VIRTUAL PPS

A Permeability Model from the Integration of Capillary Pressure, Electrical Properties and NMR to Predict Hydraulic Rock Pore Types

LPS Seminar: Permeability Theory and Applications
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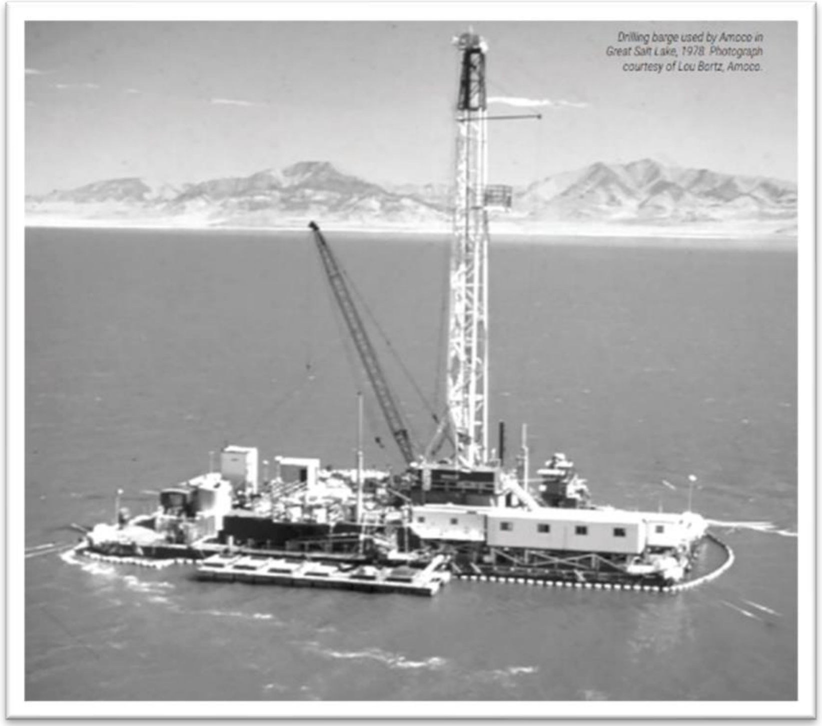
Virtual Petrophysics Technologies

https://virtualpps.com

Presentation Outline

- Introduction to REV Permeability Model
- Introduction to Hydraulic Rock Pore Types
- Capillary Pressure and Electrical Property Rock Pore Type Model
- SCAL Calibration Data for NMR Rock Pore Type
- RPT model application to NMR log



REV Permeability Model

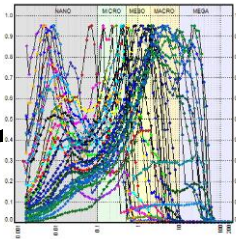
Reservoir Rock Pore Types

In 1950 Gus Archie[1]…" If it were possible to measure the fundamental properties (exact pore size and fluid distribution) *in situ* of formations penetrated by the bore hole, the volume of the hydrocarbon in place and the productivity of the layer could be calculated."

Archie Petrophysics

Type of Rock

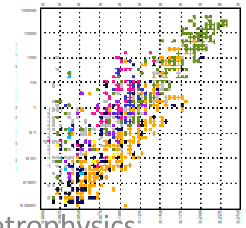
(**Rock Pore Type**)



Pore Size Distribution

Porosity

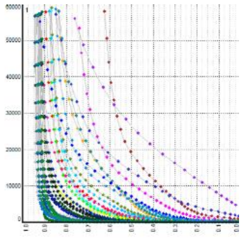
Permeability



Water Saturation (Connate)

Capillary Pressure

(Pore Interconnection)



Purcell Capillary Pressure Permeability

- Poiseuille's Law (1838)[2]
  - Laminar flow in pipes, Incompressible fluid
  - Rewritten for capillary volume, eq 1
- Darcy's Law (1856) [3]
  - Flow through porous media, eq 2
- Washburn[4] (1921)
  - Capillary pressure difference across interface of two fluids, eq 3
- Purcell[5] (1949)
  - Relates permeability of porous media to its porosity and capillary pressure curve, eq 4

$$\frac{Q}{t} = \frac{VR^2P}{8\mu L^2} \ldots eq\ 1$$

$$\frac{Q}{t} = \frac{kAP}{\mu L} \ldots eq\ 2$$

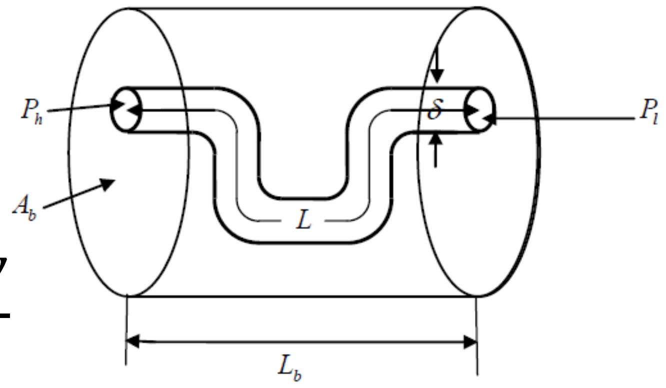
$$Pc = \frac{2\sigma\cos(\theta)}{R} \ldots eq\ 3$$

$$k = 0.66F\emptyset \int_0^1 \frac{dSw}{Pc^2} \ldots eq\ 4$$

Representative Element Volume Permeability (Ruth 2012)[6]

- The REV model is a simple application of Effective Medium Theory that is based on the averaging of multiple values that make up a composite material.

Representative Element Volume (REV)



- Mean Tube Diameter

$$D^2 = (4\,\sigma\cos\theta)^2 \int \frac{dSw}{Pc^2}$$

- When electrical properties are available on sample

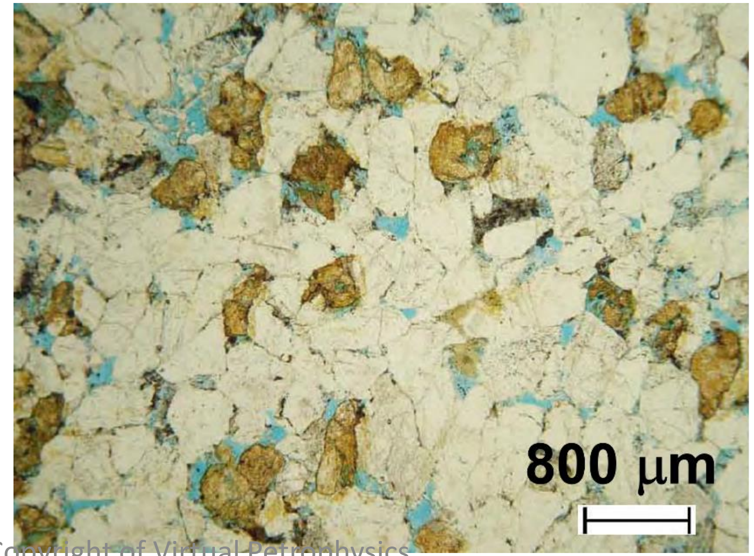
$$k = \frac{(\sigma\cos\theta)^2}{2F} \int \frac{dSw}{Pc^2}$$

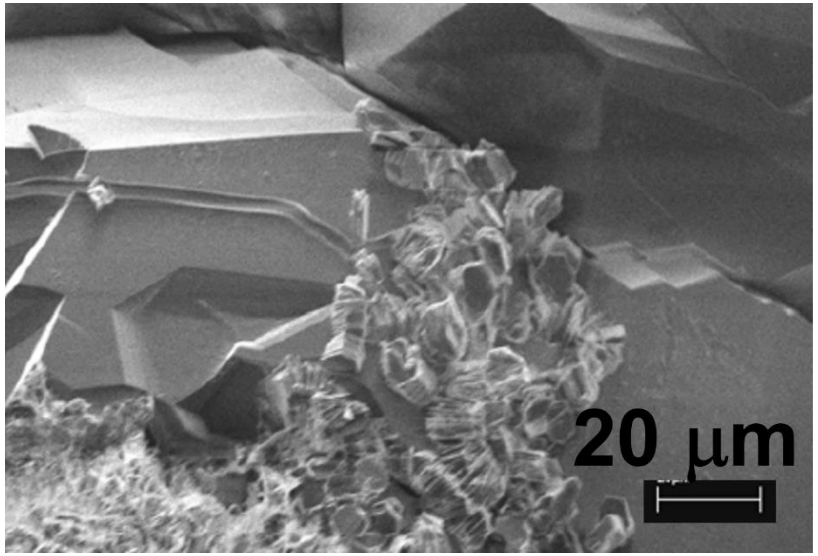
- Or more general when electrical properties are known for the formation

$$k = \frac{\emptyset^m\,(\sigma\cos\theta)^2}{2a} \int \frac{dSw}{Pc^2}$$

Unit conversion constant
21.313
Pc in psi
IFT dyne/cm
Porosity v/v

Hydraulic Rock Pore Types





Hydraulic RPT Introduction

I. Hydraulic RPT's classify rocks into hydraulic radii groups which provides a more accurate prediction of reservoir petrophysical properties than other Rock Type applications (Archie Petrophysics Principal)

II. The Hydraulic RPT model is based on joint interpretation of capillary pressure, electrical resistivity and NMR as published by Purcell[5], Ruth[6], Berg[7] and Garcia[8]

III. Early NMR RPT model developed for Abu Dhabi Upper Thamama carbonate reservoirs (2012)

IV. Model evolved to incorporate new technology workflows by the stated authors

Virtual Petrophysics **R**ock **P**ore **T**ype Model

The Rock Pore Type Model is based on **M**ean **H**ydraulic **R**adius calculated from Capillary Pressure measurements

Kozeny-Carman Equation[9,10,11]

$$k = \frac{r_H^2 \phi}{8\tau_H^2}$$

where r_H is the hydraulic radius, ϕ is the porosity, and τ_H is the hydraulic tortuosity

Definitions
Hydraulics: Hydraulic radius is the cross-sectional area in which a fluid is flowing to the wetted perimeter of the cross-section
Porous Media: Hydraulic Radius[10,12] "r_h " is the ratio of pore volume V_P to pore surface area S_P

Mean Hydraulic Radius is the intrinsic rock property that determines the absolute Permeability and is an "effective capillary size" of the rock's pore system

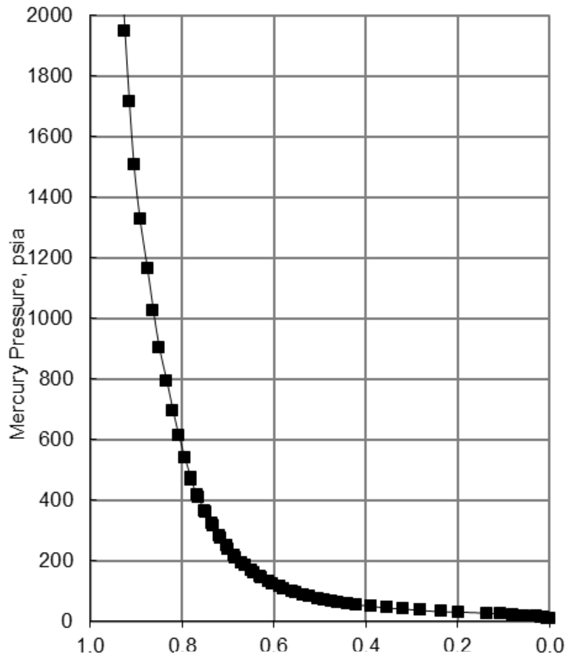
Rocks in the same RPT family will have similar static and dynamic petrophysical properties of porosity, permeability and irreducible water saturation

RPT's are used as a predictive tool for well performance and to populate petrophysical properties in static and dynamic models

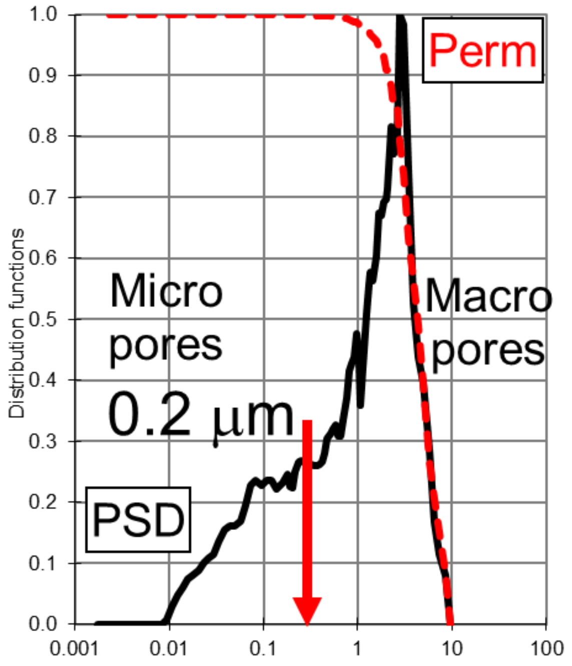
MHR Example – Credit Ed Clerke SPE Dubai 2012

Important Note: Irreducible water saturation is determined by the maximum Pc in the reservoir. In this example 500 psi = 0.2 microns hydraulic radius.

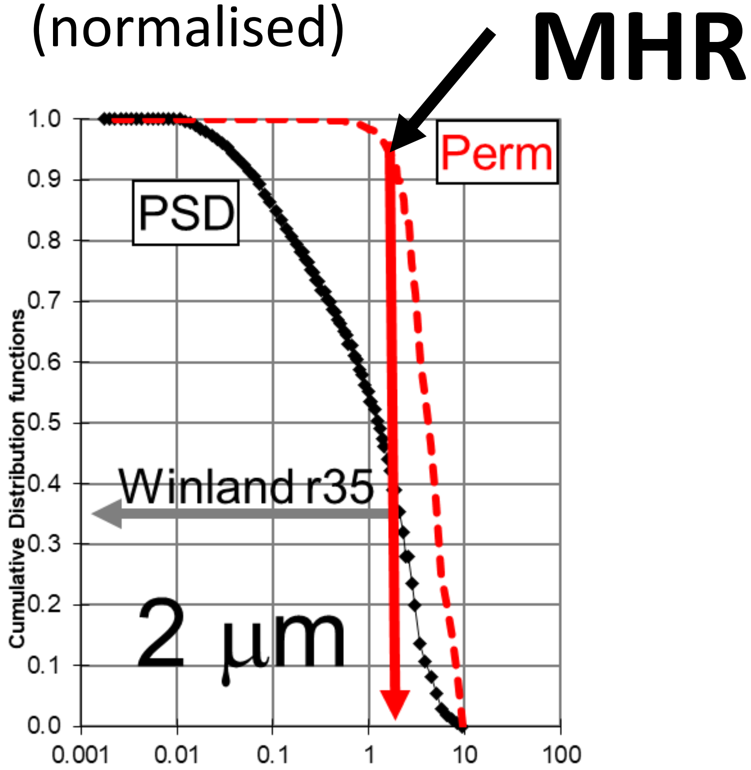
Capillary Pressure Saturation Distribution



Porosity and Cumulative Permeability Distribution (normalised)



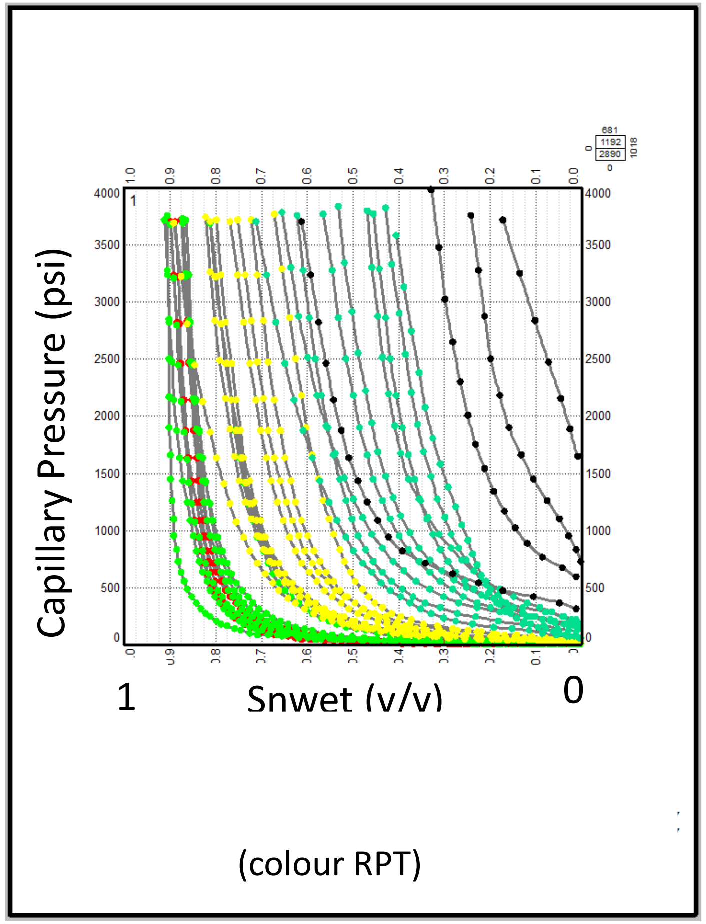
Cumulative Porosity and Permeability Distributions (normalised)



Capillary Pressure and Electrical Property
Rock **P**ore **T**ype Model Processing

Rock Pore Type Permeability Model – MHR and KREV

Drainage Capillary Pressure



MHR and **KREV** are computed using full capillary pressure range and electrical property formation factor (tortuosity)

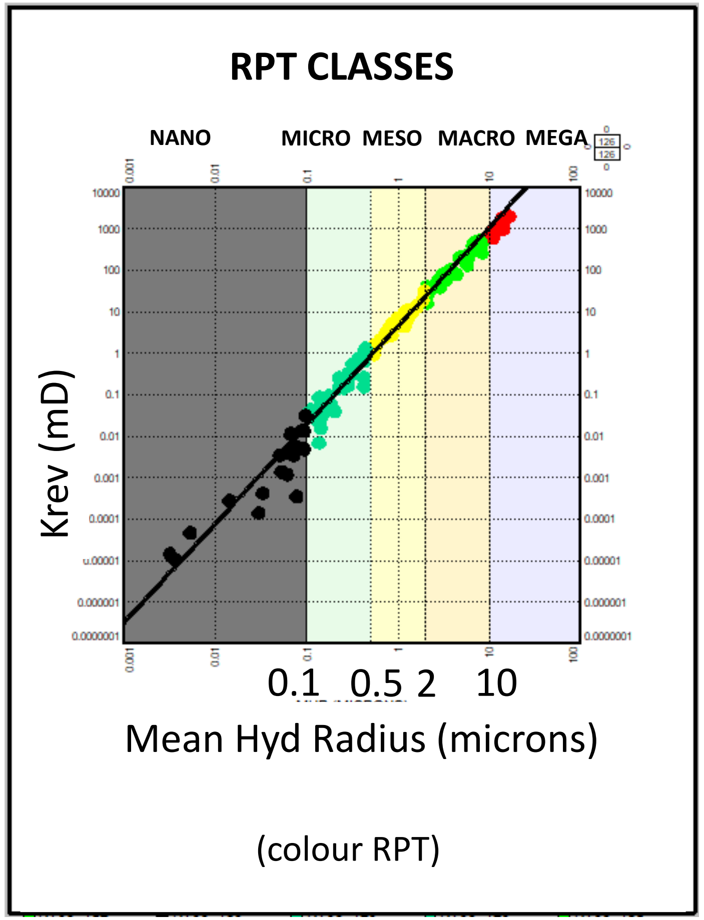
$$MHR = \frac{\sum_{i=0}^{n}(r_i^2 \times (S_i - S_{i-1}))}{2 \times \sum_{i=0}^{n}(r_i \times (S_i - S_{i-1}))}$$

$$K_{REV} = C \int \frac{dSv}{(Pc)^2}$$

where

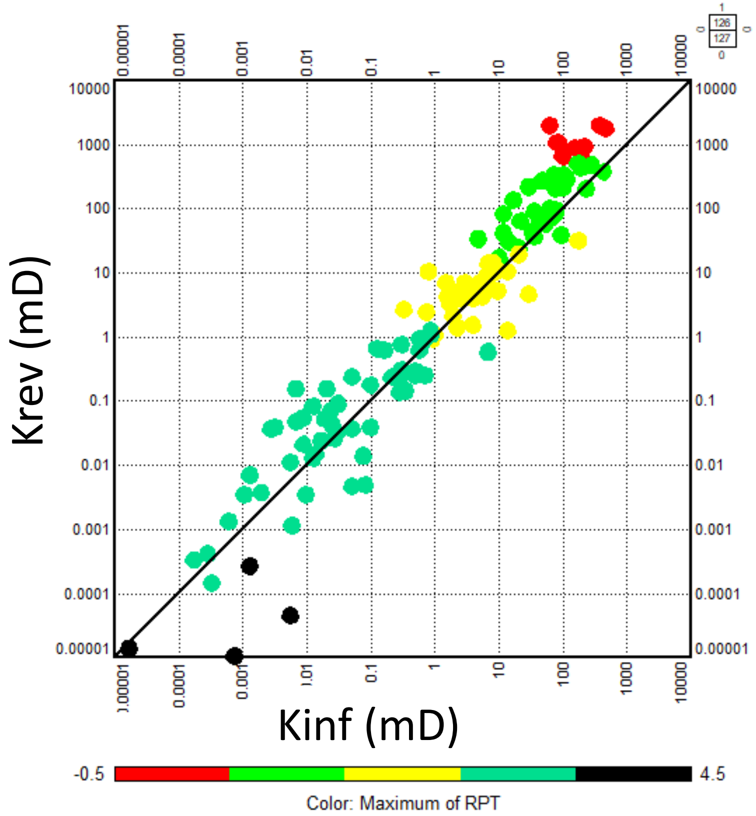
$$C = \frac{(\sigma \times cos\theta)^2}{2 \times FF}$$

Rev Permeability vs Hydraulic Radius



Comparison of RCA Kinf to MICP PERM_REV

- 1 to 1 relationship between Kinf vs Perm_Rev
- Differences in Mega class where Kinf appx 1 magnitude lower
- Note 1: Comparison of adjacent rock samples. Kinf on whole core plug while MICP PERM_REV on plug-offcut or trim-end
- Note 2: MICP measurement with no confining pressure - corrections applied for closure and stress



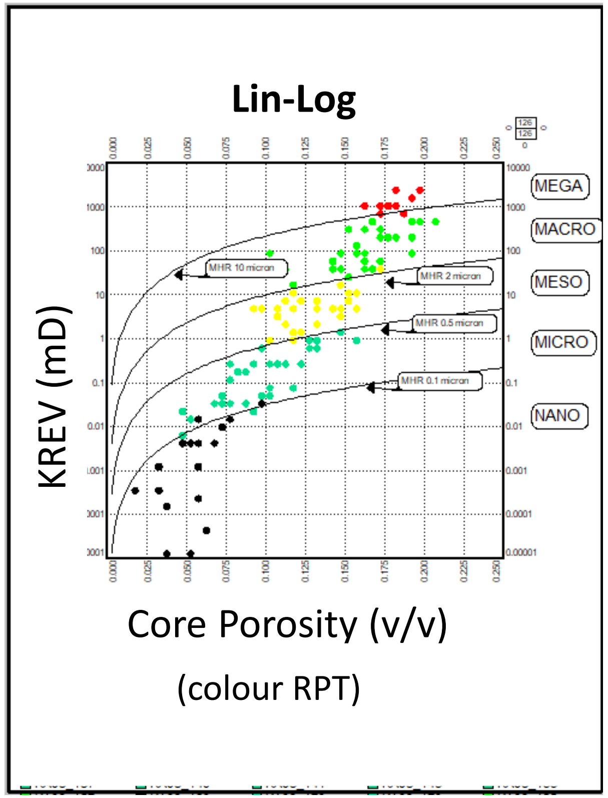
(colour RPT)

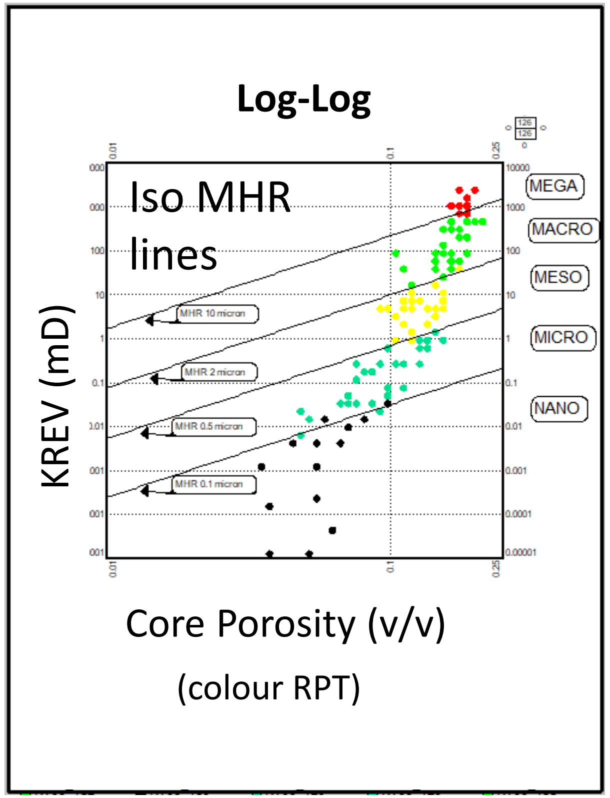
Calibrated Kozeny Model on SCAL Plugs

Kozeny-Carman Equation $$\mathrm{k} = \frac{r_H^2 \phi}{8\tau_H^2}$$ where r_H is the hydraulic radius, ϕ is the porosity, and τ_H is the hydraulic tortuosity

Modified Kozeny Equation $$\mathrm{k_{mod}} = 125 \times r_H^2\ \emptyset^m$$ incorporating formation factor for hydraulic tortuosity

Calibrated Model $$\mathrm{k_{mod}} = 330 \times r_H^{1.92}\ \emptyset^{2.11}$$ based on MICP MHR and Cpor

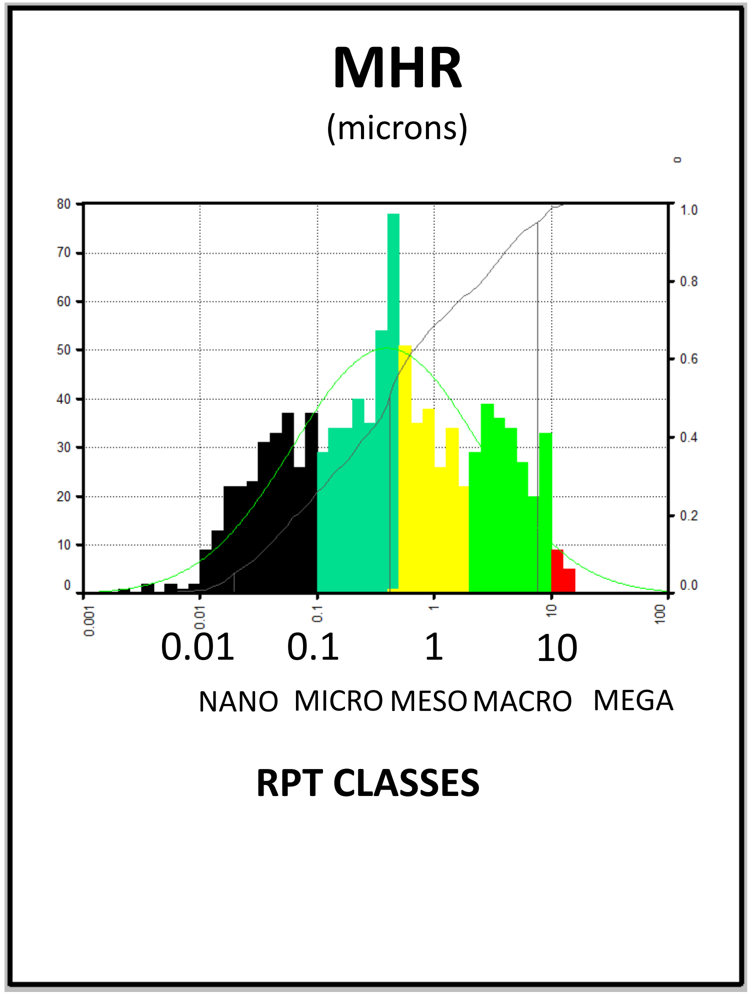


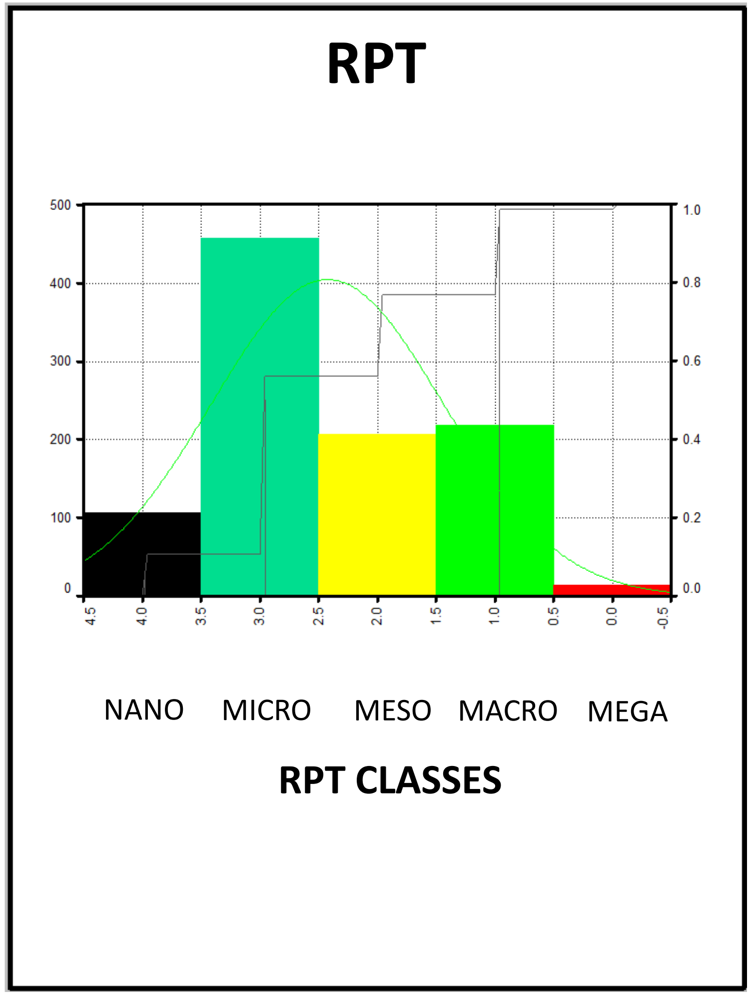


Distributions/Proportions of MHR and RPT

RPT HYDRAULIC CLASS	HYDRAULIC RADII (microns)
MEGA	> 10
MACRO	2 to 10
MESO	0.5 to 2
MICRO	0.1 to 0.5
NANO	< 0.1

MHR and RPT distributions and their associated petrophysical properties can be populated in 3D models





SCAL Calibration Data for NMR Rock Pore Type

Note that MICP measurements taken on plug offcuts from the RCA and NMR whole plugs may not be accurate in representing the whole plug RPT

VirtualPPS Workflow – T2 Time to Length Scale Conversion

T2 is inversely proportional to S/V ratio ignoring diffusion and bulk fluid relaxation

$$\frac{1}{T_2} = \rho \frac{S}{V}$$

-where ρ is the surface relaxivity of the pores (m/s), S is the total surface of the pores in contact with the fluid (m^2), V is the total volume of the pores containing the fluid (m^3)

The surface-to-volume ratio can be calculated for each pore.

The pore shape factor, PSF, is estimated by the distribution of pore types, spherical pores 3, cylindrical pores 2…

$$\frac{S}{V} = \frac{PSF}{r_P}$$

Hence, can translate T2 (time) into pore radii (length) by

$$r_P = \rho T_2 PSF$$

While the constriction factor measures the degree of variation in cross-sectional area of the fluid flow pathways (Berg, 2012)

$$C_H \cong \frac{A_P}{A_T} = \frac{r_P^2}{r_T^2}$$

-where A_P is the cross-sectional area of the pore, A_T is the cross-sectional area of the throat

And to capillary pressure pore throat radii by (Garcia, 2018)

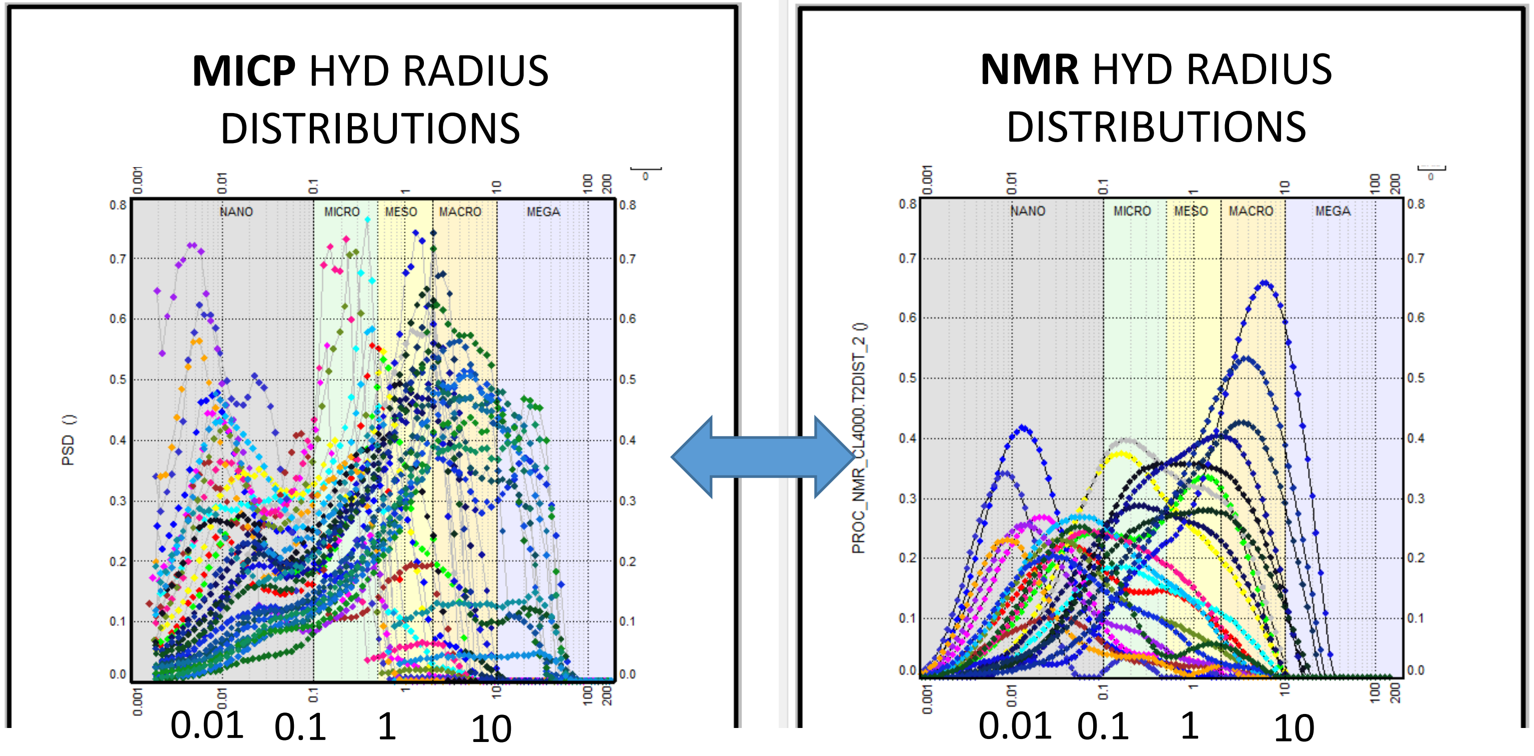
$$r_T = \frac{r_P}{\sqrt{C_H}}$$

Comparison of MICP and NMR Hydraulic Radii

T2 is inversely proportional to Surface Area/Pore Volume ratio and converted to length by the surface relaxivity, pore shape and constriction factor.

Surface relaxivity is a parameter derived by the calibration of NMR $T2_{LM}$ to MICP mean hydraulic radius, r_H

Model assumptions:
- Pore Shape Factor
- Constriction Factor

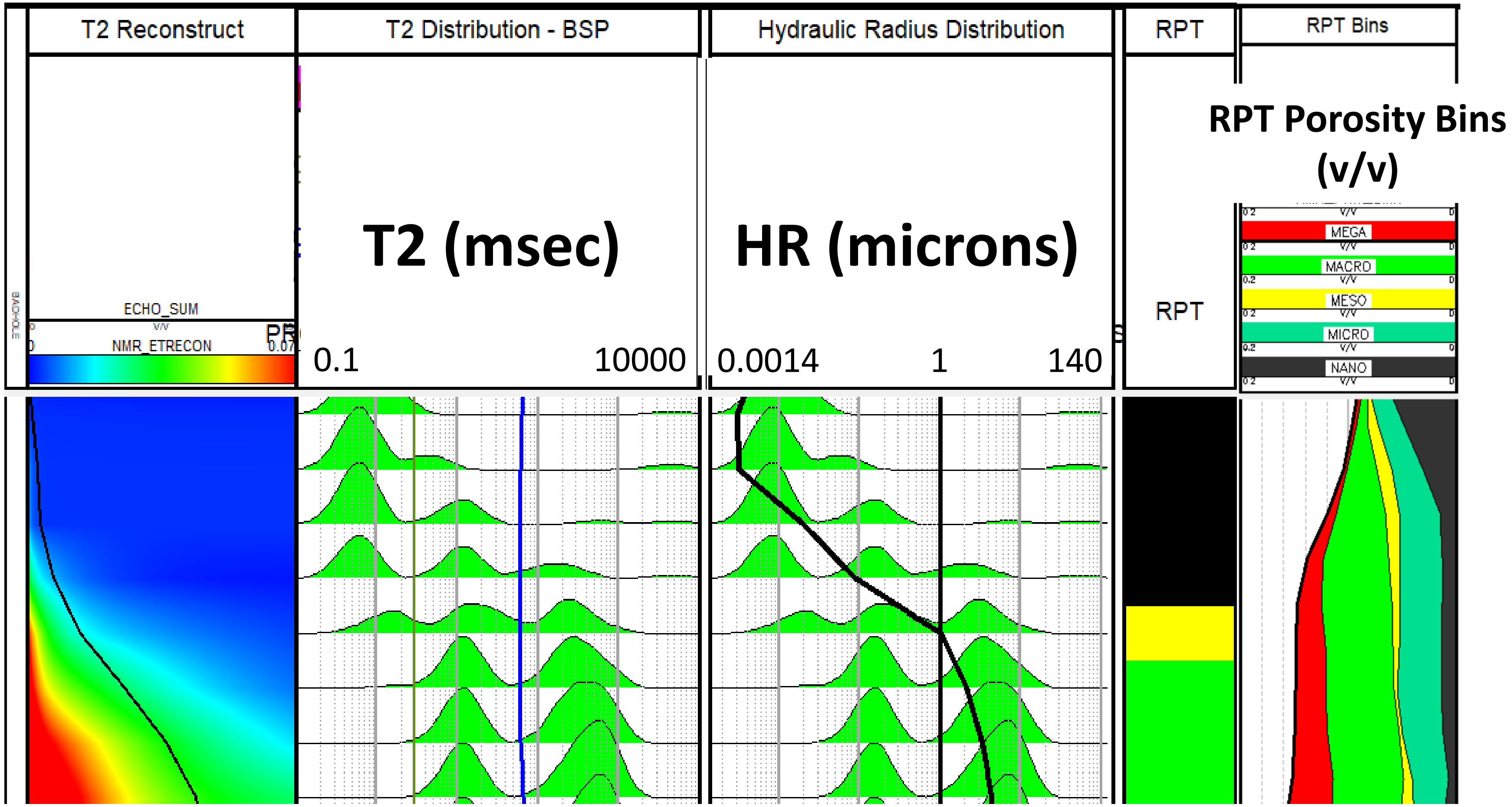


MICP HYD RADIUS (microns)

T2 HYD RADIUS (microns)

RPT application to processed NMR log

NMR log MHR and RPT application



RPT Classifications based on MHR

RPT HYDRAULIC CLASS	HYDRAULIC RADII (microns)
MEGA	> 10
MACRO	2 to 10
MESO	0.5 to 2
MICRO	0.1 to 0.5
NANO	< 0.1

Summary

- Application of REV Permeability to Purcell capillary pressure model provides a theoretical model that does not require calibration factor
- KREV can be applied to most drainage capillary pressure measurements
- Cumulative permeability distributions reveal the hydraulic radii (pore sizes) that contribute to flow
- Mean Hydraulic Radius serves as a predictor for hydraulic Rock Pore Types classification system
- NMR T2 times calibrated to capillary pressure hydraulic radii in core can be applied to NMR T2 log measurements as an MHR and hydraulic RPT predictor

REV Permeability and Hydraulic Rock Pore Type References

[1] G.E. Archie, “Introduction to Petrophysics of Reservoir Rocks”, AAPG Bulletin, Vol 34, No 5, May 1950.

[2] Sutera, S.P., Skalak, R., “The History of Poiseuille’s Law”, Annual Review of Fluid Mechanics, 25: 1-19, 1993.

[3] Darcy, H., “Les fontaines publiques de la ville de Dijon”, Paris: Dalmont, 1856.

[4] Washburn, E.W., “The Dynamics of Capillary Flow”, The Physical Review, Vol XVII, No.3, March 1921.

[5] Purcell, W.R., “Capillary Pressures – Their Measurement using Mercury and the Calculation of Permeability therefrom”, AIME Petroleum Transactions, 1949.

[6] Ruth, D., Lindsay, C., “Combining Electrical Measurements and Mercury Porosimeter to Predict Permeability”, SCA2012-28.

[7] Berg, C.F., “Re-examining Archie’s law: Conductance description by tortuosity and constriction”, Physical Review E 86 046-314, 2012.

[8] Garcia, A.P., et al, “An Integrated Workflow to Estimate Permeability through Quantification of Rock Fabric using Joint Interpretation of Nuclear Magnetic Resonance and Electric Measurements”, SPWLA 59th Annual logging symposium, June 2018.

[9] Kozeny, J., Uber kapillare leitung der wasser in boden: Royal Academy of Science, Vienna, Proc. Class I, 136, pp.271–306, 1927.

[10] Carman, P.C., “Fluid Flow Through Granular Beds”, Transactions Institution of Chemical Engineers, Vol 15, 1937.

[11] Harmsen, G.J., “The Concept “Hydraulic Radius” in Porous Media”, AIME Petroleum Transactions, Jan 6, 1955.

THANK YOU FOR YOUR TIME AND PARTICIPATION !!!

QUESTIONS?