Aberdeen Formation Evaluation Society

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AFES Online Day Seminar 2nd and 9th September

"Capillary Pressure – An Integrated Flowchart for Carbonate Reservoir Characterization from Resource Assessment to Field Development and EOR Applications"

Refer to **: 20IPTC-(20096)-MS (available in OnePetro)**

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1-- Good morning everybody.

Thank you all and AFES for this opportunity to present this flowchart for reservoir characterization with MICP integration.

A special thank also to my co-author ***NADER GERGES*** for his enduring support and cooperation in field testing and for raising so many interesting points.

The original paper, can be found in OnePetro, or please contact the authors.

Who am I ?
My background is geology, and since the very beginning of my career (1975), I have always been fascinated by logs and by what could be done with logs, my first public presentation in 1979 was on electrofacies prediction and mapping.

A few years before I got the early retirement package at the occasion of the Total/Elf merger (1999) I had the opportunity to contribute, mostly with Shin-Ju YE, to the development of algorithmic techniques for Bore Hole Image interpretation and for data clustering and prediction (they are in Geolog/FACIMAGE)….sort of what is now called big data, ML….. we have many fancy names for that now. I became addicted ! And my latest ***addiction*** is the integration of MICP with all other petrophysical data.

Overview of the Presentation

2

1. **Objectives**
2. **Describe the Flowchart**
3. **Prove the soundness of the chain of processes**
4. **Present innovative dedicated interpretation techniques**
5. **Conclusions**

2 -- the main points of the presentations are listed here.

If you have questions, please refer to the slide number. I hope it highly visible in the yellow square

Objectives : popularize the integration of MICP to all reservoir characterization projects, *as requested in 1950 by ARCHIE* **3**

1. **Save, Share, Display, Process MICP data like any log**
2. **Simplify the extraction of petrophysical parameters from MICP**
3. **Simplify the creation of :**
   - **Continuous Profiles of PSD, Rock-type…etc. → mapping and 3D modeling**
   - **Facies/Rock-Types integrating MICP petrophysical parameters**
   - **Static & Dynamic Partitioning of Porosity (Saturation, DS…..)**

→ The flowchart must be holistic, fool-proof, easy to learn and practice

3-- As mentioned by Archie, 70 years ago, the porous network description by MICP informs on rock forming processes, on their stratigraphic evolution and of course on flow properties.
Thus MICP should be integrated in any reservoir characterization projects.

Here, the key objectives of the successive integration steps are listed.

Covering all the questions which are addressed by MICP is but one of the constrains imposed to the design of the flowchart which would have little value if it cannot be widely accepted.

Thus the flowchart must be fool-proof and easy to learn and practice so that the users feel comfortable with it and rewarded by its results.

Fool proof means that it relies on ***physical laws*** and ***field proven numerical techniques***.

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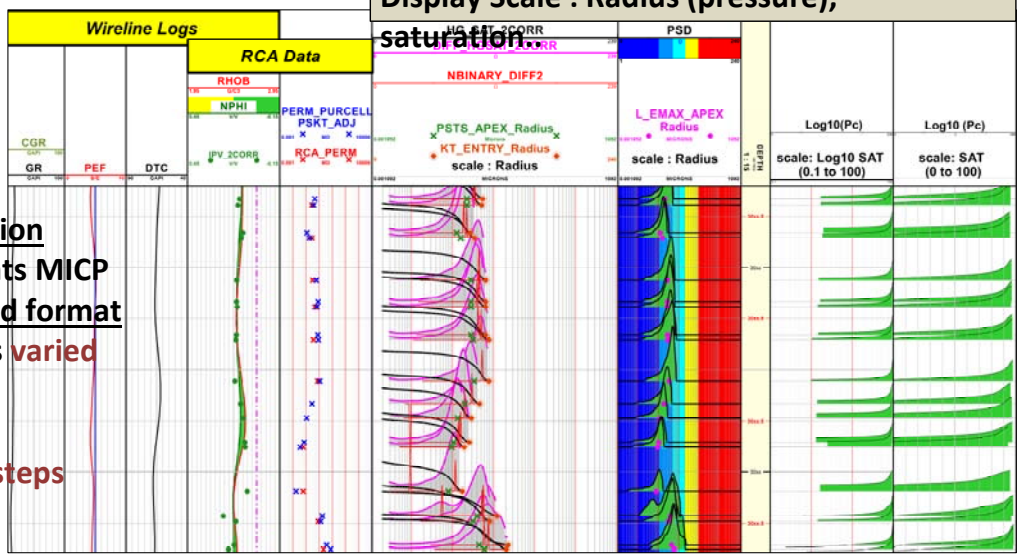
Displaying MICP data along with any log and like any log.

4

Display Scale : Radius (pressure), saturation..



<u>Unbiased</u> <u>tabulation technique</u> presents MICP curves in <u>Standard format</u> & accommodates varied

- **Pc range**
- **Pc steps**
- **number of Pc steps**

4-- NMR T2 distributions displayed on depth track are familiar to all geoscientists and MICP must also be displayed in this way.

So far, displaying, clustering and predicting MICP data was at best impractical because MICP data, which are recorded with a varied number of variable pressure steps, are not presented in a standard format.

Our flowchart solve this problem and present MICP in a standard format, by means of tabulation technique.

Curve fitting methods are not used here, because as you can see on the slide, they are not necessary while their choice is raising many controversies.
Moreover and to the detriment of detail and accuracy**, curves fitting methods do not treat all the parts of the PSD (large or small radiuses) in the same way and they can only process the intrusion curves.**

Next slide please.

Flowchart schematic :

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Stage 1

Load, Format, Correct MICP (single well, irregular sampling)
Extract *Plug Scale* petrophysical parameters

Stage 2

Create continuous MICP profiles (Multi-Wells)
by k-NN Prediction and Histogram-Upscaling of PSD
(field proven Data driven technique with embedded QC**)**

Stage 3

Process continuous MICP profiles to extract *Log Scale* parameters
➔ Output for maps and Well to Well correlations

5 --The flowchart goes from plug scale to log scale in 3 stages.

- 1st stage : formatting and analysis of single plug measurements,
- 2nd stage : building a continuous profile of upscaled PSD for all wells.
- 3rd stage : (multi-well) analysis of the continuous profile of up-scaled PSD and creation of Pc/saturation curves

Let's detail each step.

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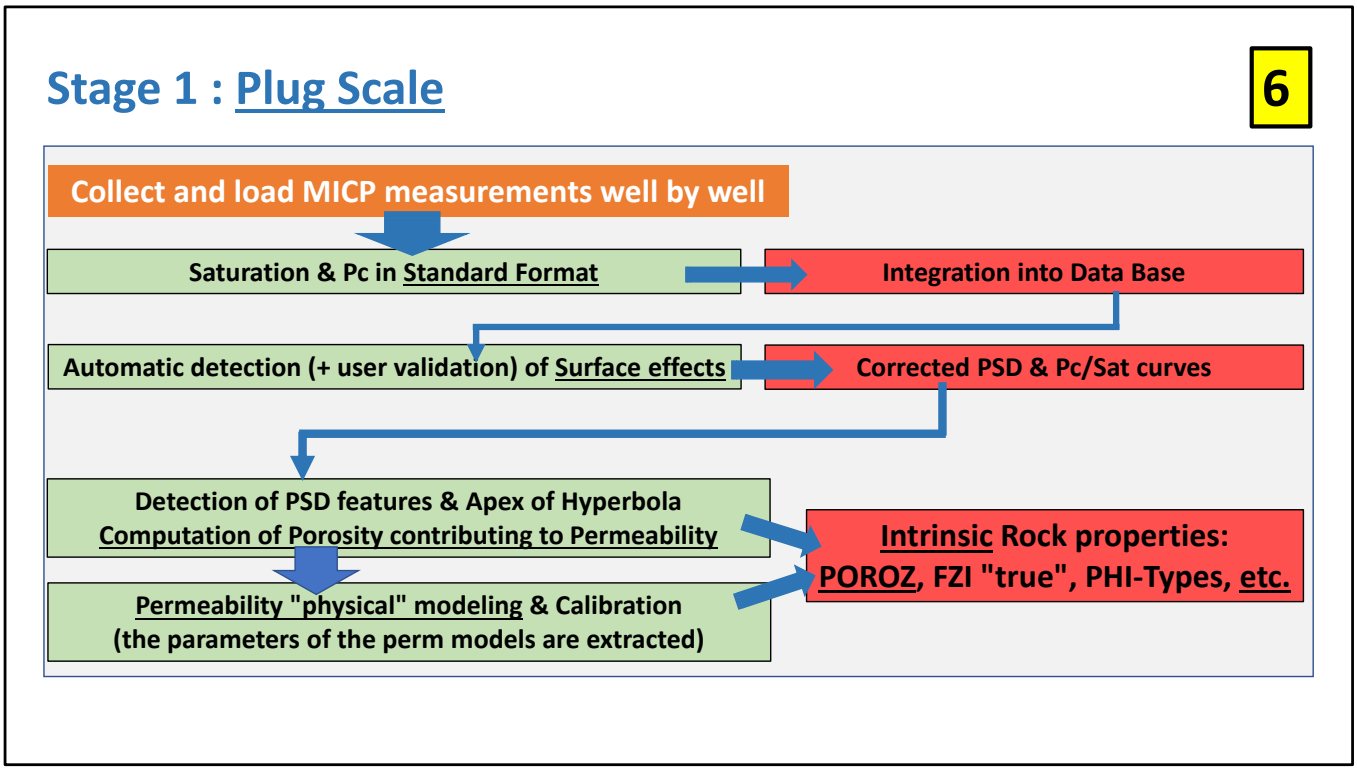

6--Here is the diagram of 1st stage.

MICP are presented in a standard format by means of a tabulation technique.

The Conformance correction is "computer aided" and graphically edited by the user.

The extraction of petrophysical parameters is performed by means of the most fundamental physical models.

The most important result are:

- The detection of the Apex of Thomeer's hyperbola (by 3 methods)
- The quantification of the Porosity contributing to Permeability.
- The quantification of permeability by multiple physical models.

Next slide please.

Step 2: from Plug scale to Log scale by Data Driven methods

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Plug Scale (Irregular sampling)

k-NN multi-well prediction and Histogram-Upscaling of PSD

- **Non-parametric & purely Data driven & Public & Field proven**
- **No user bias & steep learning curve & Minimized risk of errors**
- **Handle all logs including high dimensional array logs**
- **Highest possible resolution in Data Domain → Most suitable to address heterogeneous facies**
- **Traceability & auto QC of prediction model applicability**

Log Scale PSD & variables (**continuous profiles** / regular sampling)
→ Well to Well correlations & Maps

7-- In stage 2, a continuous profile of up-scaled PSD is created by means of a specific implementation of the field proven "k-NN" algorithm.

Why use k-NN ? No other method offer all its advantages, listed here :
it is simple, unbiased and flexible and ***it can handle array logs as predictors and as predictand***.

The specific k-NN implementation we use here is discussed further below. It ensures the Highest possible Resolution and a full Traceability of the results. Thus, the QC of the results is easy and effective.

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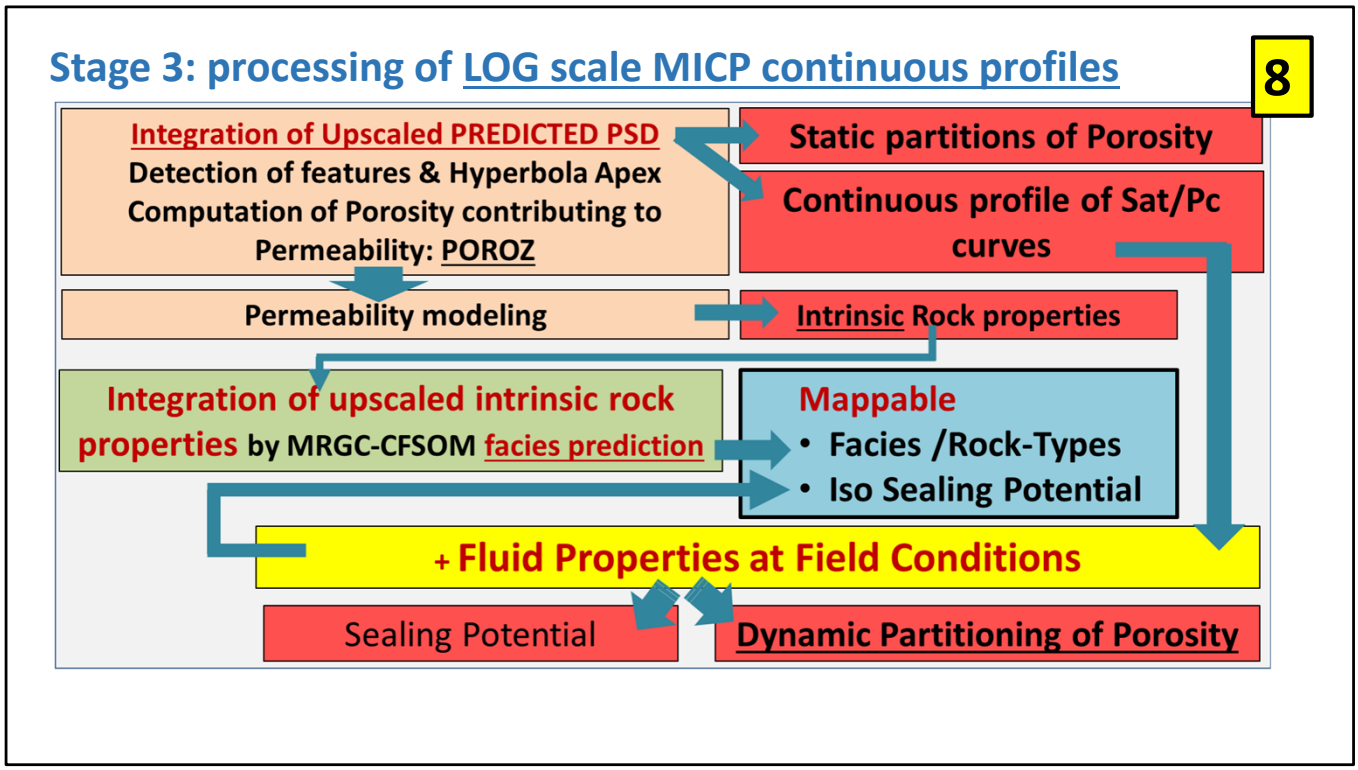

8-- In the 3rd stage :

The Upscaled PSD are processed with the same procedures used for plugs to extract Apex, POROZ, Perm….

The Upscaled Pc/Saturation profiles are generated by summing up all the elements of the upscaled PSD.

All petrophysical data (logs & core) deemed of interest are integrated with the continuous profile of MICP by means of MRGC clustering, ***(not discussed here)***

Porosity is partitioned statically and dynamically. This is detailed below.

The evaluation of sealing potential was discussed in a previous publication. It is not discussed here

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9

Test and Proof the Soundness & Efficiency of the flowchart:

1. **Effectiveness of the tabulation method**
   Demonstrated by the convergence of results of its application to the Trial Solutions proposed for the picking of the Apex of Thomeer hyperbola

2. **Validity, Accuracy, Significance & Explainability of the petrophysical parameters extracted from MICP**
   Demonstrated by the Unification of the classic physical models and laws derived from experiments

9 -- To accept a new flowchart on a sizable project you need a successful test of its concepts and effectiveness.

So we must demonstrate :

1. the Effectiveness of the tabulation method

2. The validity and explainability, in terms of petrophysics, of the results extracted from MICP

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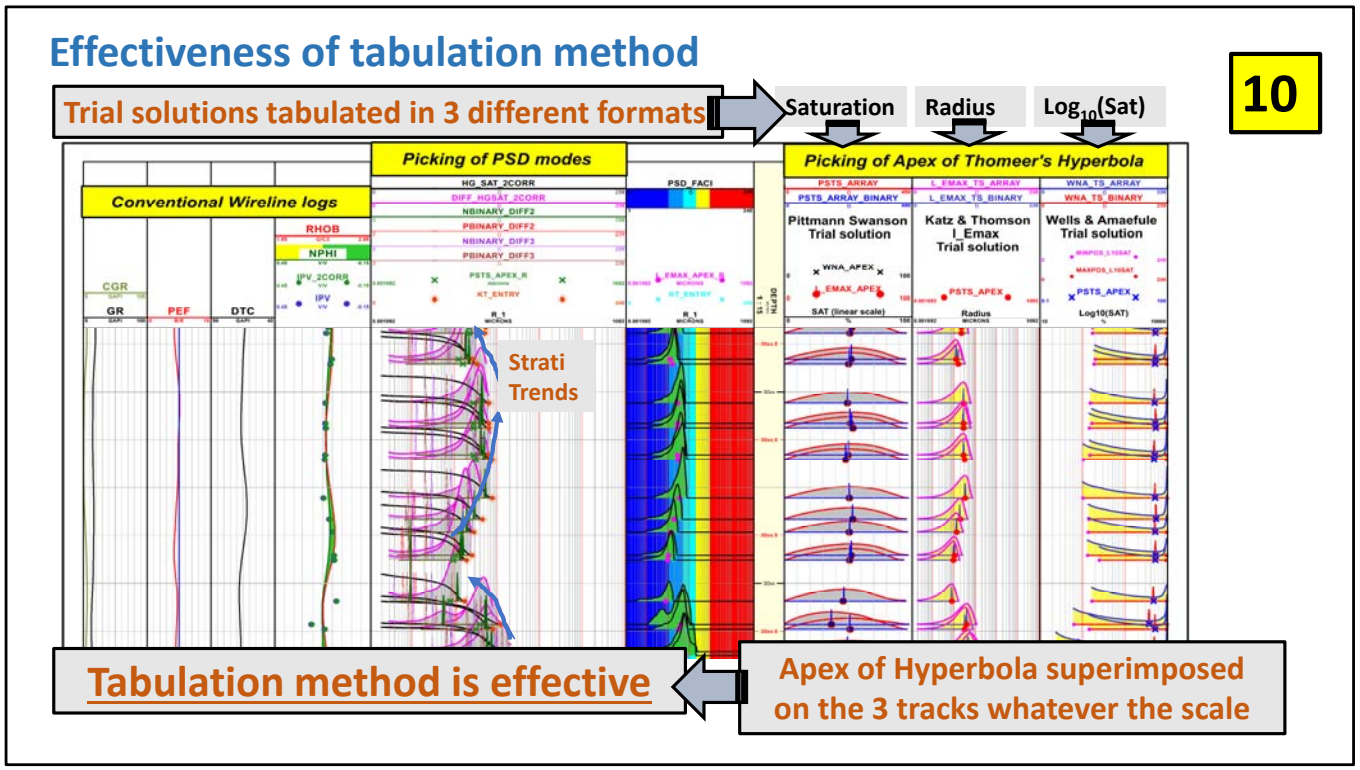

10 -- The picking of the apex of Thomeer's hyperbola is a good test of the effectiveness of the Tabulation technique.

Indeed, the radius at the apex can be picked using the 3 trial solutions, published independently by Pittmann, Katz & Thompson, Wells & Amaefule.
it can be shown that they are strictly identical, however, they use the data in 3 different formats.
Thus they are a good test because the same results must be obtained whatever the format, which is easy to verify by graphic superimposition on depth track or on X-plots.

Here, the 3 rightmost depth tracks, show a perfect superimposition of the results, whatever the scale of the variable.

Thus, the effectiveness of the tabulation method is exemplified.

Details can be found in our IPTC paper

- Pittmann: the variable is the ratio "Saturation/Pc" plotted on a saturation scale and the Apex (“PSTS_APEX”) is the maximum of the variable.
- Wells & Amaefule : the variable is SQRT(Pc/saturation) plotted on a saturation scale, the apex (“WNA_APEX”) is its minimum.

- Katz & Thomson : the variable is the product "R* saturation" {i.e. :"Saturation/Pc"} plotted on a radius scale. The apex (“L_EMAX_APEX”) is its maximum”.

Refer to Schechter for mathematics in the background of the Trial solutions

Accuracy & Explainability of MICP interpretation results

11

If the physical MICP interpretation models embedded in the flowchart

- **Purcell :** experiment on incremental mercury Injection
  → *contribution of each porosity components to permeability*
- **Swanson + Katz & Thomson :** experiments on incremental mercury Injection + electrical conduction → *defines* ***connected porosity contributing to Permeability***
- **Kozeny (with Carman restrictions) :** experiments on capillary flow in soil & powders
  → *mean hydraulic radius of* ***porosity contributing to permeability***

are shown to be consistent

- **Mutually**
- **With the Permeability (RCA, PLT, …) measured by Darcy law**

then their parameters (Permeability, Porosity, R_{mh} …)

- ***are accurately determined by the flowchart***
- ***explain the behavior of the porous network***

11 -- the 3 physical permeability models implemented in this flowchart are based on experiments.

If as expected they provide consistent results, then we must conclude that :

1. *Their implementation is sound.*
2. *The models can be unified*
3. The results produced by the flowchart can be safely interpreted in the light of previous experiments
4. The models are further supported by new sets of measurements

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A word of caution. In the Purcell experiment, a non-wetting phase is injected, while the Kozeny model considers a wetting phase.
Here it is admitted that for the Kozeny model to be applied to MICP, the surface of the mercury is not the surface of the pore system until it is fully saturated.

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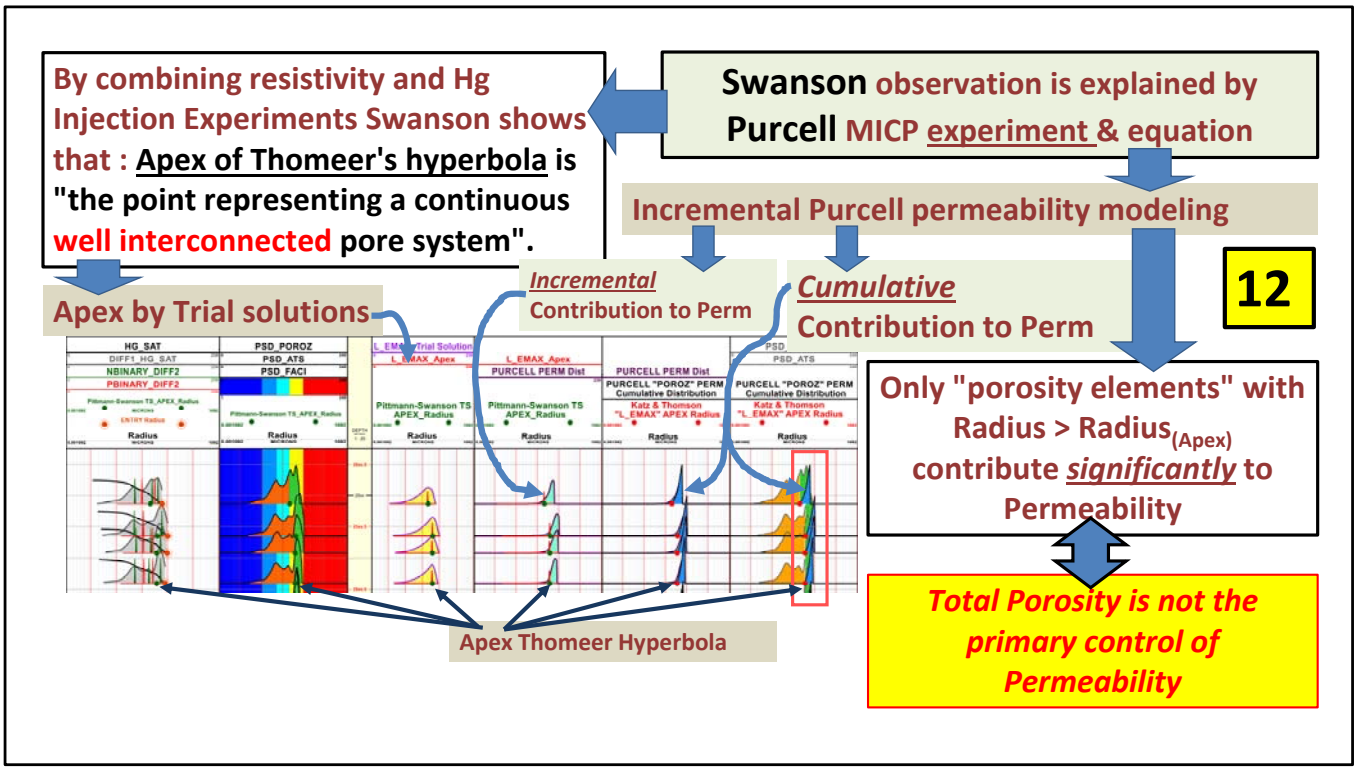


12-- In our workflow, the Purcell model is implemented in an incremental mode to show how each class of Pore Throat Radius contributes to the permeability (3rd track from right) .

Such an implementation makes it possible to compare the Swanson's interpretation of the Pc/sat curve in the light of the Purcell's permeability model.

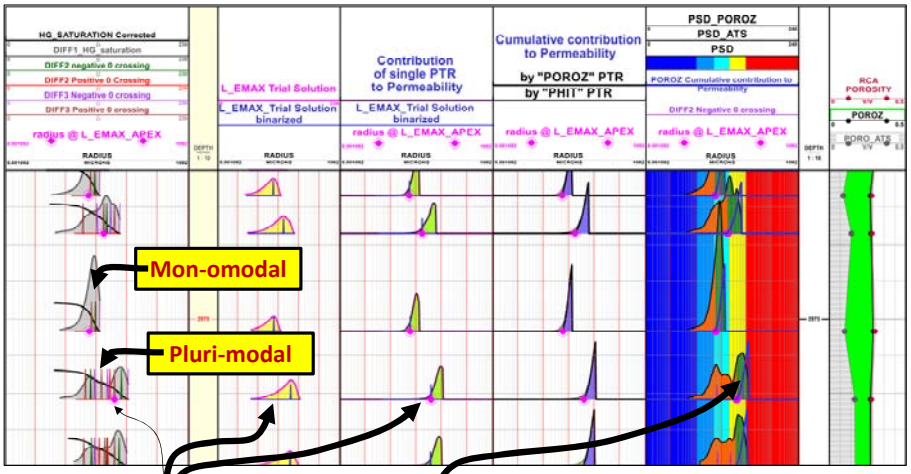
In the 2 rightmost tracks, the PSD & the Apex of Thomeer's hyperbola are superimposed over the cumulative contribution to the permeability of the porosity element (PSD bin), ***The superimposition shows that the apex of the Thomeer's hyperbola is the point at which the Permeability becomes significant.***

Thus, the experiments carried by Swanson (and later by Katz & Thomson) using injection and resistivity measurements to survey the connectivity of the porous network are consistent with the Purcell model.

As a corollary, Permeability is not controlled by Total Porosity

POROZ controls permeability and Primary depletion

13



"POROZ"

- **comprises "porosity elements" with radius greater than the radius at the Apex.**
- **Effectively contributes to permeability**

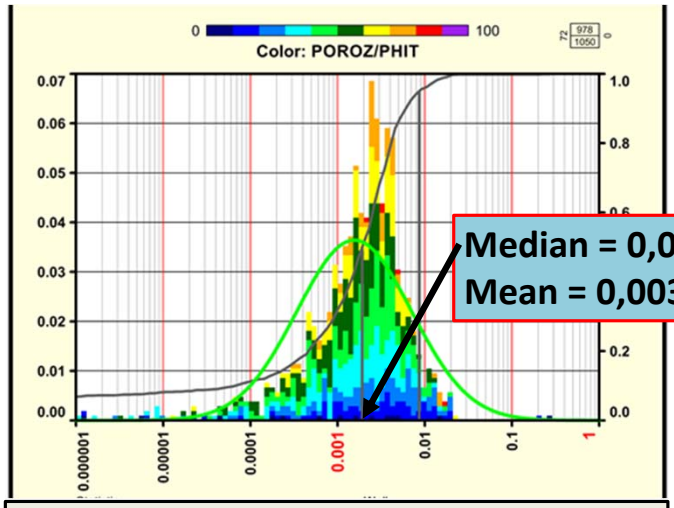
Apex position and POROZ (green area) are unrelated to PSD shape and PHI_T

13 -- the consistency between the Purcell and the Swanson models makes it possible to partition the porosity in two parts:

- "POROZ", which is comprised of radiuses larger than the apex of hyperbola. It contributes significantly to the permeability and can be accessed by Primary depletion.

- "Quiet POROSITY" or "PORO_ATS", with radiuses smaller than the Apex of hyperbola. Its contribution to permeability is insignificant.
  (ATS is the acronym of Apex Trial Solution)

Only the "porosity elements" with Radius > R $_{(Apex)}$ contribute to Permeability



X. Axis : PERM$_{(PORO_ATS)}$/PERM$_{(POROZ)}$

Color code :
POROZ/PHIT is controlled by PSD shape and decreases with increasing PSD complexity:
→ **The ratio PERM$_{(PORO_ATS)}$/PERM$_{(POROZ)}$** is unrelated to the shape of the PSD

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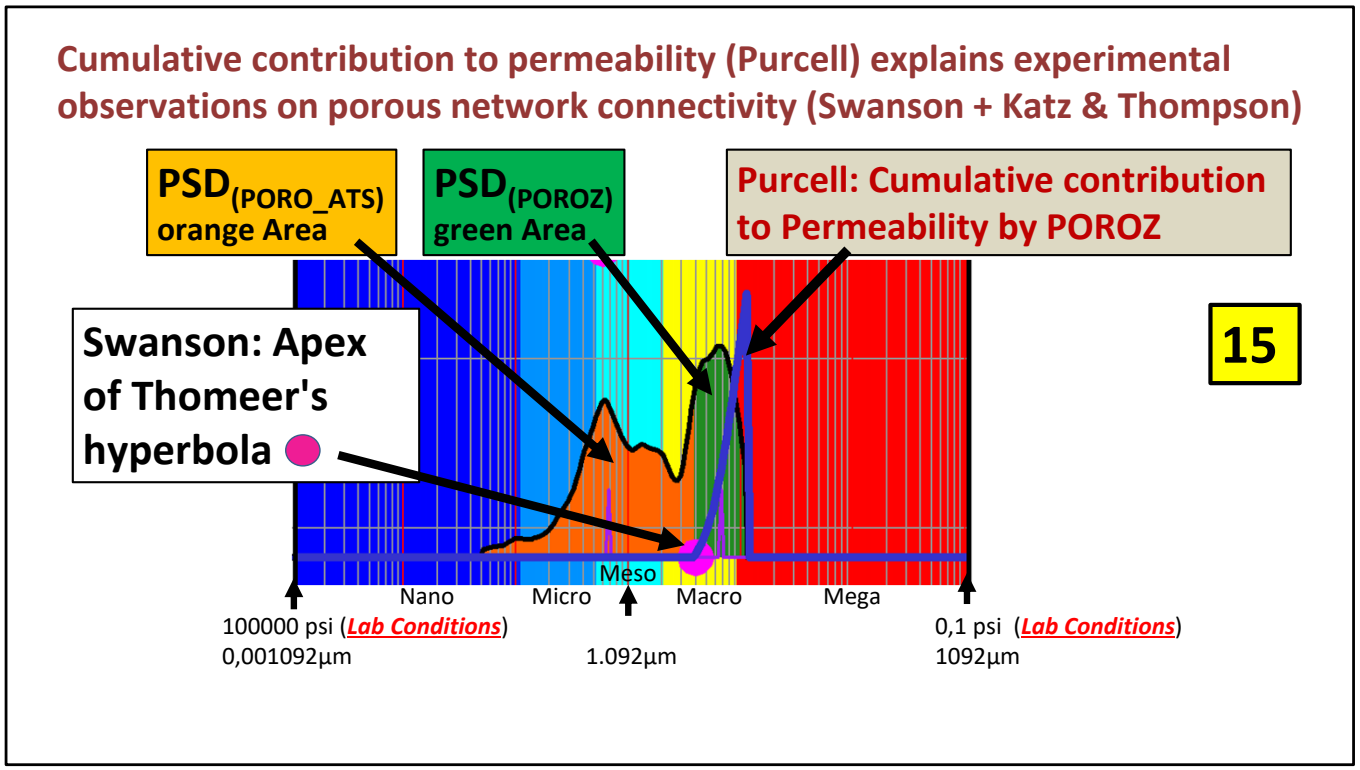
PHI/K plots are misleading
***Because* Permeability is *not* controlled by Total Porosity**

14 -- the histogram of the ratio of "Purcell" permeability modeled for POROZ and for Quiet Porosity (PORO_ATS) is another way to visualize how insignificant is the contribution of QUIET_POROSITY to permeability, despite it may account for up to 80% of PHIT, as shown by the color code (POROZ/PHIT).

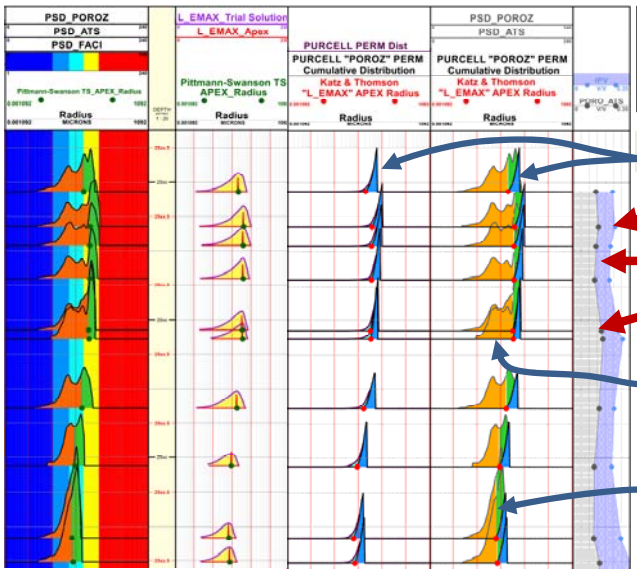
Thus, if POROZ is the main contributor to Perm, then it can be stated that ***PHI/K plots are misleading***



15 -- Detailed image to recap:

1. the convergence between Swanson and Purcell models.
2. **Apex position and POROZ (green area) are unrelated to PSD shape (and modes) and PHI_T**
3. **POROZ controls permeability hence *PHIT/K plots are misleading***

Why Primary Depletion is less effective in Complex Porous Network ?



Increasing complexity of PSD shape reduces POROZ/PHI$_T$ ratio

Contribution to Permeability (blue) superimposed to PSD

PHI$_T$

POROZ (blue interval)

PORO_ATS : "Quiet Porosity"

16

Complex multi-modal PSD shape -> lower ratio POROZ/PHI$_T$

Simple mono-modal PSD shape -> higher ratio POROZ/PHI$_T$

16 – On the 2 rightmost tracks it can be seen that ***<u>the ratio POROZ/PHIT decreases with increasing width and complexity of PSD</u>***.

The consequences are important:

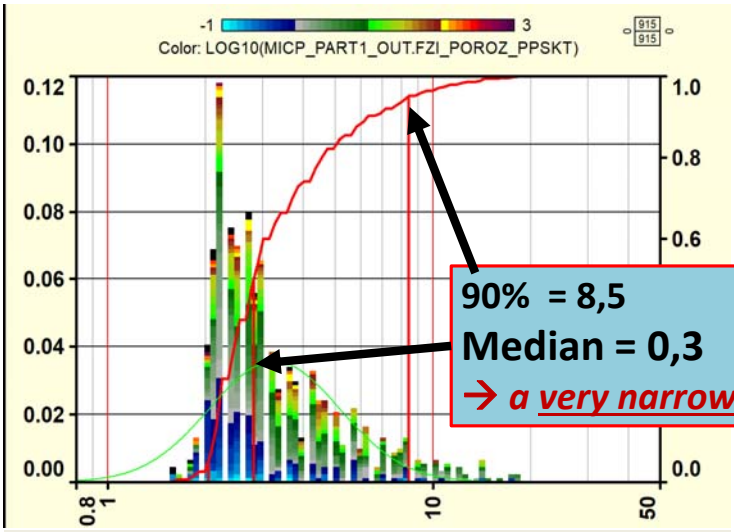
1. ***the validity of any "local" statistical relationship between PHIT (hence Saturation*) and Permeability is highly questionable in a depth interval where the ratio POROZ/PHIT varies significantly***.

2. ***for any Flow Zone Indicator, POROZ should be used instead of PHIT.***

<u>Let's examine Flow Zone Indicator with the Kozeny-Carman Equation</u>

***** It should be reminded, at all time, that a Hc column is primarily controlled by ENTRAPMENT & dysmigration, Pore Throat radius, not permeability, is secondary control.

Note how limited is the range of the Pore Throat contributing to Permeability



X Axis: (Entry Radius / Apex Radius)

- **Entry = largest radius**
- **Swanson Apex = smallest radius**

17

17 -- The histogram displays the ratio of the radiuses observed at "entry" and at the "Apex".

The Narrowness of the range of ratio **explains**

1. **The Carman restriction imposed to the Kozeny permeability model**
2. the success of the Swanson Permeability model (which is not so sensitive to errors in picking Entry/conformance).

The Kozeny equation links R_{mh} to the ratio Permeability/Porosity.
It is verified only if:

- **Porosity is effective in terms of permeability**
- **R_{mh} is computed over the part of PSD effective in terms of permeability.**

The Amaefule X-Plot exemplifies how well Kozeny equation is verified

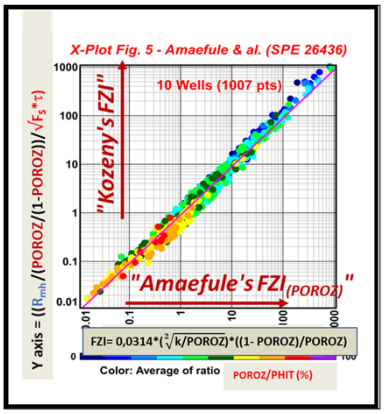
18

Reference

- **Permeability**
  1. **Measured ← RCA (Darcy)**
  2. **Modeled (*Purcell, Kozeny,…*) from PSD & Calibrated on RCA**

Parameters to test

- **Porosity**
  1. **total (PHI_T) ← RCA**
  2. **POROZ part of PSD ← SCAL (Swanson + Purcell + Kozeny)**
- **Mean Hydraulic Radius [R_{mh}] :**
  1. **PHI_T ← RCA (R_{mh} = 0,0314*SQRT(K_{RCA}/PHI_T))**
  2. **POROZ part of PSD ← SCAL (Purcell & Swanson & Kozeny)**



18 -- The Kozeny & the Purcell equations are both based on Darcy & Poiseuille laws Thus, they should produce the same permeability value if the correct parameters are used in each model.

Kozeny considers that the permeability is created by a group of similar parallel channels. Their volume is the Porosity and their "mean Average radius" is easy to compute using the permeability measurement, by Darcy law, or using the PSD from MICP.

CAVEAT: as specified by CARMAN, the Kozeny equation implies that POROSITY is "effective in terms of permeability" and for this conditions to be met "the Pores must be reasonably even in size".

As discussed above, the Purcell model shows that, if the PSDs exhibit complex shapes, then the Carman condition is not met by TOTAL POROSITY.

Thus, the next question is: does POROZ , and its corresponding R_{mh}, truly honors the Kozeny Equation ? This is likely because the range of radii in Poroz is limited.

Here, we used the X-Plotting technique designed by Amaefule to test the varied combination of Porosity, Permeability and R_{mh} values and answer this twofold

question :

- ***Which "porosity"***
- ***Which R_{mh}***

Are consistent with the permeability measured by application of the DARCY law (**<u>*which is used to calibrate the Purcell model*</u>*****) ?***

Amaefule has demonstrated that if a straight line appears on the X-Plot, then the test is positive, that is to say:

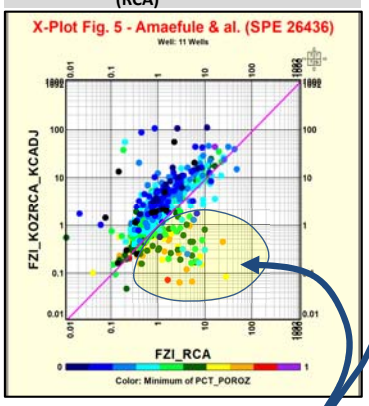
1. ***the Porosity is effective in terms of permeability and its R_{mh} is correct.***
2. ***the consistency between POISEUILLE, DARCY, KOZENY, PURCELL, SWANSON is obvious,***
3. ***The implementation of the models is correct.***
4. ***the FZI method is valid***
5. ***Finally, we must admit all the consequences about the use we make of TOTAL POROSITY .***

<u>The X-plot shows that POROZ pass the test.</u>

The Amaefule test illustrates the soundness of concept & Flowchart

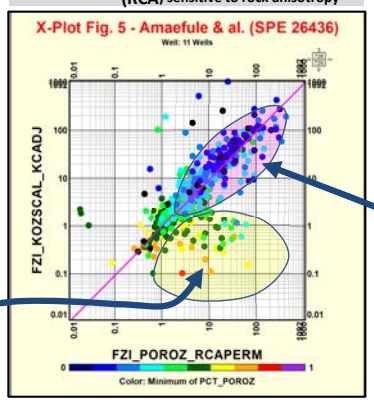
19

"$\emptyset_{test}$ = **PHI$_{T\ (RCA)}$**
k = Perm$_{(RCA)}$



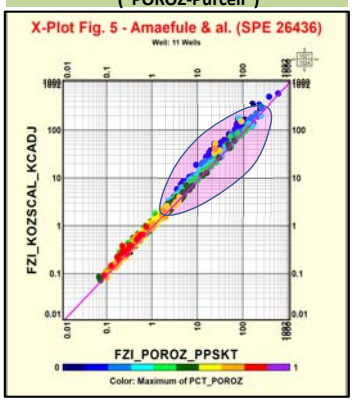
Scattering due to degraded accuracy of Permeameter in tighter rock

"$\emptyset_{test}$ = **POROZ**
k = Perm$_{(RCA)\ \text{sensitive to rock anisotropy}}$



Perm(RCA) is sensitive to anisotropy

"$\emptyset_{test}$ = **POROZ**
k = Perm$_{(\text{"POROZ-Purcell"})}$



Modeled Perm is insensitive to anisotropy

Greater scattering explained by anisotropy and lack of stress corrections

19 -- This slide shows the application of the ***Amaefule X-Plotting technique to***

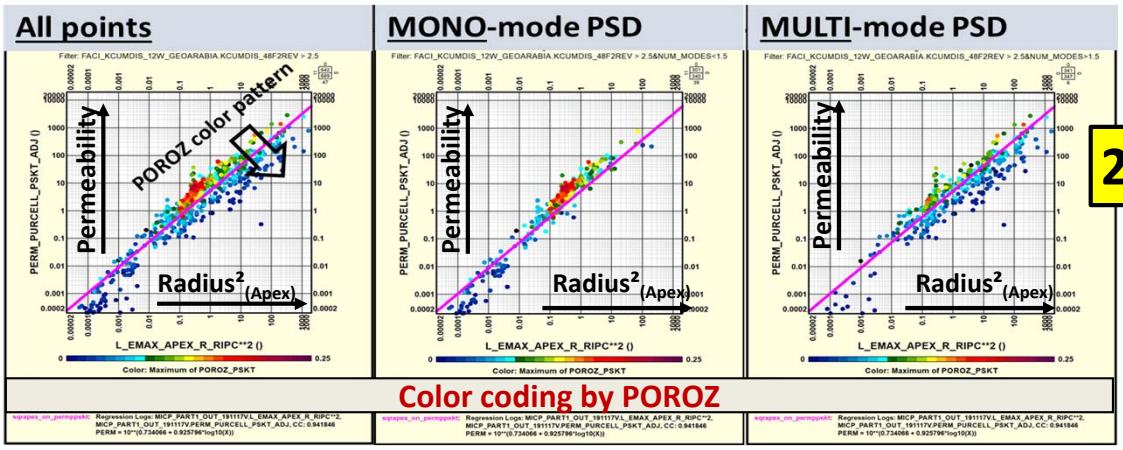
- RCA Porosity (PHI_T) and RCA Permeability **(left),**
- POROZ with RCA permeability **(Center)**
- POROZ and ***Purcell*** Permeability **(right).**

The Kozeny equation is honored only by POROZ and its corresponding R_{mh}.

Thus POROZ is consistently identify as the porosity efficient in terms of permeability by the Swanson, Katz and Thompson, Purcell and Kozeny models implemented here.

As Darcy and Poiseuille laws are honored, the soundness of the concepts and processes at the core of this flowchart is exemplified.

Key Result of MICP interpretation by Physical Permeability Models



20

Permeability :

1. **Increases with Radius at Hyperbola Apex (*insensitive to conformance artefact*)**
2. **Increases with POROZ**
3. **Decreases with increasing PSD shape complexity**

20 –- The 3 X-Plot show Perm (Y axis) versus (Apex Radius)^2

- **The Pore Throat Radius @ the Apex (**L_EMAX ***== Thomeer's == Swanson)*** is the primary control of permeability
- POROZ and PSD shape complexity are secondary controls : for the same value of **Radius @ the Apex** the permeability is greater in monomodal PSD

Apex radius appears to be a better control of permeability than Entry radius.

Key Result of MICP interpretation by Physical Permeability Models

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Because Permeability & Primary depletion are controlled by POROZ

- **PHI_T-K plots**
- **PHI_T-K functions**
- **PHI_T-K regressions** (*RMS, RMA, AI, ML, Deep Learning…you name it*)

Are misleading

POROZ must be substituted to PHI_T

➔ MICP are required or a way to measure POROZ must be designed

21 -- No need to comment any further !

New dedicated interpretation techniques

22

1. **Creation of continuous MICP profiles by k-NN method**

➔ **Alleviate scarcity of MICP**

2. **Pattern identification techniques : MRGC clustering + log-type applied on PSD** *(or any MICP data)*

   ➔ **open X-Plotting techniques to MICP** *(with log and core data)*

   ➔ **Log-type provide a synthetic view of a array data (e.g.: PSD) in an orderly way.**

3. **Static partitioning of Porosity**

   ➔ **link PSD with Core & Thin Section petrographic description**

4. **Dynamic partitioning of Porosity**

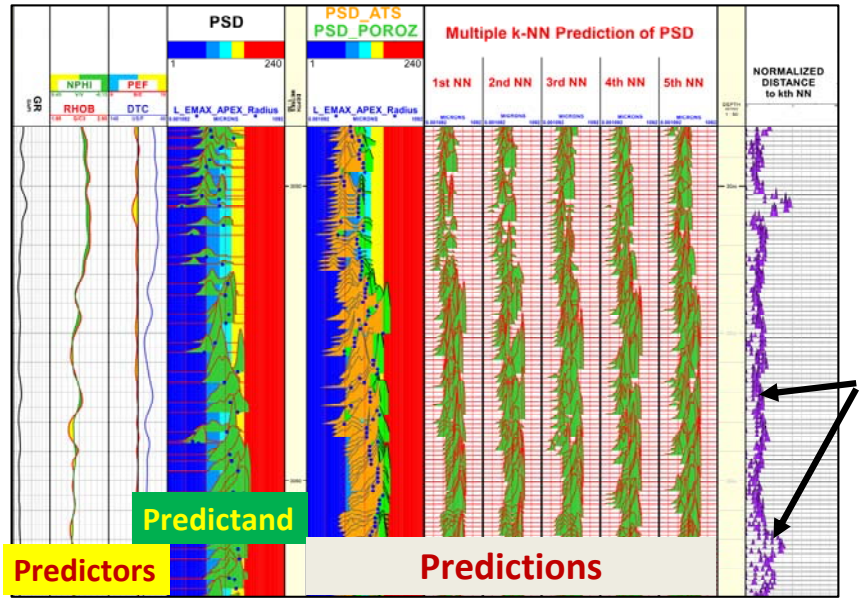
   ➔ **link porous network Facies with fluid entrapment and depletion**

22 -- The k-NN and MRGC-CFSOM techniques have been around for 2 decades and may be familiar to many of you.

Static and Dynamic partitioning of Porosity are new techniques intended to better visualize and quantify the porous network and its behavior.

1 - Continuous PSD profiles by k-NN prediction

23



Histogram-Upscaling of PSD by:

1. **Predict 1st, 2nd, ….kth NN**
2. **Optimize "k"**
3. **compute "Volume Weighted Average" of the *optimized* number of k Nearest Neighbors PSD (in log space)**
4. (+ smoothing by sliding depth window)

Normalized distance to kth NN

- **controls "k" for PSD Upscaling**
- **Signals Variability of prediction**
  - **limited representativity of Plugs**
  - **Potential Heterogeneity**
- **Quantifies quality of prediction**

23 ---- The first steps of the creation of a continuous profile of PSD are illustrated here.

Why create a continuous upscaled PSD profile ?
Because, to characterize reservoirs & define flow units, we need continuous profiles of up-scaled

- **Pc/Sat curve. (**Pc/sat curves are obtained by reversing the Purcell method by which PSD are created.)
- **POROZ**
- **Purcell or Swanson Perm**
- **True FZI.**

All this can be obtained from a continuous profile of PSD.

The k-NN method is mostly used in its k-Means form, here we use the "true" k-NN method : the "k" Nearest neighbors are retrieved individually.
Further, our implementation optimizes the value of k for each depth increment by means of conditions set on the values of the predictors.

The rightmost array track displays the distance in the "data space" between the k predicted values.
Distance is a QC index.

- ***Here the conventional logs (GR, NPHI RHOB, Dt, Pef displayed on 2nd & 3rd tracks) are used as predictors, for sake of simplicity. However it is a better practice to predict and upscale RCA Porosity, Permeability and Grain Density, aka "PKG", and use them as predictors. This method offers offer the invaluable advantage of solving log normalization issues, or more exactly their QC. It also offers the invaluable advantage to retrieve PSD from a PSD-PKG data base by searching it with the available RCA "PKG".***

- ***The predictand : MICP plug measurements are on the leftmost array track.***

- *The "1st NN" prediction of PSD is shown on the 2nd Array track. It is split into its components POROZ (green) and PORO_ATS (orange).*
  The color background (from dark blue to red) of those tracks is coding for Nano, Micro, Meso, Macro and Mega porosity.

- *The next 5 array tracks shows the prediction for k= 1 to k = 5 respectively.*
  They can be averaged.
  Most importantly ***it is possible to algorithmically select the value of k so that the averaged prediction is based only on similar values of all predictors.***

New dedicated interpretation techniques

24

- Creation of continuous MICP profiles by k-NN method
  - ➔ Alleviate scarcity of MICP

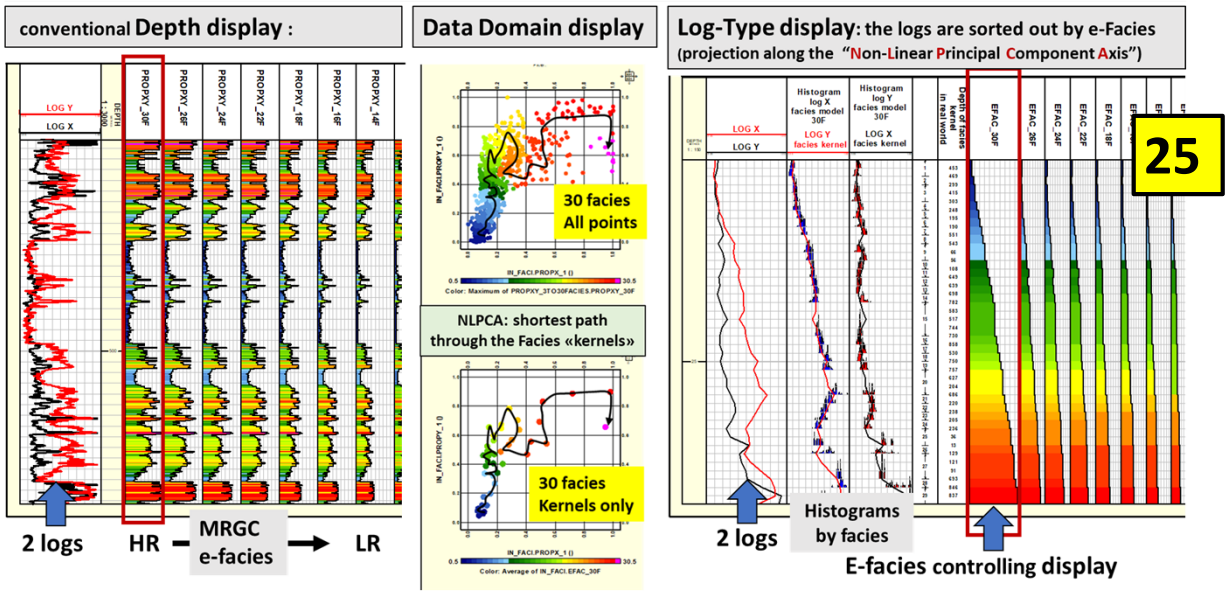
- **Pattern identification techniques:**
  use MRGC-CFSOM clustering + log-type techniques to interpret
  - ***MICP in the light of any other log or core data***
  - ***any other log or core data in the light of MICP***

- Static partitioning of Porosity
  - ➔ link PSD with Core & Thin Section petrographic description

- Dynamic partitioning of Porosity
  - ➔ link porous network Facies with fluid entrapment and depletion

24 – Let's discuss Clustering and logtyping. Logtype is a substitute to X-plot which are not appropriate for Array data.

2 – MRGC-CFSOM Clustering and the principle of the logtype techniques



25 ---- The principle of the logtype technique is best explained with 2 logs only (**left part slide**) so that its links with X-Plot can be visualized.

The Logtype technique relies on the <u>purely data-driven MRGC-CFSOM clustering</u>,
<u>available in Geolog/Facimage ™.</u>

The data points are optimally clustered by MRGC-CFSOM and the kernels of the clusters are optimally ordered, along the minimal path going trough them in the N-Dimensional data space.
Here, the clusters and their ordering are visualized by the colors on the X-Plot of **central part of slide**.

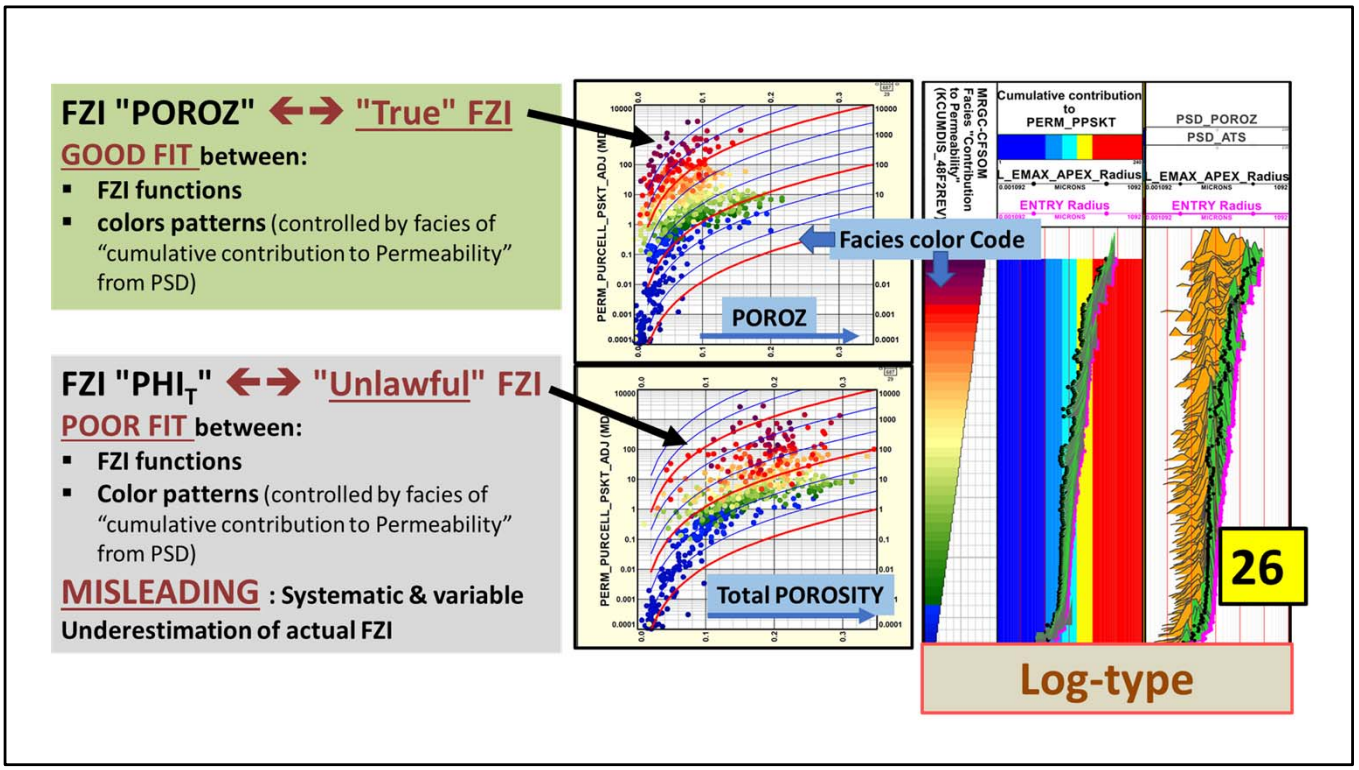
The path through the kernels is the Non-Linear Principal Axis of the data set. **The NLPCA**. All the data points can be projected on the NLPCA.

The NLPCA can be stretched on a straight line which can be used as

1. **the Z Axis of a "*depth*" display ➔ the Logtype (right part of the slide)**
2. **The X or Y axis of any X-Plot such as RHOB or GR …etc → Integration**

All the log values characteristics of the projection of each points on the NLPCA, including their real depth and well name, can be plotted in separate tracks of the Logtype.

As exemplified here It is also possible to project only the kernels with the distribution of all the points belonging to the same cluster.



26 --- Let's apply the technique to the MICP array log : 240 bins (logs) ←→ 240 dimensions.
It is a multi-well data set of about 1000 samples, but for the sake of clarity only 15% of data are displayed on the logtype.

The MRGC-CFSOM algorithm is applied to the array log "**cumulated contribution of PSD bins to Permeability**" (shown in the leftmost array track), ***thus the clusters are sensitive to those Pore Throats which contribute to POROZ & Permeability (→ FLOW).***

The cluster model selected for the logtype, comprises 48 facies, to show enough details.

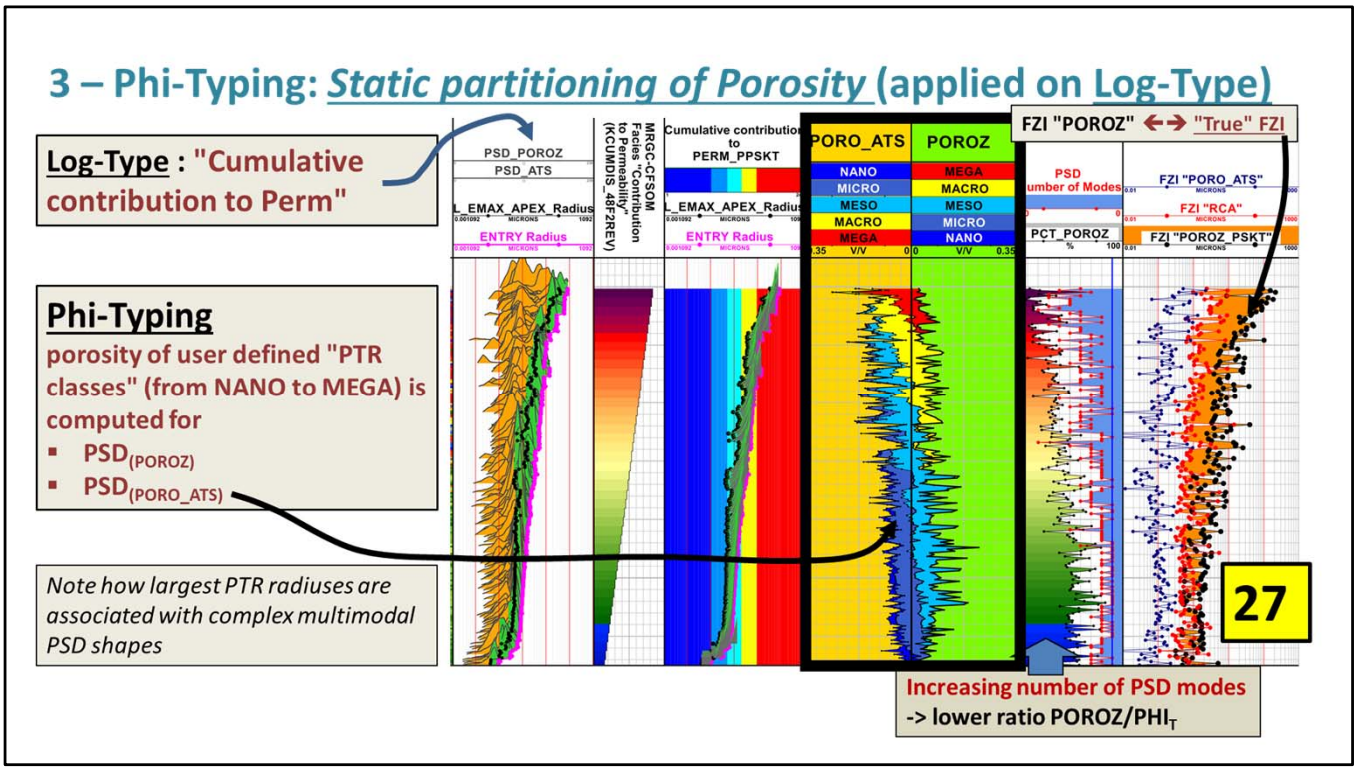
The rightmost track of the logtype displays the PSD, split into its 2 components "QUIET POROSITY" (orange) and "POROZ" (green) with the Apex position superimposed (black dots). (the "not so smooth" style of the curve is partly due to under-sampling).

Look at the color patterns on the 2 FZI Plots:
- **upper plot with POROZ**
- **lower plot with PHIT**

In the upper FZI plot, (POROZ is X axis / Purcell Permeability is Y axis) the colors fit the FZI functions and create a pattern much sharper than that of the lower plot.

Thus the fact that the "Facies" of the *"cumulated contribution of PSD bins to Permeability"* honor the physical models prove the efficiency and usefulness of MRGC-CFSOM to sort the MICP data (240 Dimensions/logs) in a naturally organized (sequence stratigraphy) and physically meaningful way. Indeed, in the data domain of the parameter honoring Darcy and Kozeny equation, the data points, form a natural data structure and it is here clearly evidenced by MRGC-CFSOM.

The color code can be used for any X-plot as a 3rd dimension -→ Integration.



27 ---- Phi-Typing or Static partitioning of Porosity is meant to help the comparison between PSD and the descriptions of thin sections in terms of types of porosity.

Here Phi-Typing is performed on the PSD of the log-type and displayed in the 2 central framed tracks Porosity (scale 0 to .35; cumulative curves) .
It quantifies, the porosity of each class of pore throat size (from Nano to Mega), for

- POROZ (green background)
- QUIET POROSITY (orange background),

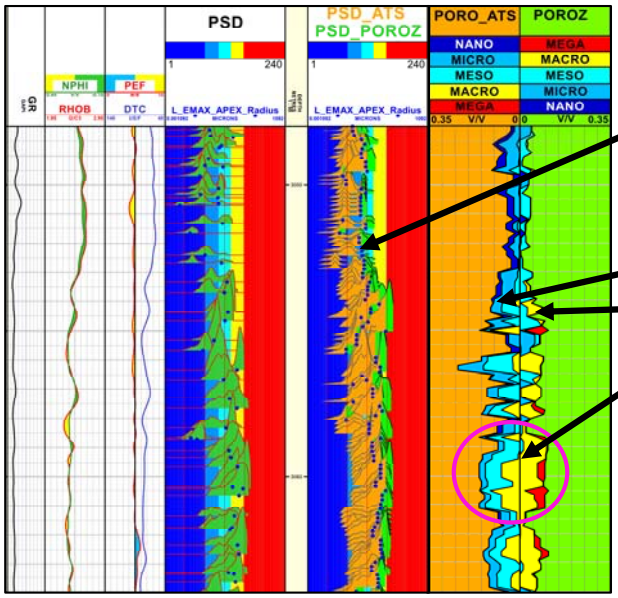
It is a common practice to value the facies with largest pore throat.

Here the Phi-Typing illustrates the counterintuitive fact that the highest values of POROZ, are found in facies whose largest pore throat belongs to the Meso class and which are also monomodal.

The values of the true FZI are shown on the rightmost track. *(the spiky style of the curve is partly due to under-sampling of the logtype).*

Static Porosity Partitioning of *real well Continuous PSD profile*

28



- **Picking of Hyperbola Apex**
- **Static partitioning of :**
  - **$PSD_{(PORO\_ATS)}$ track w orange background**
  - **$PSD_{(POROZ)}$ track w green background**

Here, Macro and Mega pore size are associated to rather narrow monomodal PSD shape, which explain highest POROZ values

28 --- Phi-Typing performed on a real well.

it is interesting to note that, Macro porosity is dominant in the interval (circled) showing the largest POROZ value.

However it must be noted that, **in this interval the *PSD exhibit a rather narrow monomodal shape***.

Thus, this observation does not contradict the conclusion drawn from the Phi-Typing of the logtype.

4 - "Dynamic Partitioning of Porosity" : the conversion Radius ⇔ Pc

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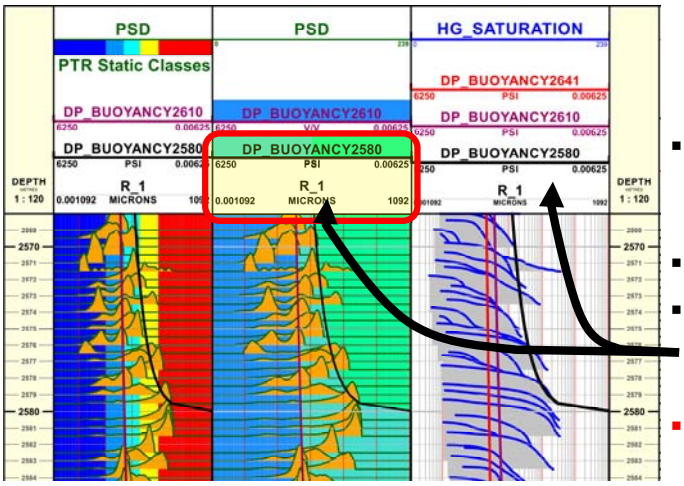
- *Radius = $(1/Pc_{(lab)})*(2*0,147*(\sigma_{(air\_Hg)}*\cos\Theta_{(air\_Hg)}))$*
- *Lab/Field conversion : $Pc_{(field)} = Pc_{(lab)} * ((\sigma_{(Hc\text{-}Brine)}*\cos\Theta_{(Hc\text{-}Brine)})/(\sigma_{(air\_Hg)}*\cos\Theta_{(air\_Hg)}))$*



- *for each depth increment above a given FWL, the value of Buoyancy ΔPc, is computed using $\rho_{(Hc\text{ - field conditions})}$*
- *$\sigma_{(Hc\text{-}Brine)}$ is computed for each depth increment*
- *Lab/Field conversion is applied to the <u>various simulations</u> of FWL to obtain ΔPc and corresponding Radius*
- *Radius corresponding to ΔPc is used to partition PSD and retrieve SATURATION*

29 ---- The application of the Lab/Field conversion allows to rescale the PSD as a function of the Delta Pc for any FWL and fluid.

Thus the Pore Throat Radius corresponding to a given Delta Pc (and FWL position) can be used to partition the PSD and derive Hc ***<u>Saturation.</u>***

However we know that the Porosity elements contribute to flow as a function of their radius.

Thus, in addition to Saturation, by using the Purcell equation, we can easily quantify the contribution to flow of each porosity element ***of a PSD for varied FWL hypothesis.***

4 -"Dynamic Partitioning of Porosity"

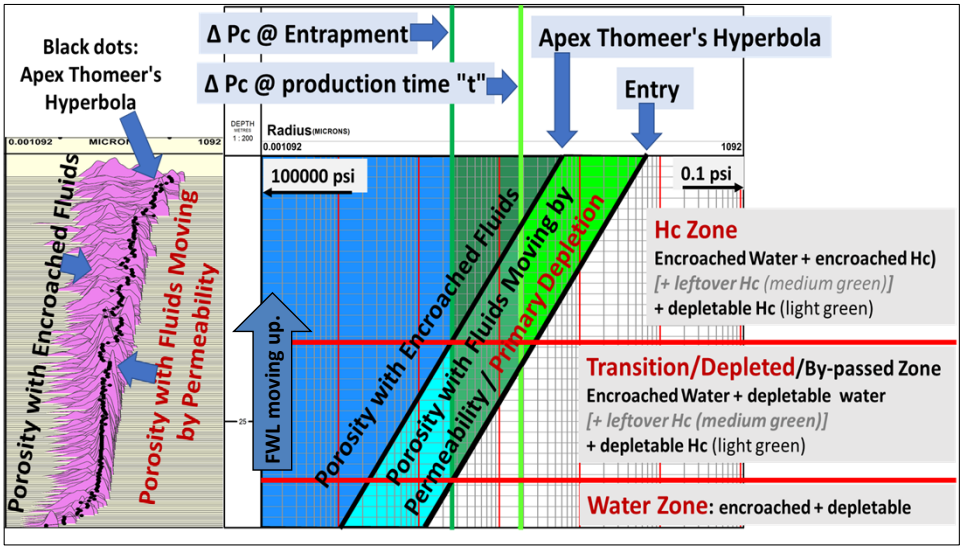
30

Log-type & *constant ΔP_c* are used to isolate the effect of type of Porous Network

Fluid displacements are controlled by :
- **Δρgh, cos Θ & IFT**
- **Pore Throat Radius at the Apex.**

« Depletable » + « depleted » porosity are upper limit of volume productible by depletion.

"DS" Water compare with "encroached" + "depletable" Water



30 ---- *Let's consider drainage conditions*

1. **Delta Pc is controlled by Hydrocarbon buoyancy at the time of entrapment (**or at any stage of primary depletion natural or provoked).

2. **Saturation is controlled by the combined (entrapment & current Delta Pc) & the shape of PSD, thus *saturation can be loosely related to permeability***

3. **The flow by primary depletion is controlled by permeability** which in turn is controlled by **$R_{(Apex)}$ (and the shape of PSD)**
   - ***a) QUIET POROSITY is* the volume of encroached fluids.**
   - ***b) POROZ* is the Maximum volume which can be transferred by Primary Depletion.**
     (*visualized by the diagonal band limited by $R_{(Apex)}$ and $R_{(Entry)}$*

Here, to illustrate the principle of the dynamic partitioning of the Porosity by conditions set on Delta Pc & $R_{(Apex)}$, we impose a constant Delta Pc @ Entrapment, and a constant arbitrary Delta Pc at depletion (arbitrary stage of primary depletion, natural or provoked) **to the PSD ordered in the logtype.**

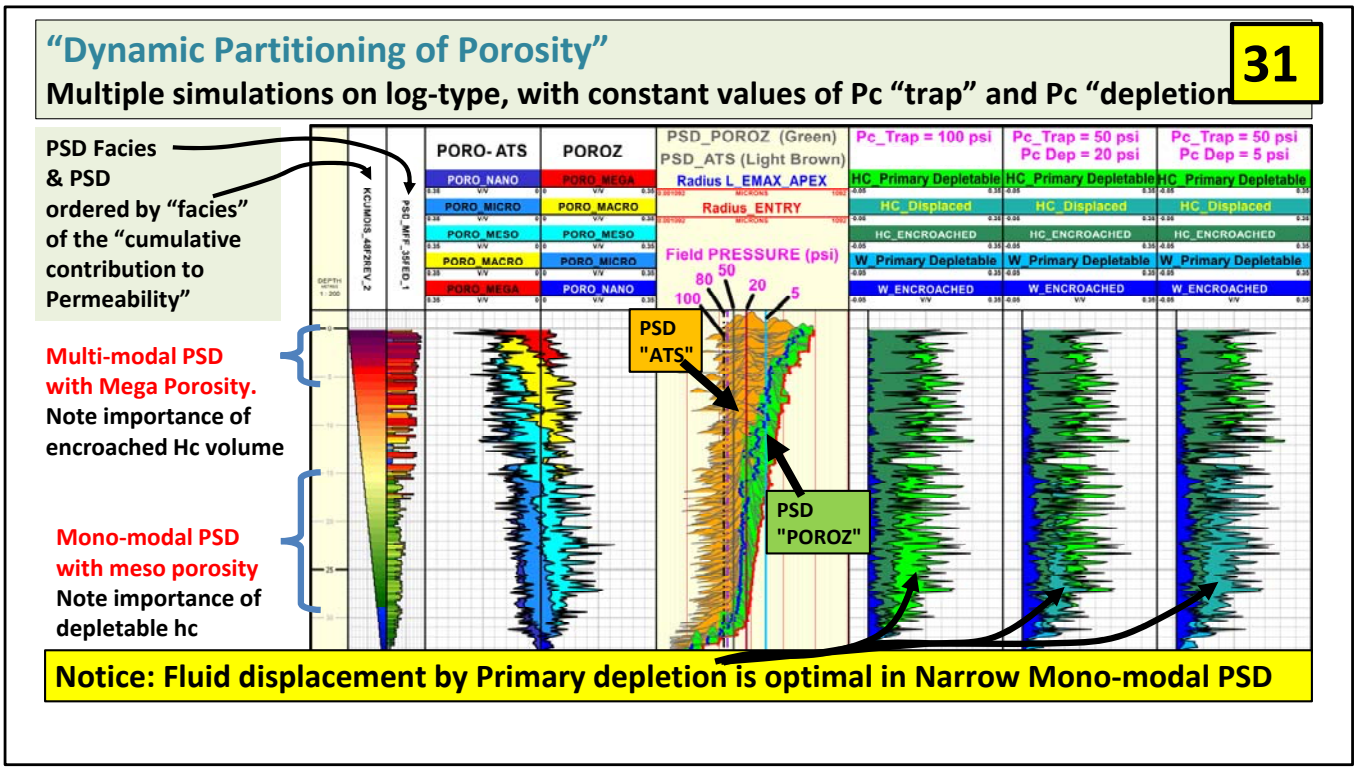
As a result: **5 partitions are defined and visualized in the complex data domain PSD vs**

Delta Pc. (each one is characterized by its volume and perm) .
*The quantification of their volume is shown in next slide***.**

1. **Encroached Water** (deep blue) in **PORO_ATS**
2. **Encroached Hc** (deep greep) in **PORO_ATS**

3. **Water movable by depletion** (light blue) in **POROZ**
4. **Initial volume of Hc in "primary depleted zone"** (medium green) in **POROZ**
5. **Hc available for depletion** (bright green) in **POROZ**

Encroached + depletable Water can be measured by DS.



31 --- Let's run Dynamic partitioning simulations on the logtype with multiple hypothesis on FWL, to illustrate how PSD shape impacts the fluid flow.
The scale for the 3 rightmost tracks is V/V from -0,05 to 0,35 and the curves are cumulated.

The 3 simulations displayed here (rightmost tracks) illustrate the not so intuitive fact that ***the volume which can be moved by Primary depletion (bright green color) is greater in monomodal PSD than in complex multimodal PSD exhibiting greater permeability values.***

Further it is likely that, due to hysteresis, the efficiency of primary depletion is smaller in complex multimodal PSD than in monomodal PSD.

To summarize

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1. **Tabulation is a sound method for Integration & valuation of the MICP heritage**
2. **The soundness of the processes embedded in the flowchart is proven by the Unified permeability models: Swanson, Purcell, Kozeny-Carman [Darcy, Poiseuille]**
3. **PHI_T/K regressions & plots are invalid, "POROZ" (defined from MICP) must be used**
4. **MICP valuation is simplified by pattern identification techniques :**
   - **Continuous profiles of PSD curves by Data Driven techniques (k-NN & MRGC-CFSOM)**
     - **PSD & POROZ can be substituted to PHI_T**
     - **sequence analysis is applicable to PSD profiles**
   - **New dedicated techniques**
     - **Static Phi-Typing ←→ link to classic petrographic analysis**
     - **Dynamic partitioning of Porosity ← → substitute of Saturation modeling + integration of DS measurements**

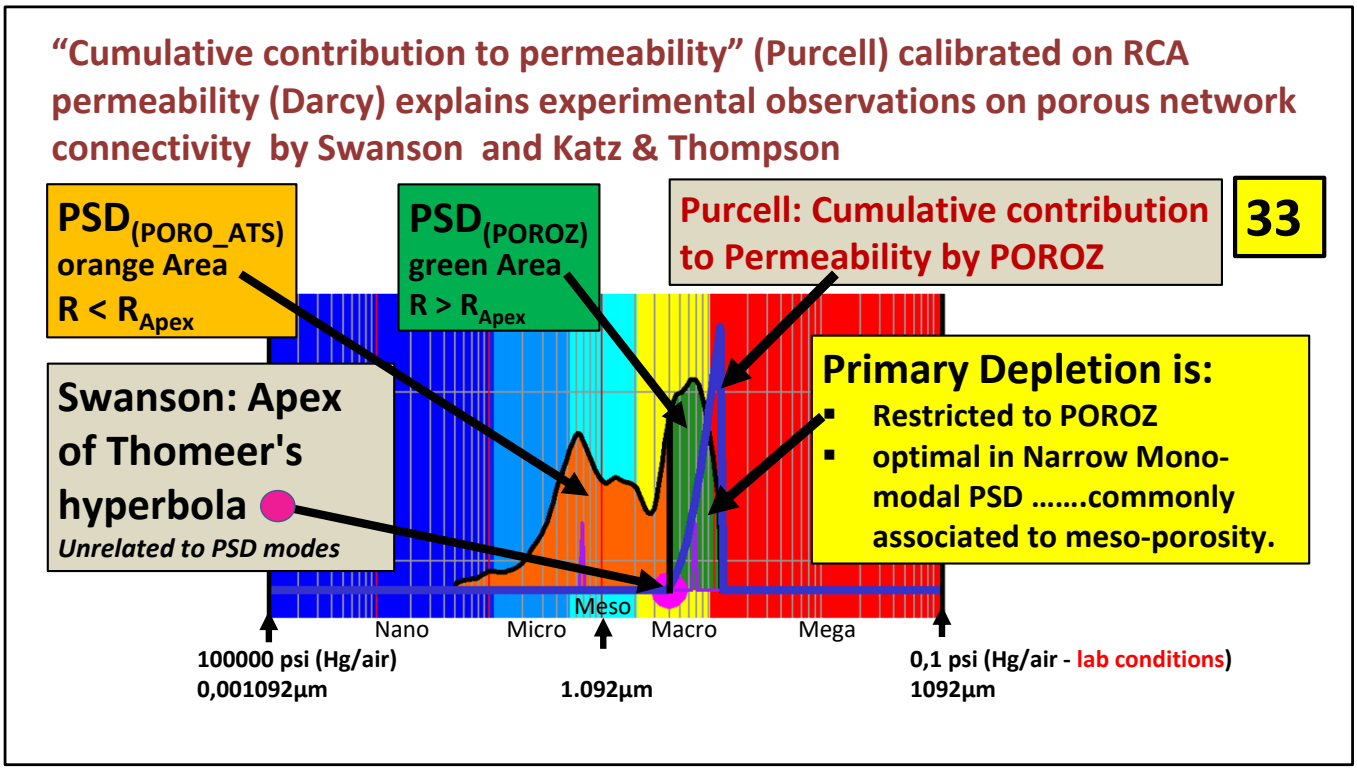
32 – Now, let's have a dream : **imagine what could be achieved by means of a "Worldwide" MICP data base also comprised of "PKG" RCA measurements.**

Searching this WW Data Base by k-NN method and using the RCA data just collected in any well not part of the WW Data Base, you would get the best possible estimation of its PSD and Pc/Sat curves …..it is that simple !

PERSPECTIVE & FUTURE WORK !

What could be visualized & UNDERSTOOD by the integration of Extrusion curves ? Of course It is also possible to manage simultaneously Intrusion & Extrusion , just use Clustering and Logtype technique !

PSD shape impact Permeability, thus very likely it also impacts Rel Perm: why not have a look at Rel Perm?



33 --- an image is worth 1000 words, I hope you find this one easy to remember.

Aberdeen Formation
Evaluation Society

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AFES Online Day Seminar 2nd and 9th September

Thank you AFES for your invitation to present !
Thank you all for your attention !