Multi-Phase Flow Petrophysics: A Physics-Based Approach for Deriving Sw from NMR and Formation Sampling in Low Resistivity Pay Carbonates*

Nicolas Leseur[1] and Charles Smart[1]

Search and Discovery Article #42547 (2020)**
Posted July 6, 2020

*Adapted from oral presentation given at 2019 AAPG Middle East Region Geoscience Technology Workshop, Low Resistivity Pay, Muscat, Oman, October 7-9, 2019
 DOI:10.1306/42547Leseur2020

[1]Baker Hughes, United Arab Emirates (nicolas.leseur@bhge.com; charles.smart@bhge.com)

Abstract

In conventional petrophysics, resistivity logs are the main pay zone identifiers due to resistivity contrast between hydrocarbon and formation water. If, however, a pay zone exhibits saturation-dependent Archie exponents or conductive minerals, these logs become incapable of identifying the producing zones and providing further insights about water mobility. Because of these limitations, many potentially productive zones with high irreducible water saturations are overlooked in many fields in the Middle East and other fields around the world. In an attempt to leverage the best of both worlds, the multi-method presented in this article introduces an integration of physics-based and data-driven approaches to de-risk and quantify the initial production performance of low resistivity fine-grained carbonate formations.

To begin with, the pore architecture of these rocks is derived from NMR and automated MICP deconvolution. Reservoir fluid properties and initial fractional flows (fw) are then measured through formation testing and sampling. Then, the knowledge of pore architecture is propagated to data-scarce intervals and other wells by means of probabilistic machine-learning. Initial water saturation is subsequently calculated on the basis of the equilibrium between buoyancy and capillary forces after what, the Buckley-Leverett formalism is used to derive a formation-testing-calibrated fw continuous log, thus further informing Sw and Free-Water Level (FWL) elevation. The aforementioned multi-phase flow petrophysics method provides the practioner with a number of critical reservoir insights unrivaled by single-tool or data-driven-only approaches. Probability distribution function of Sw, initial fw, transition zone evaluation and FWL identification are among the key outputs informing the final choice of completion strategy. The framework introduced here also enables the pore architecture understanding, constructed and ground-truthed at the well level, to be exported and scaled to 3D reservoir models.

AAPG
Advancing the World of Petroleum Geosciences™

Multi-Phase Flow Petrophysics

A Physics-based approach for deriving Sw from NMR and Formation Sampling in low-resistivity pay Carbonates.

Nicolas Leseur, Charles Smart
Reservoir Geoscience Advisor

Setting the Scene

Problem Statement and Methodology

Micro-crystalline Calcite in the Arabian Gulf

High Salinity + High Capillarity + Surface Conductance = Excess Conductivity

A complementary range of solutions

- *Correcting Resistivity (Resistivity modeling, Apparent n, ...)*
- *Alternate Measurements (Dean-Stark, Pc, Sigma, Azimuthal Resistivity, DWT NMR, ...)*
- *Multi-Physics (multi-mineral, multi-phase, ...)*

From T2 Distribution to Sw Distribution

- *Reservoir Logging* – Informing LWD logs with Contextual Data

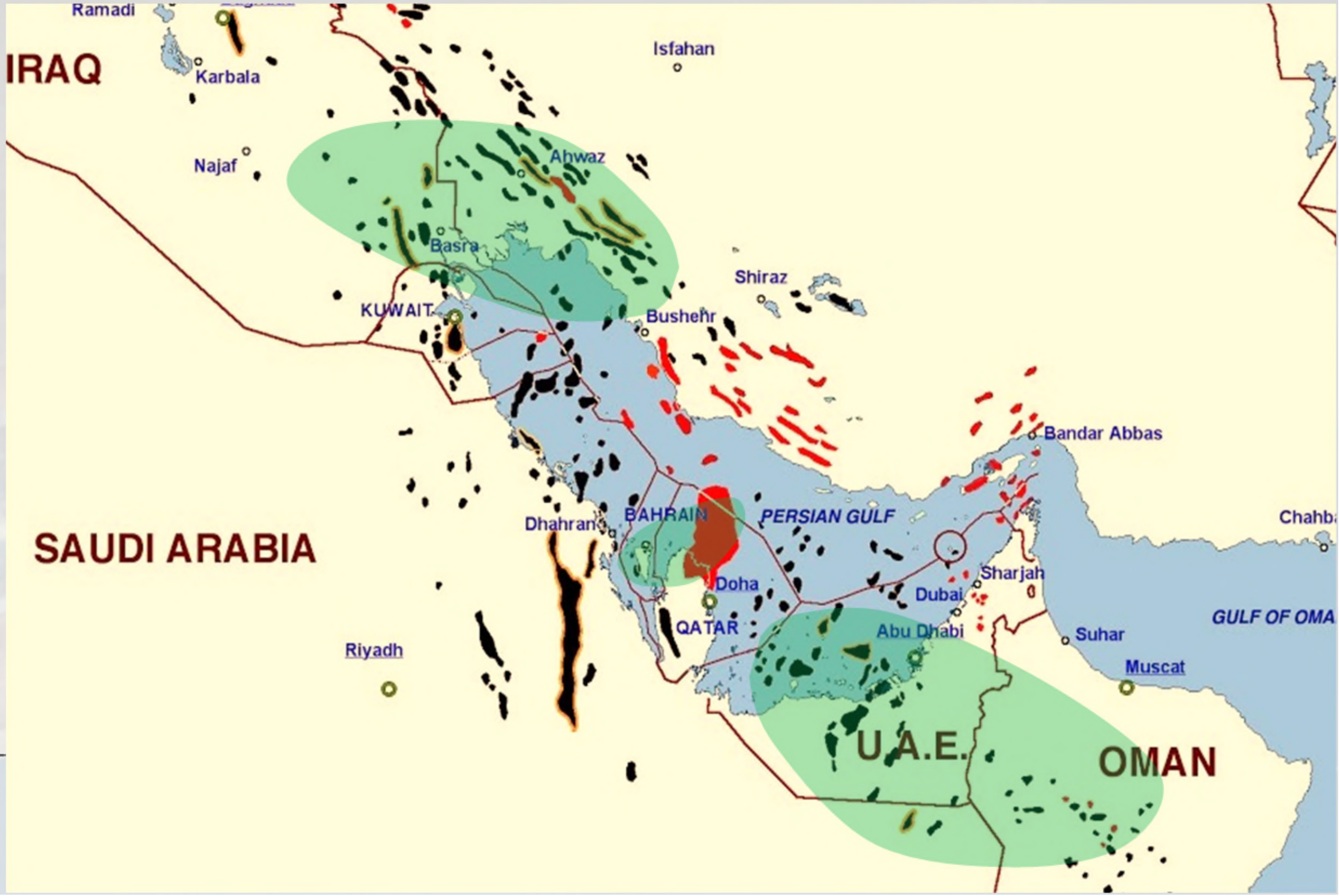
Multi-phase flow Petrophysics

- De-risk fluid typing and compartmentalization, calibrating multi-phase producibility and permeability

BAKER HUGHES a GE company

Carbonate LRP in the Arabian Gulf

- Oman
- UAE
- Bahrain
- Qatar
- Iran
- Iraq
- Saudi Arabia



BAKER HUGHES a GE company

1971

Pittman

"Large pores hold and transmit fluids whereas associated micropores may hold irreducible water. Analysis of borehole logs of micro porous carbonate rocks can result in misleadingly high calculated Sw and possibly bypassing of a potential oil or gas reservoir"

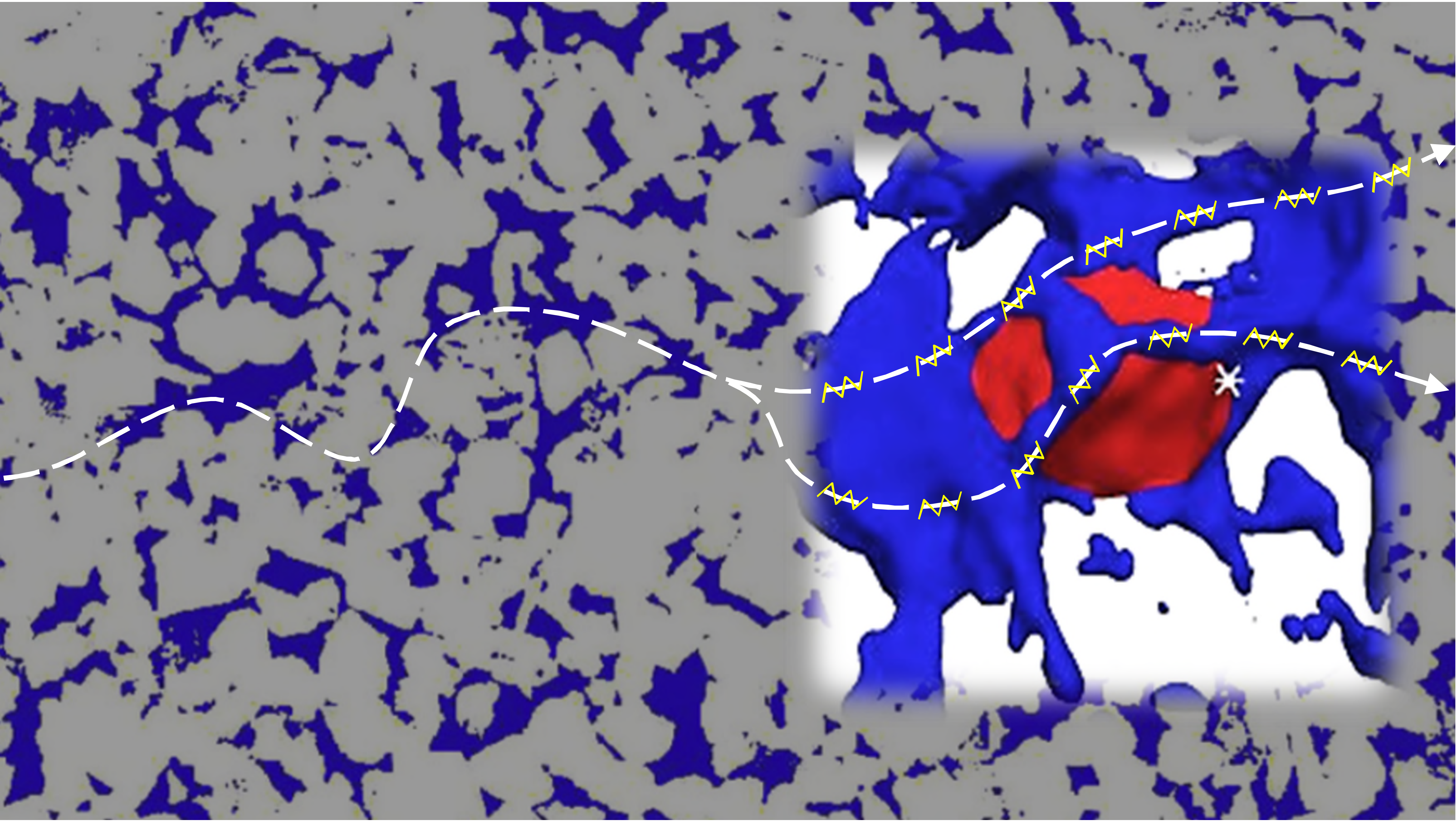
1984

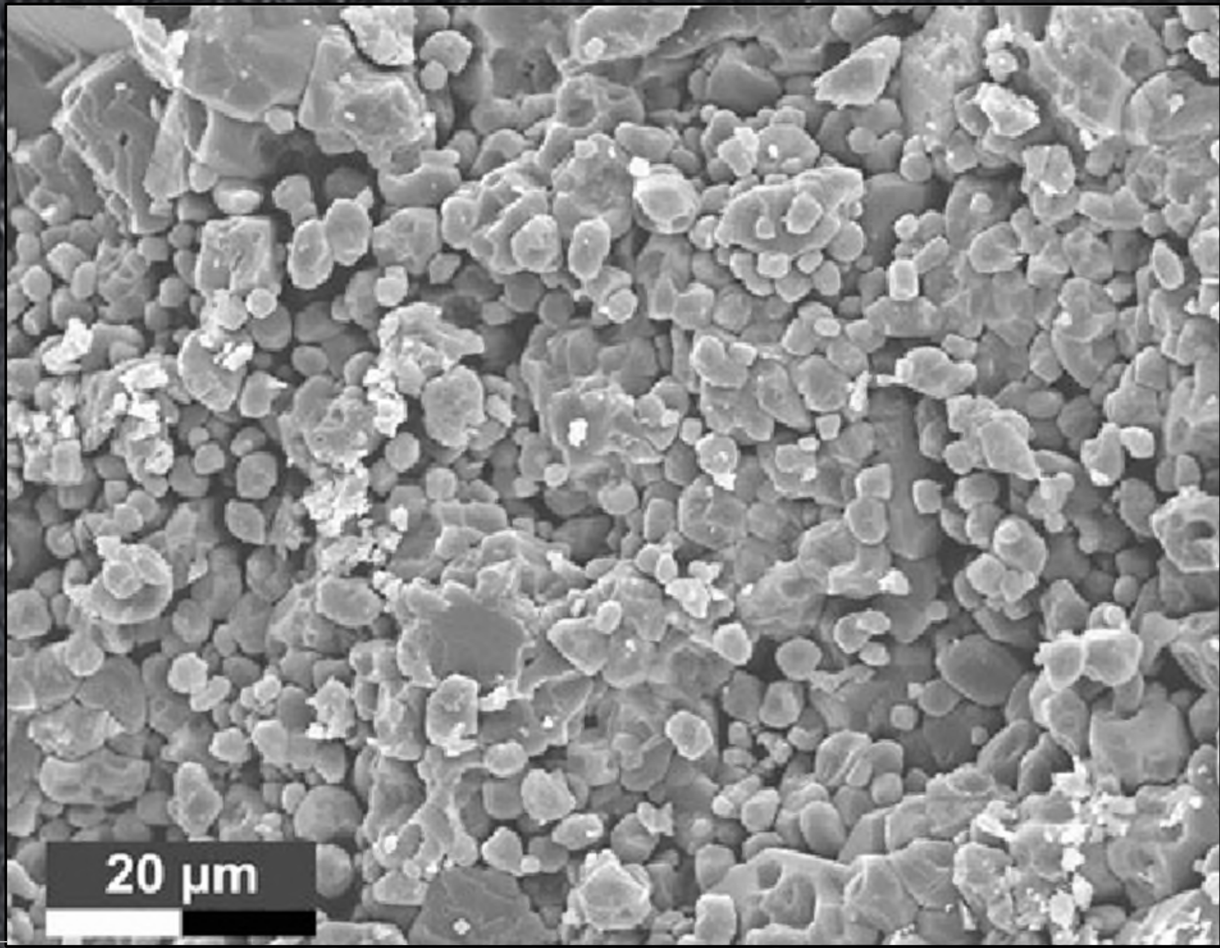
Asquith

"Because of the high Pc associated with the micro porosity in ooids, hydrocarbons cannot enter the pores and so the micropores become saturated with immovable bound water. The less tortuous path of electrical flow caused by micro porosity results in the recording of abnormally low values on resistivity logs"

Irreducible Sw
Low Salinity
Fractures
Pyrite
Connected Vugs
Conductive Mineral
Saline Deep Invasion
Glauconite
Thin beds
Micro-porous lamination
Micro-crystalline
Cross beddings
High angle
High Capillarity
Multi-modal porosity
Paramagnetic


Irreducible Sw
Fractures
Pyrite
Low Salinity
Connected Vugs
Glauconite
Saline Deep Invasion
Conductive Mineral
Thin beds
Micro-porous lamination
Cross beddings
Micro-crystalline
High angle
High Capillarity
Multi-modal porosity
Paramagnetic

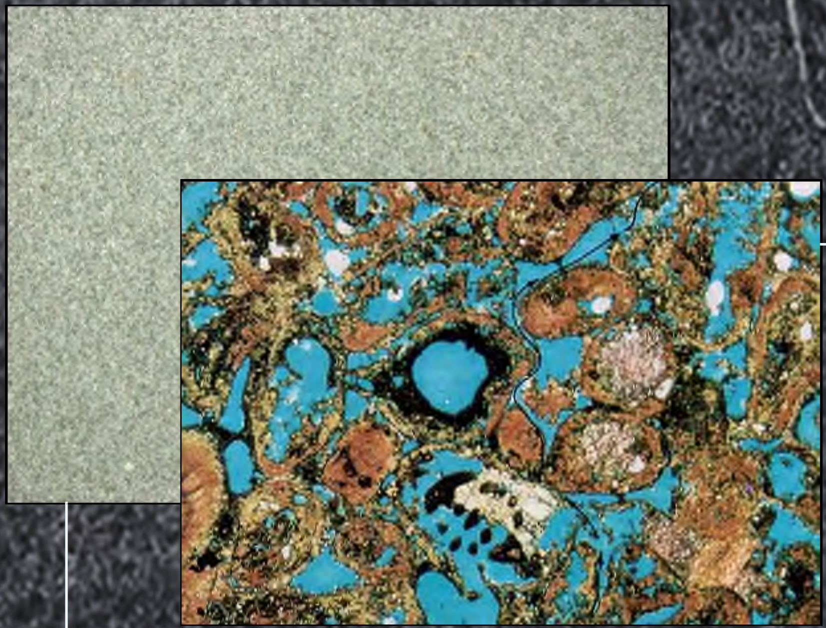




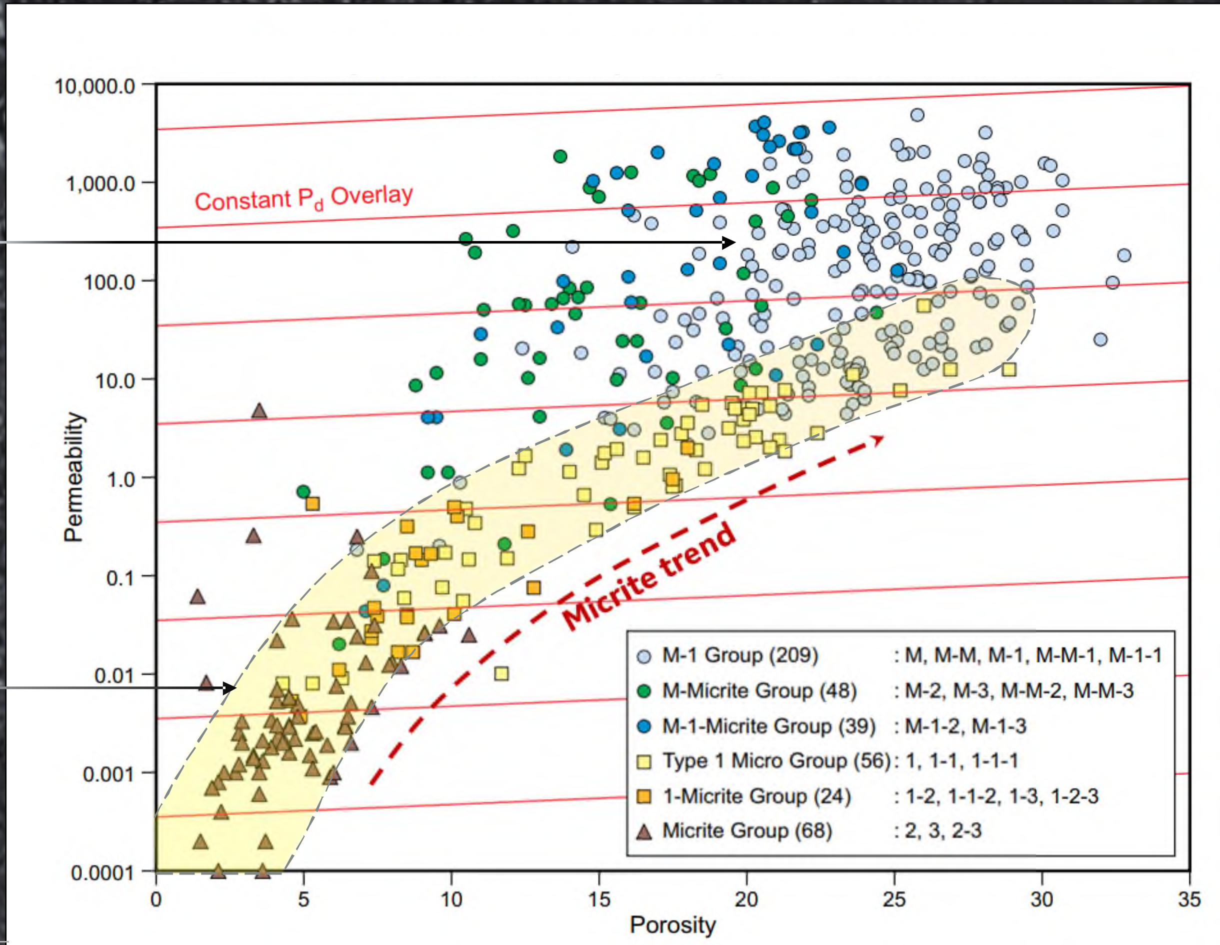
Micro-Crystalline Calcite

Mishrif, Iraq

micrite

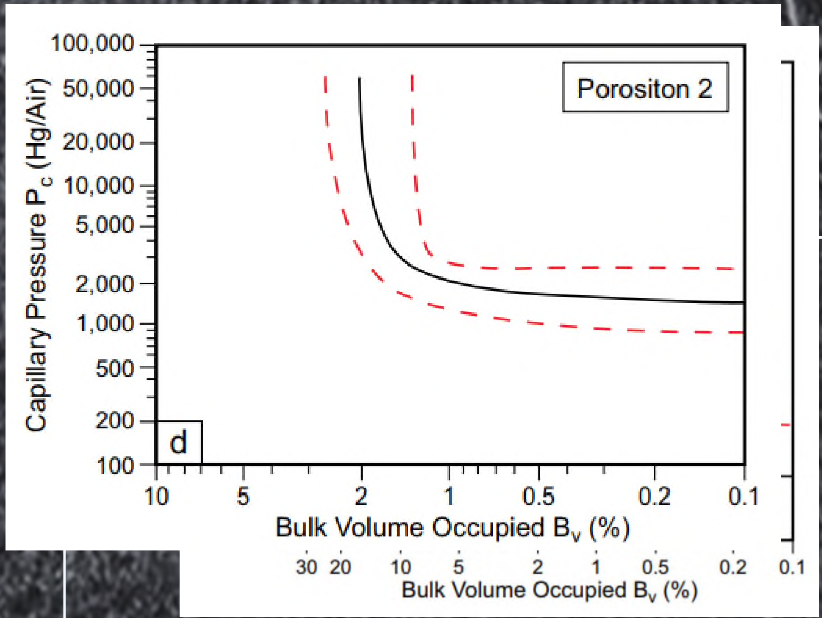


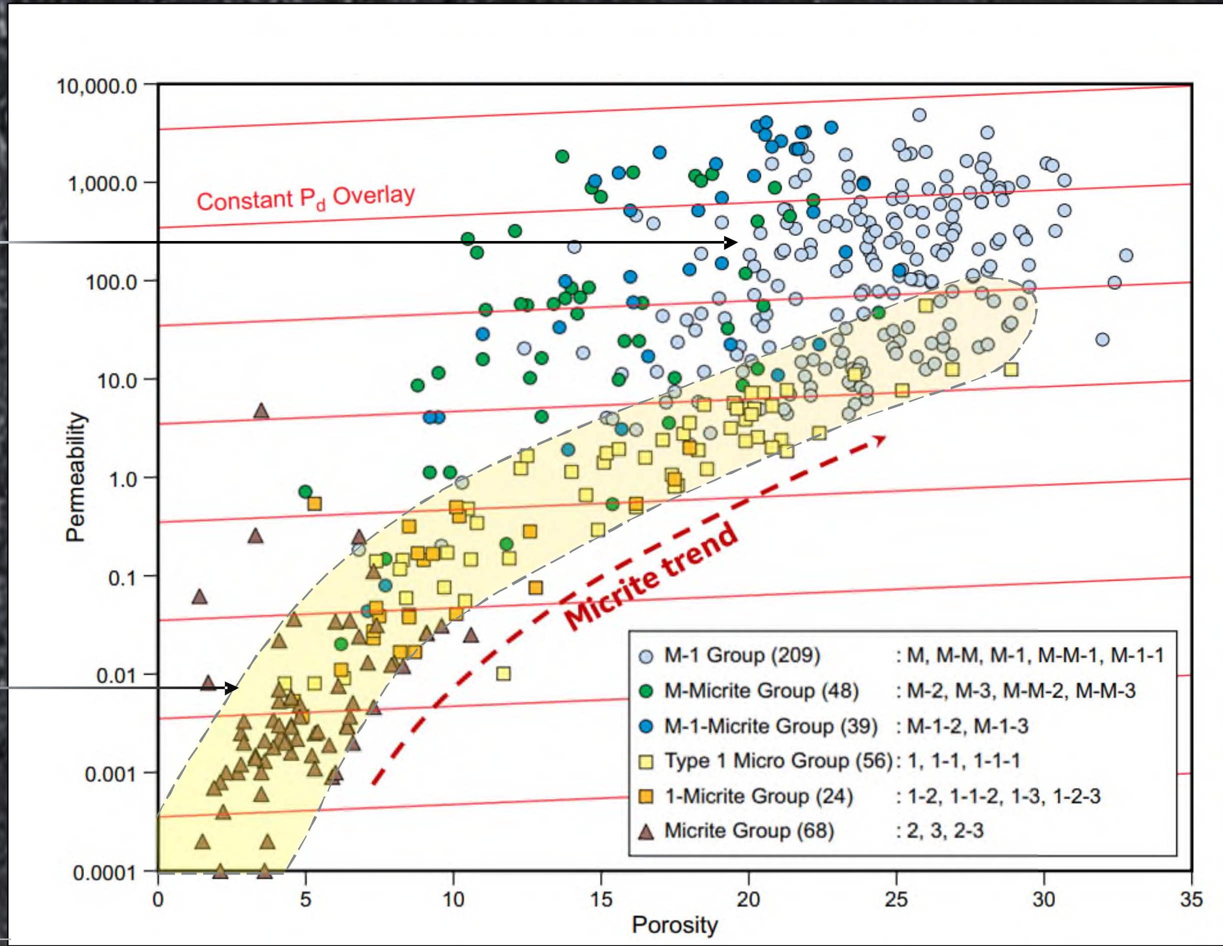
bio-clasts



Clerke et al. (2008)

Micrite, a **subset** of the **Carbonate world**

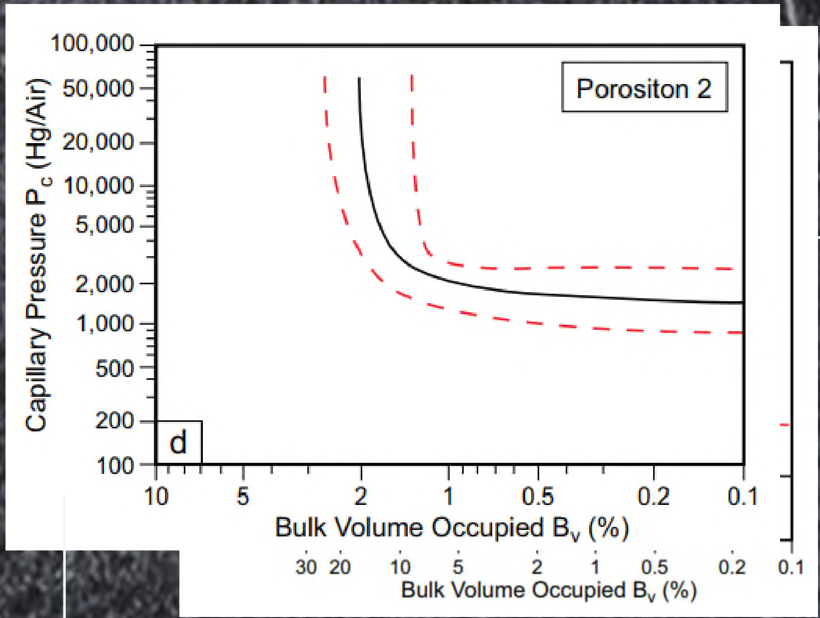


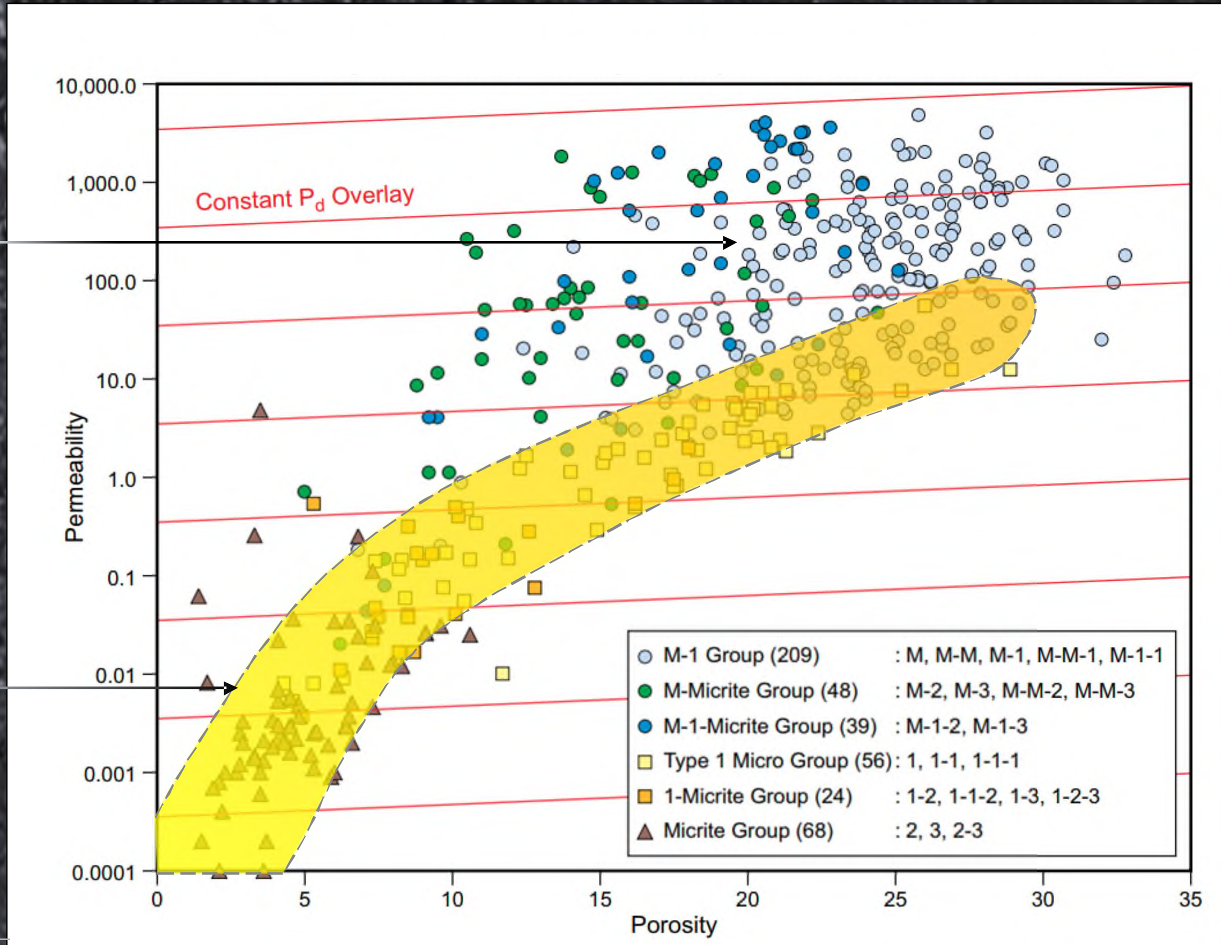


Pure micrite, is primarily

Monomodal

Clerke et al. (2008)





Pure micrite, is primarily

Monomodal

Clerke et al. (2008)

The Method

Logging only vs. Logging & Coring

Logging	Logging & Coring
NMR	MICP
Formation Testing	Formation Testing
+	+
Capillary Pressure	Capillary Pressure
Buckley-Leverett	Buckley-Leverett

The Method

Logging only vs. Logging & Coring

Logging

Logging & Coring

NMR

***From* T2 Distribution**
***to* Sw Distribution**

Formation Testing

+

Capillary Pressure
Buckley-Leverett

BAKER HUGHES a GE company

The Method

Logging only vs. Logging & Coring

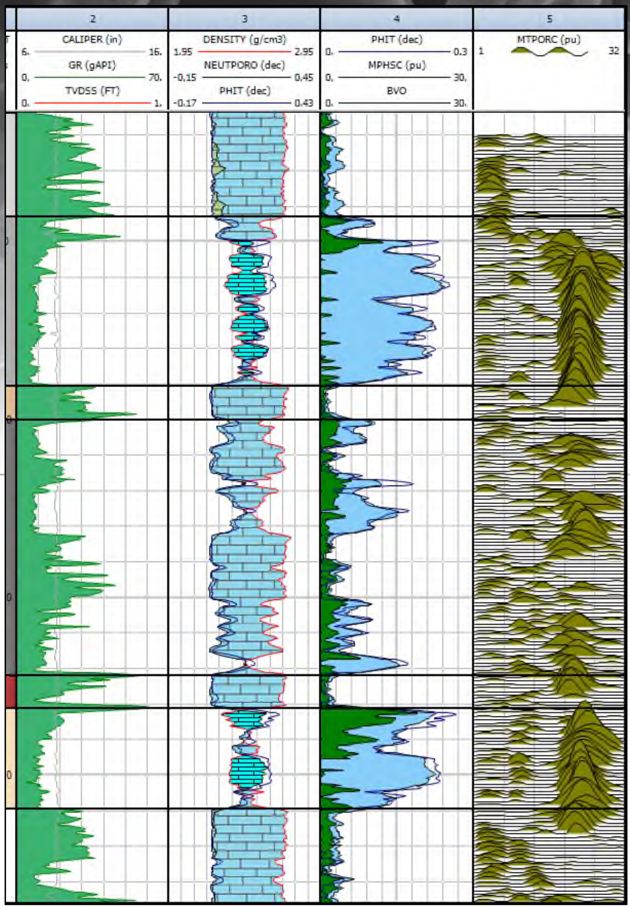
Logging

Logging & Coring

MICP
Formation Testing
+
Capillary Pressure
Buckley-Leverett

Multi-phase Flow
Petrophysics

From T2 Distribution to Sw Distribution



INPUTS

- Fluid Densities
- Free-Water Level
- Wettability

ASSUMPTIONS

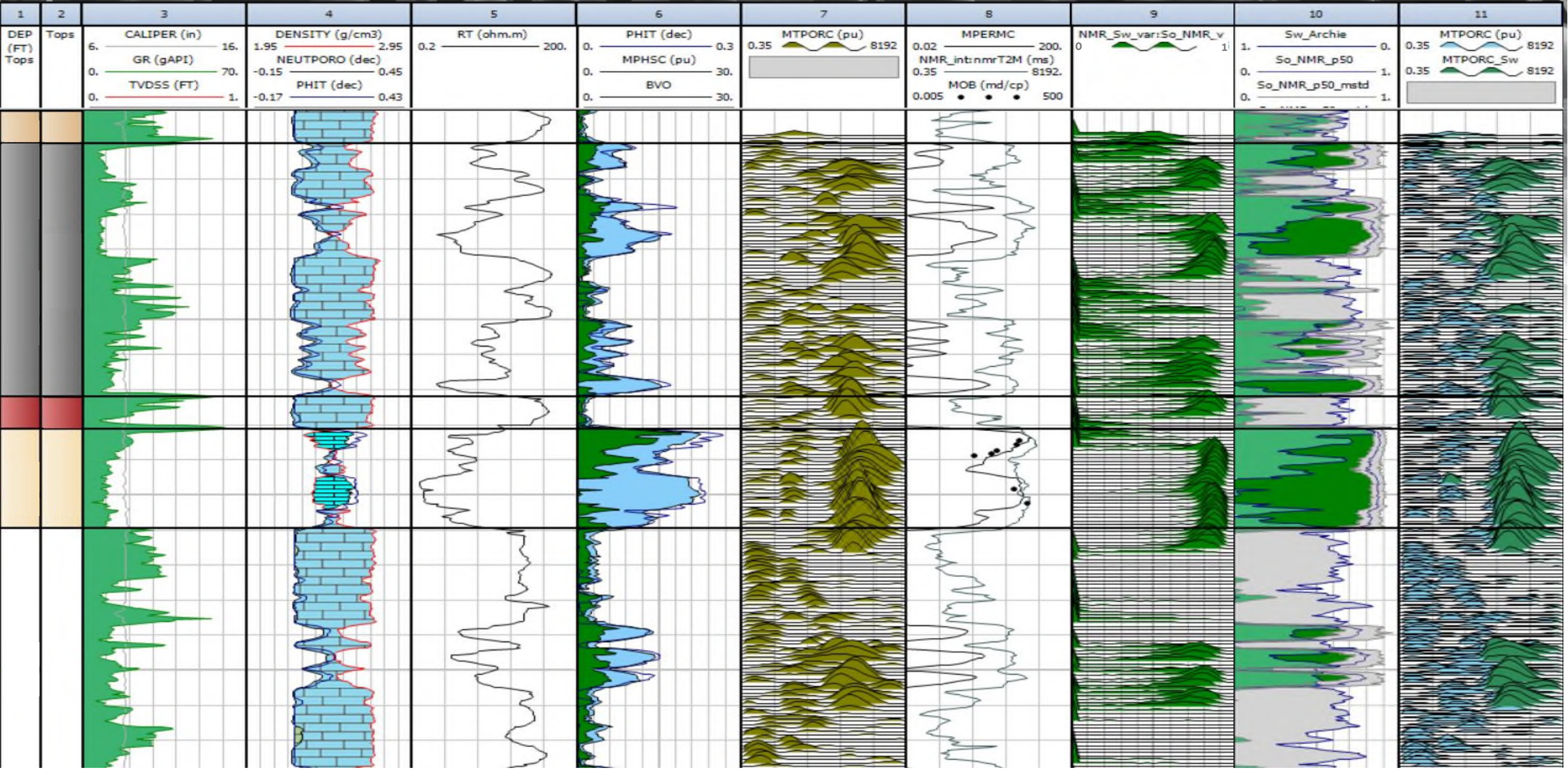
- Monomodal Micritic Rocktype: Limited Pore Architecture Heterogeneity.

** This is valid for tight carbonates with permeability < 10mD*

MODEL

- Poiseuille's Bundle of Tube
- Equilibrium between Capillary and Buoyancy Forces

From T2 Distribution to Sw Distribution



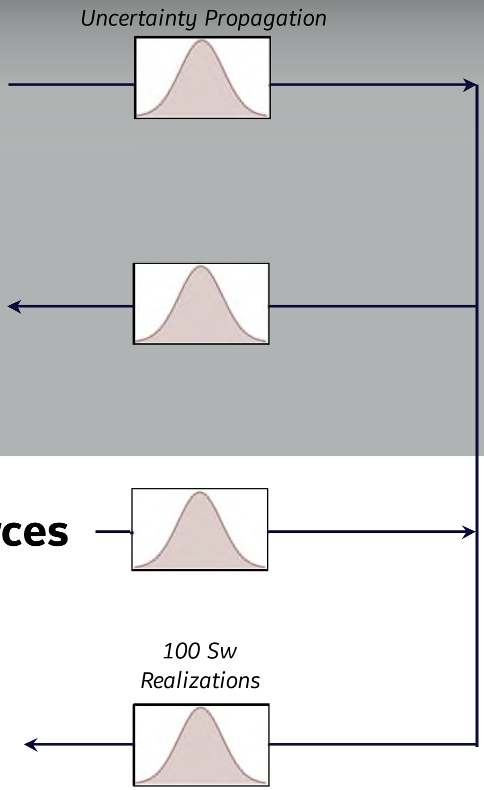
From T2 Distribution to Sw Distribution

1 **Pore Heterogeneity**

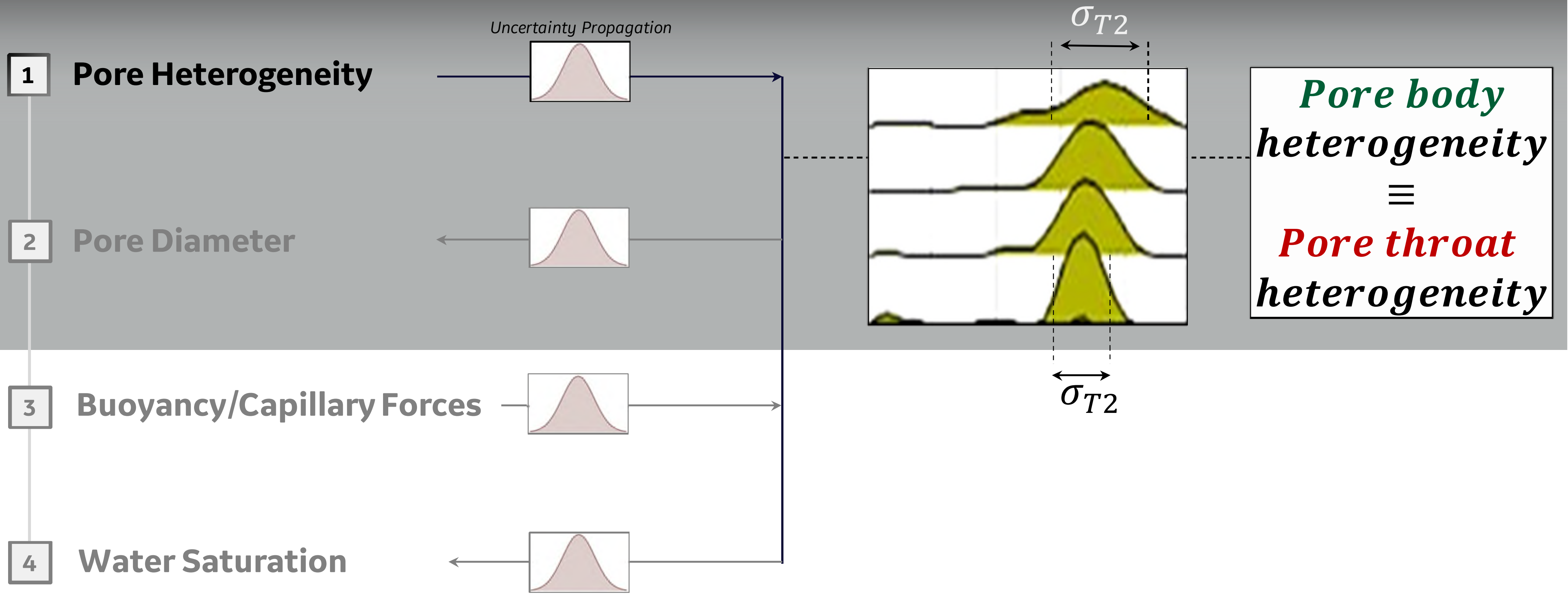
2 **Pore Diameter**

3 **Buoyancy/Capillary Forces**

4 **Water Saturation**



From T2 Distribution to Sw Distribution



From T2 Distribution to Sw Distribution

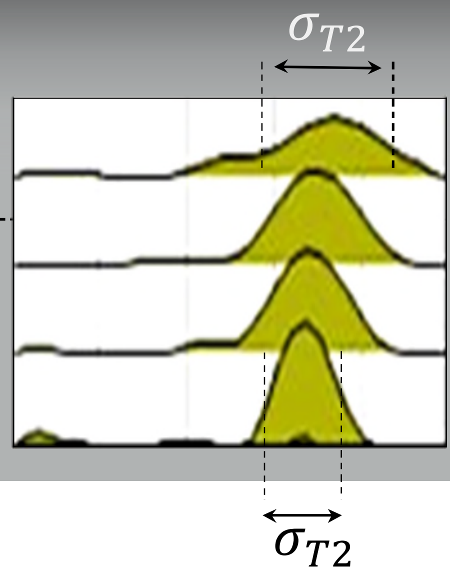
Uncertainty Propagation

1 **Pore Heterogeneity**

2 Pore Diameter

3 Buoyancy/Capillary Forces

4 Water Saturation



- *Thomeer* -

$\boldsymbol{\sigma_{T2} \propto G}$

- *Corey* -

$\boldsymbol{\sigma_{T2} \propto \lambda^{-1}}$

From T2 Distribution to Sw Distribution

Uncertainty Propagation

1 **Pore Heterogeneity**

2 **Pore Diameter**

3 **Buoyancy/Capillary Forces**

4 **Water Saturation**

Poiseuille

$$P_d = \sqrt{\alpha \frac{\Phi}{k} e^{-\beta\sqrt{G}}}$$

(Buiting and Clerke, 2013)

- Thomeer -

$$\sigma_{T2} \propto G$$

- Corey -

$$\sigma_{T2} \propto \lambda^{-1}$$

in monomodal micrite $B_v^{\infty} \cong \Phi$ *and* $G \in [0.1\ 0.35]$

From T2 Distribution to Sw Distribution

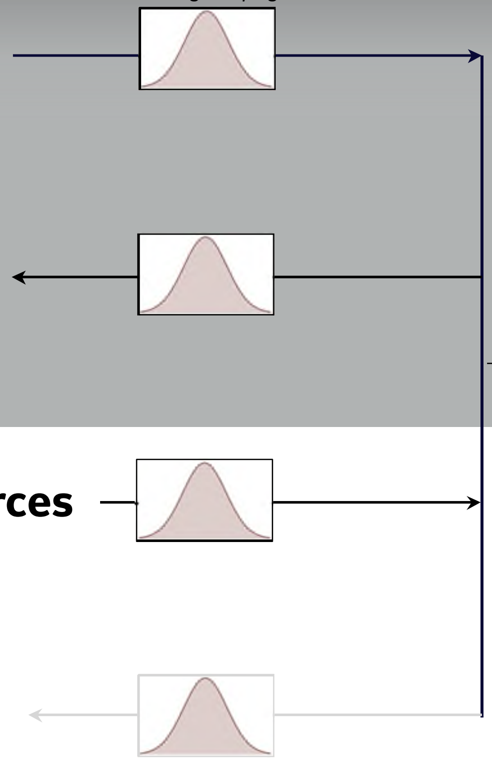
Uncertainty Propagation

1 **Pore Heterogeneity**

2 **Pore Diameter**

3 **Buoyancy/Capillary Forces**

4 Water Saturation



$$P_d = \sqrt{\alpha \frac{\Phi}{k} e^{-\beta\sqrt{G}}}$$

- Thomeer -

$$\sigma_{T2} \propto G$$

$$P_c = 0.433 \Delta\rho H_{fwl}$$

$$P_{c,Hg} = \frac{\sigma\cos\theta_{Hg/a}}{\sigma\cos\theta_{o/b}}$$

From T2 Distribution to Sw Distribution

Uncertainty Propagation

1 **Pore Heterogeneity**

2 **Pore Diameter**

3 **Buoyancy/Capillary Forces**

4 **Water Saturation**

$$P_d = \sqrt{\alpha \frac{\Phi}{k} e^{-\beta\sqrt{G}}}$$

- Thomeer -

$$\sigma_{T2} \propto G$$

$$P_c = 0.433\Delta\rho H_{fwl}$$

$$P_{c,Hg} = \frac{\sigma cos\theta_{Hg/a}}{\sigma cos\theta_{o/b}}$$

$$S_o = \frac{B_v^{\infty}}{\Phi} e^{\frac{-G}{log\frac{P_{c,Hg}}{P_d}}}$$

From T2 Distribution to Sw Distribution

Uncertainty Propagation

1 **Pore Heterogeneity**

2 **Pore Diameter**

3 **Buoyancy/Capillary Forces**

4 **Water Saturation**

$$P_d = \sqrt{\alpha \frac{\Phi}{k} e^{-\beta\sqrt{G}}}$$

- Thomeer -

$$\sigma_{T2} \propto G$$

$$P_c = 0.433 \Delta\rho H_{fwl}$$

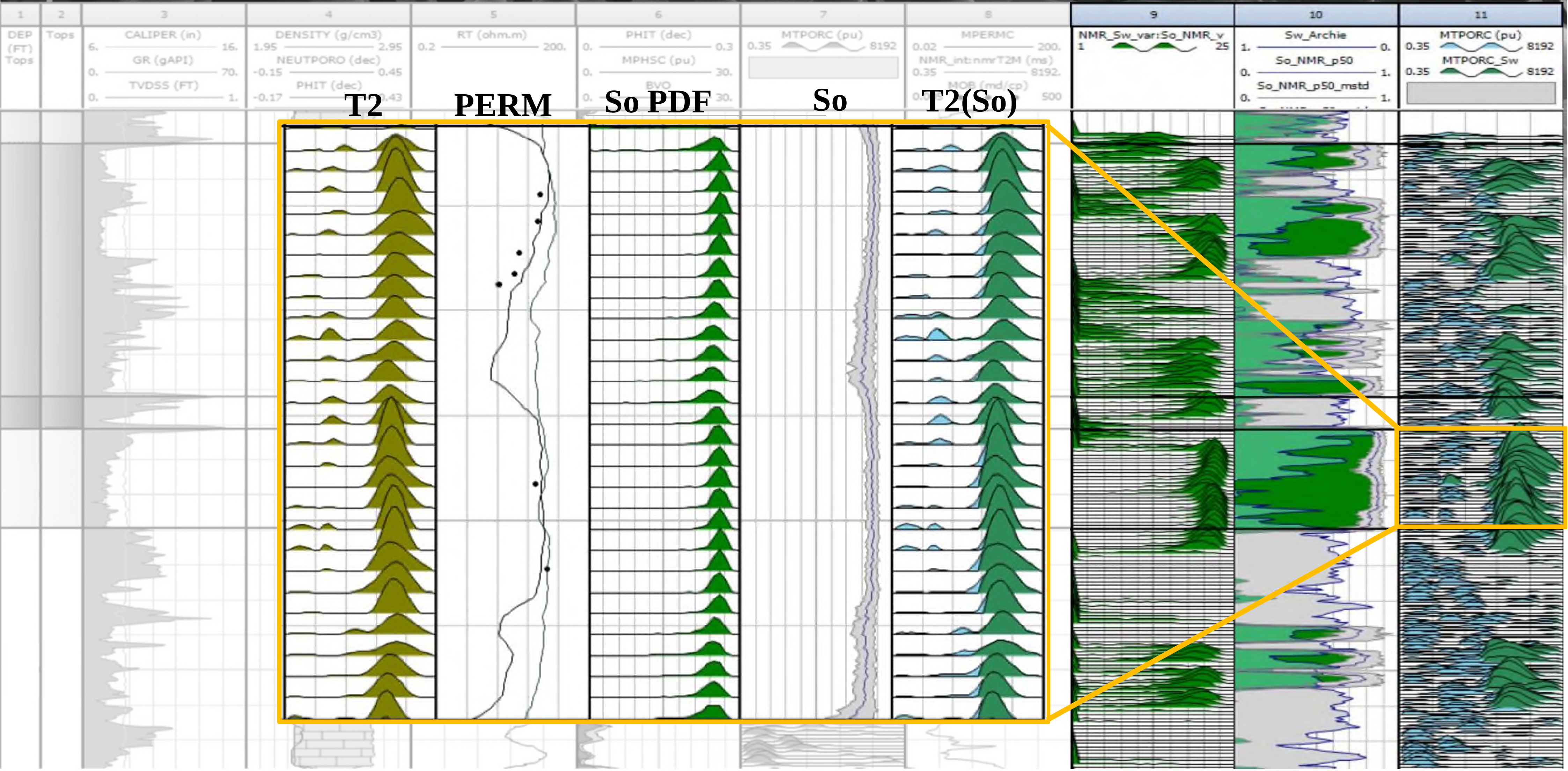
$$P_{c,Hg} = \frac{\sigma cos\theta_{Hg/a}}{\sigma cos\theta_{o/b}}$$

$$S_o = \frac{B_v^{\infty}}{\Phi} e^{\frac{-G}{log\frac{P_{c,Hg}}{P_d}}}$$

Uncertainty Propagation via Monte-Carlo Simulation

BAKER HUGHES a GE company

From T2 Distribution to Sw Distribution



The Method

Logging only vs. Logging & Coring

Logging

NMR

Formation Testing

+

Capillary Pressure

Buckley-Leverett

Logging & Coring

***From* T2 Distribution**

***to* Sw Distribution**

The Method

Logging only vs. Logging & Coring

Logging

Logging & Coring

Multi-phase Flow

Petrophysics

MICP

Formation Testing

+

Capillary Pressure

Buckley-Leverett

MultiPhase Flow Petrophysics

A 3-step Approach

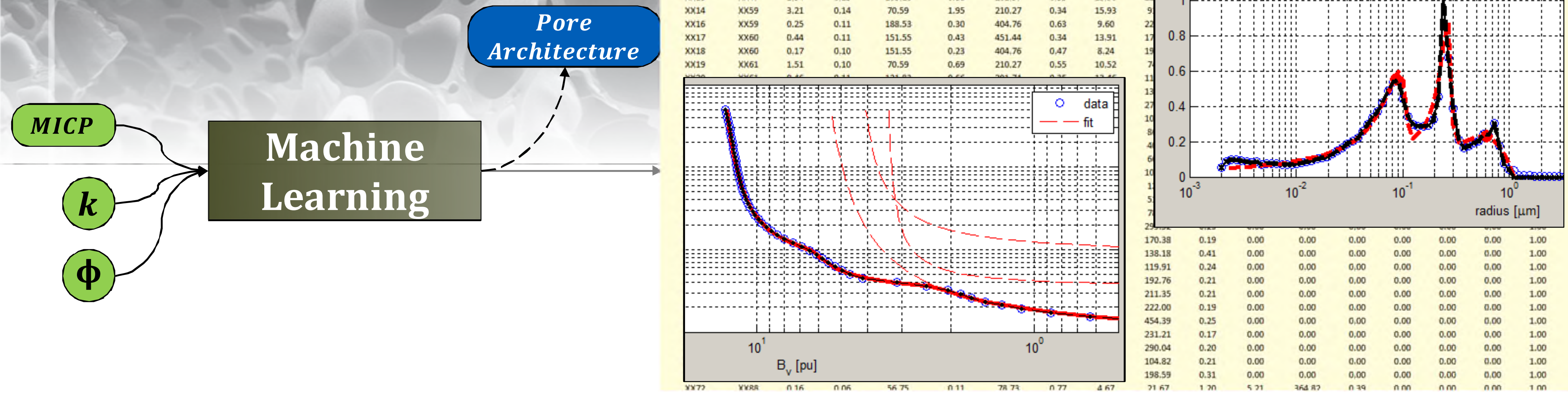
Machine Learning → **SatH. Function & Land** → **Buckley Leverett**

June 22, 2020

MultiPhase Flow Petrophysics

Pore Architecture Modeling

Automated Type Curve Fitting



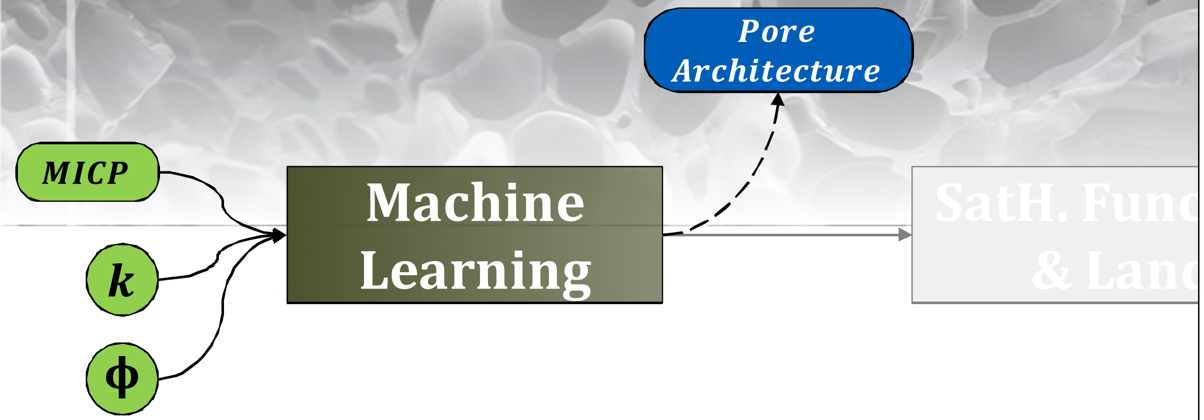
Based on global non-linear optimization
1875 samples in 10 minutes

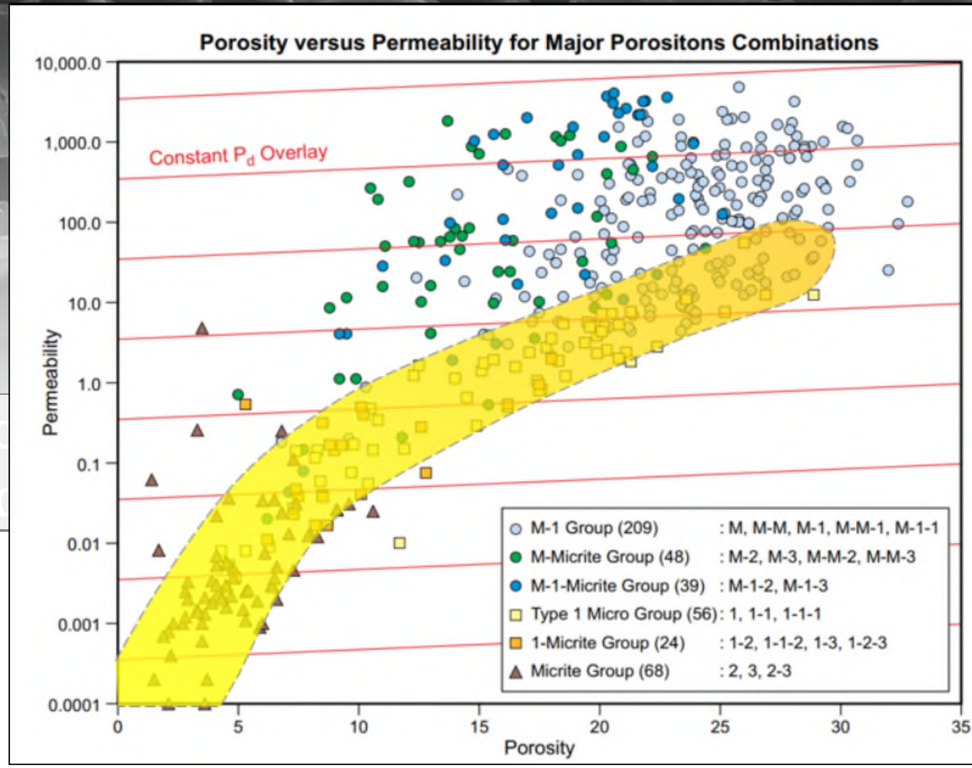
BAKER HUGHES a GE company

June 22, 2020

MultiPhase Flow Petrophysics

Pore Architecture Modeling

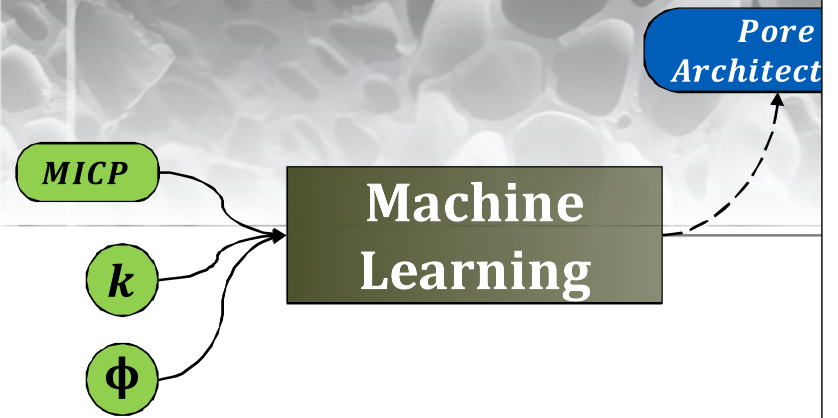


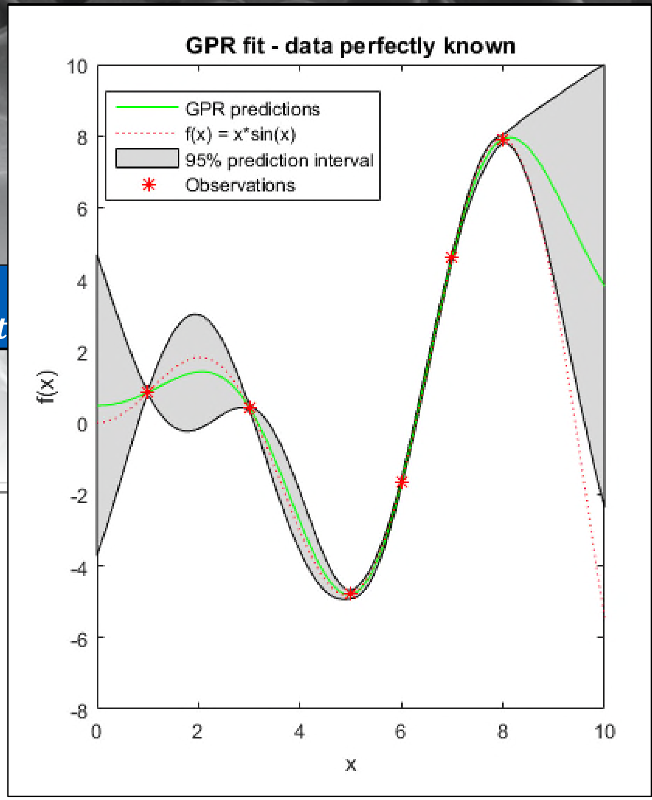


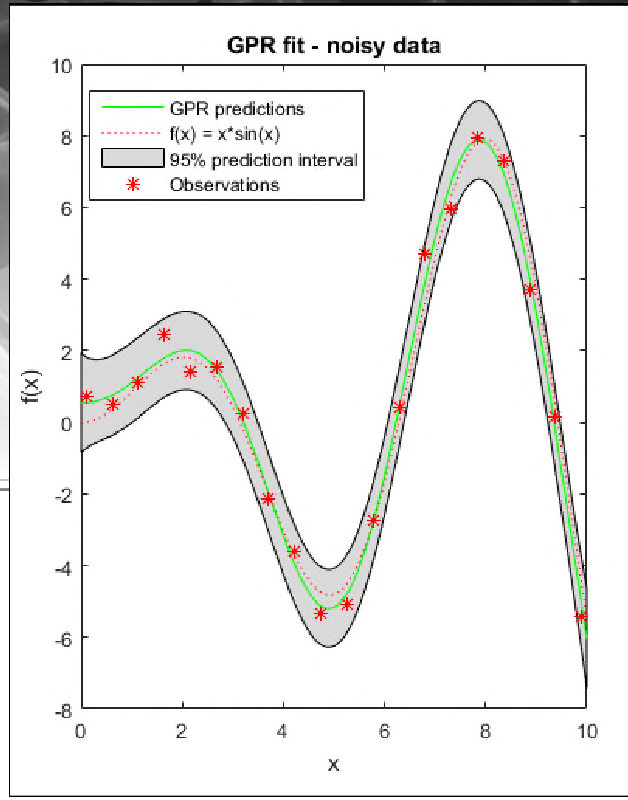
The $k - \phi$ relationship of Tight monomdal, micritic Carbonates is generally well behaved

MultiPhase Flow Petrophysics

Pore Architecture Modeling



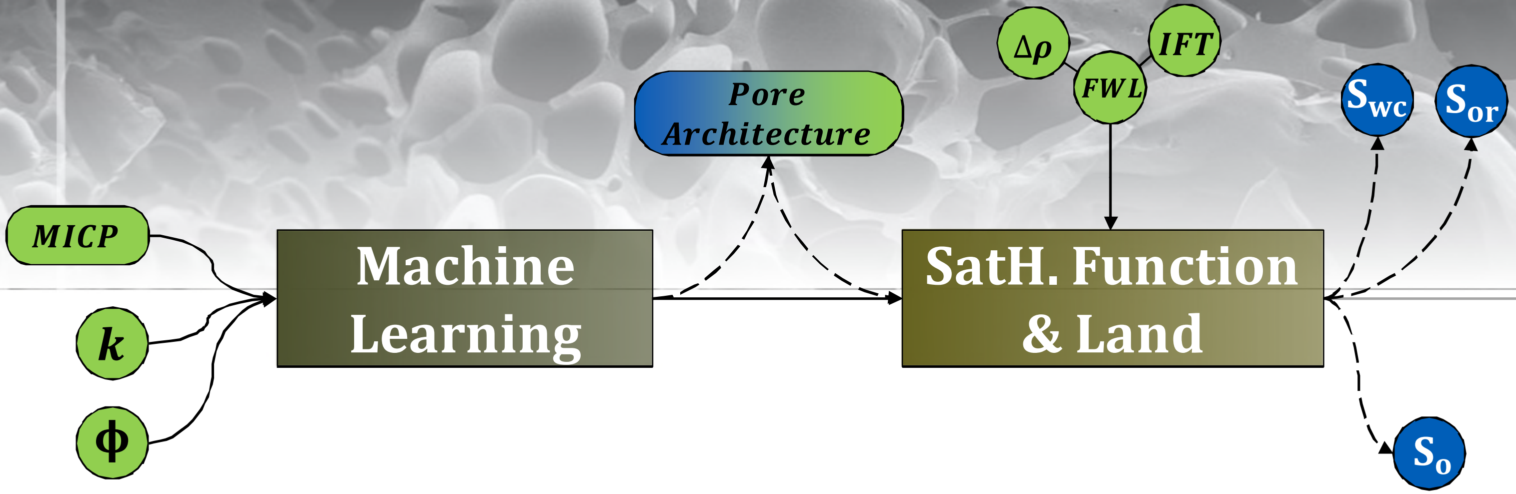


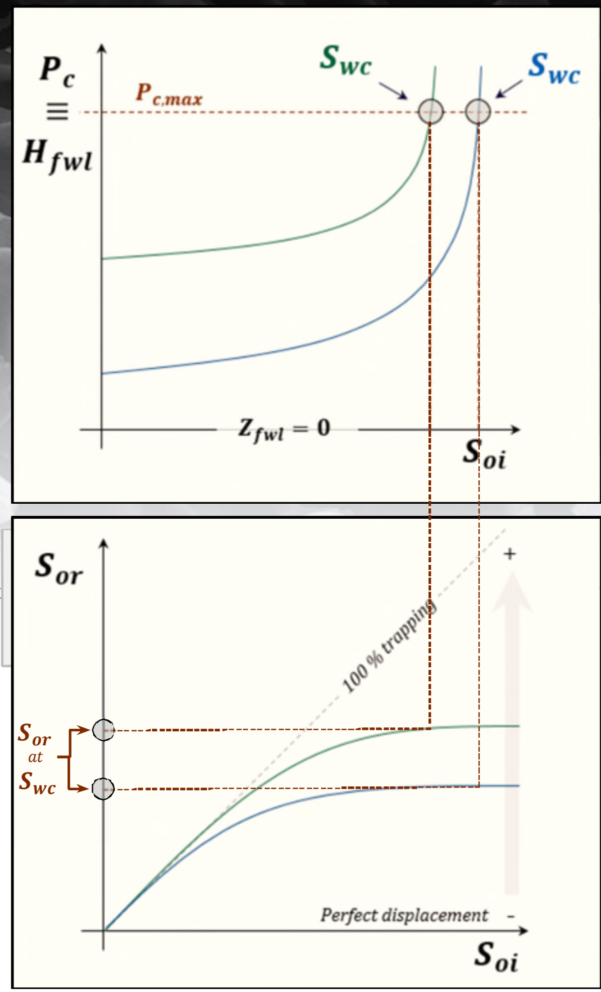


Probabilistic Machine Learning approach
Includes measurement uncertainty

MultiPhase Flow Petrophysics

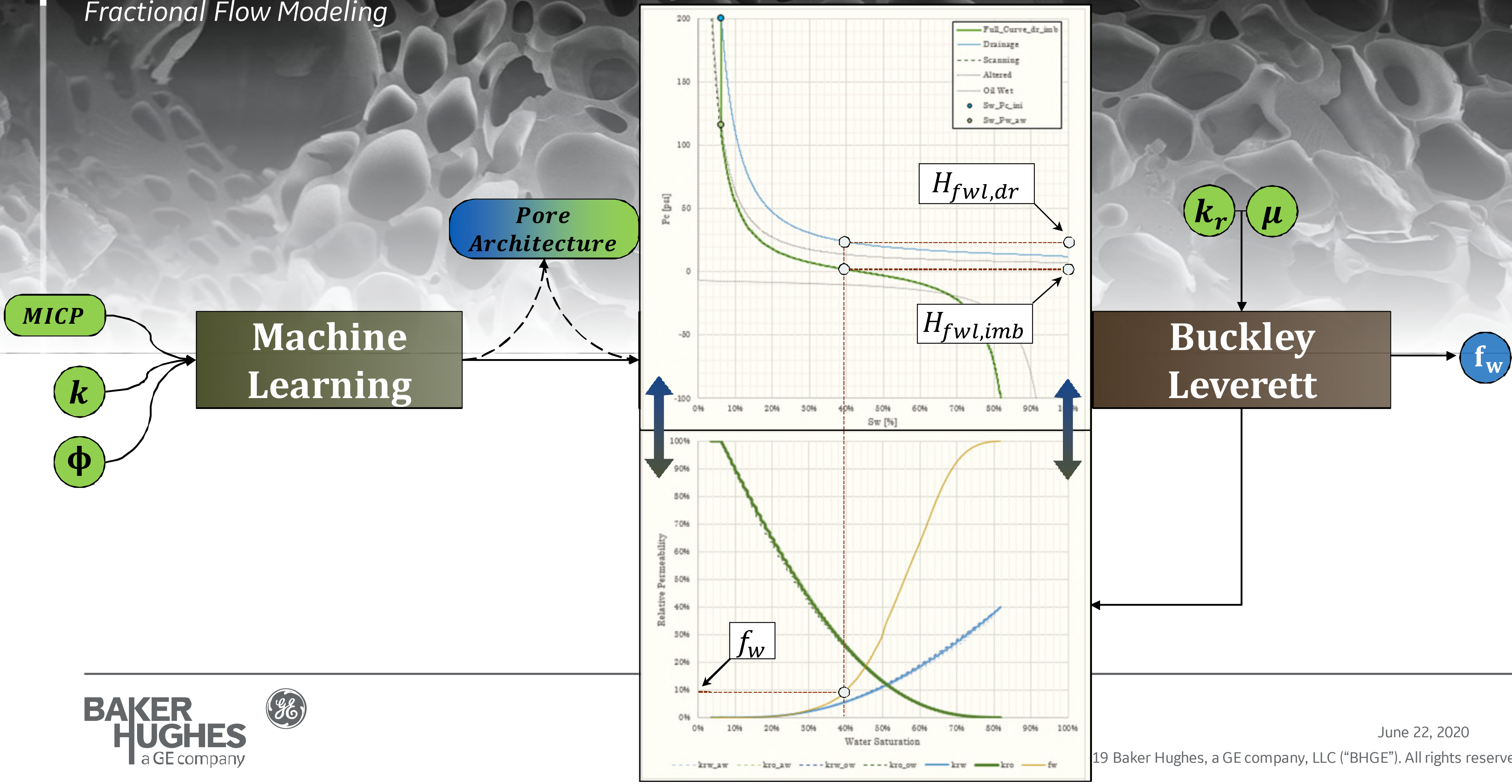
Saturation Modeling





MultiPhase Flow Petrophysics

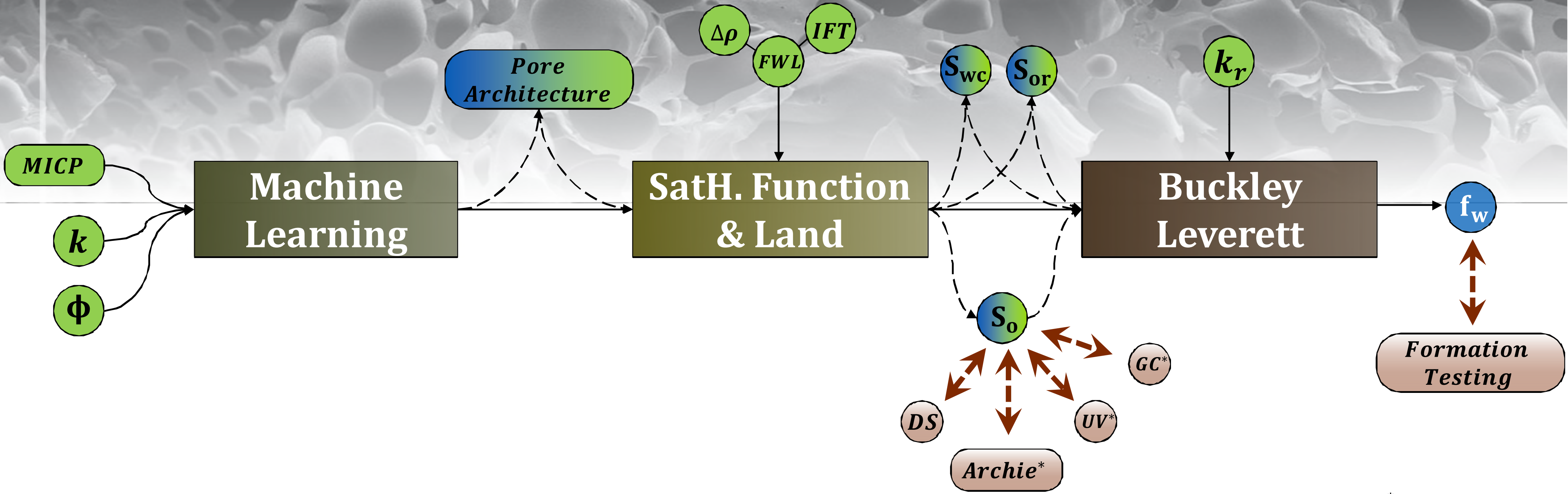
Fractional Flow Modeling



June 22, 2020

MultiPhase Flow Petrophysics

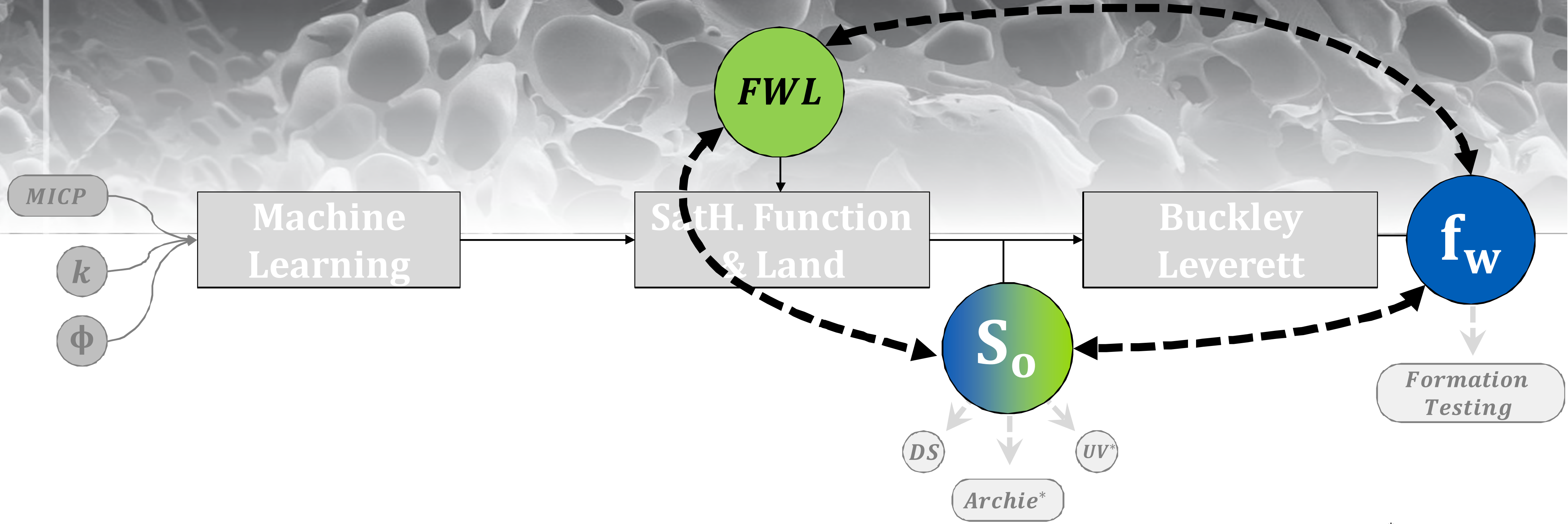
Fractional Flow Modeling



*qualitative

MultiPhase Flow Petrophysics

From Pore Architecture to Fractional Flow



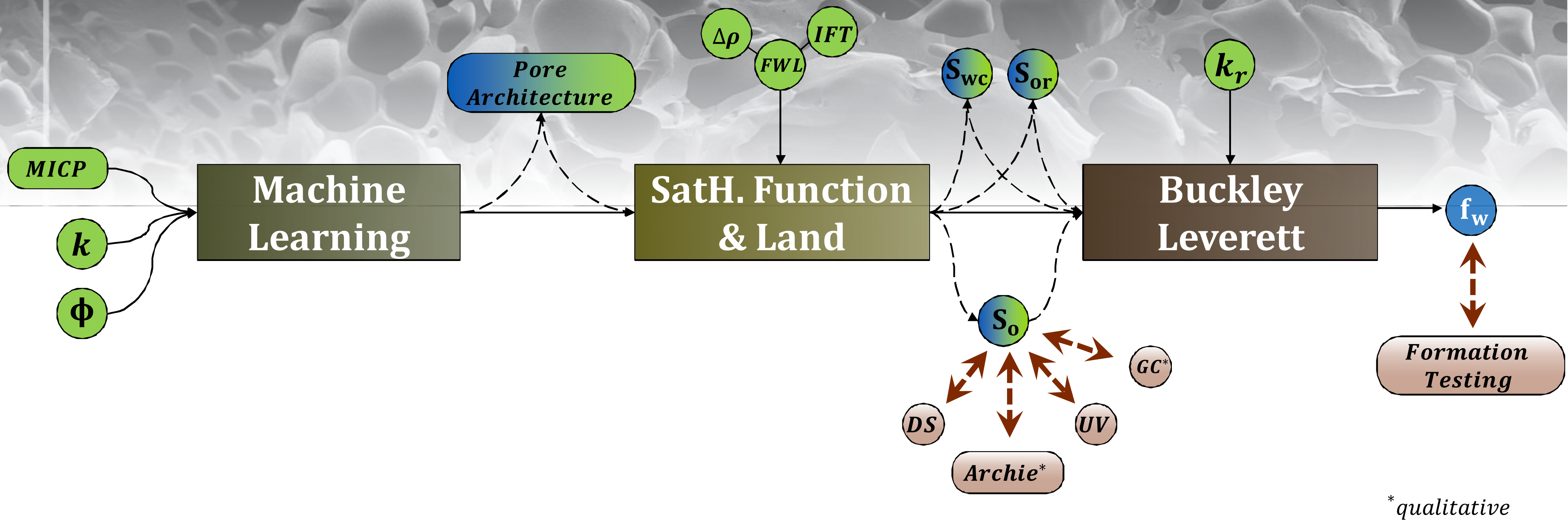
*qualitative

BAKER HUGHES a GE company

June 22, 2020

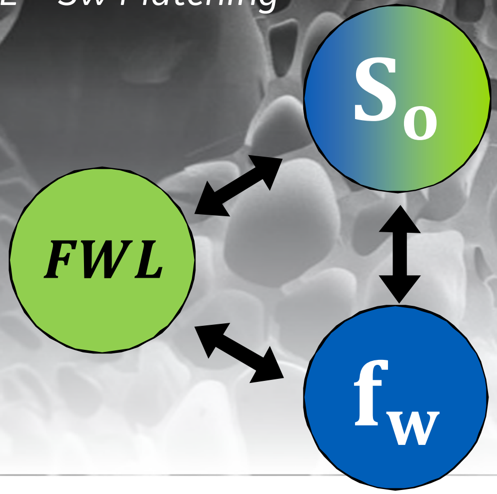
MultiPhase Flow Petrophysics

From Pore Architecture to Fractional Flow



MultiPhase Flow Petrophysics

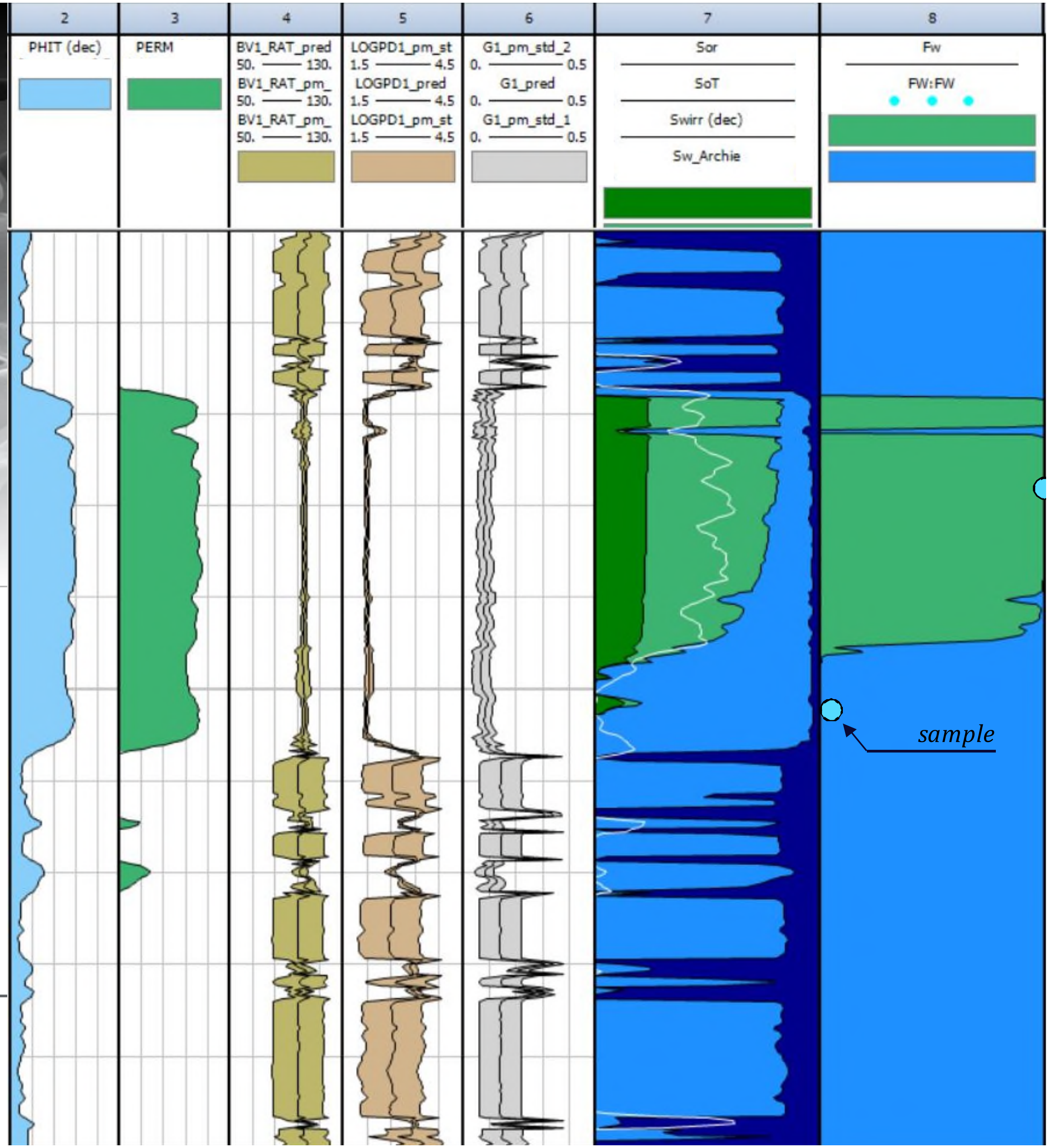
Fw – FWL – Sw Matching



Optimization under Constraint

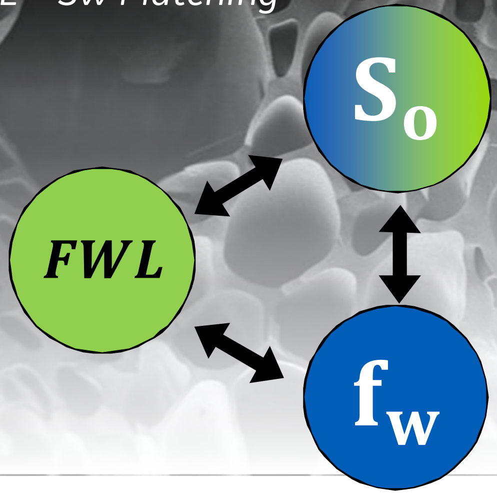
CASE #1

- **Match the Fw from formation sampling**
- **While honoring the Sw deflection**



MultiPhase Flow Petrophysics

Fw – FWL – Sw Matching

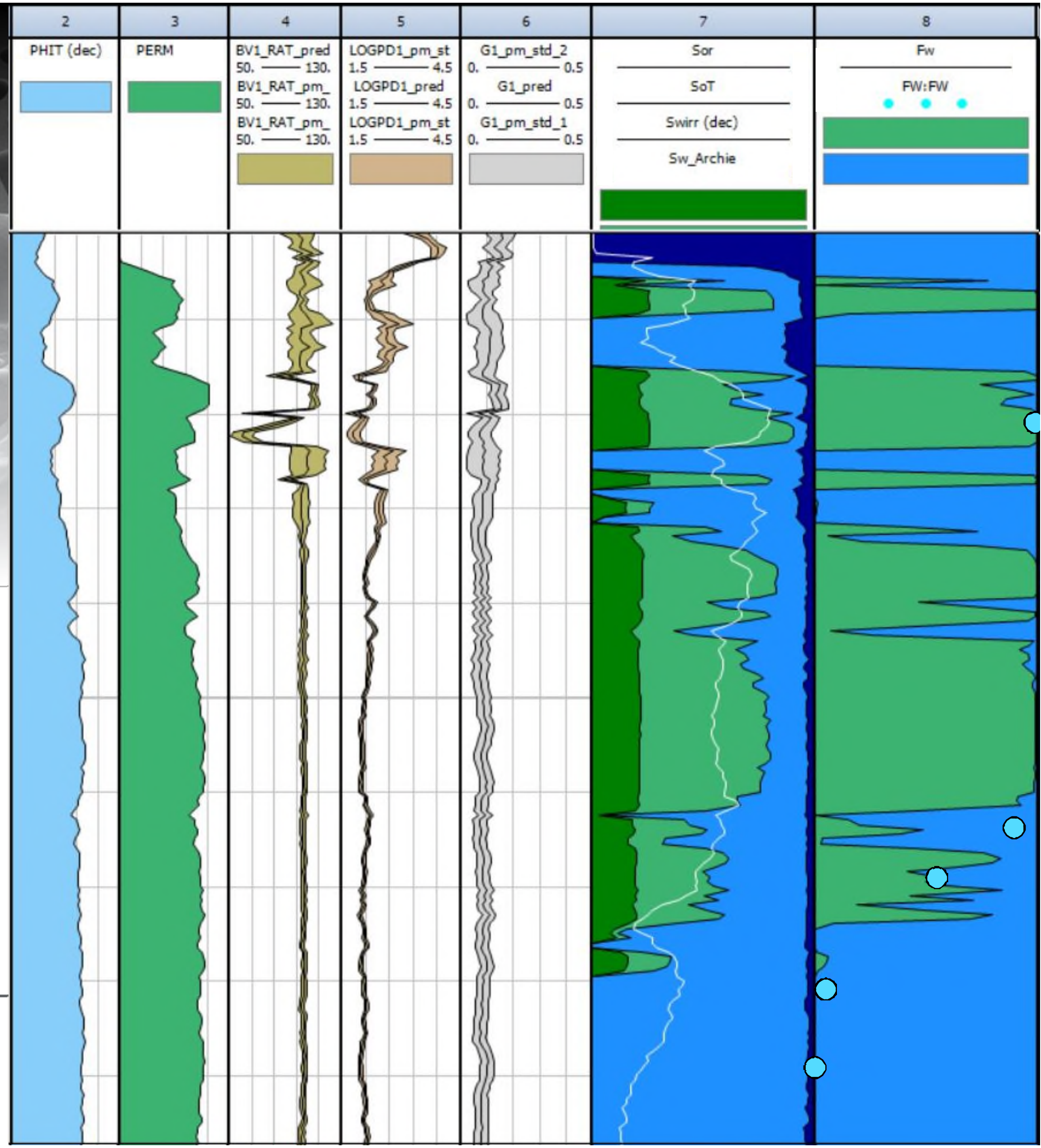


Optimization under Constraint

CASE #2

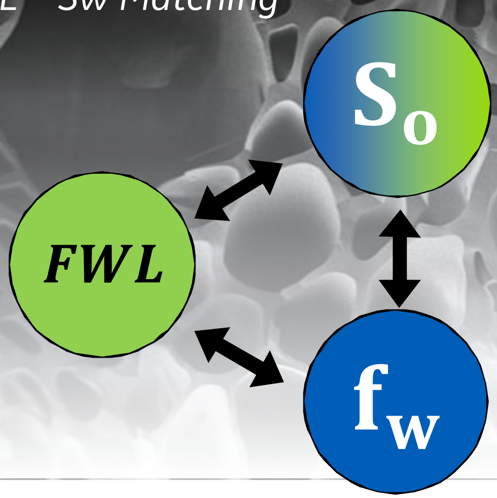
- **Match the Fw from formation sampling**
- **While honoring the Sw deflection *despite an ROZ*** *(remaining oil zone)*

BAKER HUGHES a GE company



MultiPhase Flow Petrophysics

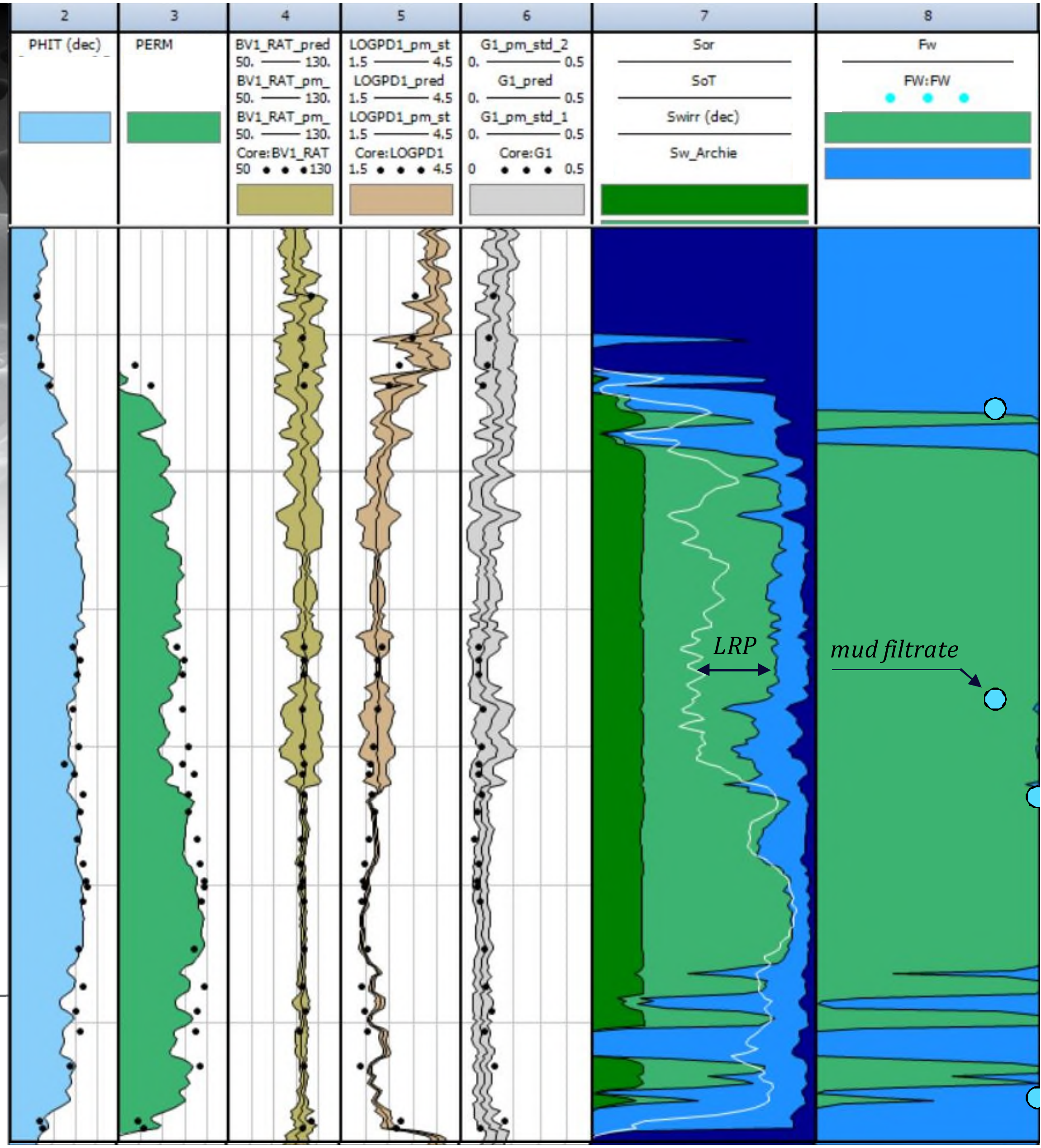
Fw – FWL – Sw Matching



Optimization under Constraint

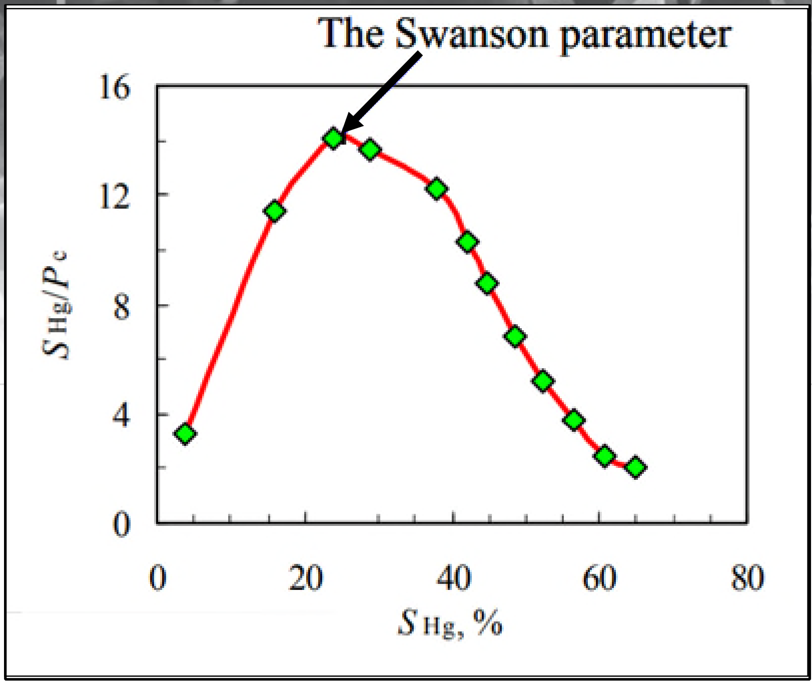
CASE #3

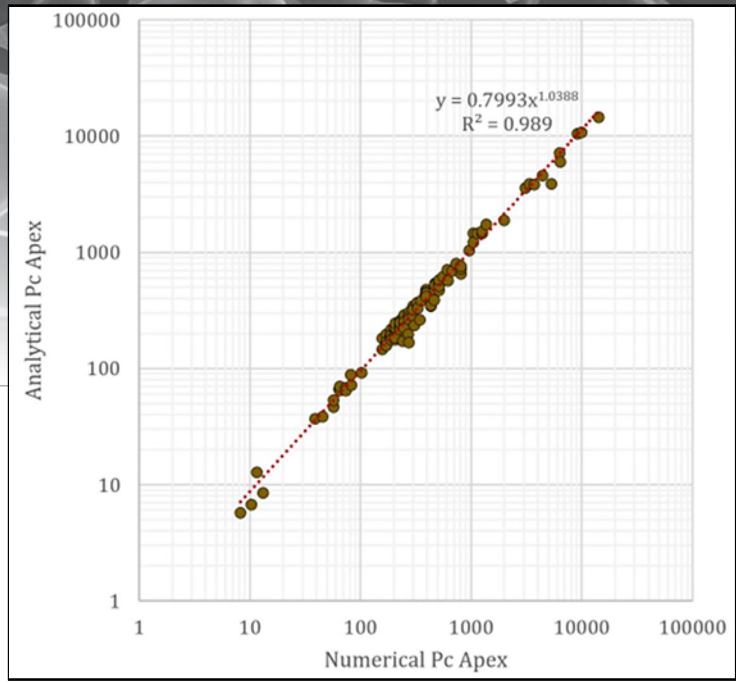
- **Match the Fw from formation sampling**
- **While honoring an ODT**



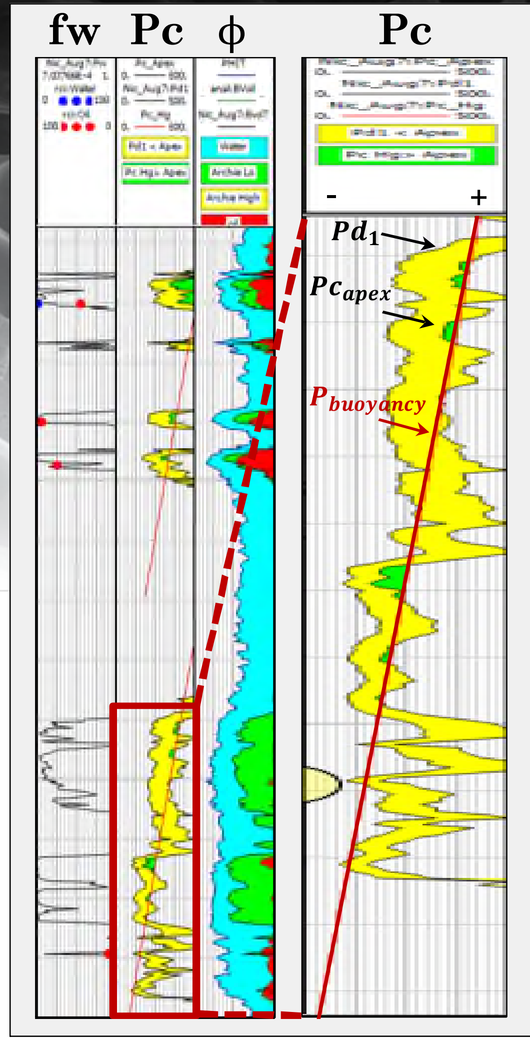
MultiPhase Flow Petrophysics

Using the Swanson Apex Heuristics





$$P_{c,apex} \approx 2P_{d_1} e^{-\frac{\sqrt{G_1}}{2}}$$



Wrap-up

A physics-based approach for real-time in-situ Sw in LRP

- **No full proof logging solution for OH in-situ Sw determination in non-Archie rocks on the market. Only indirect methods.**
- **The proposed approach has a well-defined domain of applicability is physics-driven, forward-modelling and has the potential to be applied real time.**
- **The NMR-based Sw processing provides in-situ water saturation, associated uncertainties as well as a single-phase producibility index.**
  However, Sw only does not guarantee producibility
- **The combination with Formation Sampling enables to de-risk compartmentalization and fluid typing challenges, calibrate NMR permeability while providing real-time multi-phase flow petrophysics actionable results.**

BAKER HUGHES a GE company

Take Away

A physics-based approach for real-time in-situ Sw in LRP

- **No full proof logging solution** for OH in-situ Sw determination in non-Archie rocks on the market. Only indirect methods.
- The proposed approach has a well-defined domain of applicability is **physics-driven**, forward-modelling and has the potential to be applied real time.
- The NMR-based Sw processing provides in-situ water saturation, associated uncertainties as well as a single-phase producibility index.
  However, **Sw only does not guarantee producibility**
- The combination with **Formation Sampling** enables to de-risk compartmentalization **and** fluid typing challenges, calibrate **NMR** permeability while providing real-time multi-phase flow petrophysics actionable results.

BAKER HUGHES a GE company