Combining porosimetry and Purcell permeability modeling to calibrate FZI and define a dynamic permeability cut off.

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This paper was prepared for a presentation at the International Symposium of the Society of Core Analysts held in Vienna, Austria, 27 August – 1 September 2017.

ABSTRACT

An integrated algorithmic workflow is proposed for the interpretation of MICP experiments. By combining, among other features, the detection of local minima, maxima and inflexion points of the distribution of Pore Throat Size (PSD) and the permeability modeling of the latter by Purcell method, it introduces new possibilities to calibrate RCA poro-perm on MICP and thus to improve the reliability of the FZI method and the definition of a dynamic permeability cut off. Saturation/height modeling is also part of this workflow which, to date, has been used over 4000 MICP measurements in complex carbonates of varied geological settings.

Because the Purcell's method for permeability modeling quantifies the contribution of each class of pore throat size to the permeability, the set of those classes which actually controls the fluid flow can be accurately delineated, even if the PSD does not exhibit clearly individuated subsets, and characterized by its lower and upper (entry pressure) limits, its equivalent pore throat radius, the radius of the pore throat class contributing most to permeability and the fraction (PHI_Z) of the effective porosity involved. The entry pressure is defined according to the experimental results of Katz and Thompson (1987) and, so far, the observations support the idea that a good approximation of the lower limit of this subset is the Mean Hydraulic Radius (MHR) which roughly corresponds to the apex of the trial solutions proposed by Pittman or Walls and Amaefule. We show that, in formation exhibiting complex porous network, PHI_Z should be used for the computation of "true" RQI and FZI, instead of the effective porosity which inevitably results in degrading FZI. The impact of the change of porosity values is illustrated and its relationship with the complexity of PSD curve shape is examined in terms of texture. We expose how the calibration of RCA poro-perm on SCAL porosimetry allows retrieving the true RQI from RCA poro-perm and its associated PHI_Z value and how a dynamic permeability cut off can be defined.

INTRODUCTION

The FZI method, first introduced by J. Amaefule [1] is a familiar way to use RCA Poro-Perm measurements for reservoir characterization and for computing Sw. Reservoir Rock Type (RRT) can be defined on the basis of the position of their points, on X-Plots view, along the FZI function. However, the use of MICP data reveals pitfalls which can be encountered in the application of FZI method; it also explains their origin and offer the possibility to avoid them, in which case the use of FZI method could be further extended by computing the FZI from continuous profiles of porosity and permeability.

The permeability is driven by the subset of pore throats exhibiting the largest radiuses and Purcell permeability modeling clearly shows that this subset of largest pore throat is not necessarily giving access to the whole pore volume (PHI_T) but rather only to a variable fraction of it. Subsequently, the FZI method reliably describes the relationship between porosity and permeability only in formations where this subset of largest pore throat gives access to about the same fraction of PHI_T while it fails to do so in formations for which only a fraction, variable from sample to sample, of PHI_T contributes to the permeability. The failure is due to the fact that, in the second case, the FZI computation is performed by means of parameters which do not pertain to the same volume of the porous network of the plug. Thus, to ensure a reliable application of the FZI method, it is critical to insert a calibration step, based on reference MICP, meant at estimating the fraction of the porosity which is accessed through the subset of those pore throats contributing to the permeability. The acronym "PHI_Z" is used here to refer to this fraction of the pore volume. We describe ways to

- accurately computes PHI_Z, from SCAL data, by combining porosimetry and a specific implementation of the Purcell permeability model,
- derive PHI_Z and the true RQI and FZI from "RCA" measurements,
- predict the calibrated RQI and permeability in heterogeneous facies,
- derive a dynamic permeability cut off.

WORKFLOW AND FUNDAMENTALS OF THE METHOD.

As stated by Amaefule [1] and his co-workers, the FZI method implies that the porosity is effective in terms of permeability, i.e.: instead of PHI_T, "PHI_Z" must be used. PHI_Z is not measured in the lab, and less so by RCA, yet both the application of the Purcell model and the observations carried by several researchers [2-4], to cite only a few of those who published recently, indicate that in complex porous network, PHI_Z may significantly differ from PHI_T. It is shown here, that PHI_Z is derivable from MICP, which allows the calibration of PHI_Z from RCA porosity, and that, a good relationship is found between the "true" RQI and MHR (Mean Hydraulic Radius), as explained in the FZI theory, and the Entry Pressure. In this project, the computation of PHI_Z, is but a part of a larger workflow [5] dedicated to the MICP interpretation and the Saturation Height modeling.

In a first stage the "true" PHI_Z, RQI and FZI are computed, which imposes:

- the computation of the PSD (Pore Throat Size Distribution) from the Saturation and Pressure curves, the application of the necessary conformance correction and the determination of the entry pressure.
- The delimitation of the lower limit of the subset of those largest pore throats contributing to the permeability.
- The derivation of Permeability and PHI_Z by means of a specific implementation of the Purcell model, called "Purcell-PSKT" model. RQI_{true} and FZI_{true} are then computed using Permeability and PHI_Z.

In a second stage, a method is proposed to derive PHI_Z from RCA;

In a third stage a method is exposed to create a dynamic permeability cut-off by predicting MHR, derived from RQI, over un-cored intervals.

DERIVING PHIZ AND FZI FROM MICP

Picking the Minimum Pore Throat Radius of PHI_Z.

The minimum Pore Throat Radius of the PTR classes comprising PHI_Z is algorithmically picked by means of the trial solutions, illustrated in figure 1, proposed by: Katz & Thompson [6], Pittmann [7], Walls & Amaefule [11]. It is worth noting that, the trial solution proposed by Walls & Amaefule [11], is intended for low permeability rocks.

Pittman [7] summarizes how the minimum Pore Throat Radius is defined by Swanson [8] who "*established the position on the mercury injection curve that represents a continuous, well-interconnected pore system through the rock"*, noted that at this point, *"the mercury saturation expressed as percent of bulk volume is indicative of that portion of the space effectively contributing to fluid flow"* and *"determined that on a mercury injection curve, this point corresponded to the apex of the hyperbola of a log-log plot"*. Acknowledging that "*for some samples, the inflection point was vague and difficult to determine*", Pittman proposed "*A plot of Hg saturation/capillary pressure versus Hg saturation, as a means of determining the apex of Thomeer's hyperbola*". All those authors have discussed the physical meaning of their methods in the light of a well-established theoretical background. Comisky & al. [9] provide with a most interesting review of those methods and expose that the Purcell model provides the best estimate of permeability. D. S. Schechter [10] proves the validity of the Walls & Amaefule method to determine the Swanson's parameter. It is striking that the picking of the Katz & Thompson trial solution for "maximal electrical conductance" provides exactly the same results than the picking of the Pittman or Walls & Amaefule trial solutions, these are illustrated by figures 2a & 2b. Thus, because of the convergence of the results and because it shares the same scale than the PSD, the Katz & Thompson trial solution can be used to confidently pick the PSD curves, particularly after their upscaling.

The Purcell-PSKT Model.

The computation of PHI_Z, "*the fractional pore volume connected to the largest pore throat system which actually controls the fluid transport*", relies on a new implementation of the Purcell model: the Purcell-PSKT model, specifically designed to integrate the findings of Pittmann, Swanson, Katz & Thompson, Walls & Amaefule. In this implementation, the Purcell equation is applied to each term of the suite of the PTR subsets formed by incrementing the first subset of this suite by 1 element of the PSD array log: $PTR_{[a]}$, $PTR_{[a \rightarrow (a+1)]}$, $PTR_{[a \rightarrow (a+2)]}$, $PTR_{[a \rightarrow (a+3)]}$, …, $PTR_{[a \rightarrow (n)]}$, where

- "n" is the element of the PSD array log which corresponds to "entry pressure"
- "a", which is defined in the previous step, is the PSD element corresponding to the point at which *"the mercury saturation expressed as percent of bulk volume is indicative of that portion of the space effectively contributing to fluid flow"*.

The permeability at each increment is computed using the porosity of the specific subset of pore throat of this increment without any adjustment of the lithological factor. Thus, only the PTR subset actually contributing to the permeability is characterized both in terms of Permeability and in terms of porosity (PHI_Z), by the Purcell-PSKT model. RQI_{true} and FZI_{true} are then derived. The figures 3 exemplify that the Purcell PSKT model achieves a better prediction of the permeability than does the classic Purcell model.

Validation of the "True" FZI, RQI and PHI_Z.

Amaefule & al. [1] propose a graphic method to test the FZI method: they show that, on the plot of the ratio (MHR/PHI) versus FZI, a straight line whose slope is the Kozeny constant (Kc) is formed by the data points and "*provides corroborative evidence of the soundness of the theory*", because such result complies with Poiseuille and Darcy laws. In this project, the same test is proposed to check the validity and the accuracy of RQI_{true} and FZI_{true} provided by the Purcell-PSKT model: on Figure 4a, the ratio (MHR_{true}/PHI_Z) is plotted versus FZI_{true} and for ease of comparison, it is divided by the value proposed by Amaefule & al. for Kc; because all the data points are aligned along the first diagonal, it can be concluded that PHI_Z, as derived by the Purcell-PSKT model, honors the fundamentals of the FZI theory. This is not the case in Figure 4b, where PHI_T is used instead of PHI_Z and FZI_{RCA} instead of FZI_{true}: a "cloud" appears instead of a straight line.

The X-plot proposed by Amaefule & al. can be rearranged so that PHI_Z is on the Y axis and the product (FZI_{PHI_Z} * Kc) is plotted on the X axis (Figure 4c). Because a good relationship between MHR and RQI is postulated by the FZI theory and is revealed by the SCAL measurements, then this plot provides a simple means to visualize if a set of RCA measurements honors the FZI theory, in which case, the data points fall on a line. Should a cloud be observed, then the RCA samples do not honor the FZI theory and the scatter of the cloud visualizes (and ranks) the variability of the ratio PHI_Z/PHI_T. An additional benefit of the derivation of $RQI_{true\text{-}RCA}$ and $FZI_{true\text{-}RCA}$ is that the Entry Radius can be estimated from the RCA by means of the good relationship observed between RQI_{true} and Entry Radius measured on SCAL data.

ESTIMATION OF PHI_Z, RQI_{TRUE} AND FZI_{TRUE} FROM "RCA".

The principle of an algorithmic procedure used for estimating PHI_Z from RCA measurements is illustrated Figures 5a & 5b, using 7 wells and 481 points. It relies on the calibration of the RQI_{RCA} computed from RCA porosity and permeability against the RQI_{PHI_Z} computed from PHI_Z and permeability obtained by means of the Purcell-PSKT.

- In a first step the trend RQI_{PHI_Z} vs. permeability (ordinate) is manually picked; it is desirable to pick an upper and a lower trend so as to account for the natural variability of the samples.
- In a second step the trend is "transferred" on a X-plot displaying the RQI_{rca} vs. permeability (ordinate). For a given permeability, the calibrated RQI is the ordinate of the corresponding point of the trend RQI_{PHI_Z} vs. permeability. If a lower and a upper trends are defined then the lower and upper boundaries of RQI_{RCA} are defined.

Once the calibrated RQI is obtained the PHI_Z is defined. Further, as it was shown previously, the correlation between RQI_{PHI-Z} , MHR and Entry radius can be used to estimate those parameters from RCA. The capability of this algorithmic procedure to retain the natural variability observed in samples is somehow hampered by the very process of defining a trend on which it is based. For a greater accuracy and efficiency, the author prefers to apply k-NN data prediction techniques to PHI_Z and the other parameters describing the set of pore throat truly contributing to permeability.

DERIVING A DYNAMIC PERMEABILITY CUT-OFF

MHR is the Pore Throat Radius below which the contribution to permeability of any PTR subset is negligible. MHR can be retrieved from RQI_{RCA}, or predicted directly from RQI_{true} by means of k-NN modeling (in very much the same way as porosity and permeability are predicted) and used to define a dynamic cut-off of the permeability in field conditions. To that purpose, MHR is displayed on a track honoring the convention used for PSD, (i.e.: $\log_{10}$ scale of radius (µm)) and by superimposing, with a scale compatible for the radius (using the field/lab conversion) the value of P_c field conditions, computed for the any given HAFWL, the facies which may contribute to production by permeability mechanism, and those which may not, are identified. The principle of the algorithmic procedure, which consists in converting Pc into PTR radius, is illustrated by Figure 6. If the multiple k-NN predictions method is used to predict MHR, then those multiple predictions can be displayed as an array binned with the conventions defined above for PSD; thus the range of variation of MHR at each depth increment is visualized, and the most probable value together with the extrema and percentiles of interest are easily picked algorithmically, in very much the same way as it was shown for PSD.

CONCLUSIONS.

The Purcell-PSKT model, developed in this project, integrates the results of Katz & Thompson[6], Pittman [7], Walls & Amaefule [11] within the Purcell model [12]. It provides a better prediction of permeability than the Purcell model.

By providing a measure of PHI_Z, "*the fraction of porosity that effectively contributes to the permeability*", the Purcell-PSKT model allows generalizing to any complex porous network, the use of the FZI method, which in turn is used to prove the validity of the derivation of PHI_Z by the Purcell-PSKT model.

An algorithmic method, graphically illustrated, is proposed to

- derive RQI and FZI from RCA data. Based on the FZI theory, this method relies on the calibration on the RQI_{true} and FZI_{true} computed from SCAL data.
- Derive MHR and Entry pressure from RCA data
- Create a dynamic permeability cut-off allowing, for any HAFWL, to flag only those facies which may contribute to production by permeability mechanism.

By deriving PHIZ from RCA it is anticipated that the applicability of the FZI and the Leverett methods to compute S_w will be not restricted to the sole facies sampled for SCAL and their application will provide more accurate and reliable results.

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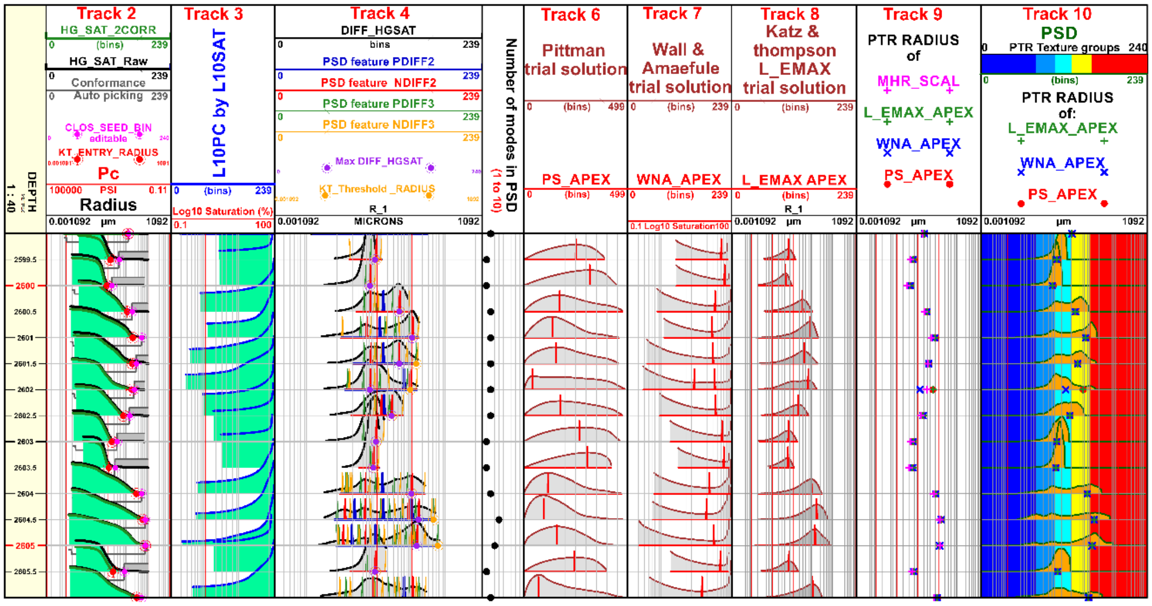
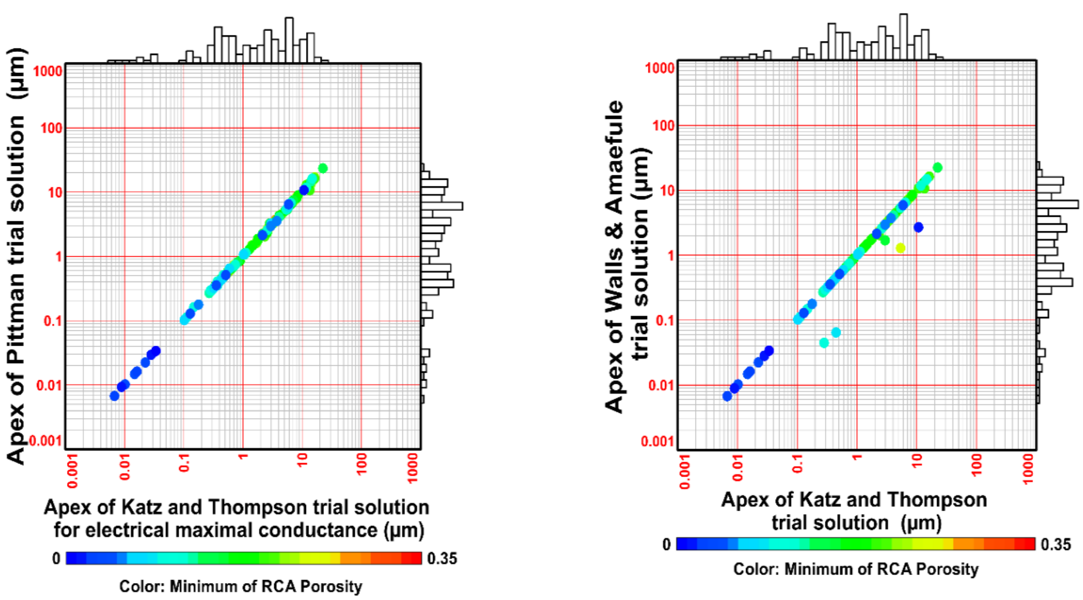
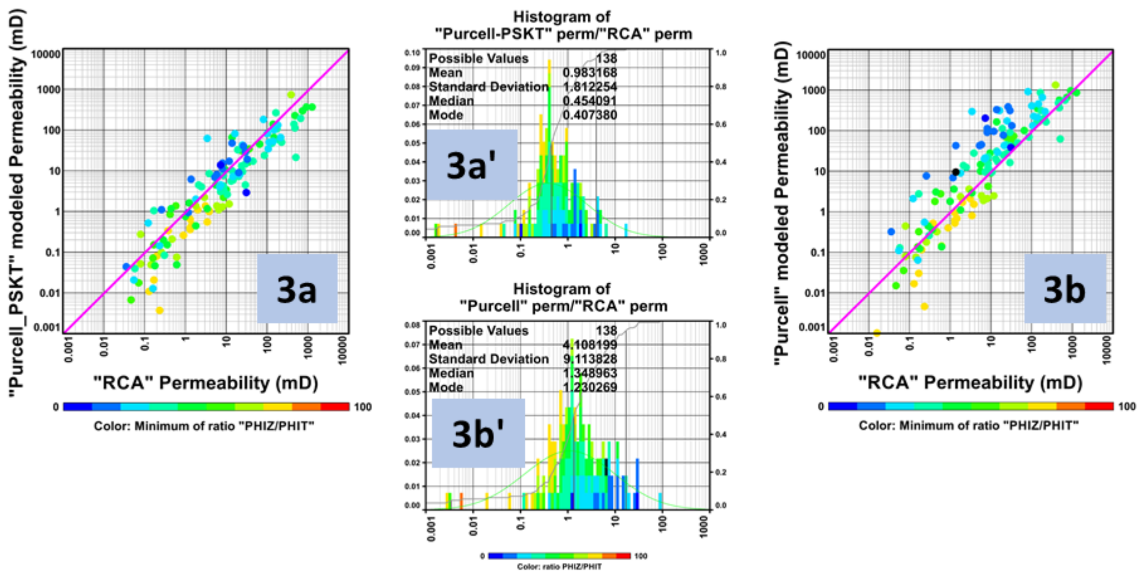


Figure1: The minimum Pore Throat radius of the PTR classes forming PHI_Z is algorithmically picked by means of the trial solutions proposed by: Katz & Thompson [1987], Pittmann [1992], Walls & Amaefule [1985]. The fourth track illustrates the picking of the varied "features" of the PSD curves. Note, on track 9, the strong correlation between MHR and the apex of the varied trial solutions.



Figures 2a & 2b: The trial solutions proposed by Pittman [1992], Walls & Amaefule [1985], and Katz & Thompson [1987] ("maximal electrical conductance") provides exactly the same results and thus the latter simplifies the picking of the hyperbola apex on the upscaled PSD curves, as it eliminates the need to generate a trial solution.



Figures 3a to 3b': To avoid any bias, the conformance and the Entry pressure were left unedited. The Purcell-PSKT model provides a better prediction of the permeability than the Purcell model proper. It is naturally less sensitive to the complexity of the porous network shown by the color code controlled by the ratio PHI_Z/PH_T.

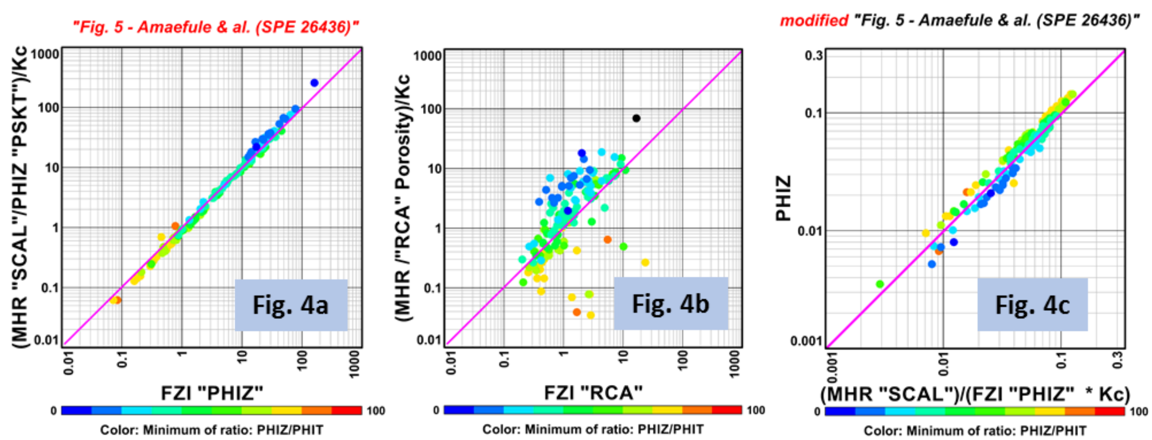
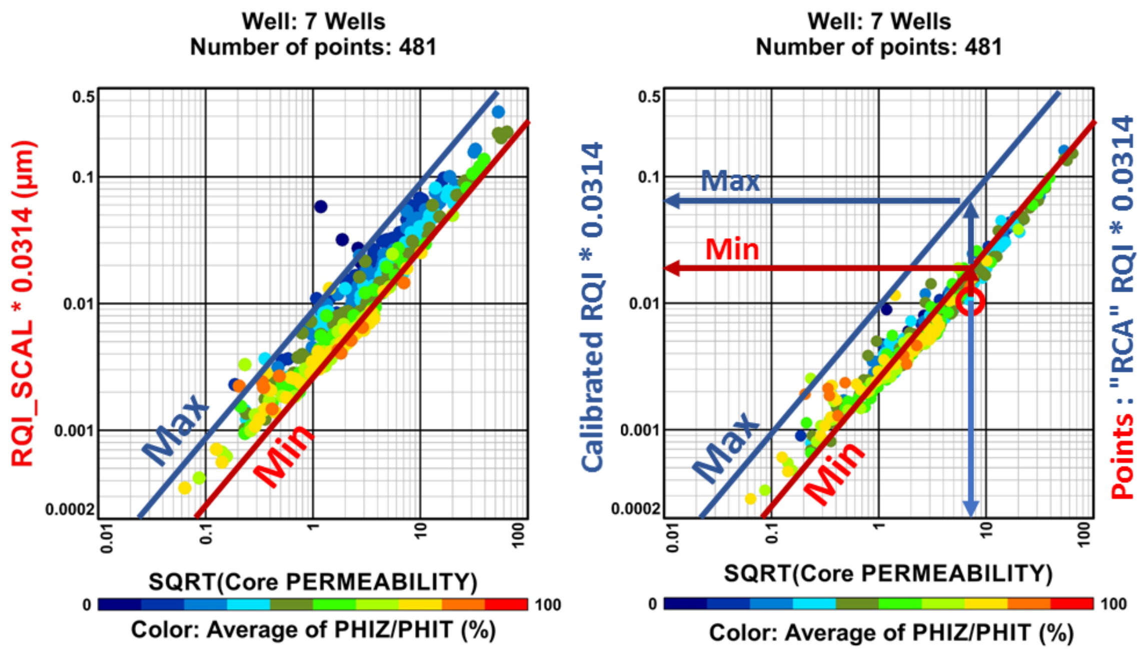


Figure 4a: The ratio (MHR_{true}/PHI_Z) divided by the Kozeny constant, is plotted versus FZI_{true} (i.e.: FZI for "PHI_Z"). The straight line in the center of the plot (4a) validates the derivation of PHI_Z by the Purcell-PSKT model.
Figure 4b: If a "cloud" appears instead of a line, when PHI_T is used instead of PHI_Z and FZI_{RCA} instead of FZI_{true}, then it must be concluded that the RCA data does not honor the foundations of the FZI theory and thus they need to be calibrated.
Figure 4c: The plot proposed by Amaefule & al. is rearranged so that PHI_Z is on the Y axis and the product (FZI_{PHI_Z} * Kc) is plotted on the X axis. As in the original X-plot, a straight line is observed if FZI theory is honored.



Figures 5a & 5b schematize the principle of an algorithmic procedure used for estimating PHI_Z from RCA measurements. The calibration trends are picked on SCAL data.

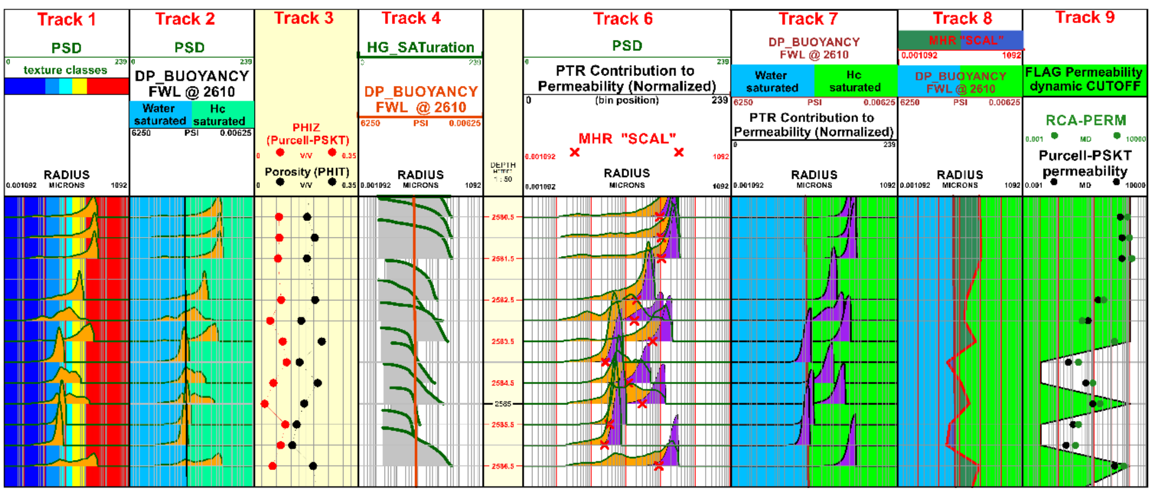


Figure 6: Track 6 shows PSD (orange) and the contribution (purple) of each PTR class to permeability superimposed together with MHR; it clearly illustrates that only the largest PTR contribute to permeability. The track 7 displays the Pc "Field" superimposed to the contribution of each PTR class to permeability and thus allows to determine the fluids moved by the permeability mechanisms in this Pc conditions. The principle of the algorithmic procedure, to determine a dynamic cut off for permeability is illustrated by tracks 8 and 9. The MHR Radius is converted into Pc Field conditions and compared to Pc defined from Hc Buoyancy to create the cut off.