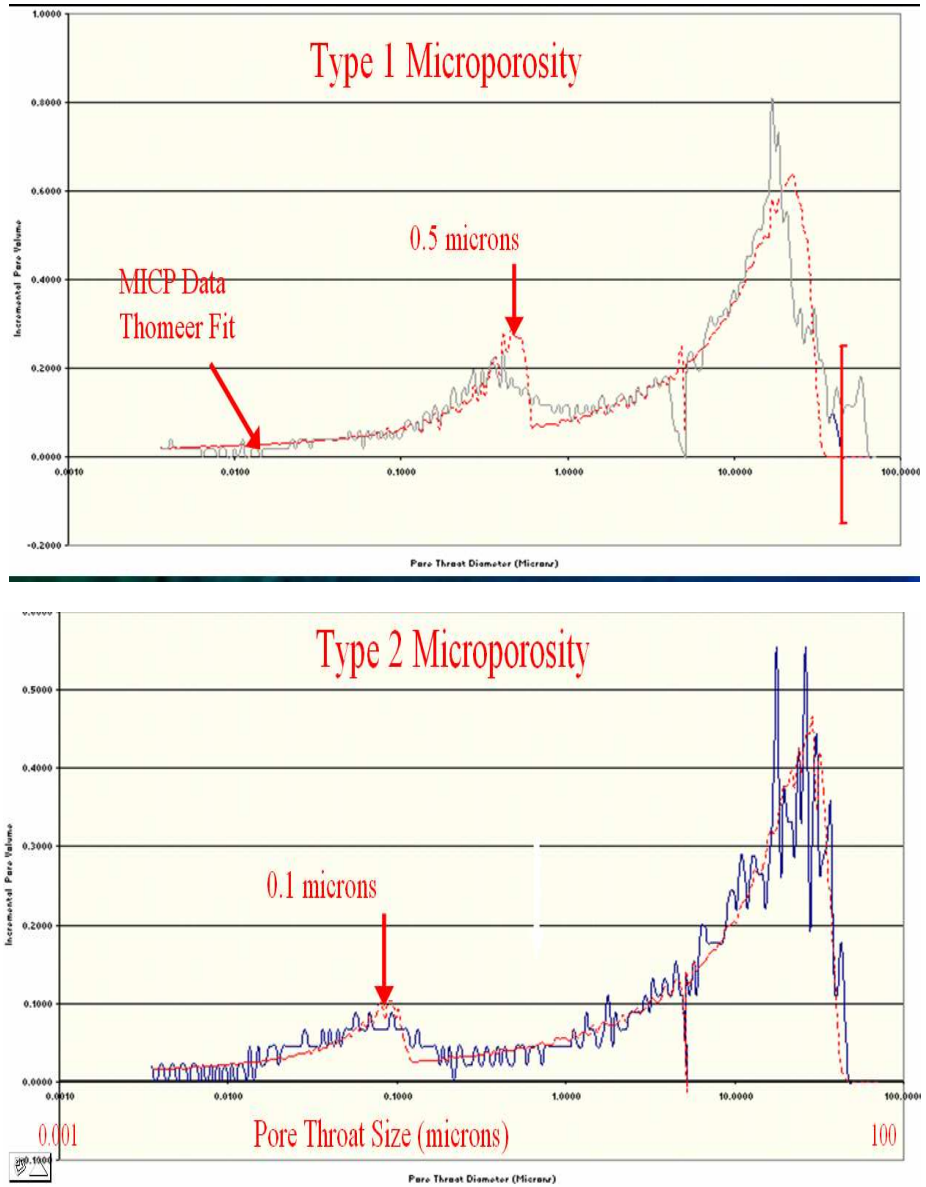
Cantrell & Haggerty

- Micro Porosity Types
  - Microporous Grains
  - Microporous Matrix
  - Microporous Cements
- Mechanisms
  - Leaching
  - Crystal growth
  - Boring of grains
- Macro Porosity
  - Visible (>10 microns)



Clerke Pore Type from Mercury

- Macro Porosity
  - 260 microns
- Micro I (Intra-Granular)
  - 1 micron
- Micro II (Micritic)
  - 0.1 micron
- Micro III (Micritic)
  - Sub 0.1 micron



Clerke 2007

Carbonate Petrophysical Classifications

- Grain Size
  - Archie, Lucia
- Pore Size
  - Choquette & Pray, Pittman, Ramakrishnan
- Pore Throat Size
  - Marzouk, Hassall, Ramamoorthy, Clerke

Pore Size from T_2

$$\frac{1}{T_2} = \frac{1}{T_{2B}} + \rho \frac{c}{r}$$

…. Eq 1*

Where c= 3 for spherical pores
= 2 for cylindrical pores
= 1 for planar pores

* Looyestijn, 2004

Carbonate Petrophysical Workflow

- Ramamoorthy et al, SPWLA 2008
  - Lithology & Porosity
  - Pore System & Permeability (2 transforms)
  - Saturation & Relative Permeability
- Designed for Water Base Mud
- Oil Base Muds?

$$K_{SDR} = A\phi^{C}\left(\rho T_{2lm}\right)^{B}$$

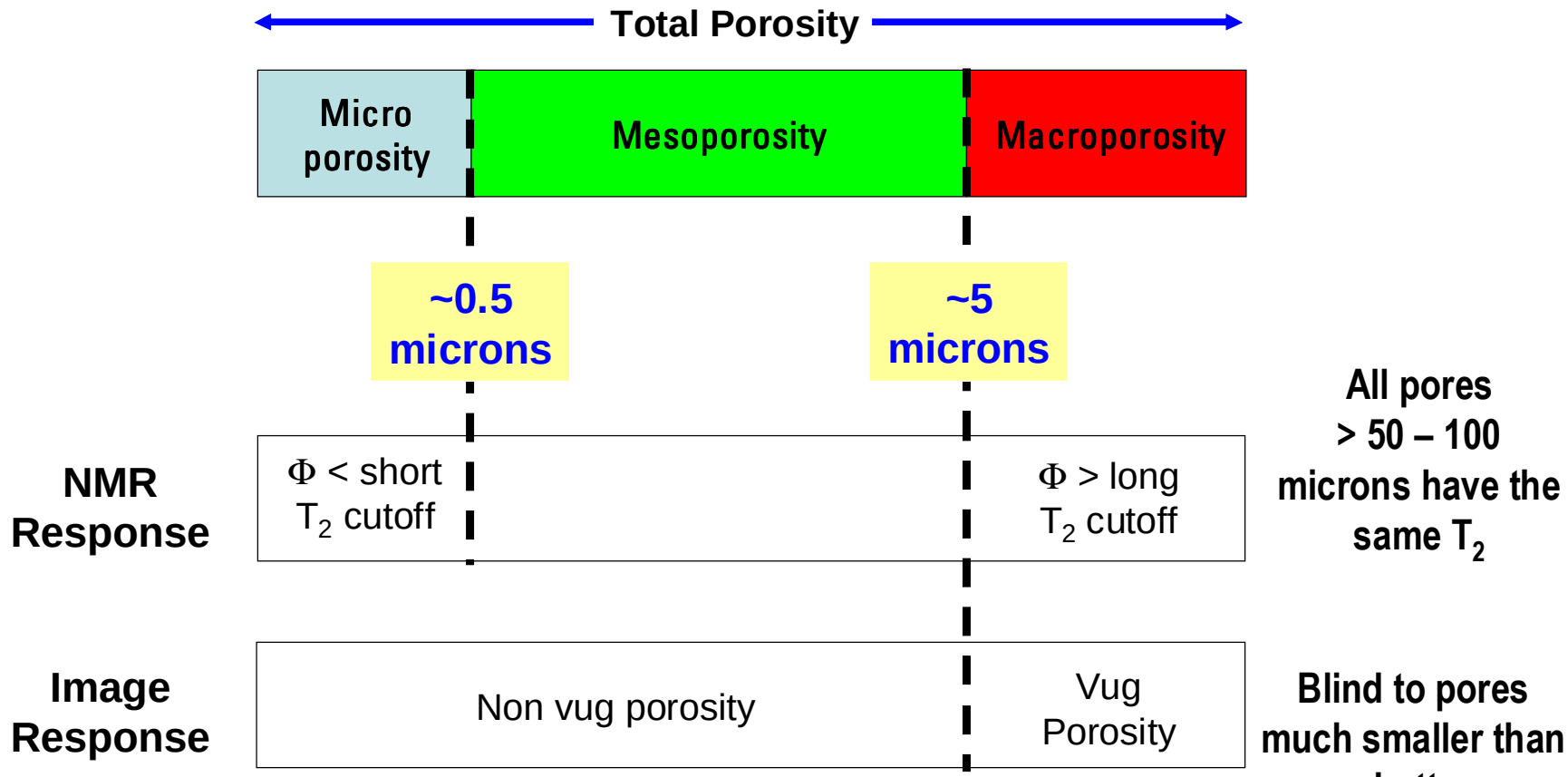
$$K_{MACRO} = A\phi^{C}\left(\frac{V_{MACRO}}{\phi - V_{MACRO}}\right)^{B}$$

Where

K_{SDR} = permeability (mD)
A = pre-multiplier
Φ = porosity fraction (pu)
C = porosity exponent
ρ = surface relaxivity (microns/second)
T_{2lm} = log mean of T_2 distribution (secs)
B = exponent

Pore System & Permeability

Carbonate Porosity Partitioning from Logs



Pore Size from NMR T_2

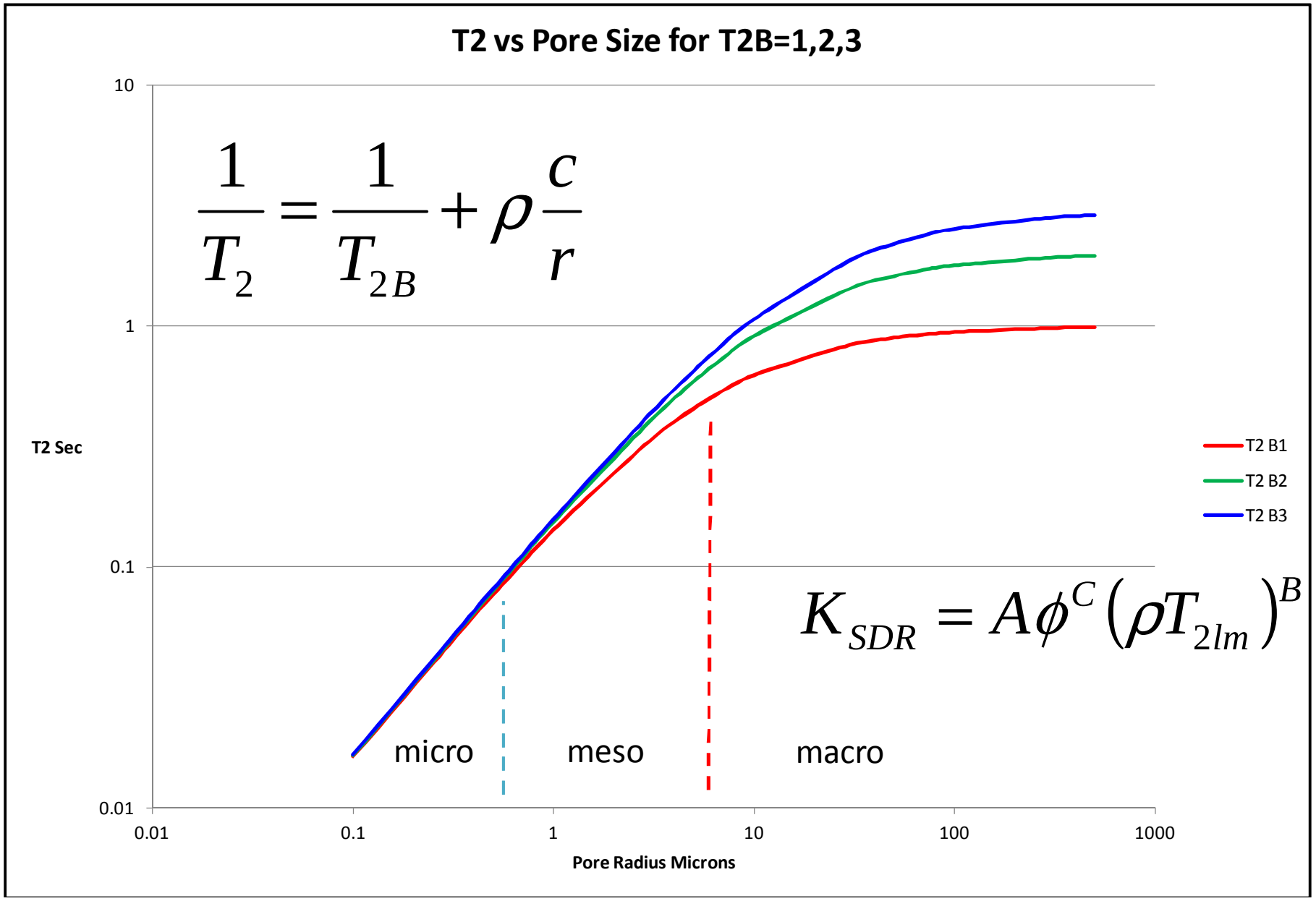
- No diffusion on long T_2
  - Short Echo Spacing
  - or low gradient
- T_{2B} > 1 second
  - Water, OBMF, Light Reservoir Oils
- No diffusive coupling
  - Oil wet helps
- Pore fluids wetting the grains
  - Water in micro pores
  - Oil/OBMF in meso & micro pores

$$\frac{1}{T_2} = \frac{1}{T_{2B}} + \rho \frac{c}{r}$$ .... Eq 1*

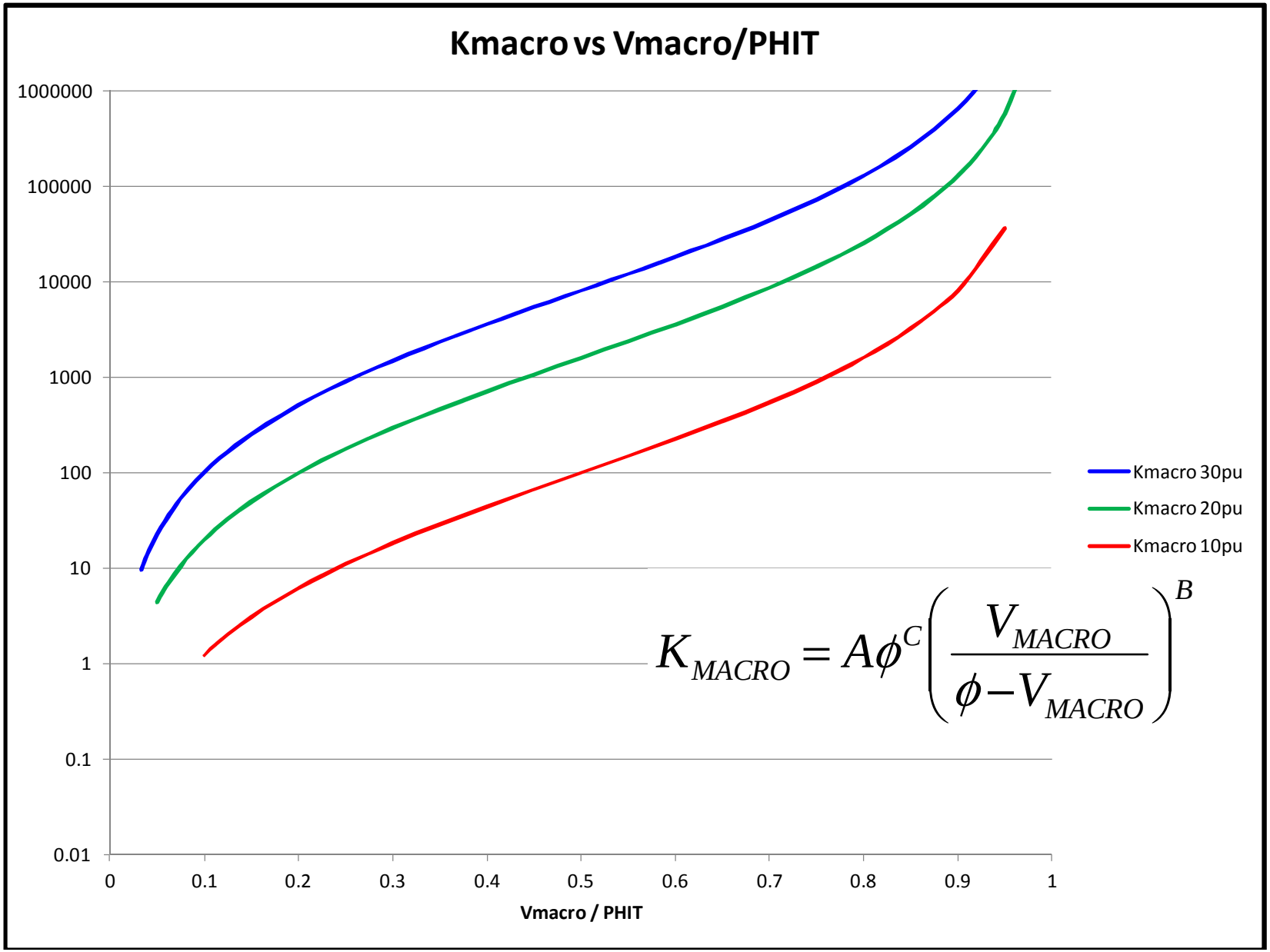
Where c = 3 for spherical pores
= 2 for cylindrical pores
= 1 for planar pores

* Looyestijn, 2004

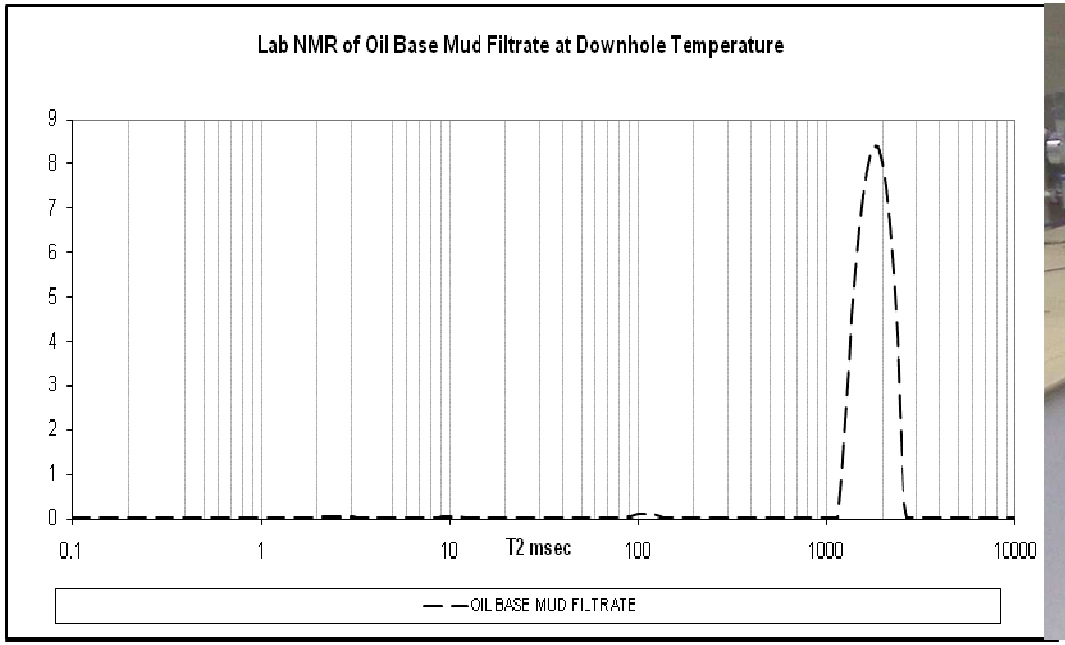
T_2 versus Pore Size: Effect of T_2 bulk



Permeability and Macro Porosity

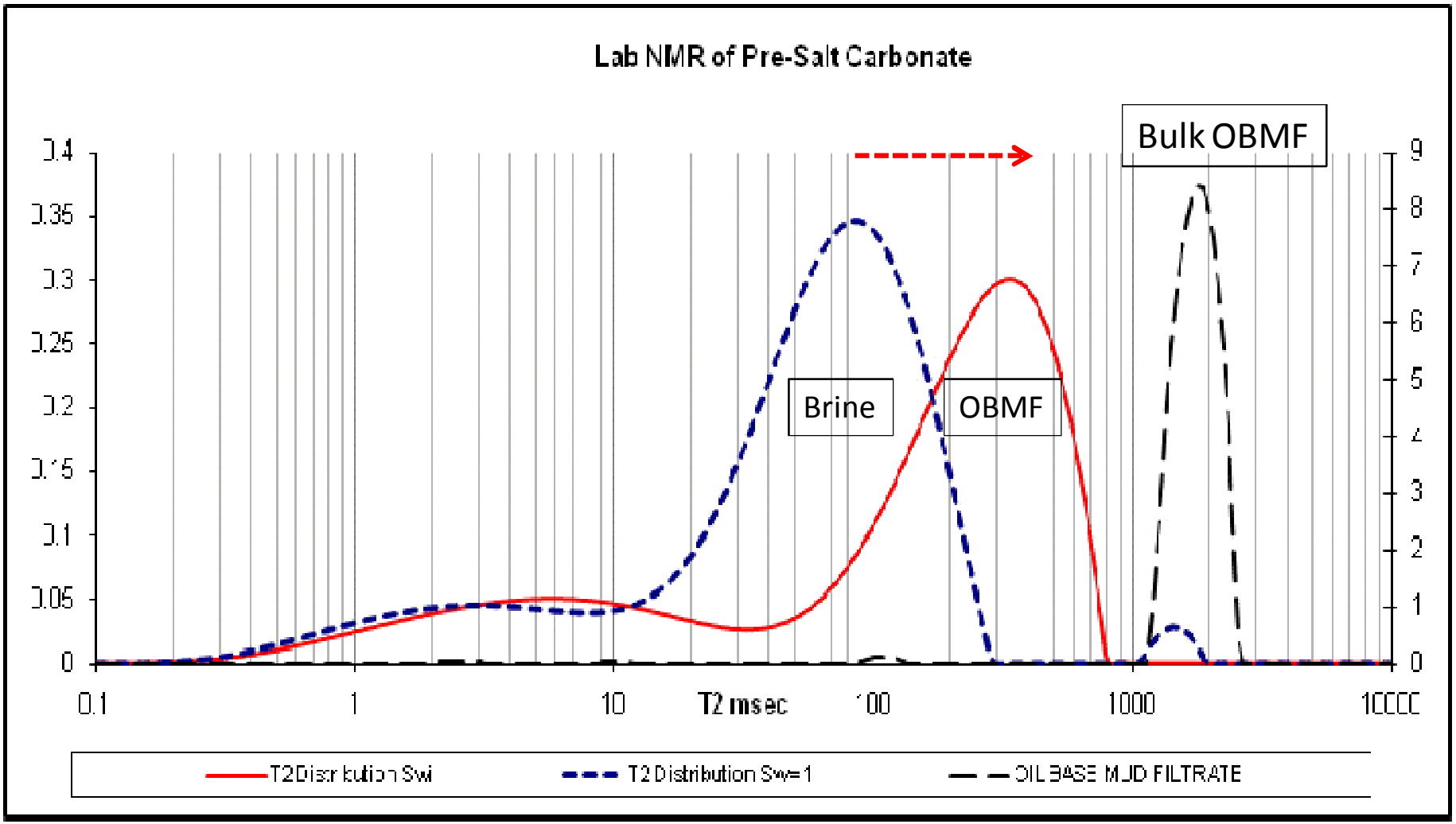


T_{2bulk} of Oil Base Mud Filtrate

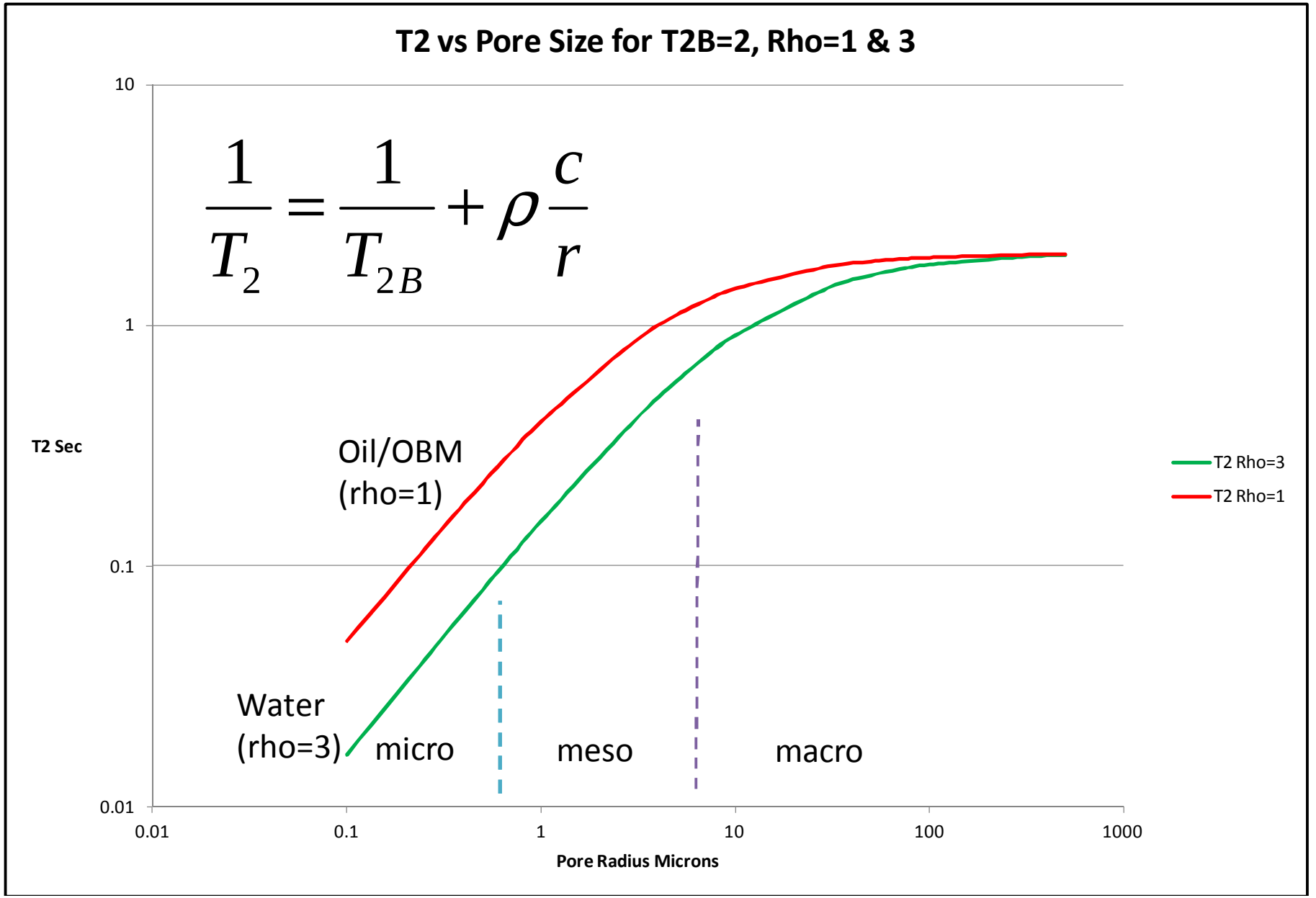


Petrobras Research (CENPES)
Brazilian Universities Lab NMR:
UFF, USP, UFES, UFRJ, ON

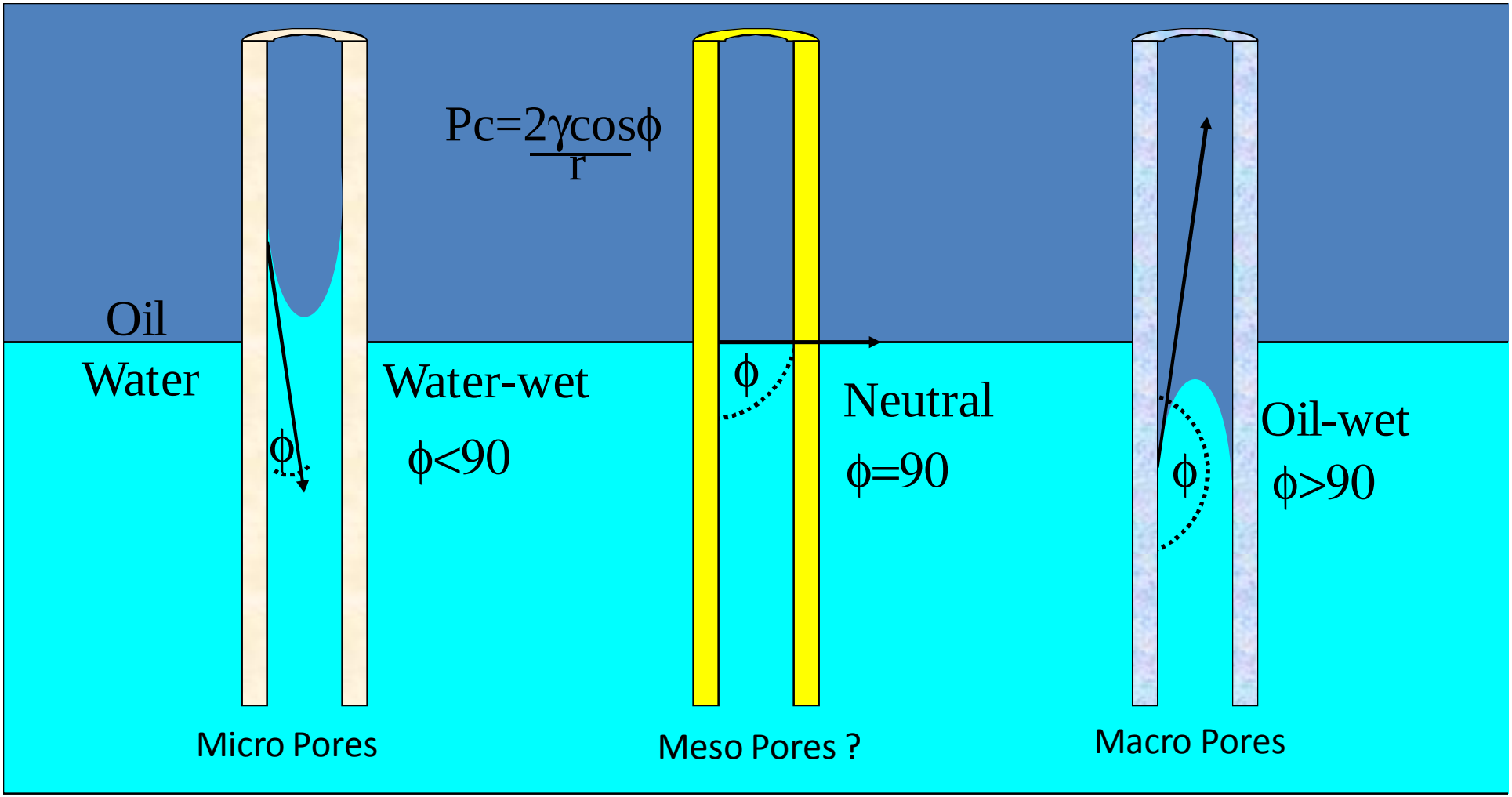
Pre-Salt Carbonate Core: Lab NMR



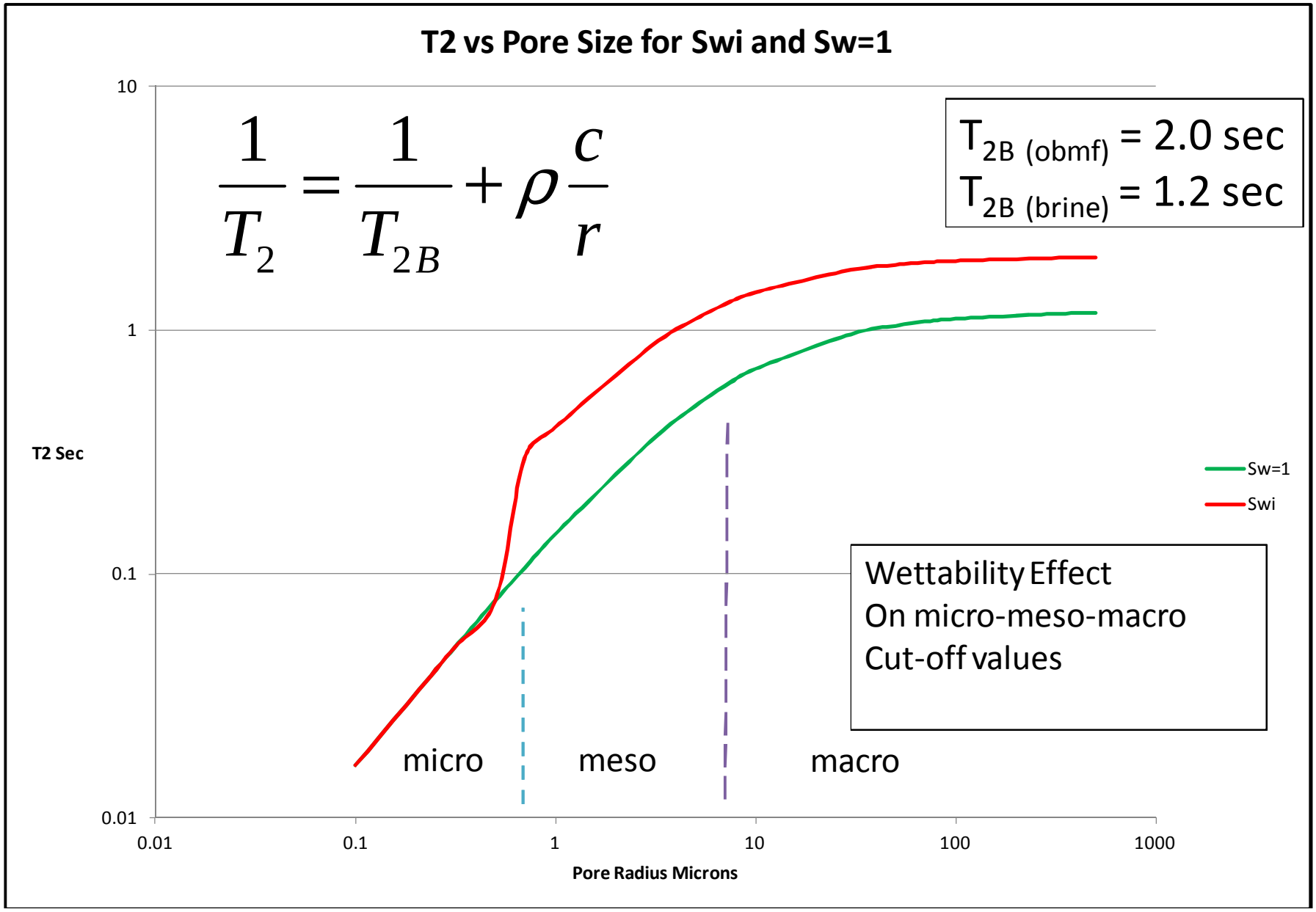
Effect of Surface Relaxivity (ρ)



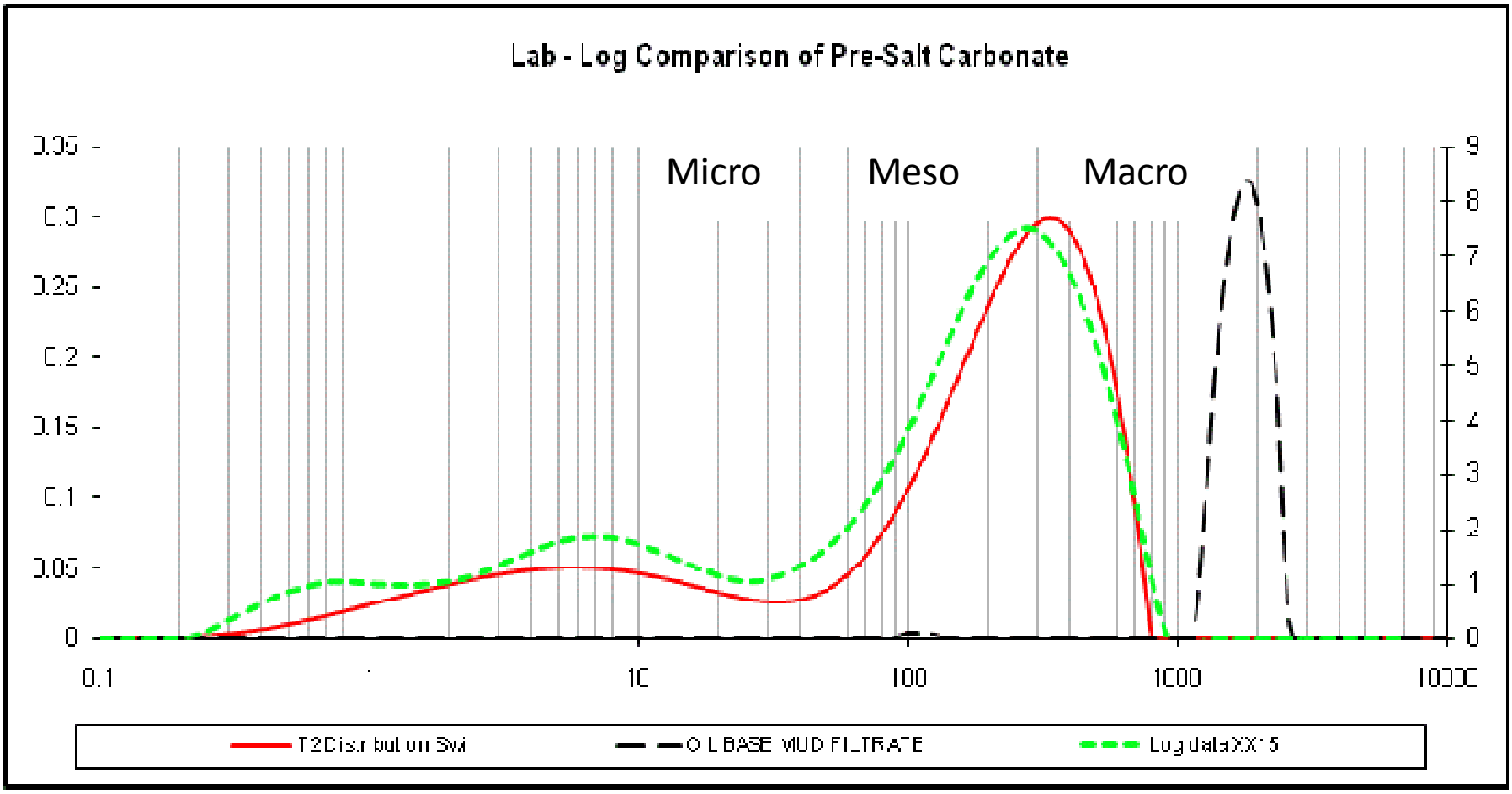
Wettability & Pore Size



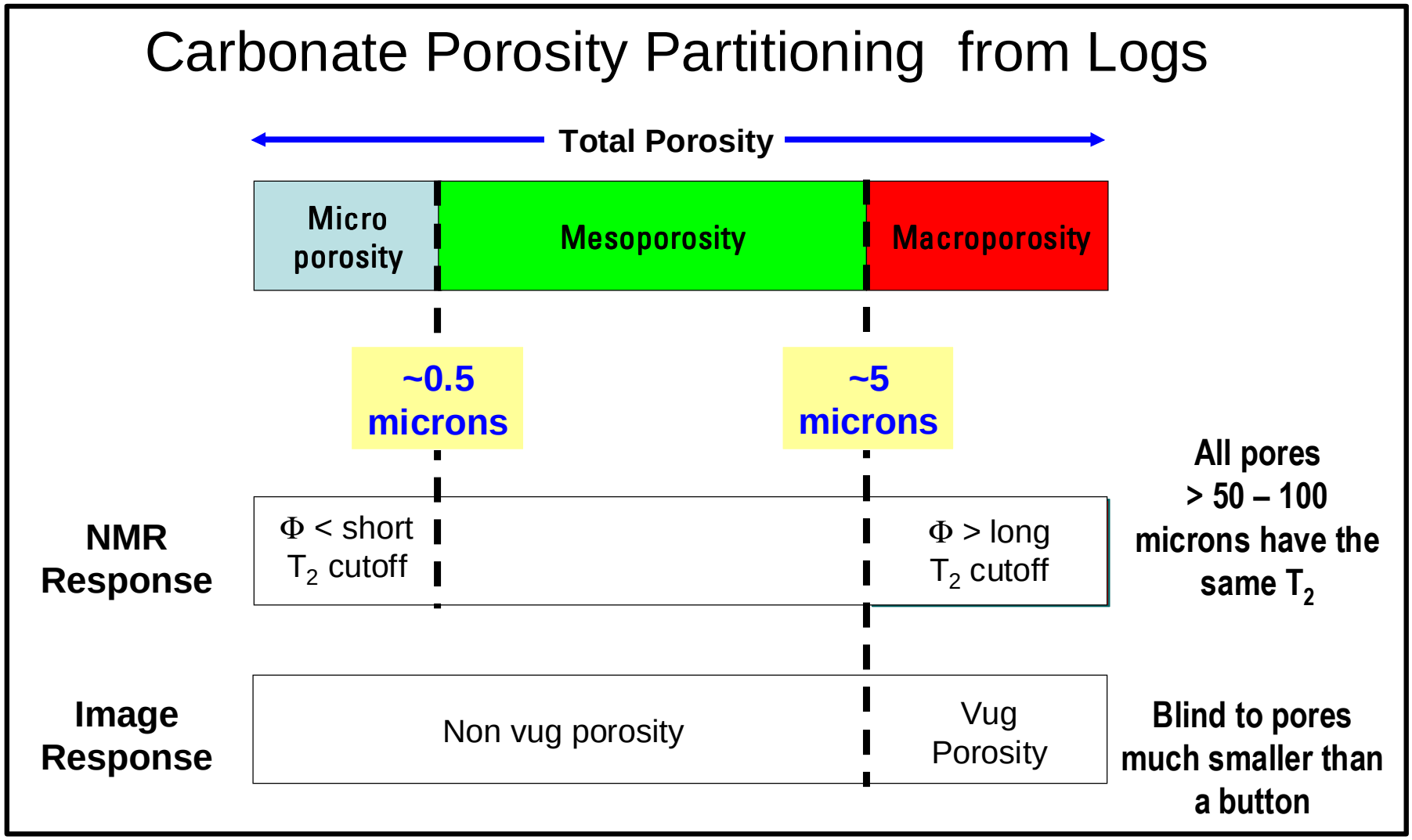
Effect of Surface Relaxivity and Bulk T_2



Lab – Log Comparsion of Pre-Salt Core

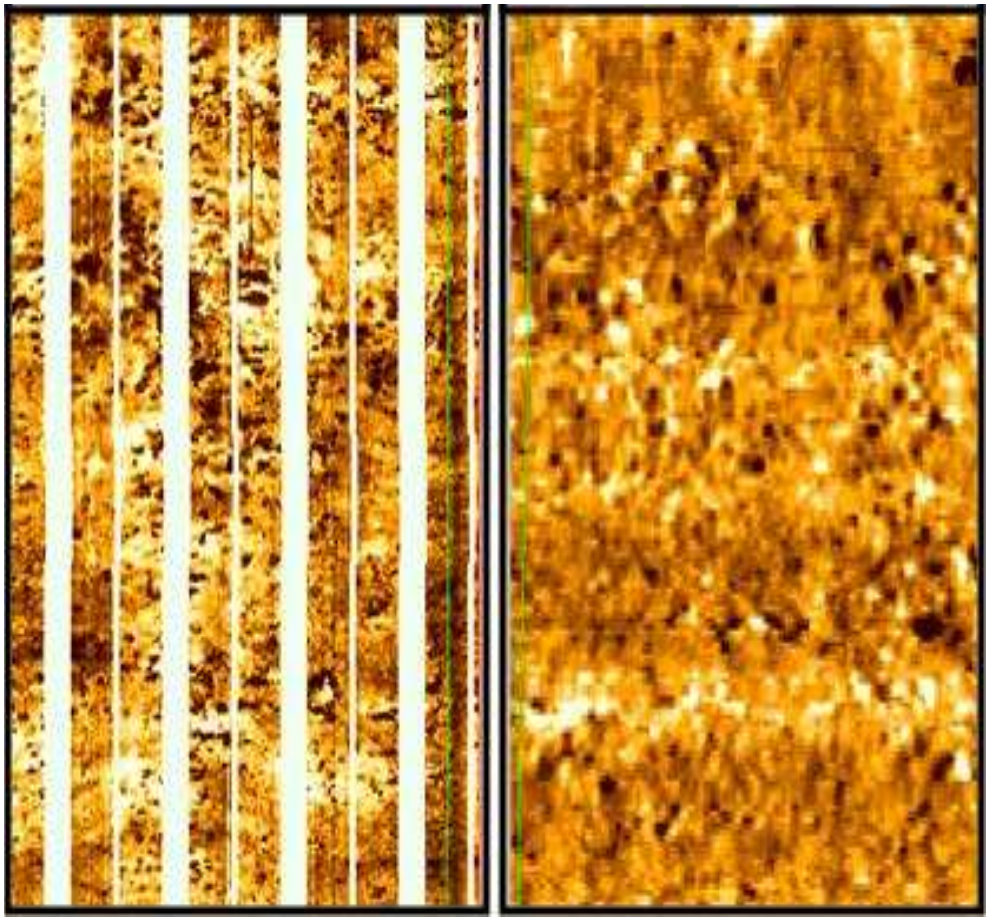


Carbonate Porosity Partitioning



Electrical and Acoustic Images in Vuggy Carbonate

ELECTRICAL IMAGE LOG ACOUSTIC IMAGE LOG



Under Evaluation:
Vugs from Electrical Images &
Acoustic Images in OBM

Summary: Carbonate OBM Petrophysics

- Porosity & Lithology
  - NMR Porosity helpful with complex mineralogy
- Porosity Partitioning & Permeability
  - Oil Wet and Light Oil
  - K_{SDR} for Micro-Meso Porosity
  - K_{MACRO} when Macro Porosity > cut-off
- Saturation
  - Swirr from NMR

References

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2) Geologic Nomenclature and Classification of Porosity in Sedimentary Carbonates, CHOQUETTE and PRAY, AAPG 1970

3) Microporosity in Carbonate Rocks, Edward Pittman, AAPG 1971

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5) Rock-Fabric/Petrophysical Classification of Carbonate Pore Space for Reservoir Characterization , F. Jerry Lucia AAPG 1995

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7) Microporosity in Arab Formation Carbonates, Saudi Arabia, Cantrell &Hagerty, GeoArabia, Vol. 4, No. 2, 1999

8) Permeability, Relative Permeability, Microscopic Displacement Efficiency, and Pore Geometry of M-1 Bimodal Pore Systems in Arab D Limestone, Edward Clerke, SPE 10529, 2009