The Permian Basin Prototype Super Basin

Permeability Measurement & Modeling for Source Rock Mudstones

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Core Lab®

RESERVOIR OPTIMIZATION

Introduction

- Conventional permeability measurements on whole core samples have evolved to include accurate measurements on lower permeability, nanodarcy samples. In conventional quality reservoirs, measurement techniques transitioned from steady-state to unsteady state. However, in unconventional reservoirs the majority of permeability measurements are conducted on disaggregated samples using unsteady-state techniques, closely following SPE 26633 Luffel et. al., 1993. These methods have now evolved to include measurements on full plug samples at an appropriate reservoir net confining stress, something that was previously not possible.
- Evaluation of mudstone reservoirs requires a new set of analytical methods and core to log models. Early permeability modeling in source rock mudstones used GRI (crushed rock) data to model Km(eff) by combining core porosity/permeability relationships and the porosity log model. These early models were appropriate for a single formation or producing interval. Later models handled multiple zones by using Vclay cutoffs. These models became increasingly granular and were able to model both effective and absolute permeability. However, they were most effective in the mudstones, but less resilient in carbonates. Current models employ 3D surfaces to model both mudstones and non-mudstones with equal precision.
- Current petrophysical modeling efforts are focused on (1) regional petrophysical models where core data is absent, (2) pressure modeling in complex, compartmentalized reservoirs found in the Delaware Basin, and (3) predicting mobile water.

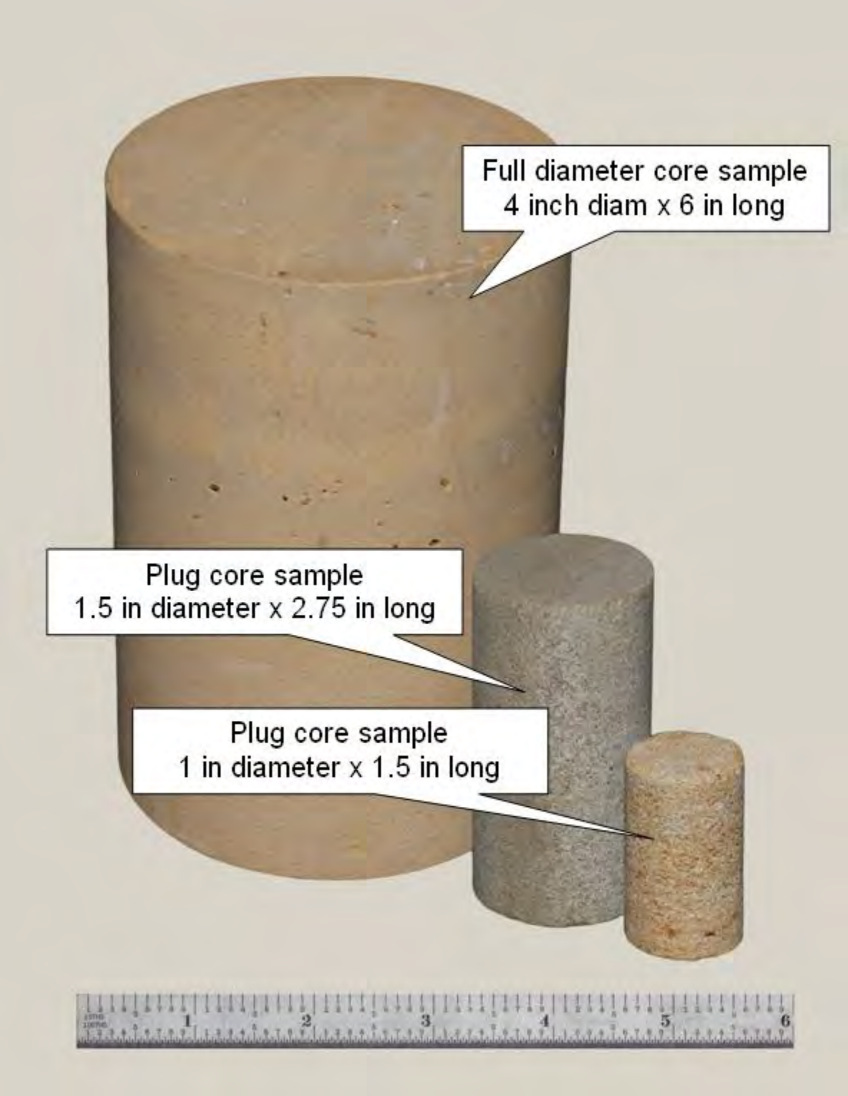
Permeability – Summary

- A primary objective of Core Analysis is to characterize the end point, or 'absolute', permeability.
- Additional measurements are required to study how permeability may vary at reservoir conditions.
- A primary objective of core-log integration is to develop a model to predict permeability from log responses.

Factors Affecting Permeability

- Inertial or Rate Effects
- Klinkenberg Slippage
- Net Confining Stress (NCS)
- Flowing Phase
- Qv & Salinity
- Secondary Phase Saturation & Direction of Saturation Change

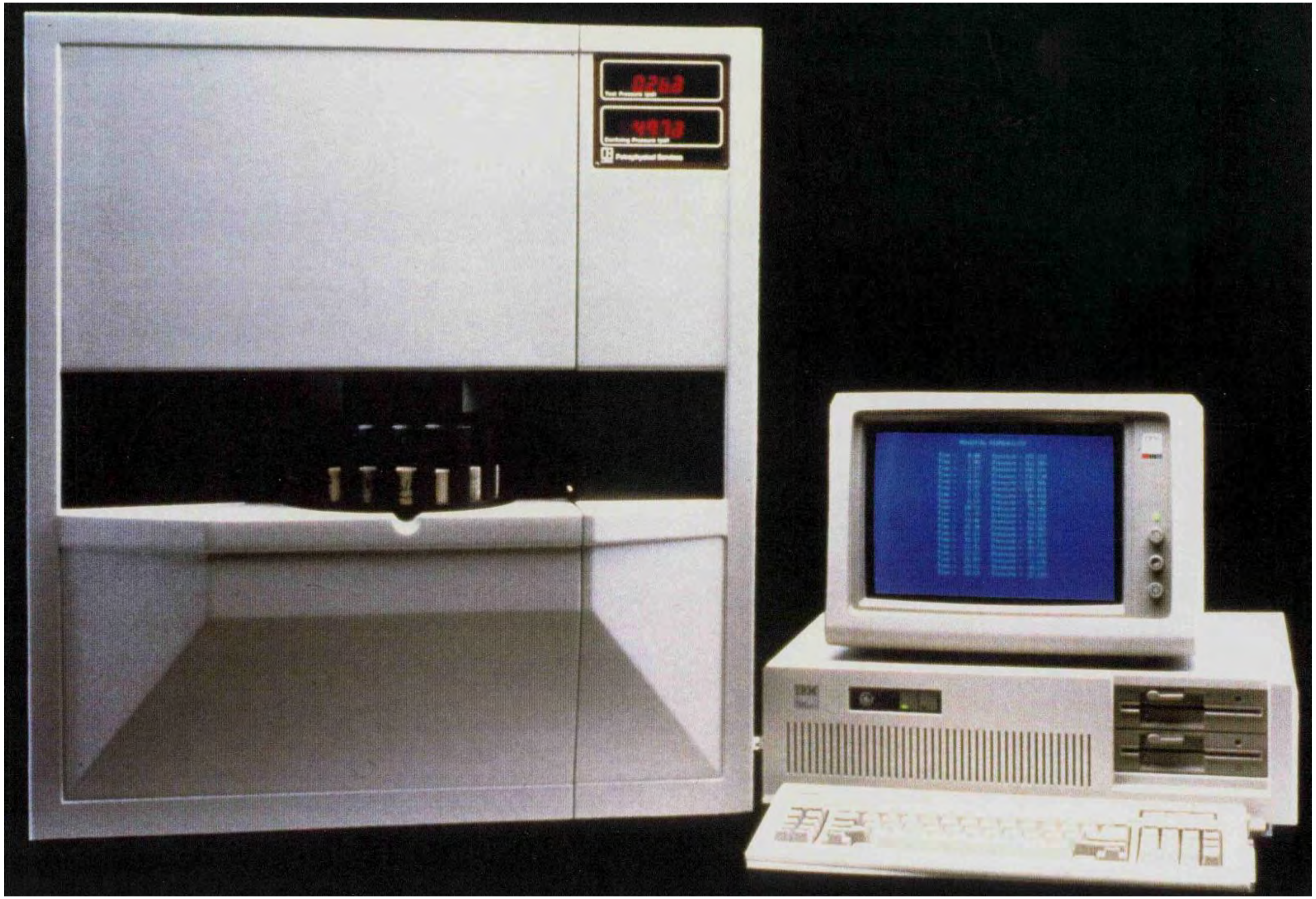
Example Core Sample Sizes



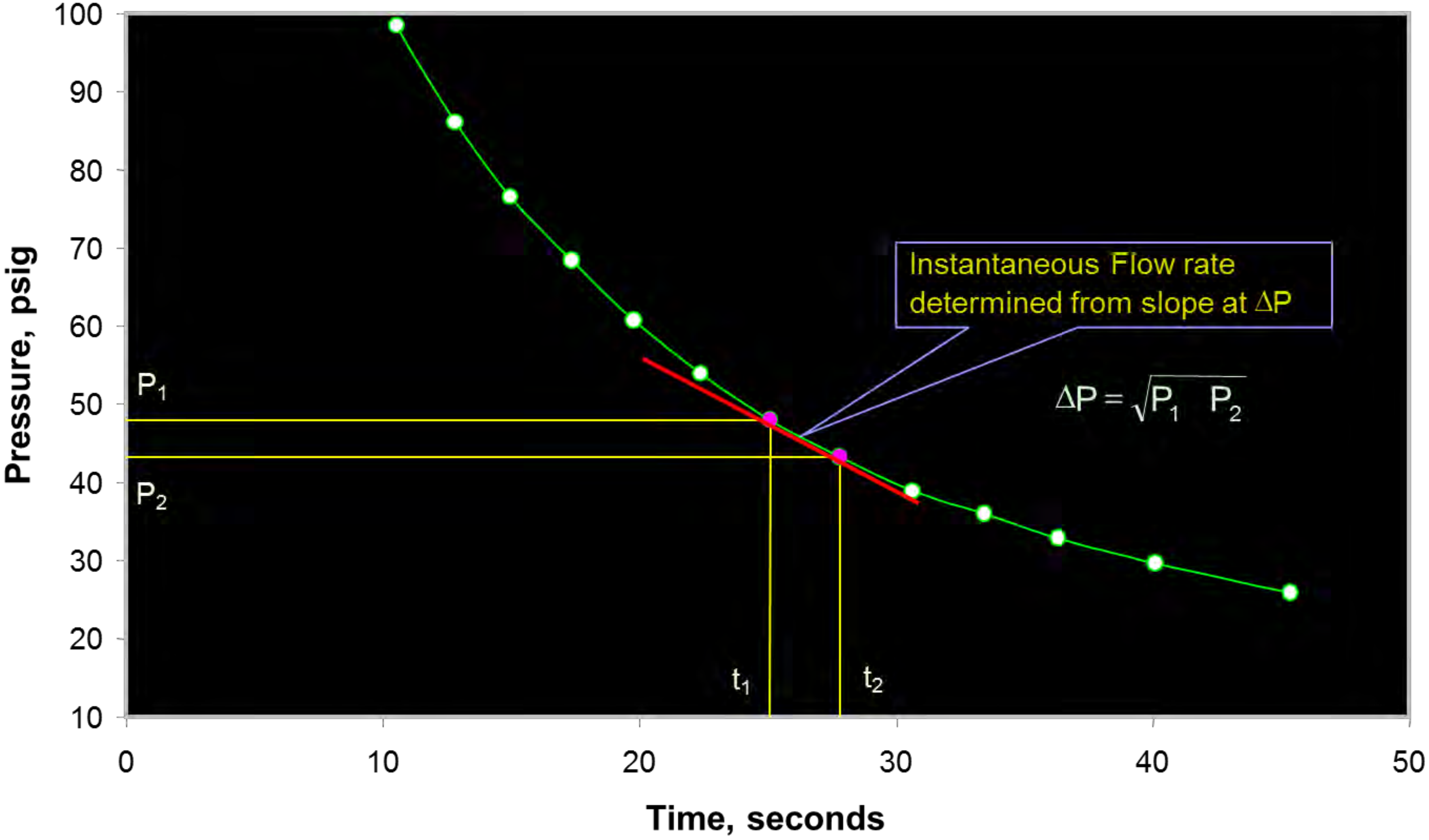
Core Sample Sizes			
Core Sample	Diameter, in	Displayed Length, in	Common Lengths, in
Full Diameter*	4	6	4 to 12
1.5" od Plug	1.5	2.75	1.5 to 3
1" od Plug	1	1.5	1 to 2.5

* diameter dependent on coring hardware

CMS-300™: An Automated Klinkenberg Permeameter - Porosimeter



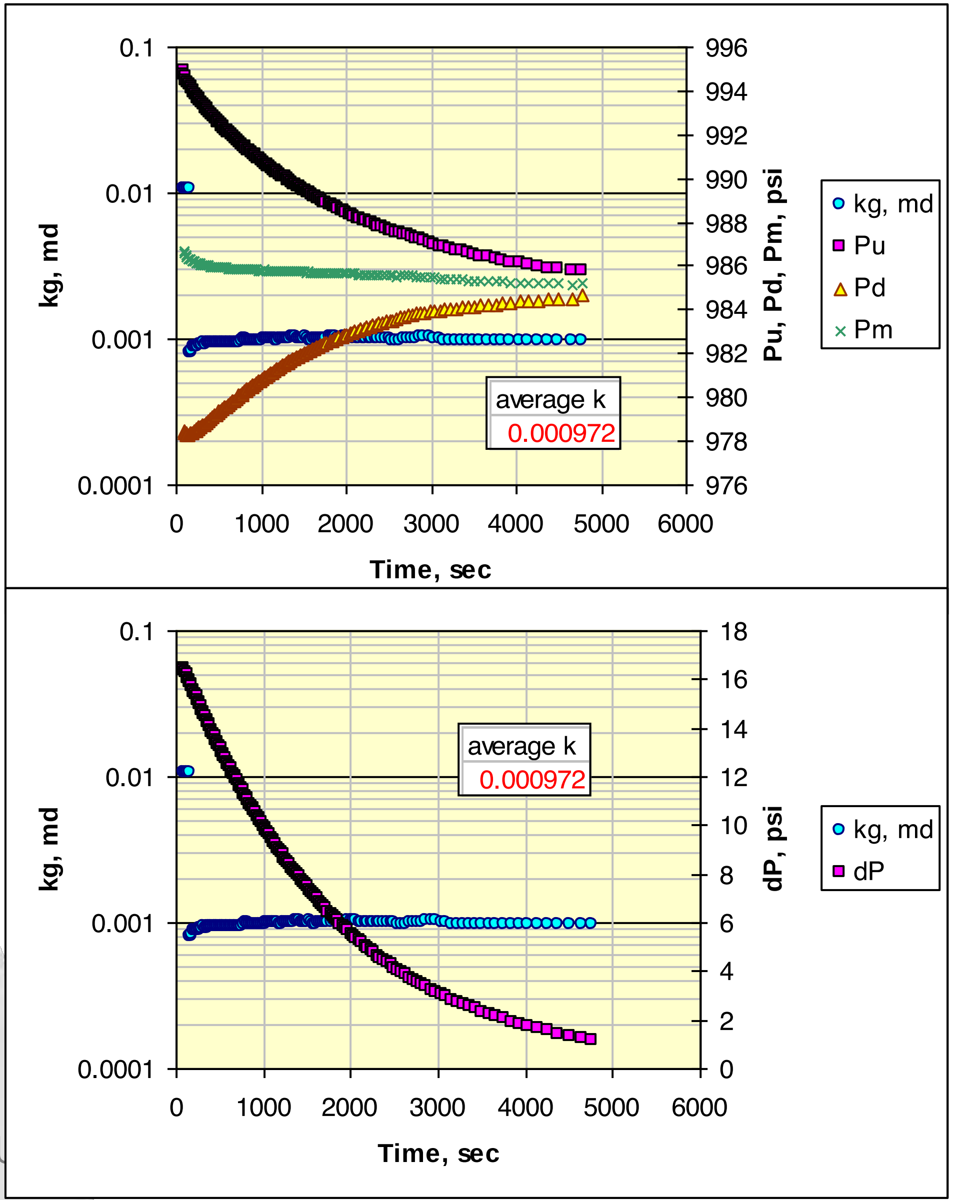
Pressure Transient (Falloff) Data for Permeability Parameters (range 30,000 md to 0.001 md)



Comparison of Kair to K∞ Typical Values (Core Lab. training manual up to 2013)

Air Permeability, md	Klinkenberg Permeability, md	Ratio of k∞/ka
0.18	0.12	0.66
1	0.68	0.68
10	7.8	0.78
100	88	0.88
1,000	950	0.95

Pulse Decay Permeability Data



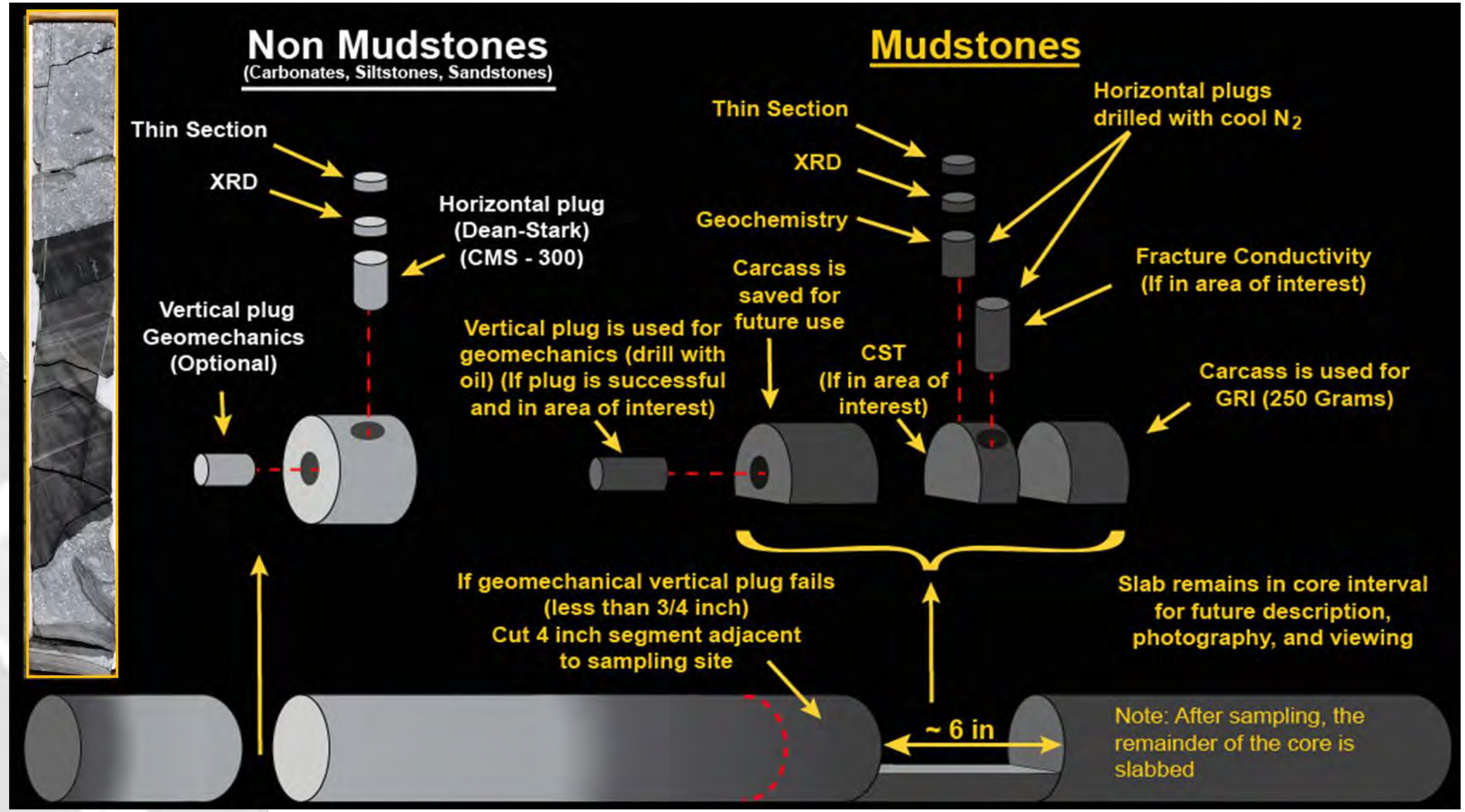
METHOD ADVANTAGES

- Rapid, accurate
- Practical kg range: 0.1 to 0.00001 md
- Slip minimized at 1000+ psi P_{mean}
- Very low ΔP:
  - Minimized inertial effects
  - No alteration of Sw
- Very low net stress gradient
- Ideal for effective kg@Sw

Crushed Sample

- 20-35 U.S. Mesh
  - Coarse sand size
  - 0.0335" to 0.0197"
  - 0.85 to 0.5 mm
- 50 grams
  - Matrix permeability (km)
- 100 grams
  - Total porosity
  - Grain density
  - Saturations

Measured Rock Properties
Reservoir Core Analysis: Hybrid Reservoirs



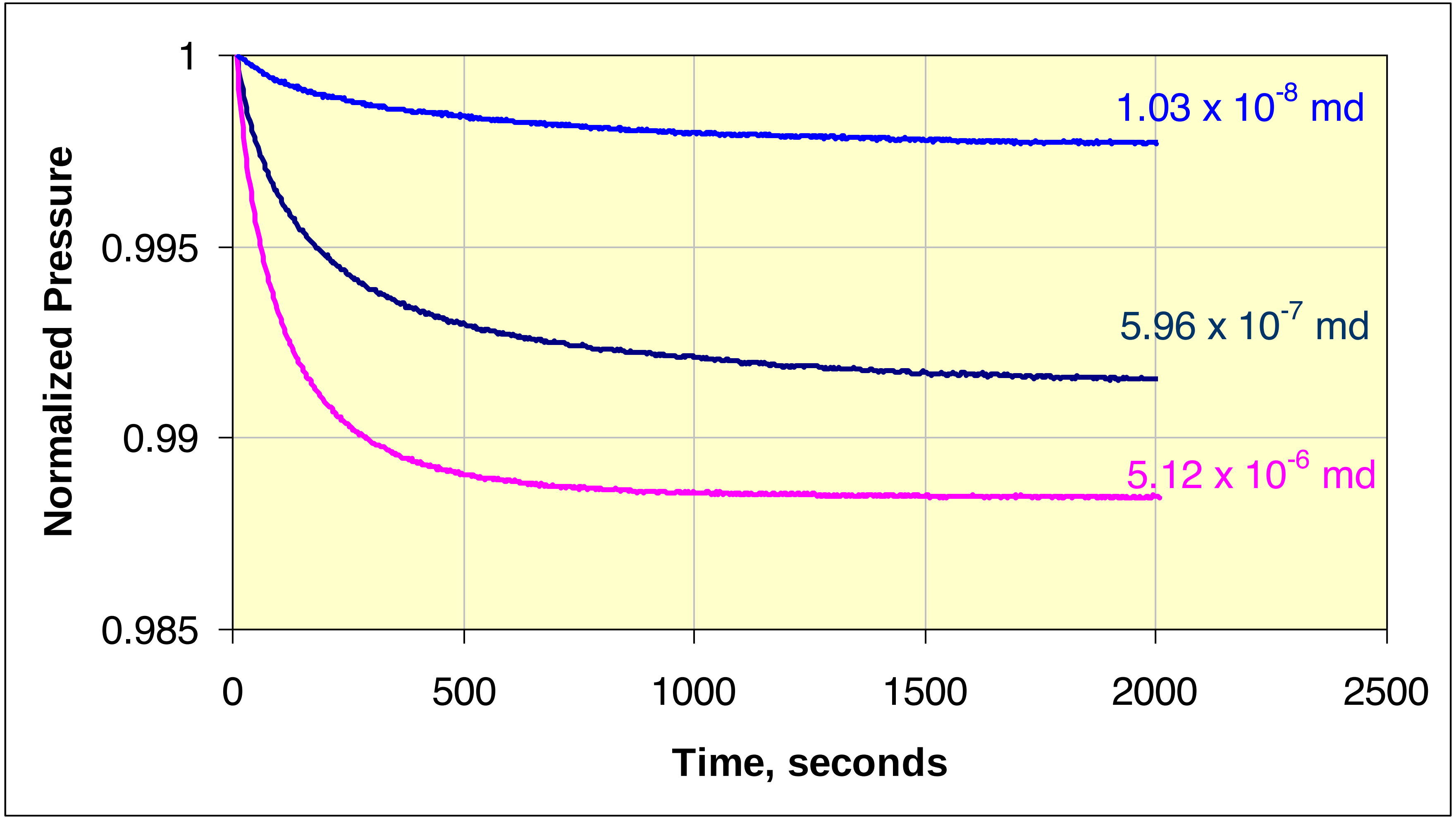
- Petrographic analysis
- XRD - Bulk and Clay Analysis
- AIM-SEM
- TOC
- Absolute Permeability
- Effective Hydrocarbon Porosity

GRI Process Details
Matrix Permeability, km (SPE 26663)

- Equipment
  - Boyle's Law Matrix Cup device
- Experiment
  - 30 cm^3 helium at 200 psig expanded to sample chamber
  - Pressure-time data recorded for up to 2000 seconds
- History match yields effective permeability
  - Input
    - Weight & bulk density
    - Gas-filled porosity
    - Pressure-time data

SPE 26633, Luffel et al, 1993

Matrix Permeability, km
Pressure vs Time

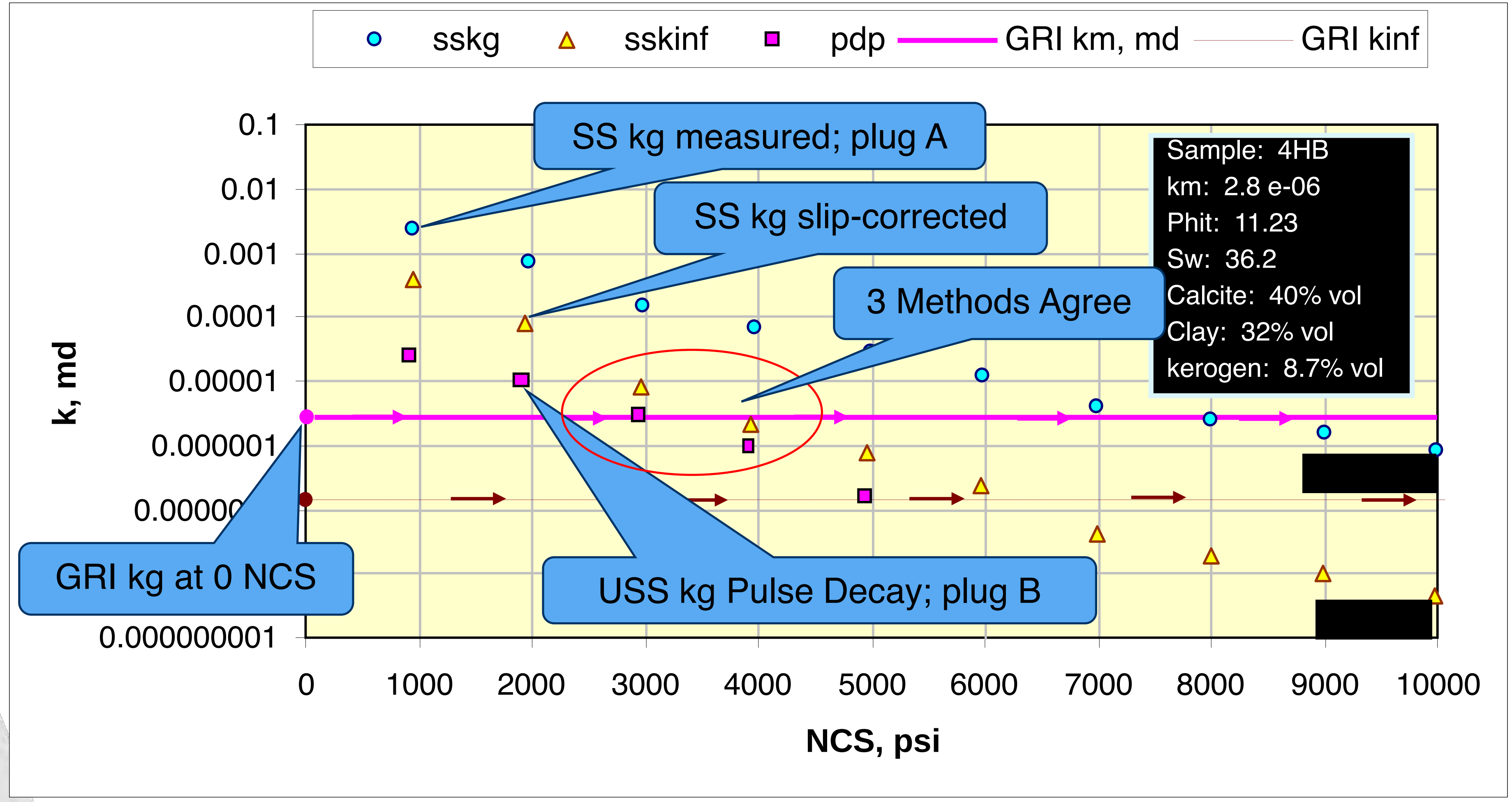


Comparison of Kair to K∞ Typical Values (2016)

Air Permeability, md	Klinkenberg Permeability, md	Ratio of k∞/ka
0.0001	0.000007	0.07
0.001	0.00013	0.13
0.01	0.0024	0.24
0.1	0.05	0.50
1	0.68	0.68
10	7.8	0.78
100	88	0.88
1,000	950	0.95

Gas Shale Services
Permeability Comparisons

(Upper Eagle Ford Example)



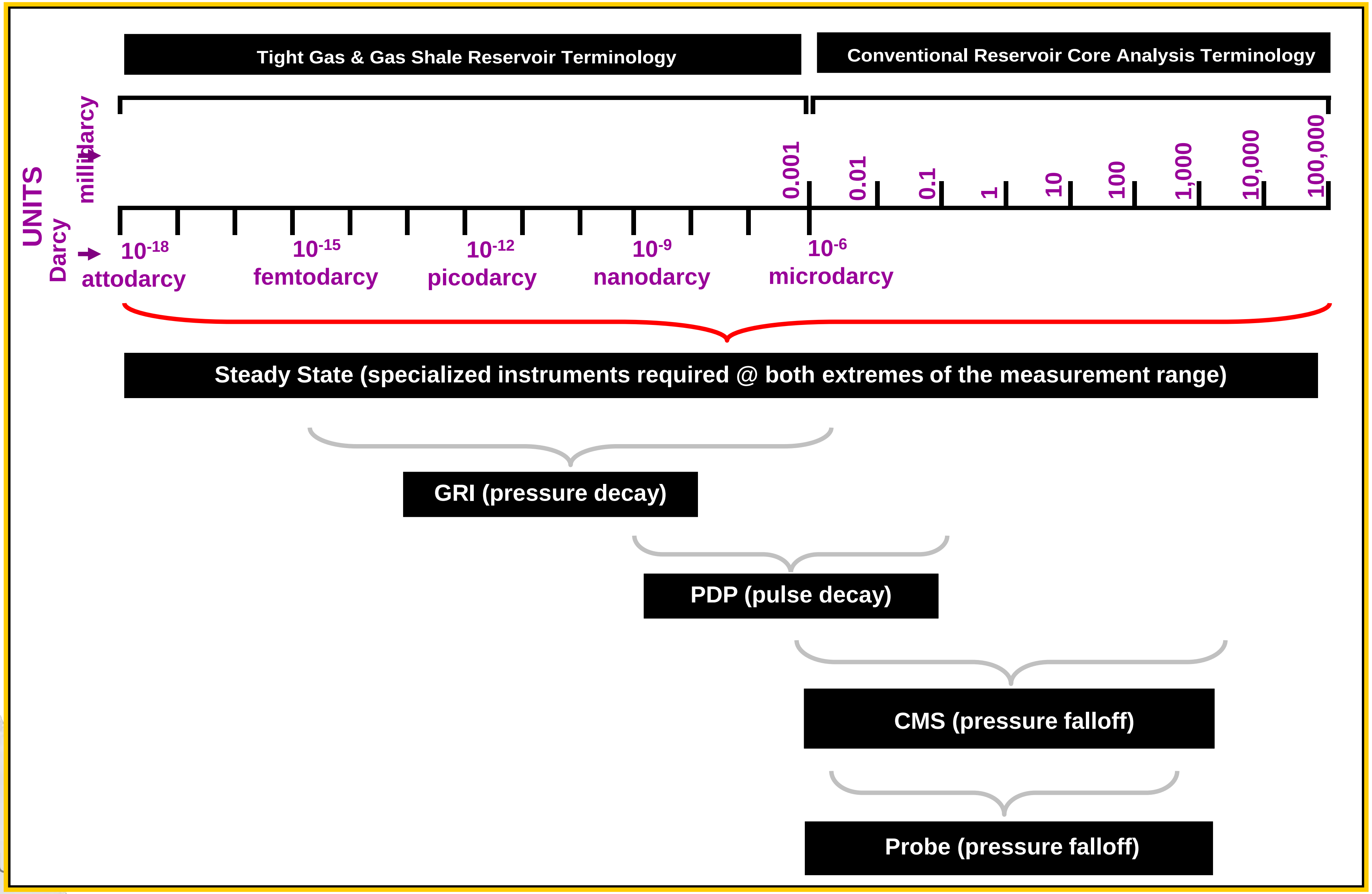
Effect of Stress on Permeability
Steady-State Nano-Permeameter

- Upstream Pressure (P_1) ~ 32 psig
- Downstream Pressure (P_2) ~ 0 psig
- Gas Used: Nitrogen
- Net Confining Stress (NCS) to 10,000 psi
- Typically 3 measurements per NCS
- Effective or Absolute Permeability
- Kinf from multi-point kg vs 1/Pm

$$K_g = \frac{2000\, P_a\, \mu\, Q\, L}{(P_1^2 - P_2^2)\, A}$$

K_{air} = Permeability, millidarcies
Q_a = Flow rate, cm3/sec, at Pa
μ = Viscosity of air, cp
L = Length of sample, cm
A = Cross sectional area of sample, cm^2
P_1 = Upstream pressure, atm
P_2 = Downstream pressure, atm
P_a = Atmospheric pressure, atm

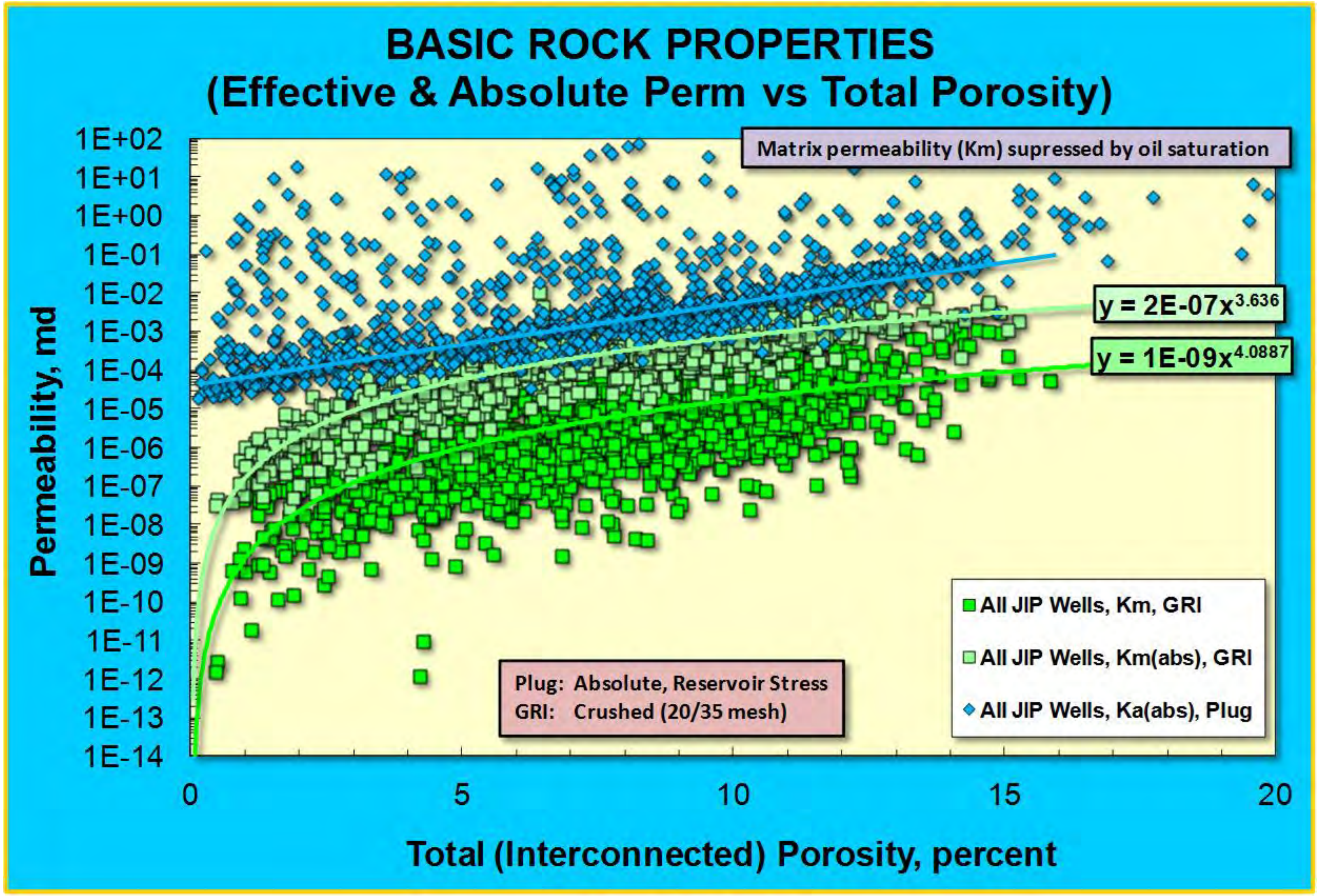
Permeability Comparisons



Core-Log Petrophysical Modeling

- Goal is to calibrate downhole logs with measured core data.
- Develop a model(s) for key reservoir properties (e.g. porosity, water saturation) that can be applied to uncored intervals or non-cored wells.
- Source rock mudstone reservoirs pose a challenge to the industry since they can not be adequately modeled with traditional techniques developed for conventional reservoirs.
- Conventional models are developed for milidarcy to darcy rock and cannot adequately model nanodarcy permeabilities.
- Hence empirical, mudstone-specific models have been developed.

Measured Rock Properties



Early Models – Single Producing Interval

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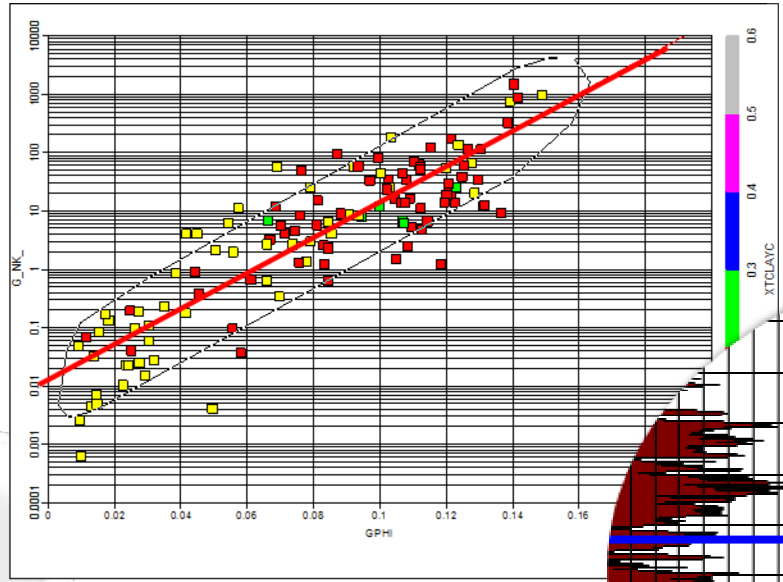
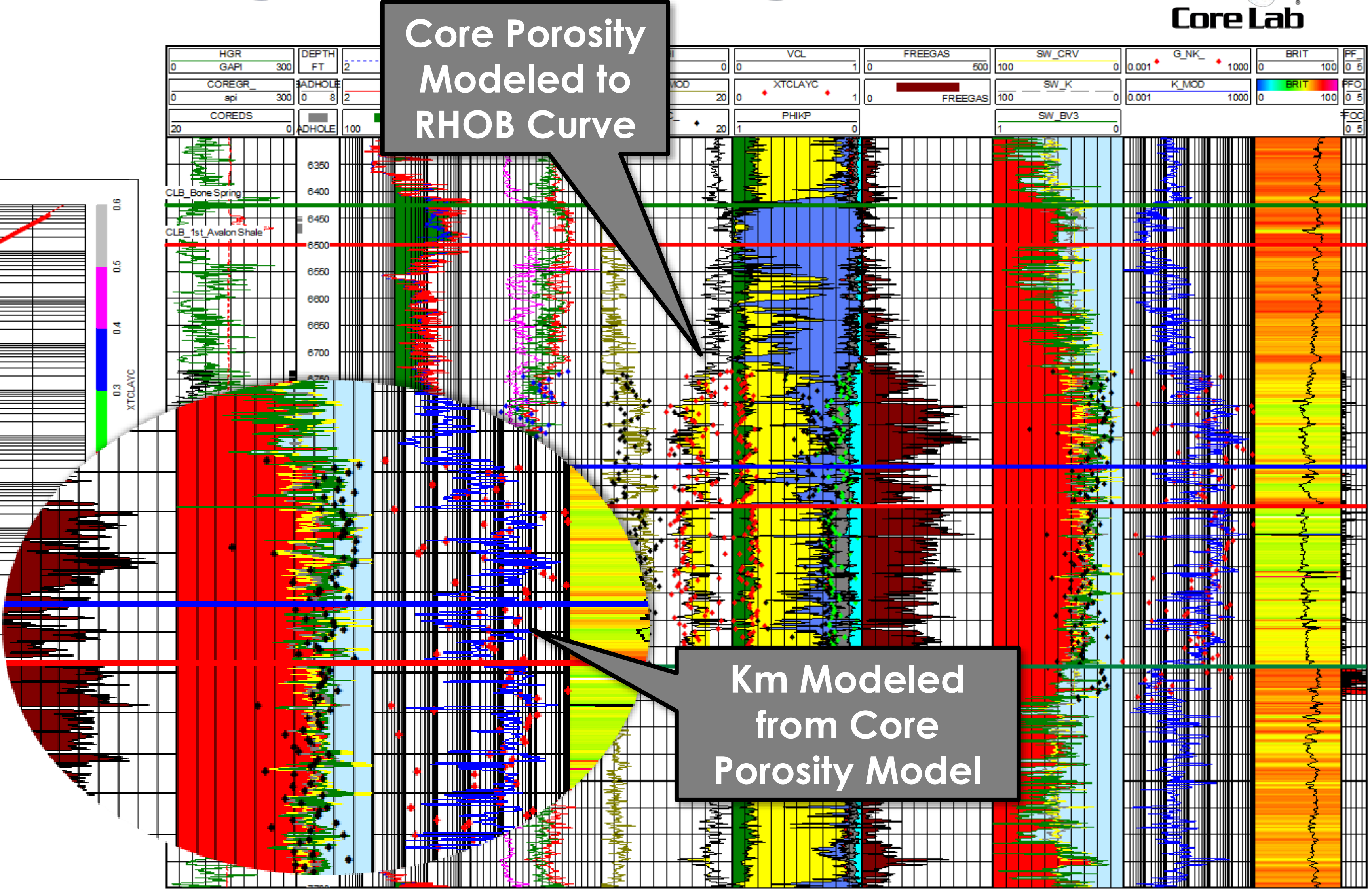
GRI EFFECTIVE PERMEABILITY (nD

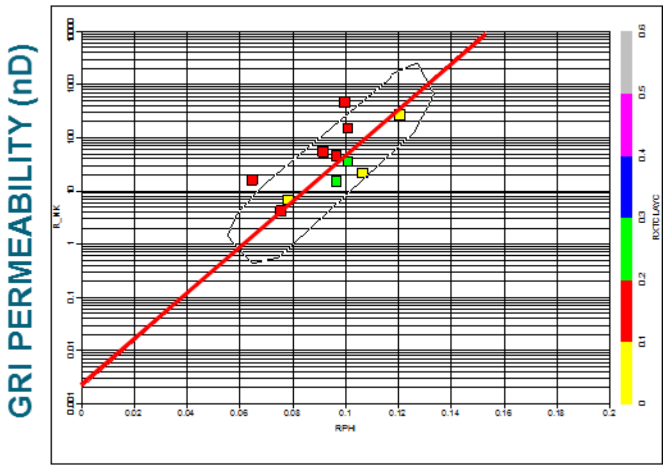


GRI POROSITY



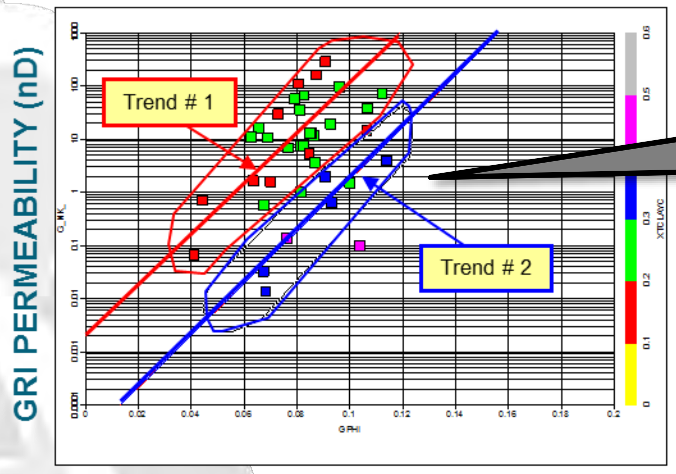
Later Models – Multiple Intervals

Avalon Shale

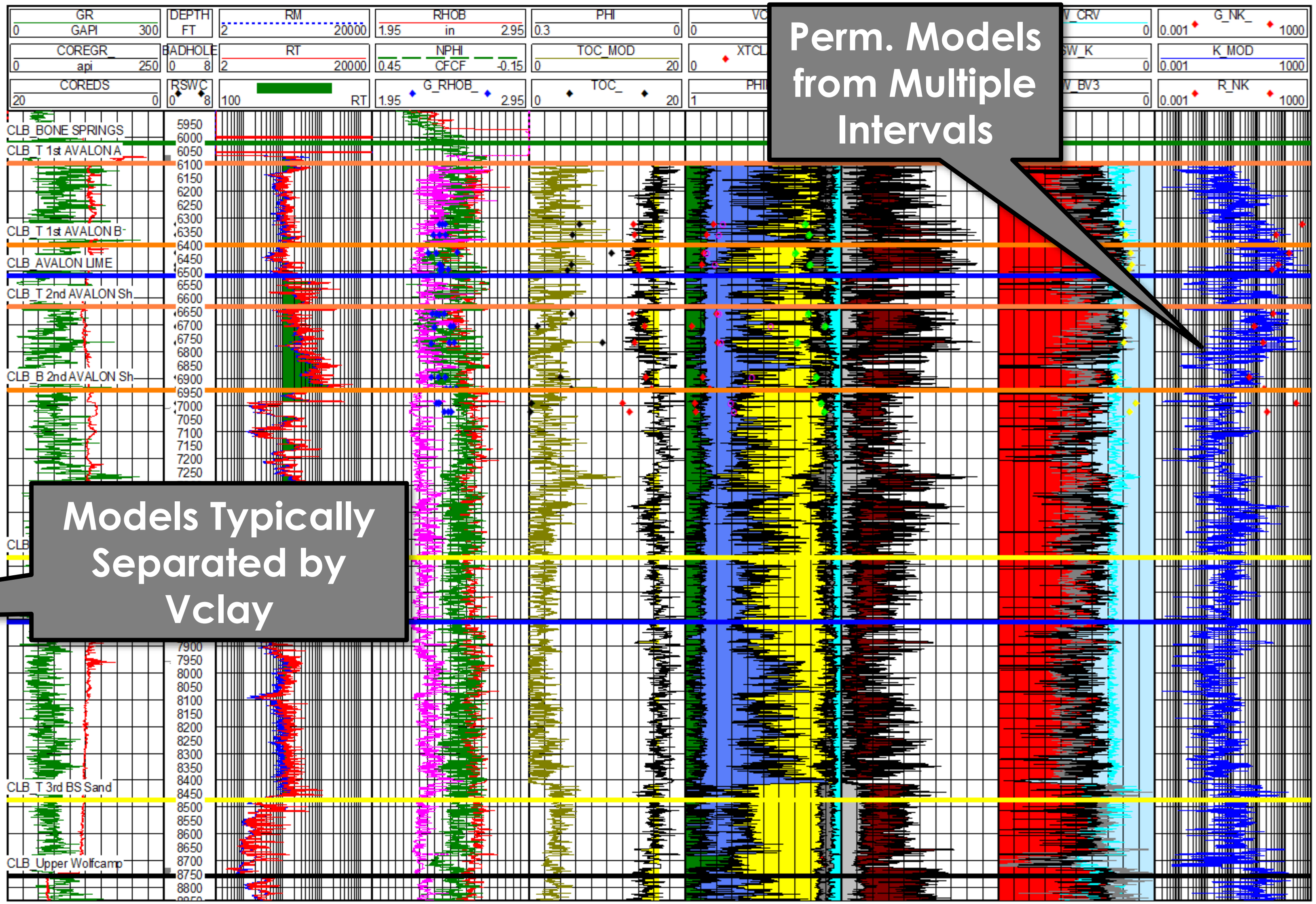


GRI POROSITY

3rd Bone Spring/Wolfcamp



GRI POROSITY



Later Models – Km_{abs} & Km_{eff}

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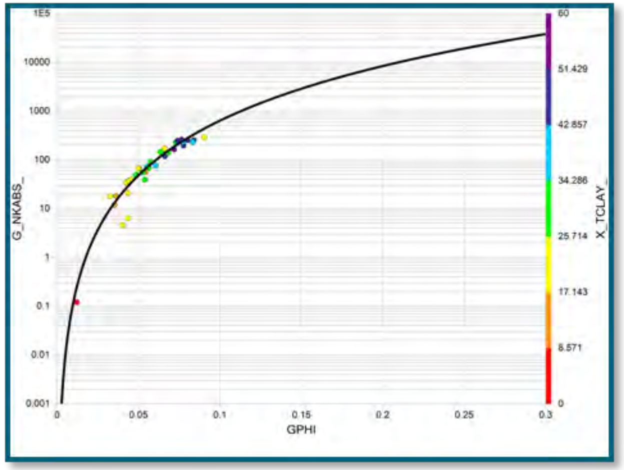
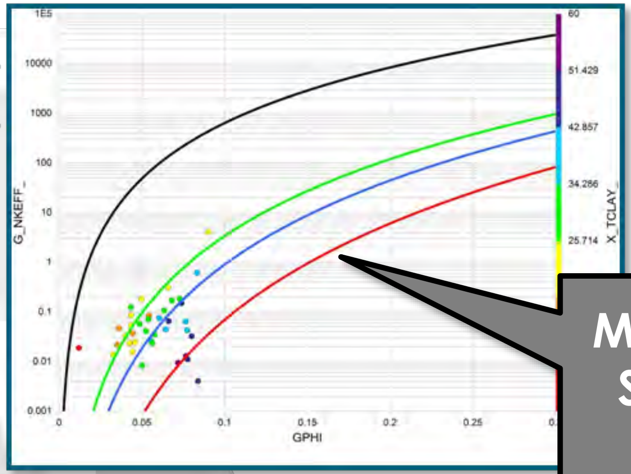
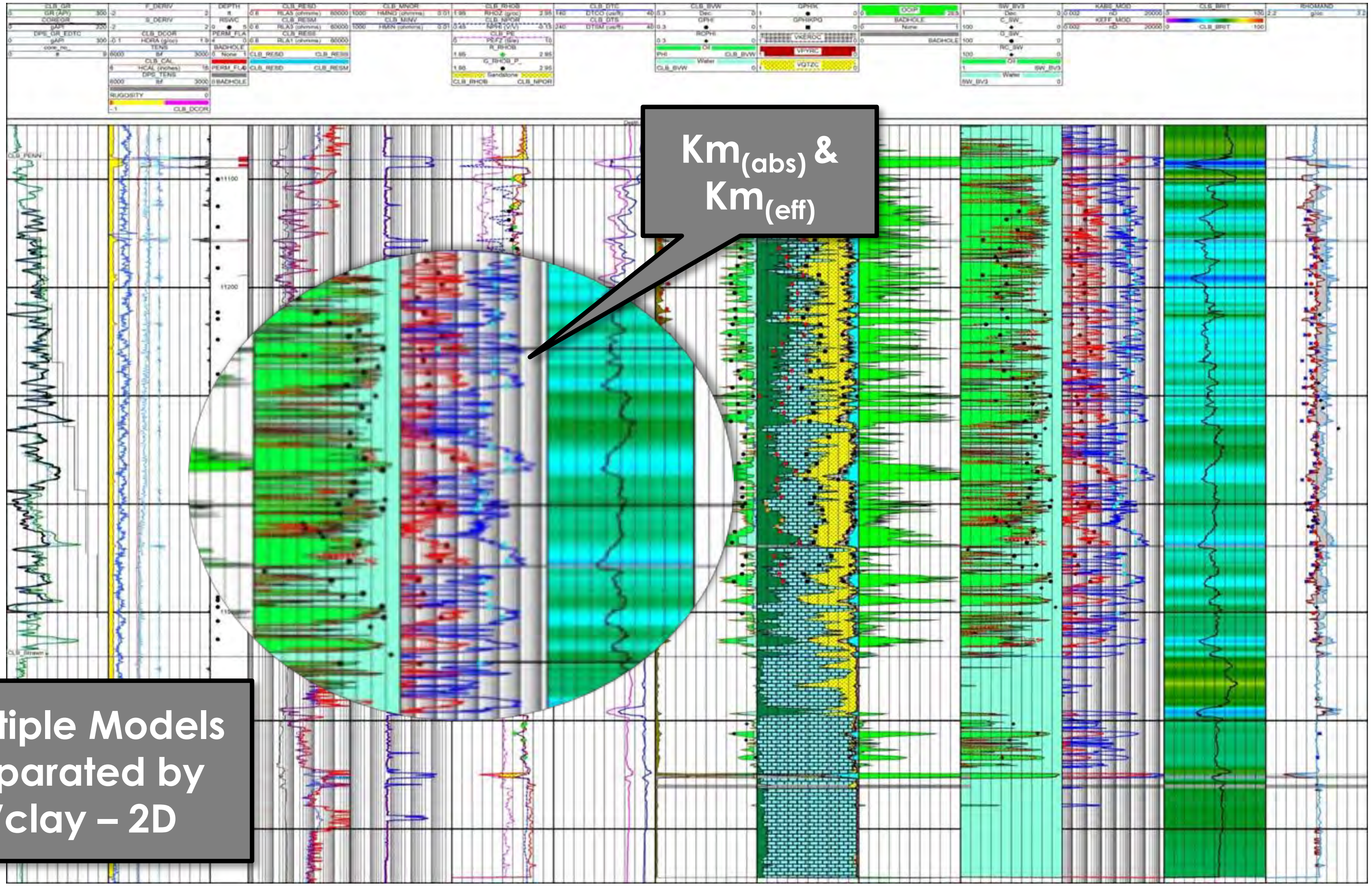
ABSOLUTE PERMEABILITY (nD)



EFFECTIVE PERMEABILITY (nD)

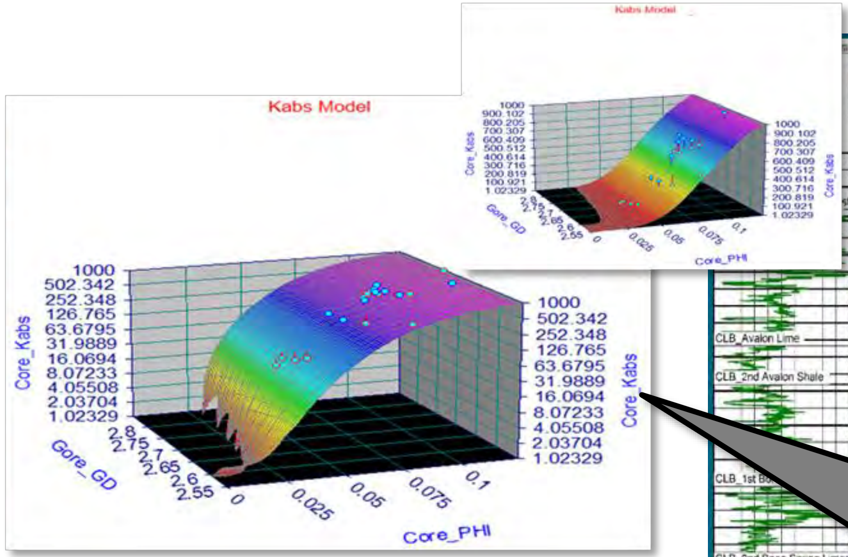




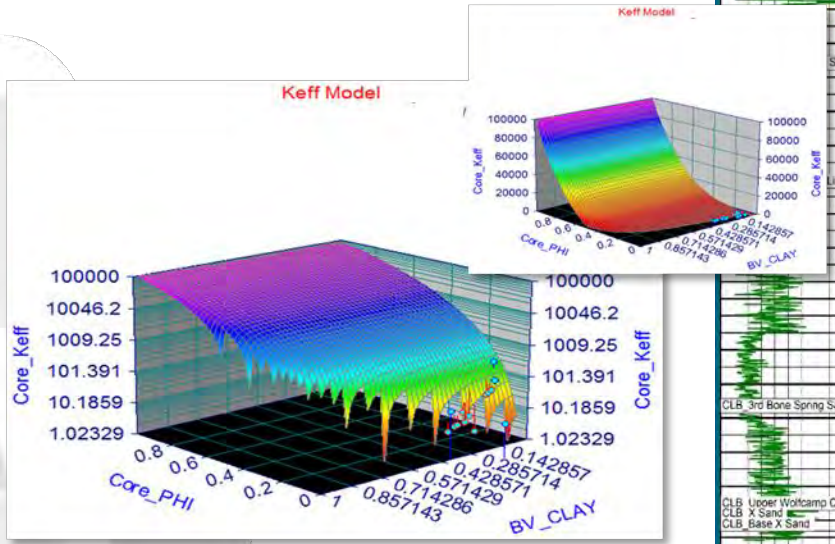
Multiple Models Separated by Vclay – 2D

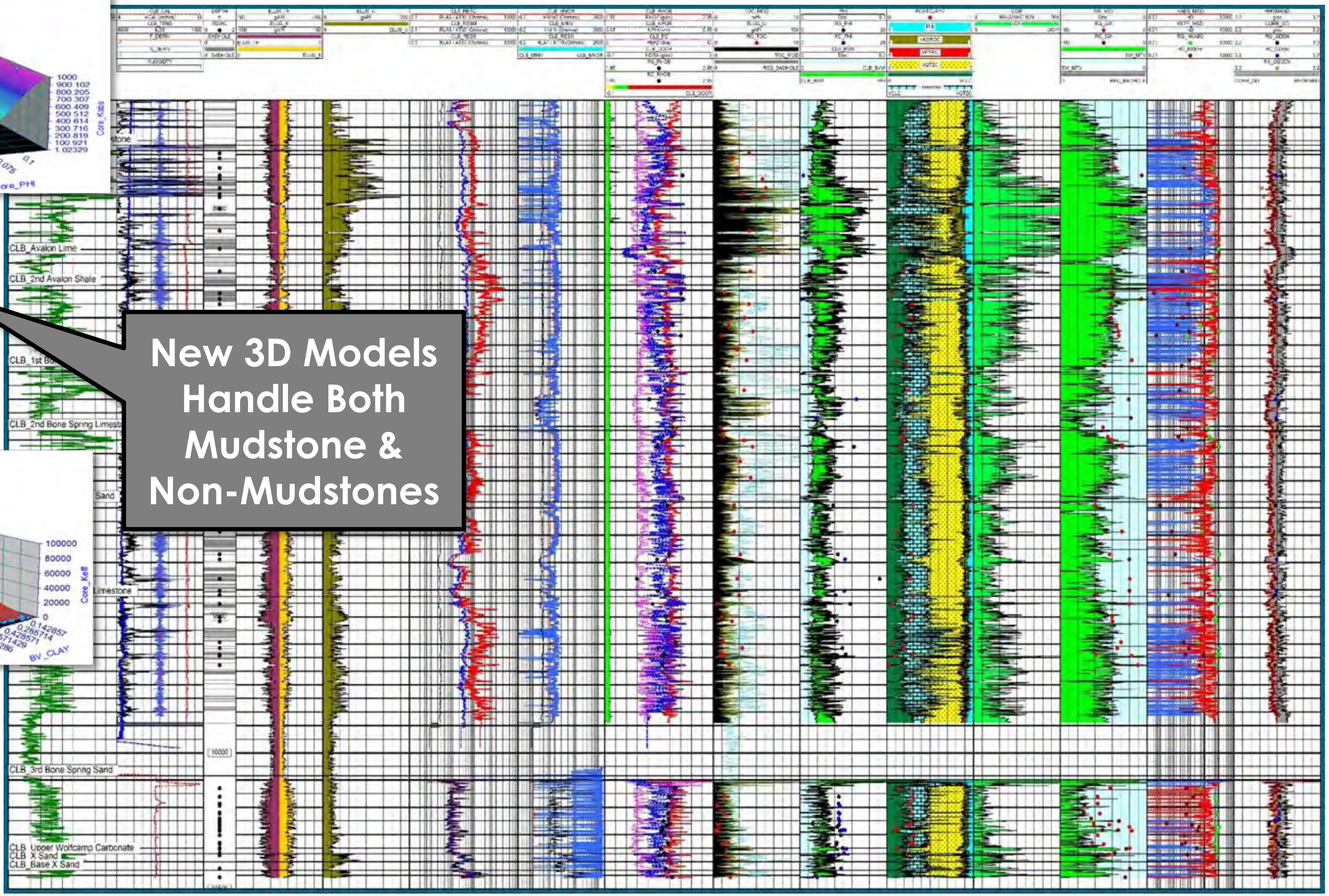
Later Models – 3D Models

ABSOLUTE PERMEABILITY (nD)



EFFECTIVE PERMEABILITY (nD)





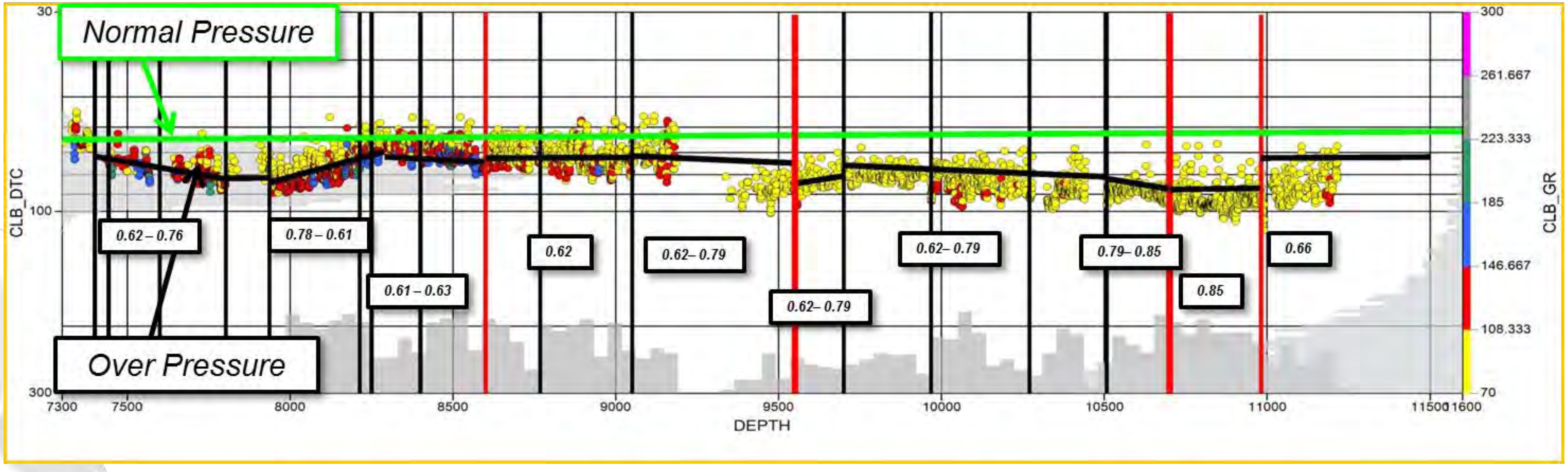
New 3D Models Handle Both Mudstone & Non-Mudstones

What Does the Future Hold?

- Regional Petrophysical Modeling.
- Use an aggregate of core-calibrated log models to model a specific formation (e.g. Wolfcamp or Bone Spring).
- Useful where rock data is sparse or absent – almost all wells are logged, few are cored.
- Only needs logs, so a comprehensive petrophysical interpretation can be made prior to completion to define:
  - Best porosity/TOC intervals
  - Lowest Sw
  - Potential frac. barriers

What Does the Future Hold?

- Pressure modeling in structurally compartmentalized basins – Delaware Basin.



What Does the Future Hold?

- Mobile water prediction to avoid zones with higher water cut.