Using Advanced Logging Measurements to Develop a Robust Petrophysical Model for the Bakken Petroleum System*

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Abstract

The Bakken petroleum system (BPS) can be considered a hybrid play because it is composed of both conventional and unconventional elements. The conventional aspects include the presence of separate reservoir intervals (Scallion, Middle Bakken, Sanish and Three Forks) and source rock intervals (Lower Bakken and Upper Bakken shales), along with more problematic intervals (Basal Bakken). This is in direct contrast to most unconventional shale plays, in which a single lithologic or stratigraphic interval comprises both the source rock and reservoir. The unconventional aspects of the BPS include very low permeability conventional reservoir sections, as well as combined shale-rich source and reservoir intervals. Additional complexity results from stacked depositional environments with significant variations in lithofacies, mineralogy, total organic carbon (TOC), and rock textures ranging from highly bioturbated to finely laminated.

Historically, development programs and petrophysical analyses in the Bakken were centered on a volume of shale calculated via deterministic models using triple combo log data that were focused primarily on the Middle Bakken reservoir. Production type-curves generated from such analyses showed reservoir recovery factors that were inconsistent with actual production data as well as knowledge of the reservoir. Additionally, rock mechanical properties used to model hydraulic fracturing performance and real-time measurements of microseismic events recorded during hydraulic fracturing indicated fracture height growth that extended into surrounding formations.

Based on these results, a series of science wells were drilled, cored over the entire BPS and logged extensively using advanced logging devices to better understand the overall system. Results from these wells provide a basis to refine production type curves and to re-calculate stock-tank oil originally in-place (STOOIP). The formation evaluation program consisted of conventional triple combo logs supplemented with advanced downhole measurements including: (1) triaxial resistivity for thin-bed analysis; (2) nuclear magnetic resonance for porosity, free fluid and kerogen identification; (3) dielectric dispersion for water saturation; (4) geochemical spectroscopy for mineralogy and total organic carbon

(TOC); and (5) dipole sonic for dynamic rock properties. Petrophysical models were developed using both deterministic and probabilistic methods to integrate the measurements acquired for analysis of porosity, saturation, and mineralogy, and describing the hydrocarbon production potential of the BPS more accurately. The advanced evaluation results will enable the development of computation models in areas of the basin where only minimal logging suites, such as triple combo logs exist as data. Petrophysical models that encompass the entire BPS will be the basis for updated STOOIP calculations that can be used to revise production-type curves and improve confidence in estimated recovery factors that have better agreement with measured production results.

Reference

Gary A. Simpson, G.A., J. Hohman, I. Pirie, and J. Horkowitz, 2015, Using advanced logging measurements to develop a robust petrophysical model for the Bakken petroleum system: SPWLA-2015-Z, Society of Petrophysicists and Well-Log Analysts, SPWLA 56th Annual Logging Symposium, July 18-22, 2015, 24p. Website accessed May 11, 2016, https://www.onepetro.org/conference-paper/SPWLA-2015-Z.

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PRESENTS

USING ADVANCED LOGGING MEASUREMENTS TO DEVELOP A ROBUST PETROPHYSICAL MODEL FOR THE BAKKEN PETROLEUM SYSTEM

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Iain Pirie, Jack Horkowitz, Schlumberger

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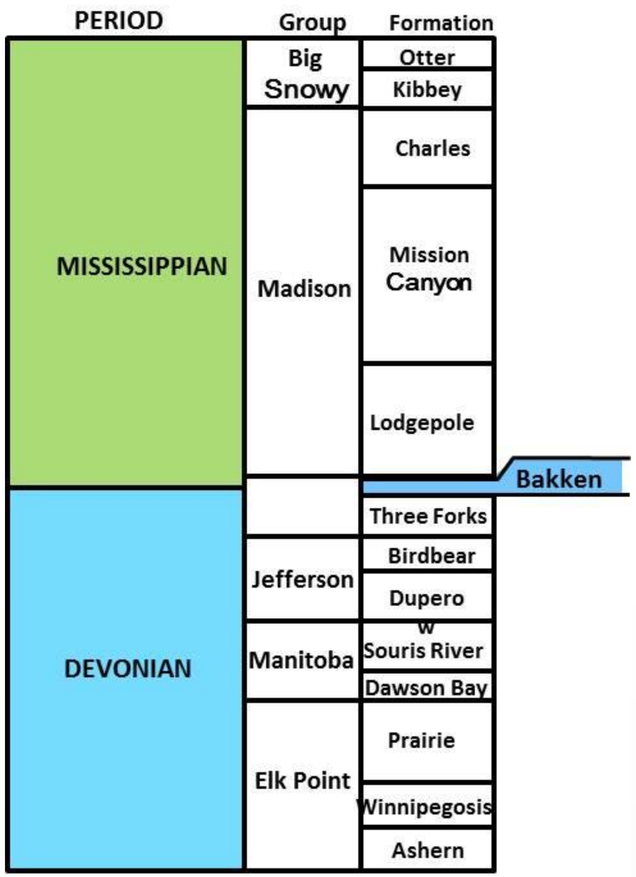
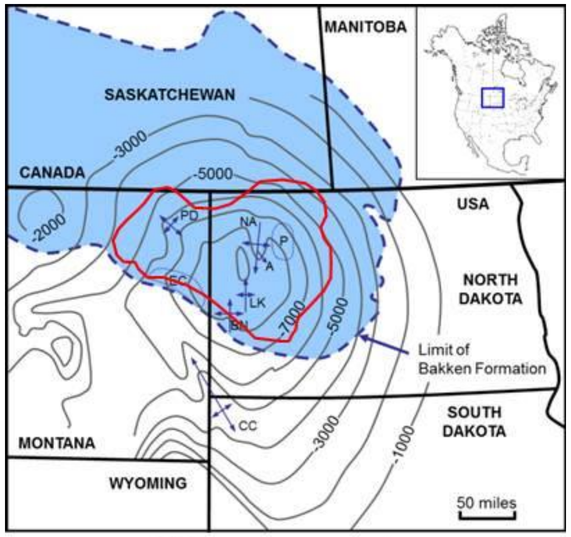
Outline

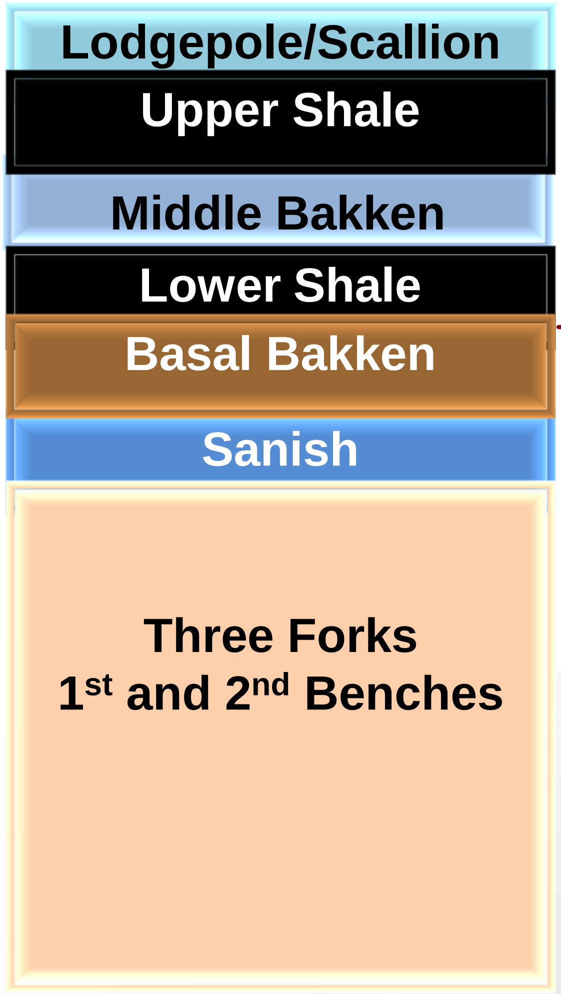
- The Bakken Petroleum System (BPS)
- Complexities of the BPS
- Building the Petrophysical Models
- Petrophysical Evaluation Unique to the Three Forks and Bakken Formations
- Developing a Basin-wide Petrophysical Model
- Summary

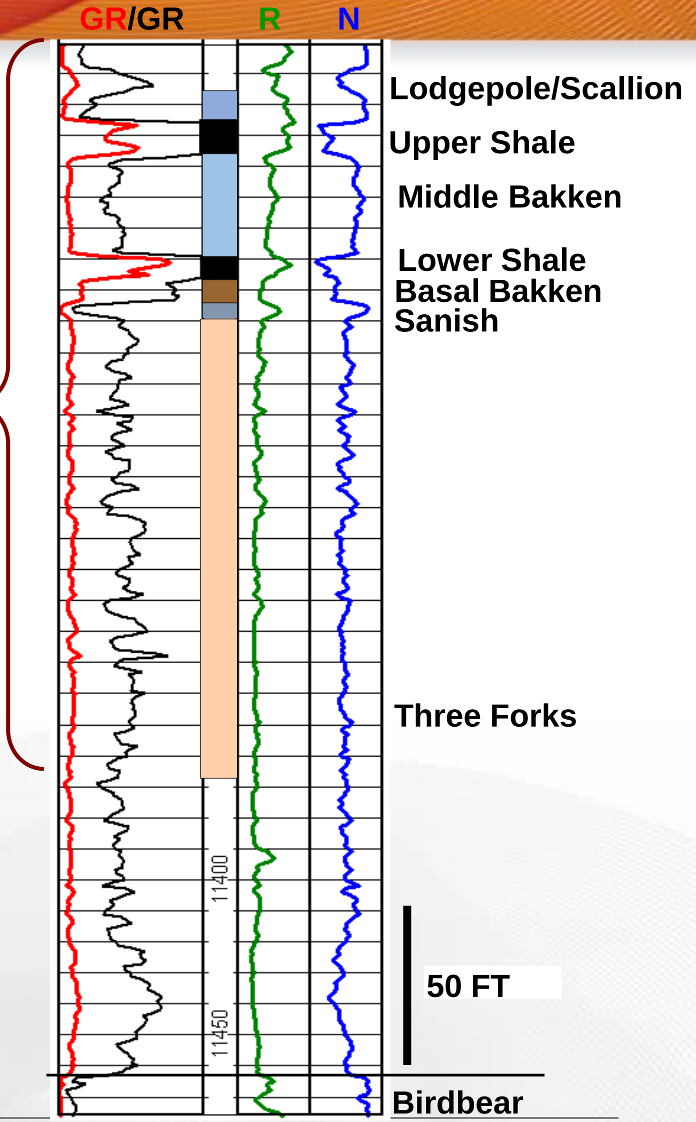
Bakken Petroleum System



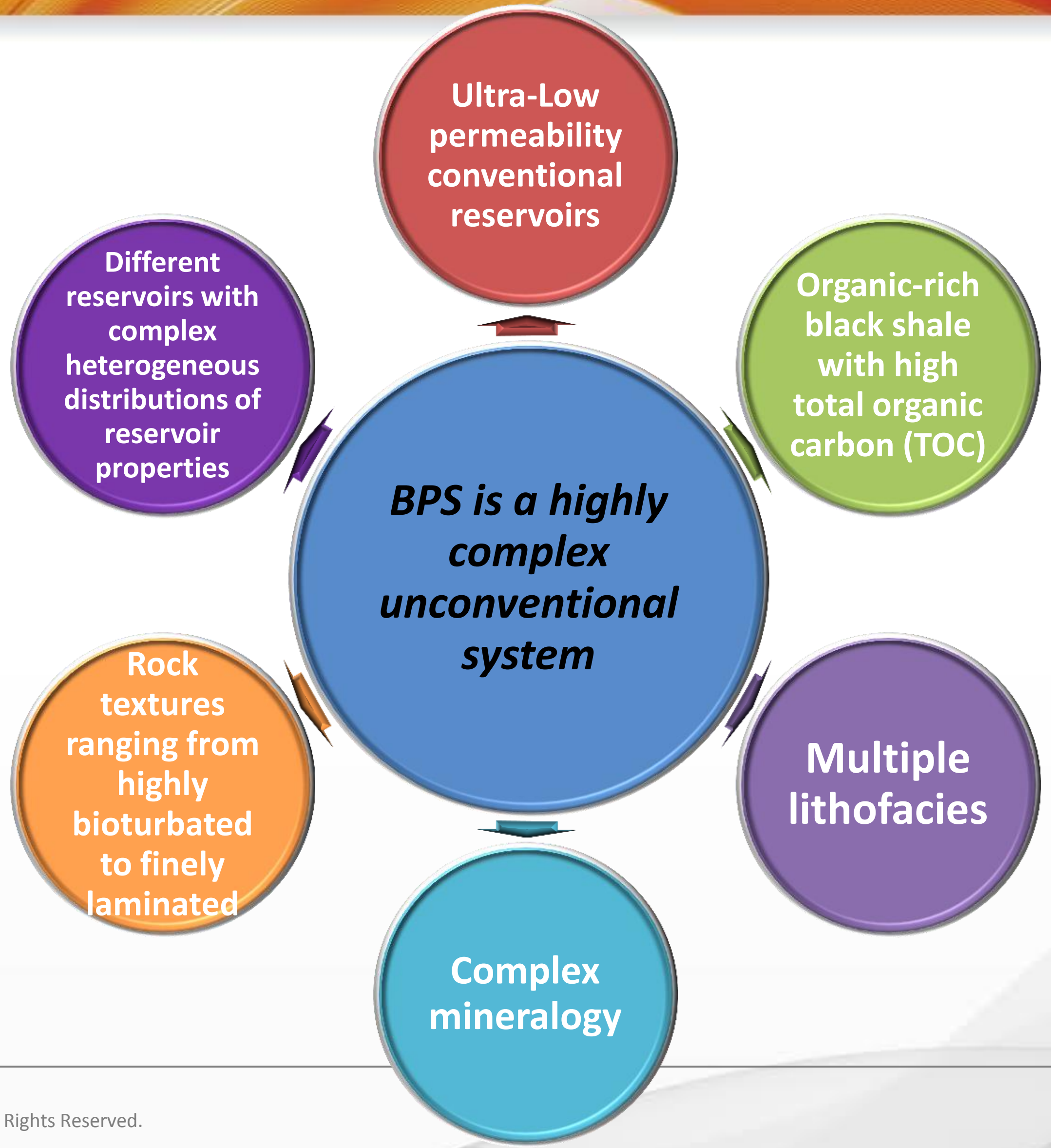


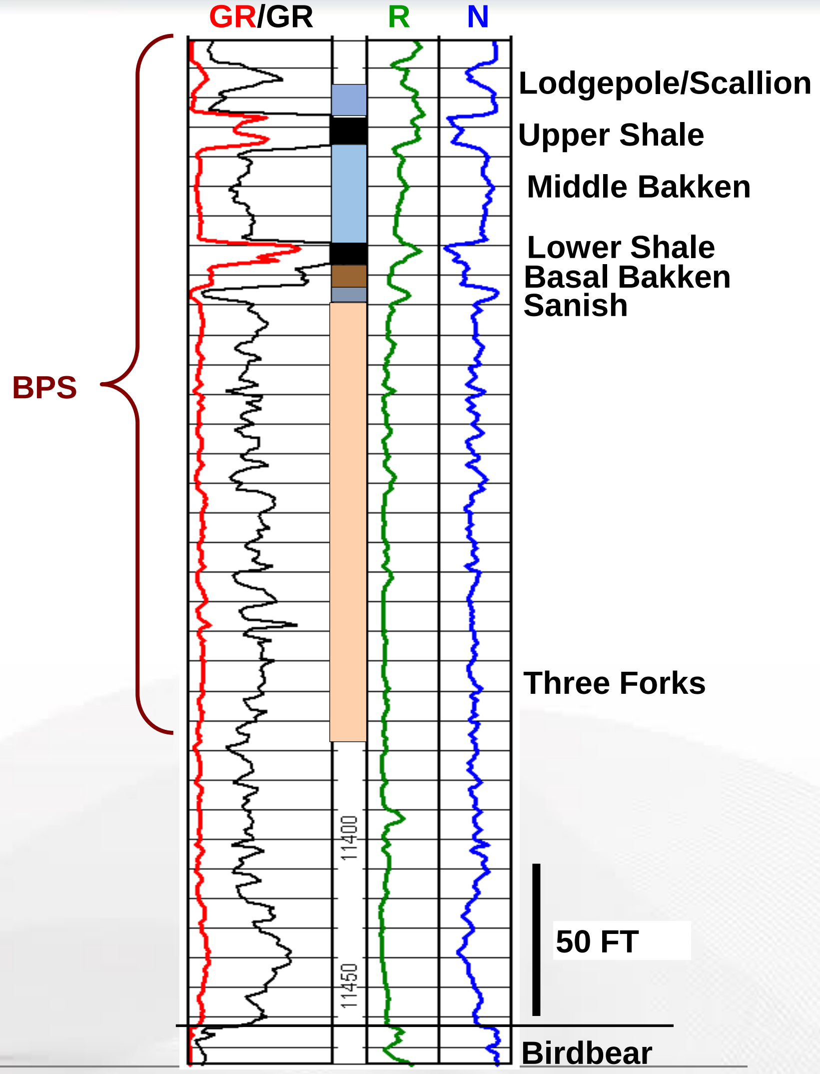
Williston Basin



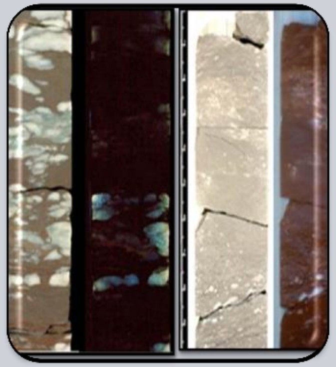


Complexity of the BPS





Complexities of the BPS



Three Forks 4th & 3rd Benches

Dolo-mudstone with anhydrite and Conglomeratic dolo-mudstone

Non Productive

Three Forks 1st & 2nd Benches

Highly Laminated Dolo-siltstone, Reservoir Rock and Dolo-mudstone, Non-Reservoir

Lower & Upper Bakken Shale

Organic Rich Shale

10 to 20 wt% TOC

13 to 40 % clay

Siliceous radiolaria-rich

K-Feldspar & Plagioclase

Dispersed Pyrite

2 to 13% Carbonate

Lower Middle Bakken

Bioturbated siltstone and

Laminated, sandy-siltstone

with Calcite Cement

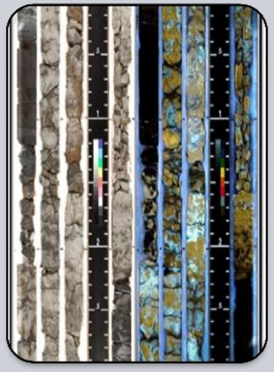
Upper Middle Bakken

Cross bedded sandstone

Fine-grained, well-sorted

and Dolomitic sandy siltstone

Thin-bedded



Lodgepole/ Scallion

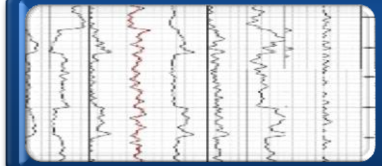
Limestone

Low porosity

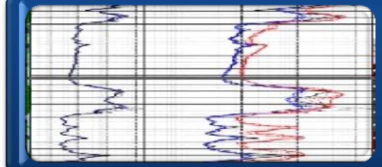
Vertical fractures

Rubble zones

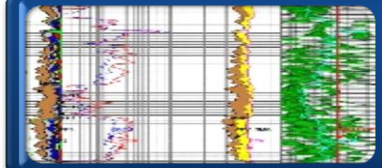
Advanced Logging Measurements



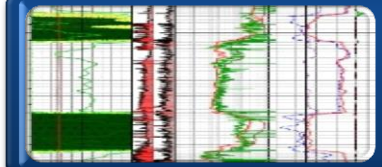
Induced Capture/Inelastic Gamma Ray Spectroscopy



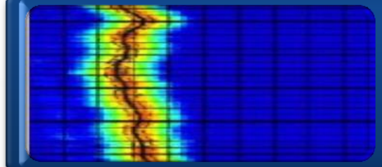
Triaxial Resistivity



Nuclear Magnetic Resonance



Multi-Frequency Array Dielectric



3D Multi-component Cross Dipole Sonic

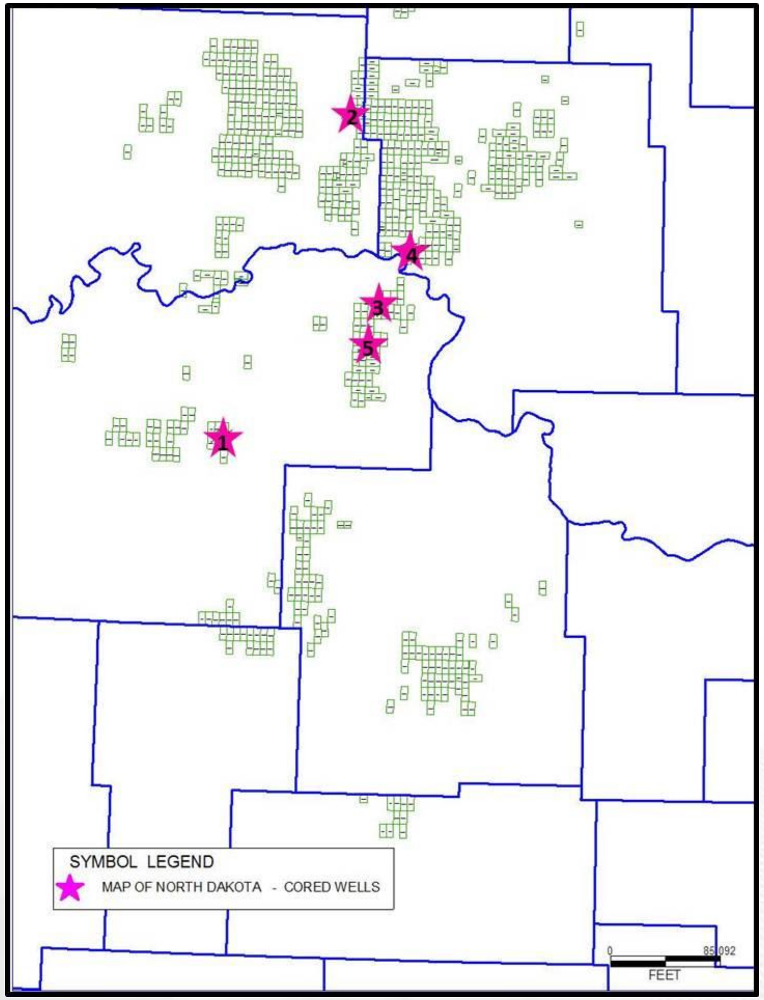
Building the Petrophysical Models

Background

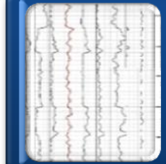
- Five Science wells
  - Full Log Suites
  - 360 Ft. of Whole Core/Well
- Cornerstone of the Petrophysical Models require accurate mineralogy
- Probabilistic interpretation approach was used to solve for complex mineralogy and fluids

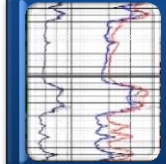
Petrophysical Analysis Challenges

- OBM used to drill wells, traditional R_{XO} devices cannot be used
- Unique evaluation challenges exist for the Three Forks and Bakken formations
  - Laminated thin bed reservoir sections
  - Organic Shales, with high TOC
- Hyper-Saline formation waters
  - Impacts core analysis results

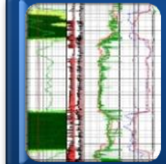


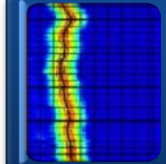
Logs to Core to Models

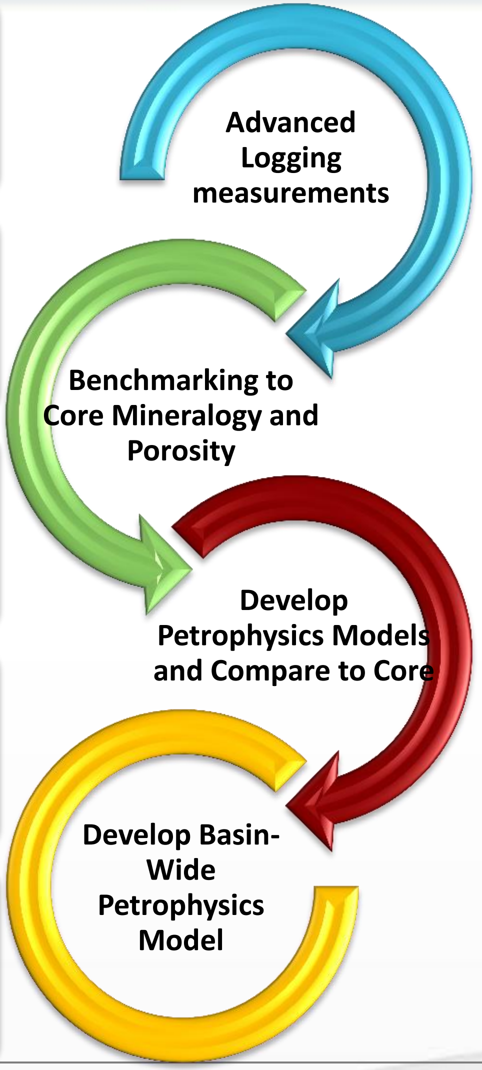

Induced Capture/Inelastic Gamma Ray Spectroscopy


Triaxial Resistivity


Nuclear Magnetic Resonance


Multi-Frequency Array Dielectric


3D Multi-component Cross Dipole Sonic




X-Ray Fluorescence (XRF)

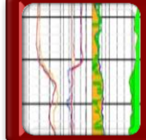

Dual-Range Fourier Transform Infrared Spectroscopy (DR-FTIR)


Diffuse Reflectance Infrared Fourier Transform Spectroscopy (DRIFTS)

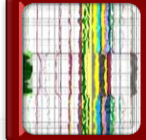

X-Ray Diffraction (XRD)

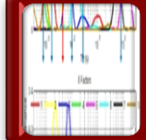

Core Porosity and Water Saturation

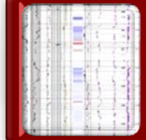

Multi-Mineral Analysis


Laminated Thin Bed Analysis

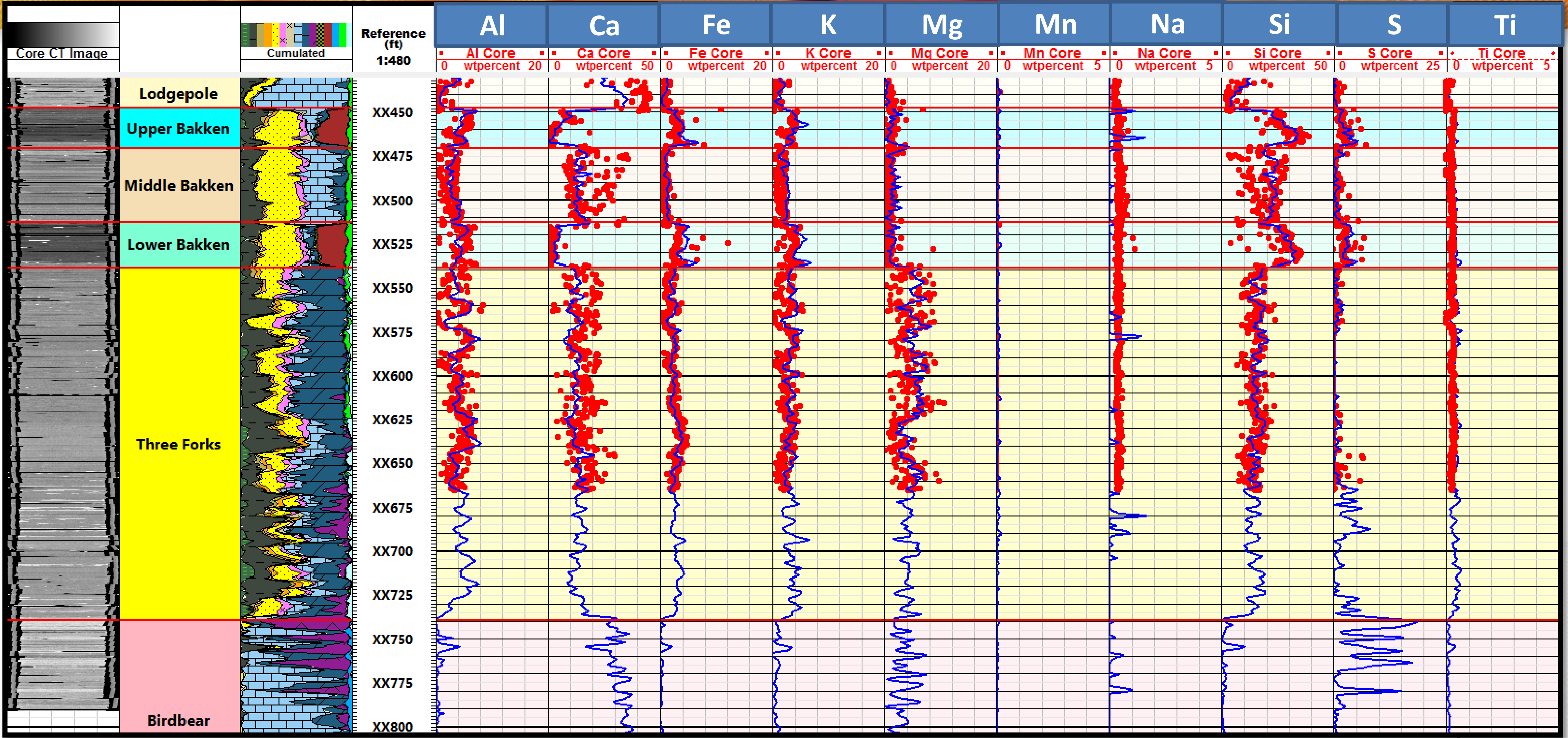

Dielectric Saturation Model


Probabilistic Fluid and Porosity Model

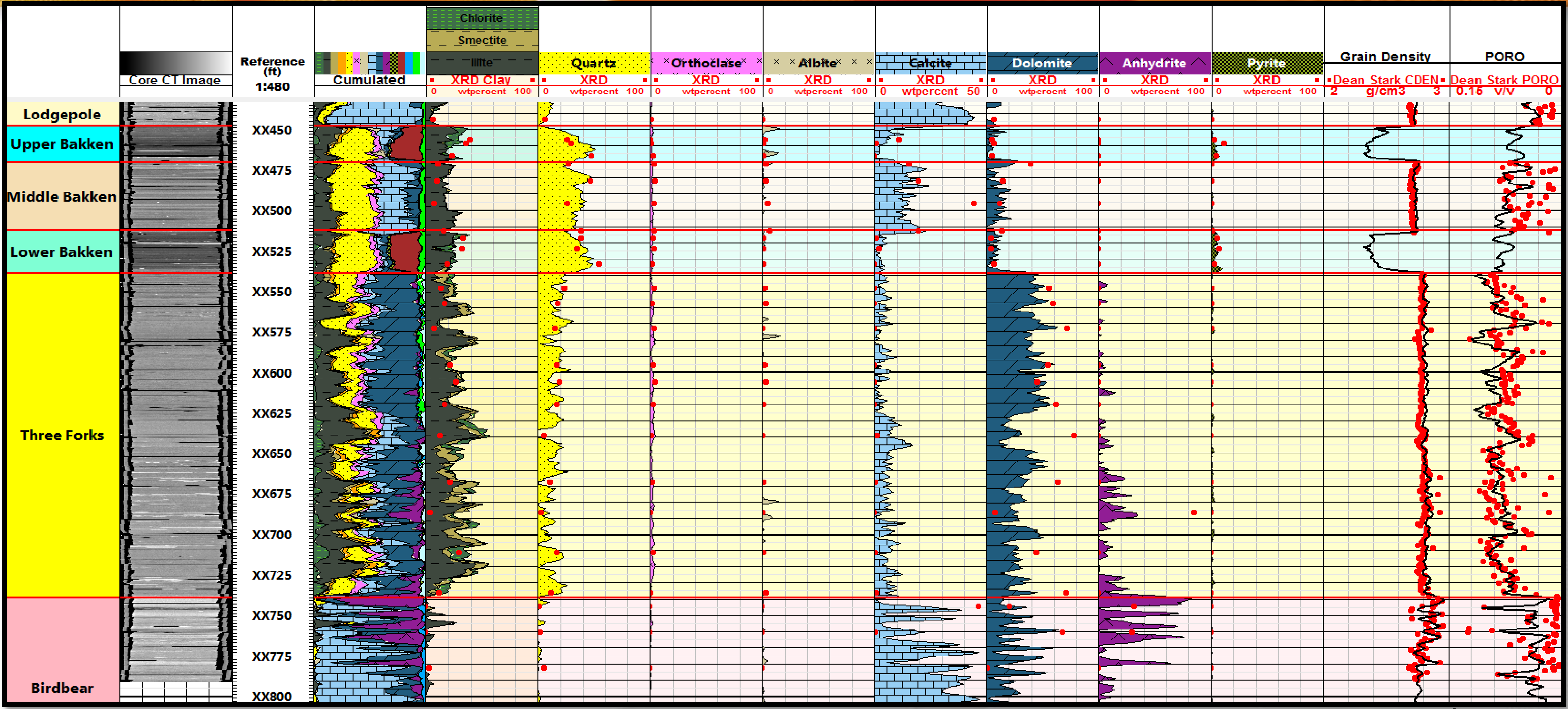

NMR Model


Rock Mechanical Properties – 3D VTI

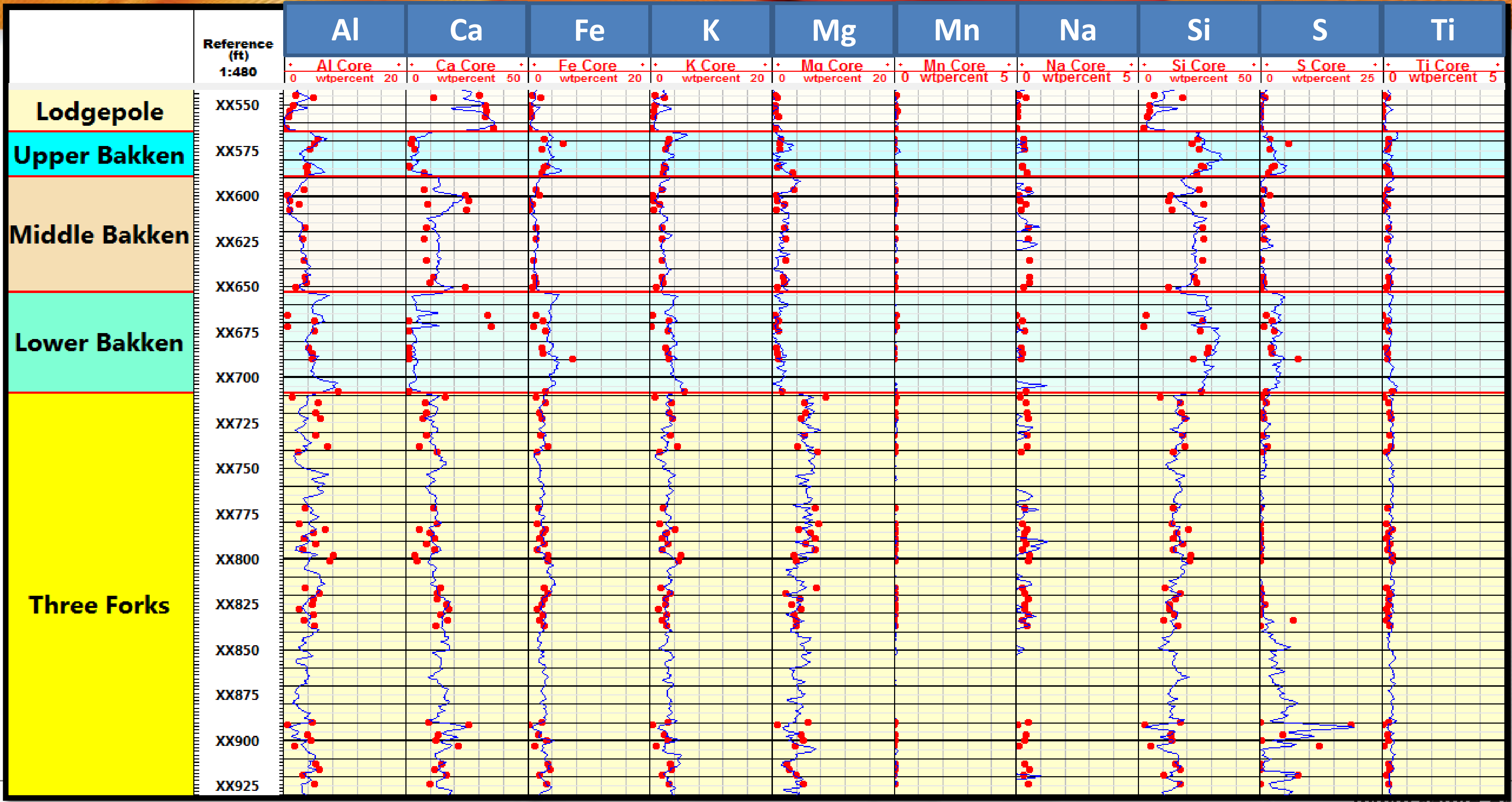
Spectroscopy Log to Hand Held XRF



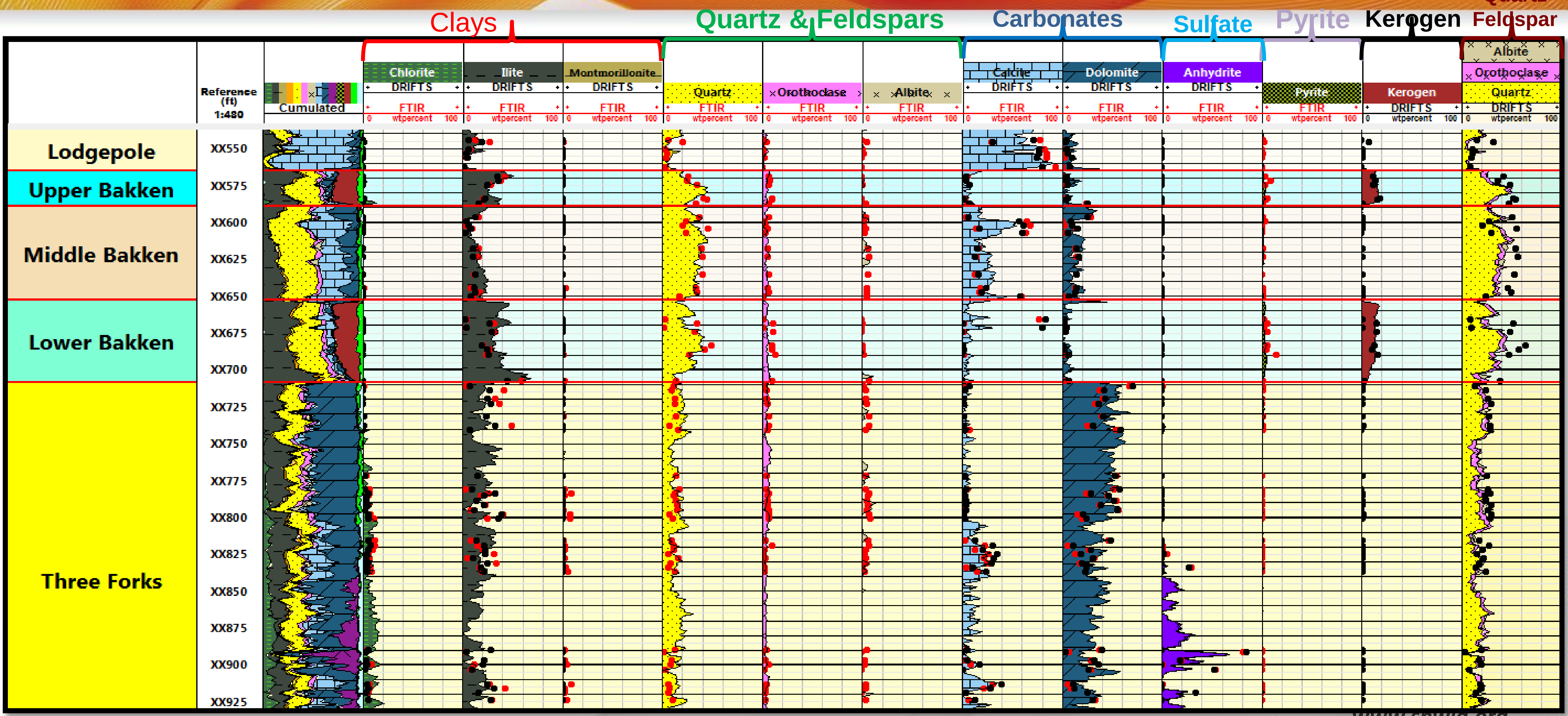
X-Ray Diffraction (XRD) vs. Log Mineralogy



DR-FTIR VS Log Elements



DRIFTS & FTIR Mineralogy vs. Log Mineralogy



NMR Porosity and Permeability vs. Core

NMR - mineralogical (matrix) independent total porosity

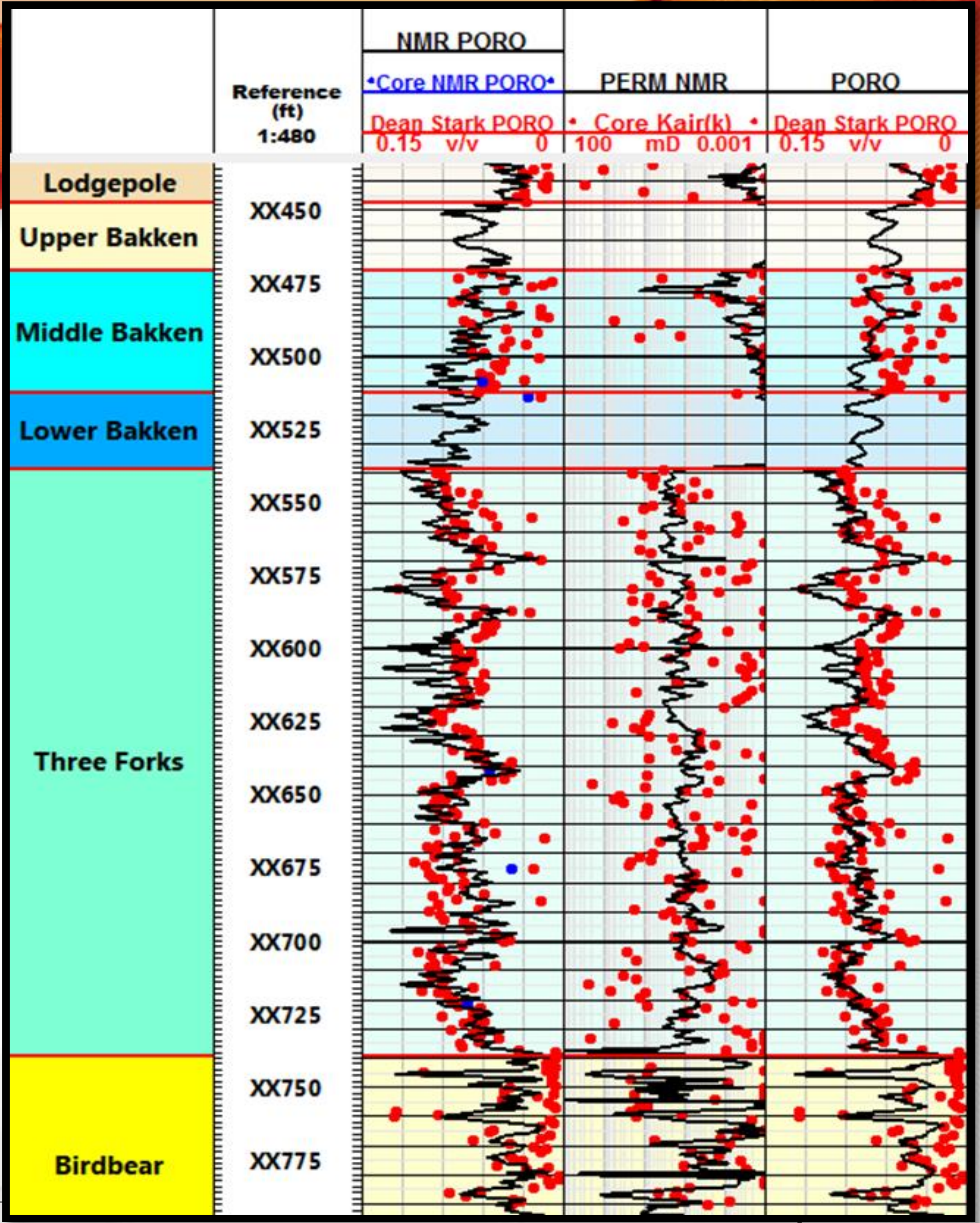
NMR was run with short echo spacing of 0.200 ms

- Combination with an enhanced precision mode

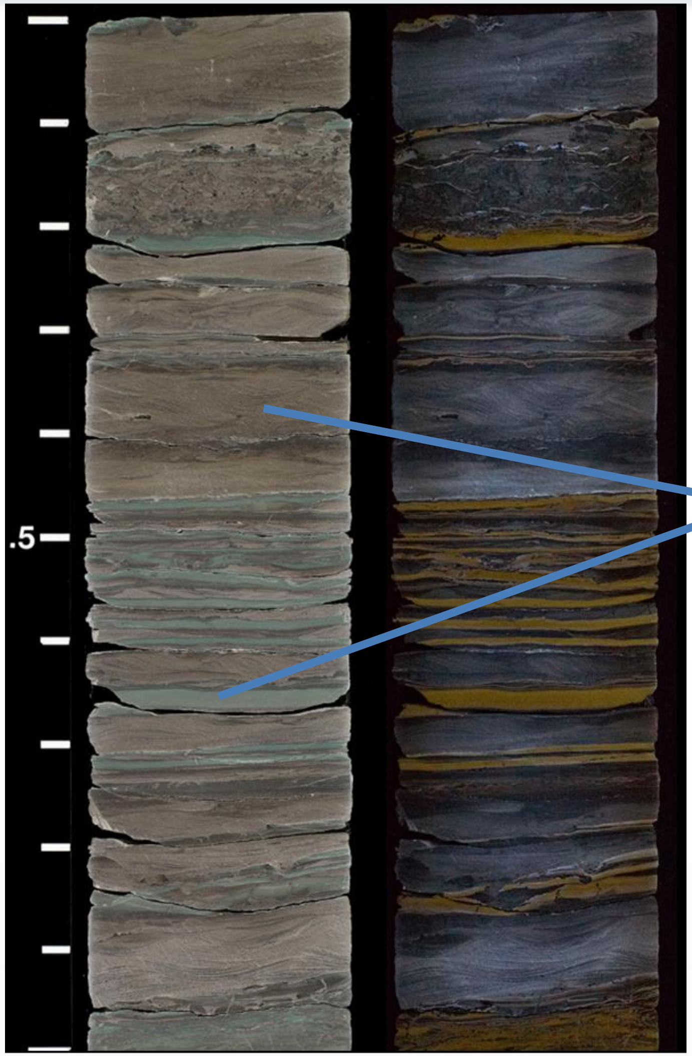
Capture fast-relaxing T_2's,

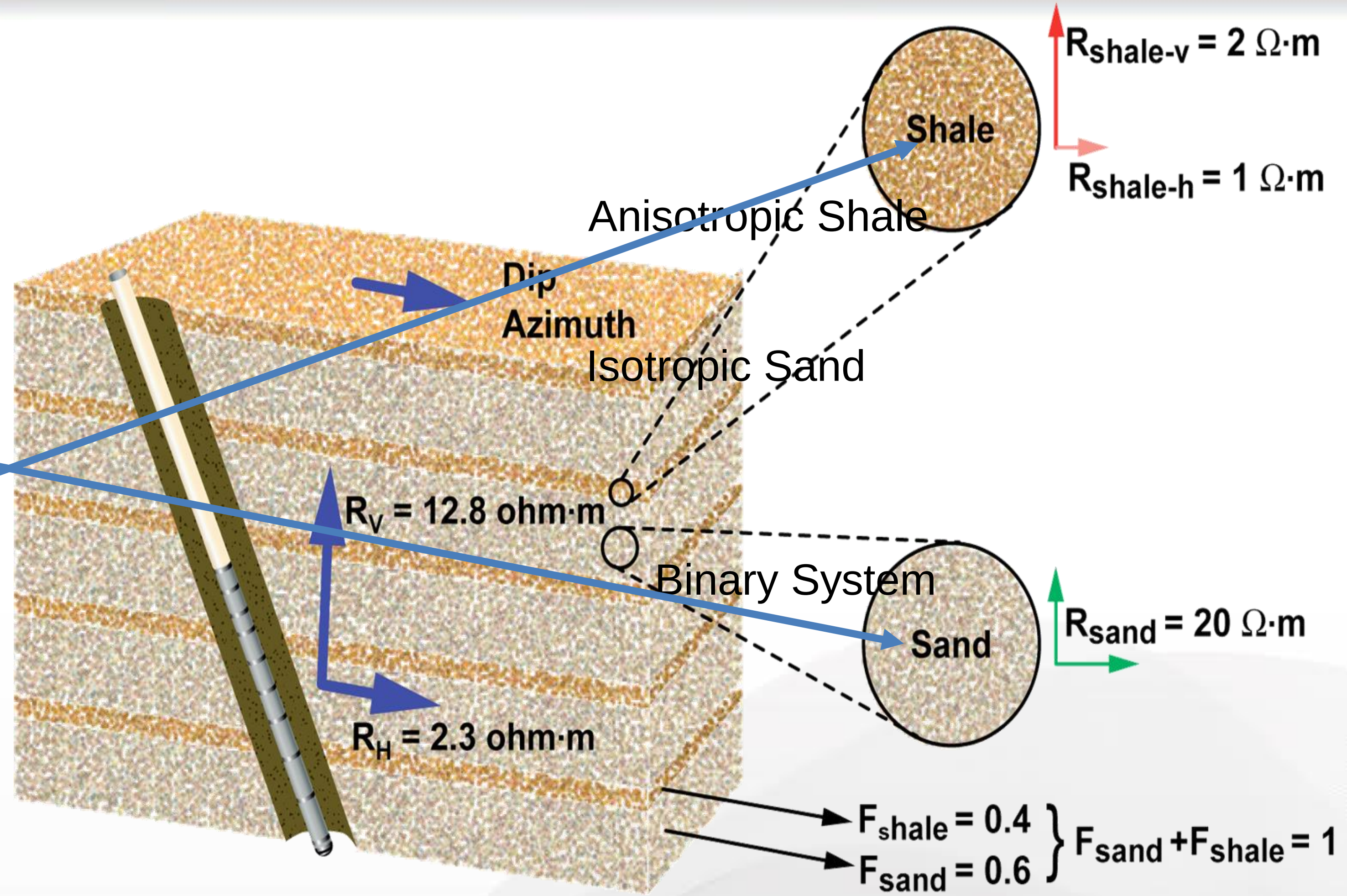
- quantifying small porosity
- clay bound fluids

Yielding an accurate NMR total porosity compared to core



Thin Bed Analysis via Triaxial Induction Three Forks and Middle Bakken





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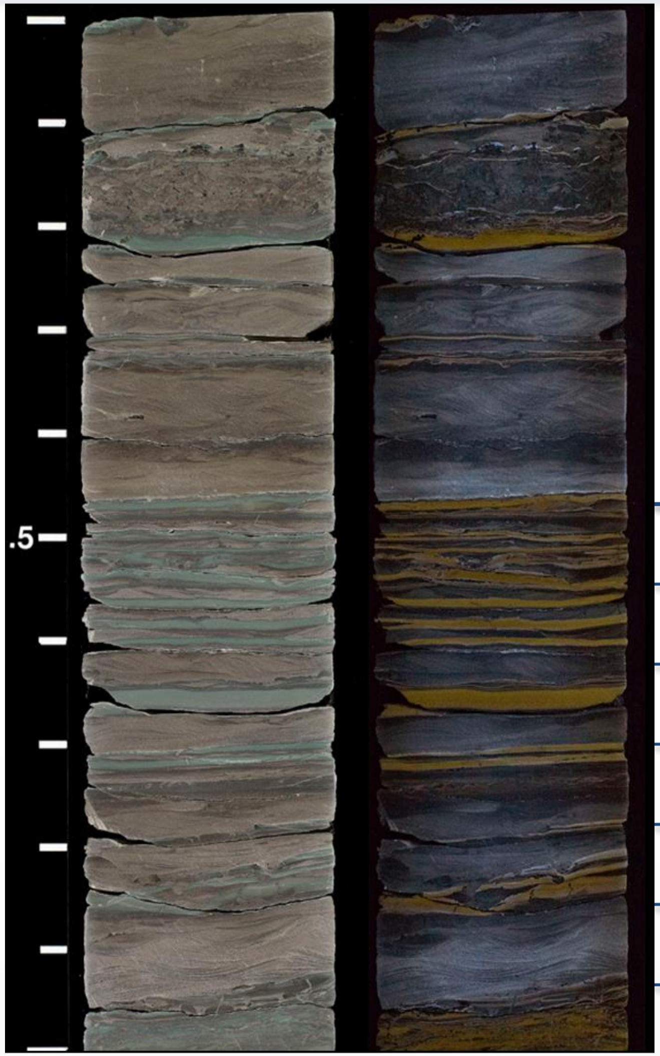


$$R_V = \left(1 - F_{shale}\right) R_{sand} + F_{shale} R_{shale-V}$$

$$R_H = \frac{R_{sand} R_{shale-H}}{\left(1 - F_{shale}\right) R_{shale-H} + F_{shale} R_{sand}}$$

$$1 = F_{shale} + F_{sand}$$

where:

R_h = Horizontal resistivity (Ωm)

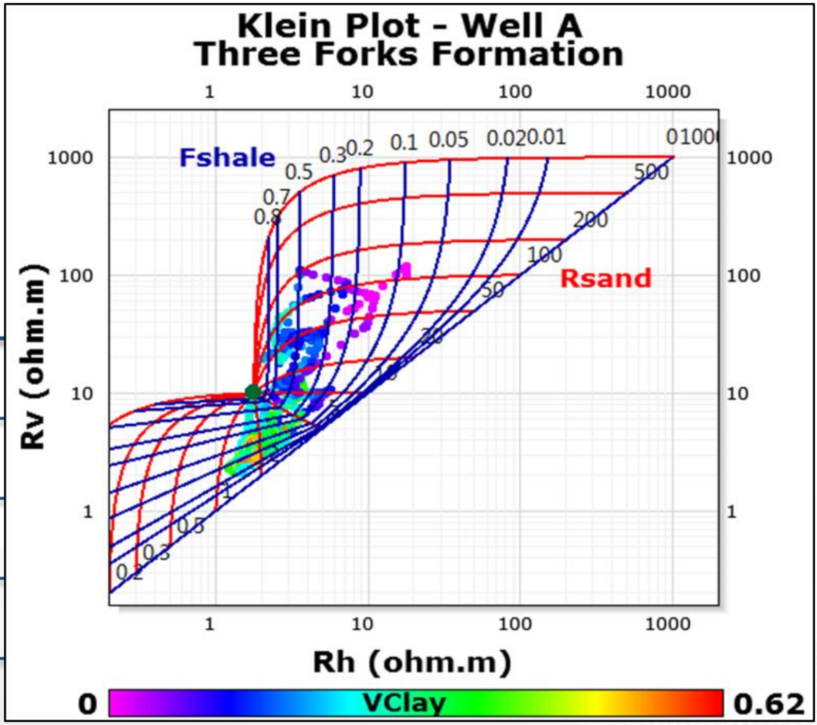
R_v = Vertical resistivity (Ωm)

R_{sand} = Resistivity of reservoir component (Ωm)

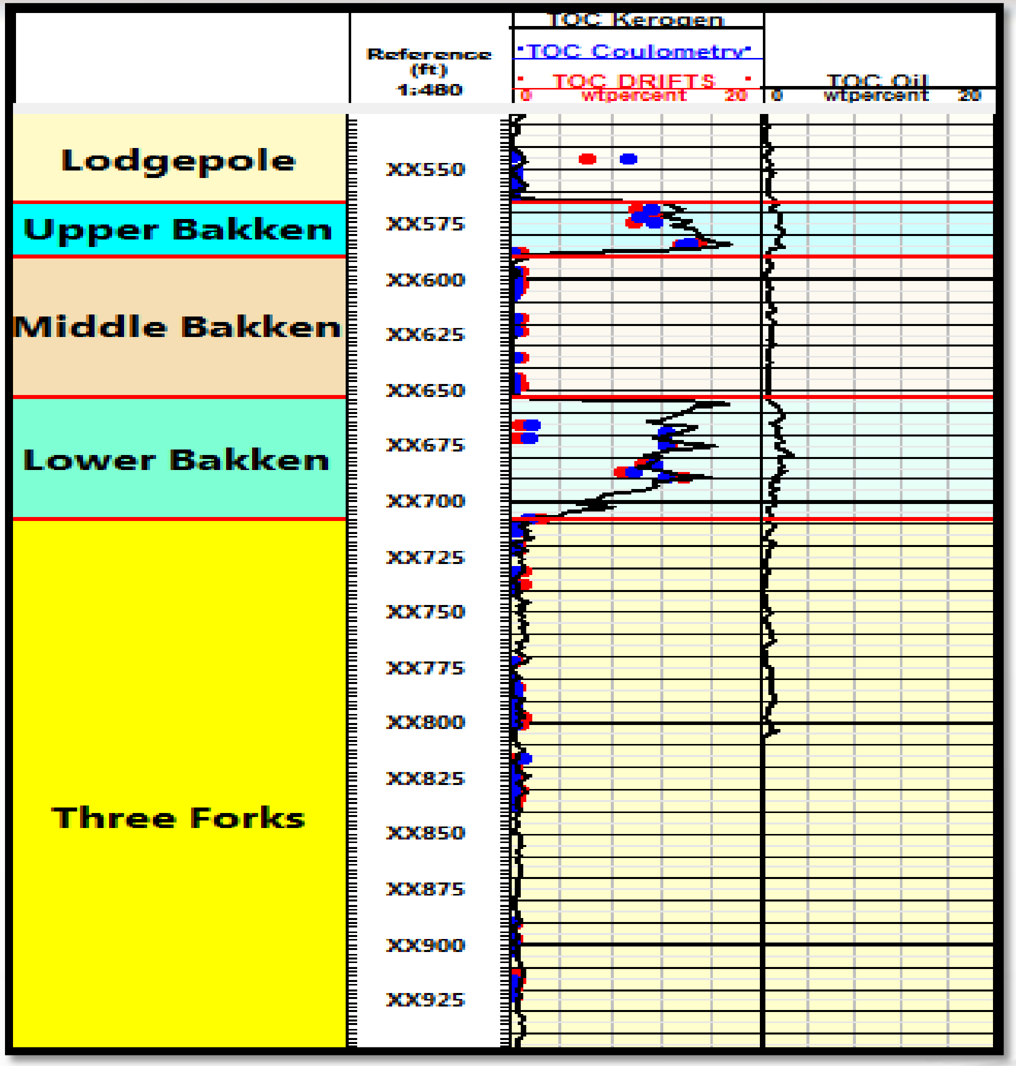
R_{shale} = Resistivity of shale component (Ωm)

F_{sand} = Volume fraction of reservoir component (v/v)

F_{shale} = Volume fraction of shale component (v/v)



TOC from Spectroscopy to Correct Porosity Bakken Shales



$$\Phi_T = \frac{\rho_m - \rho_b\left(1 - W_{TOC} + W_{TOC}\left(\frac{\rho m}{\rho_{TOC}}\right)\right)}{(\rho_m - \rho_{fl})}$$

Where:

Φ_T = Total porosity (v/v)

ρ_b = Bulk density (g/cm³)

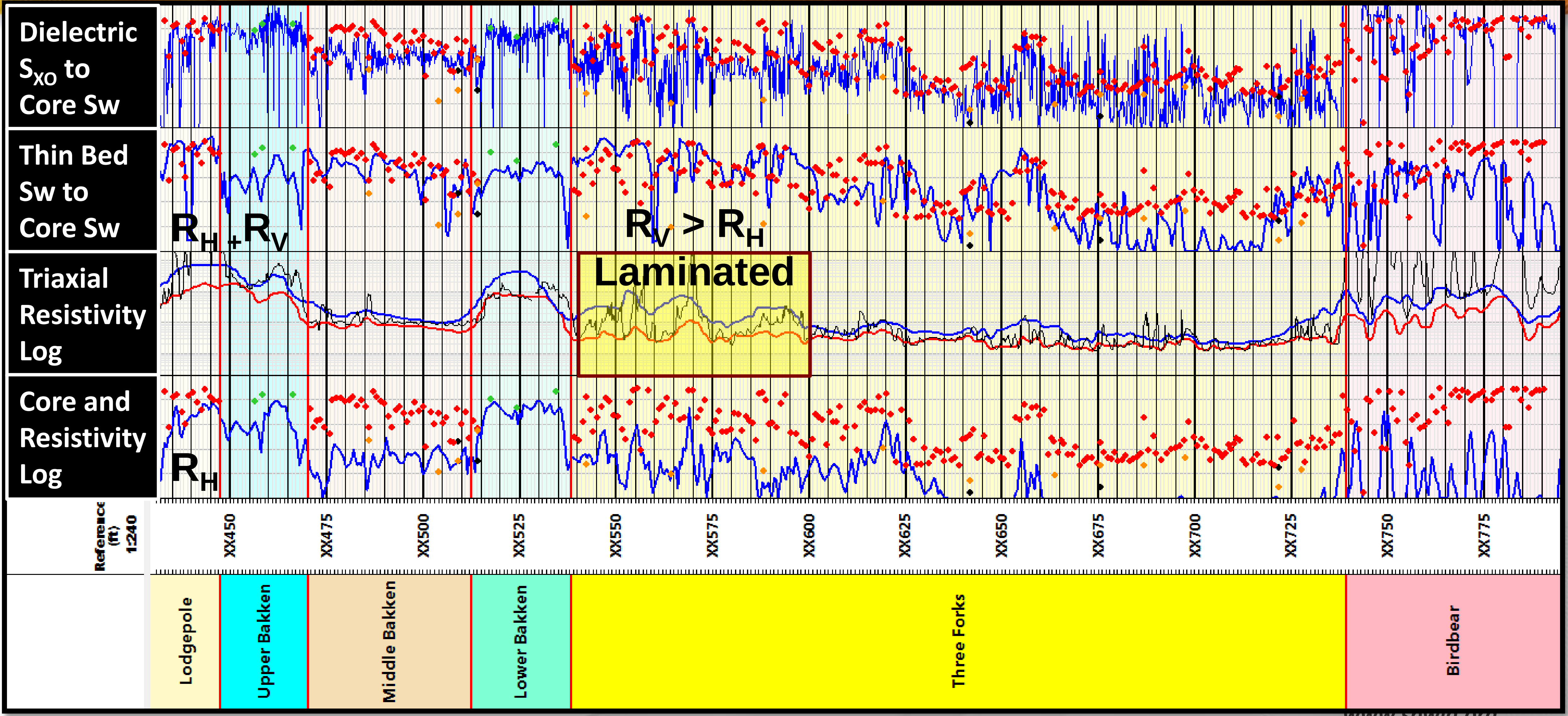
W_{TOC} = Dry weight of TOC (wt%)

ρ_{TOC} = Density of TOC (g/ cm³)

ρ_m = Matrix density (g/ cm³)

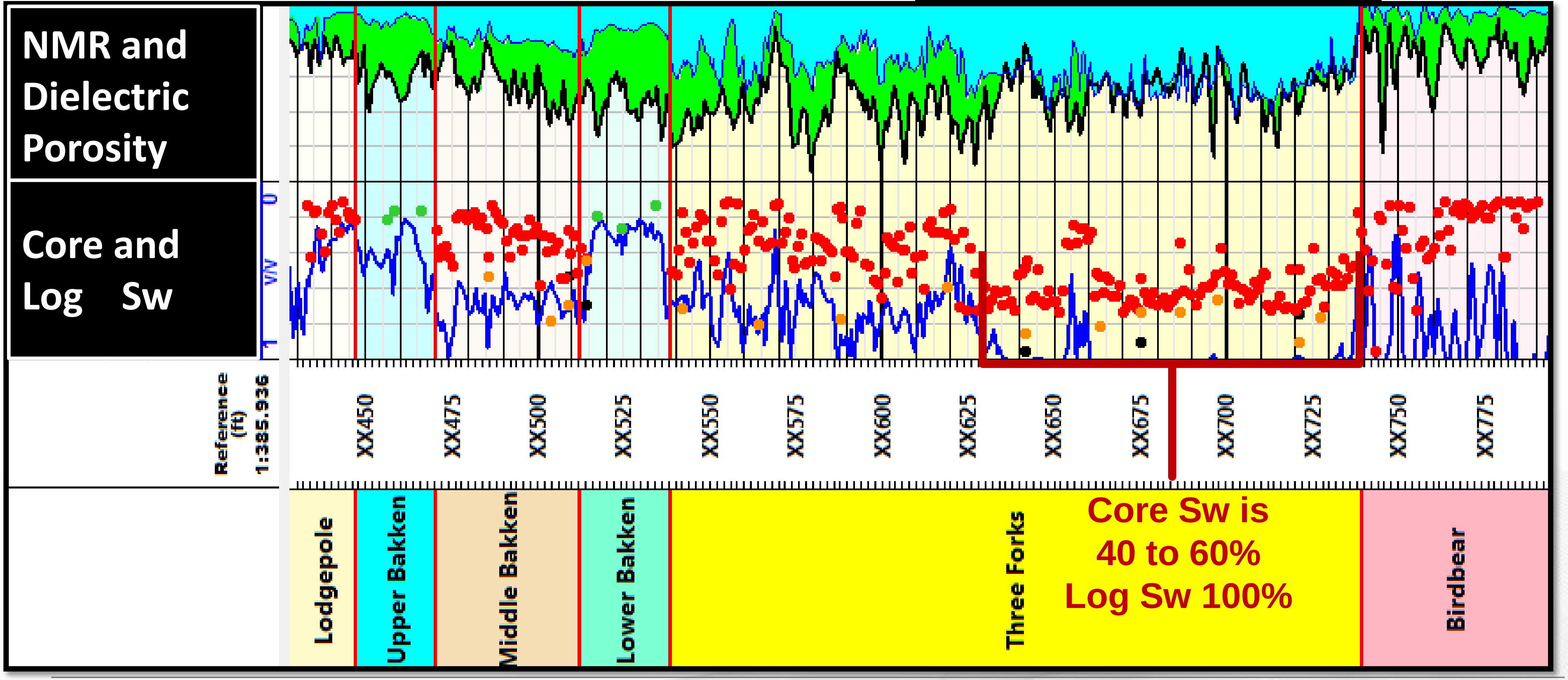
ρ_{fl} = Fluid Density (g/cm³)

Core to Log Sw Comparison Dielectric and Triaxial Induction



Core vs. Log Sw in Lower Three Forks NMR and Dielectric

NMR & Dielectric Overlay Show Interval is Water Filled Porosity



Impact of Hyper-Saline Brines

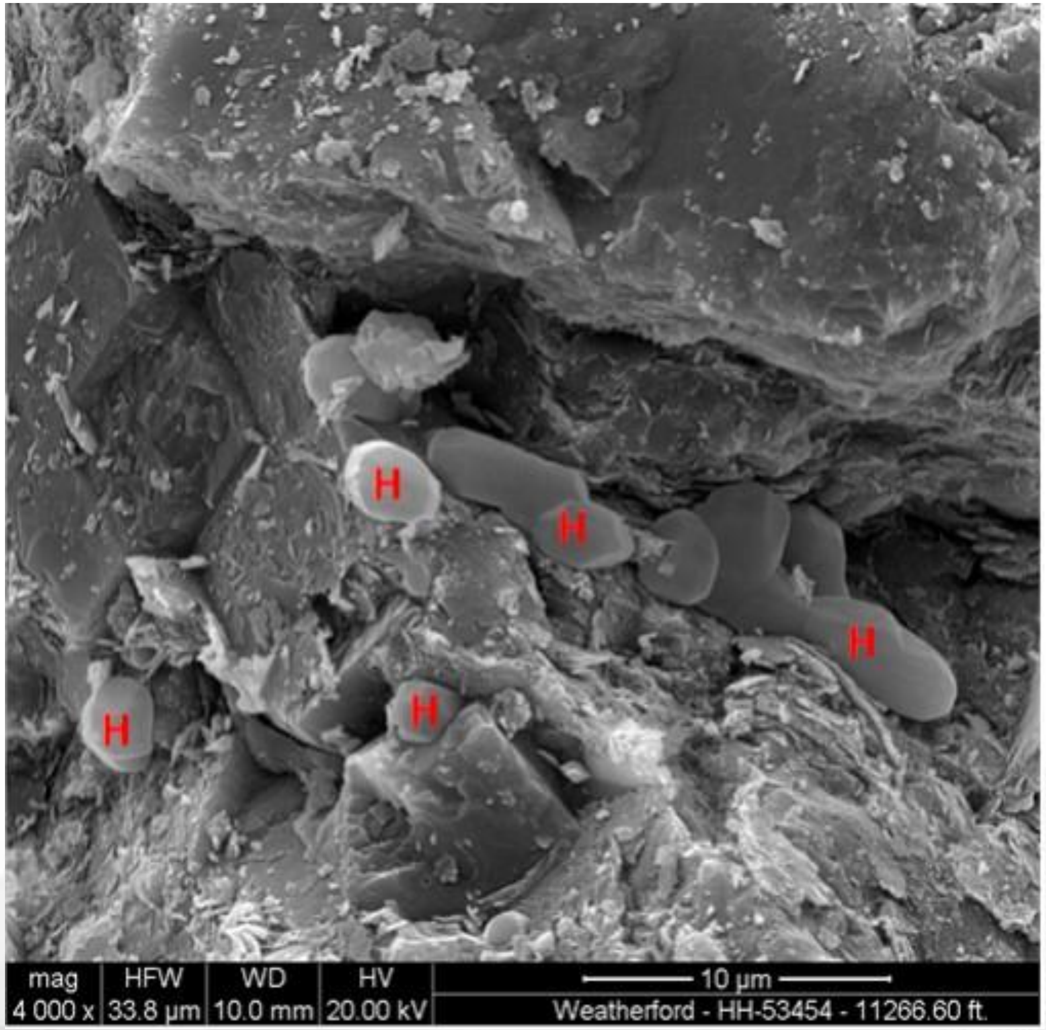
20 Month investigation into protocols for evaluating unconventional tight oil

Salinities in the BPS

- 300,000 to 400,000 ppm
- Maximum salt in solution at ambient conditions is 240,000 ppm

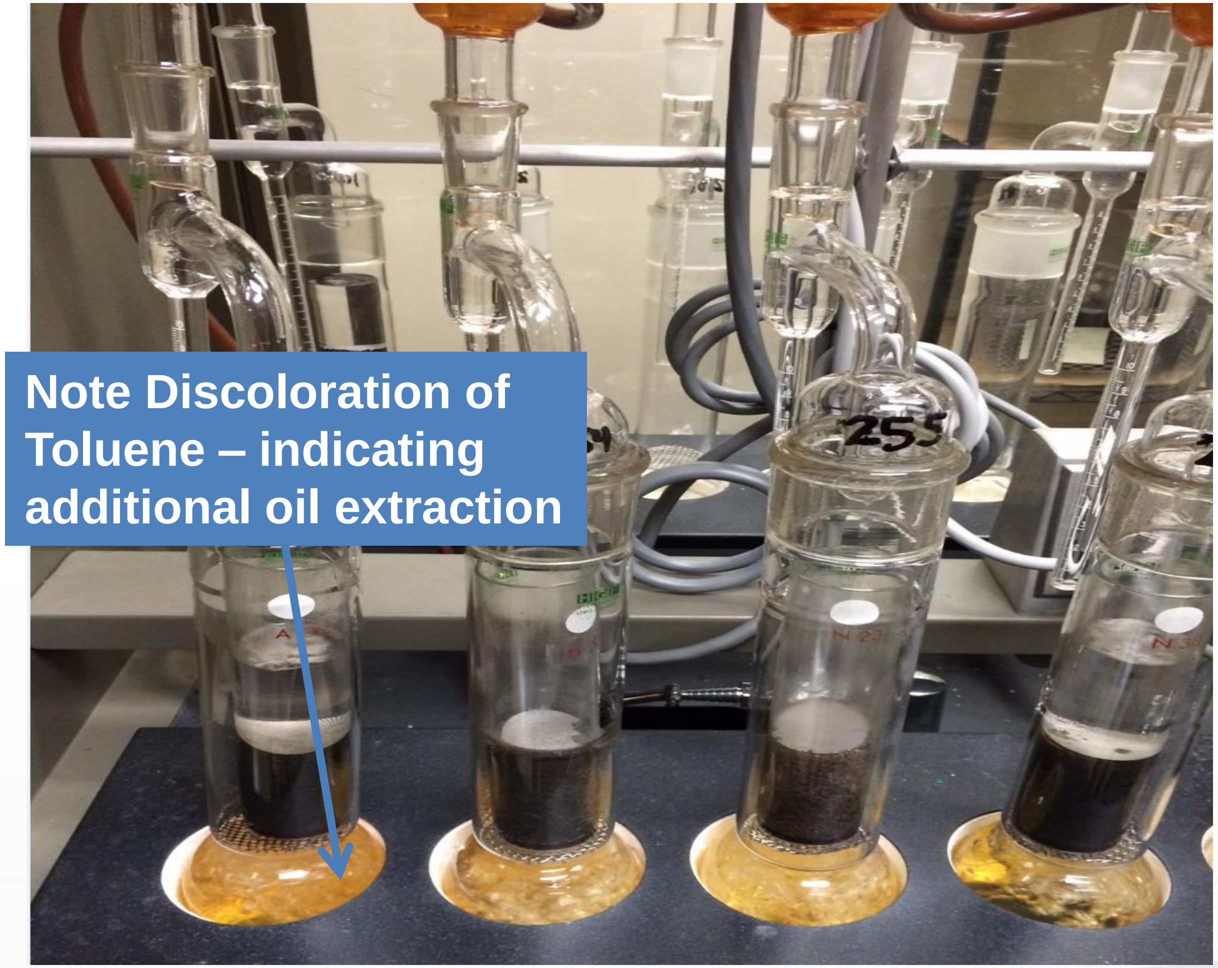
Halite crystals plug pore throats

- Incomplete core cleaning
- Inaccurate core Sw, porosity and permeability measurements

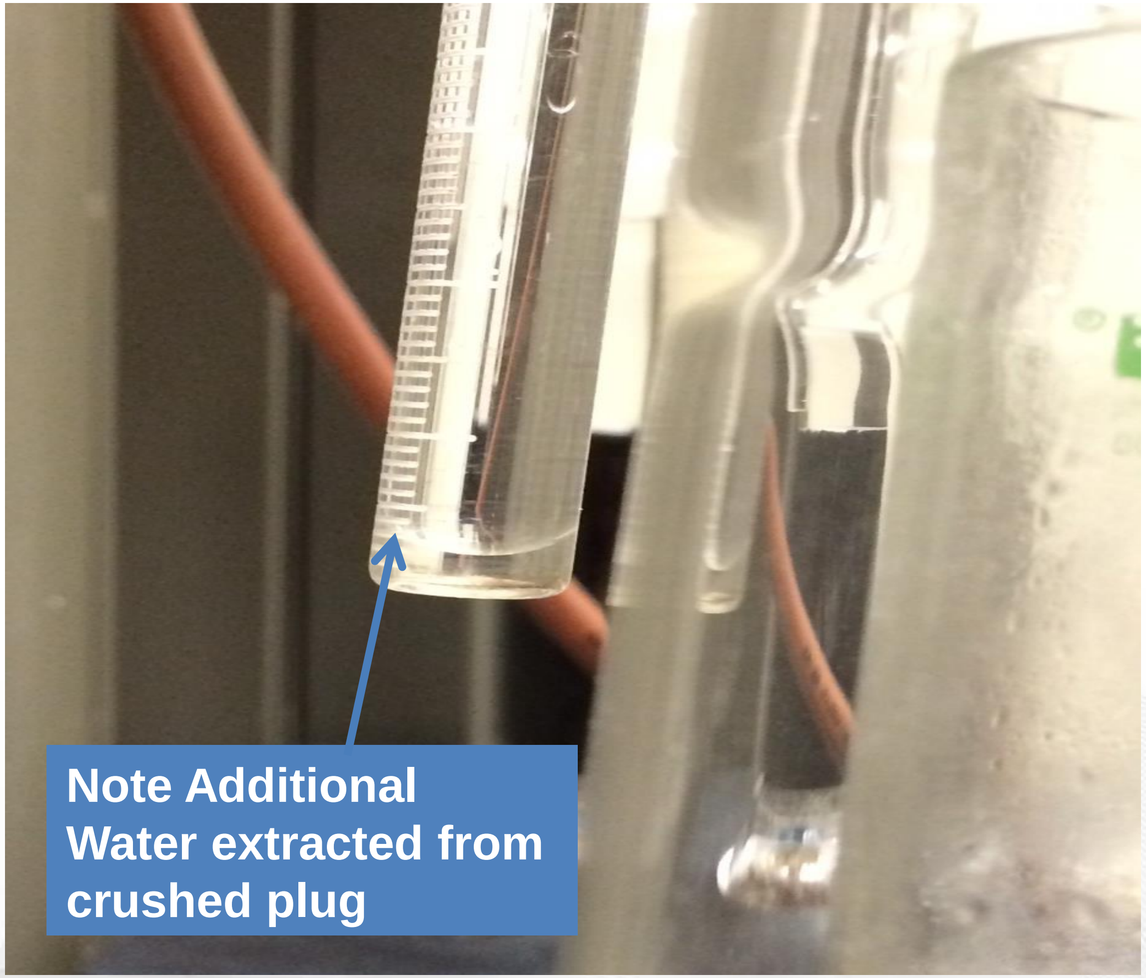


Incomplete Core Cleaning = Inaccurate Results

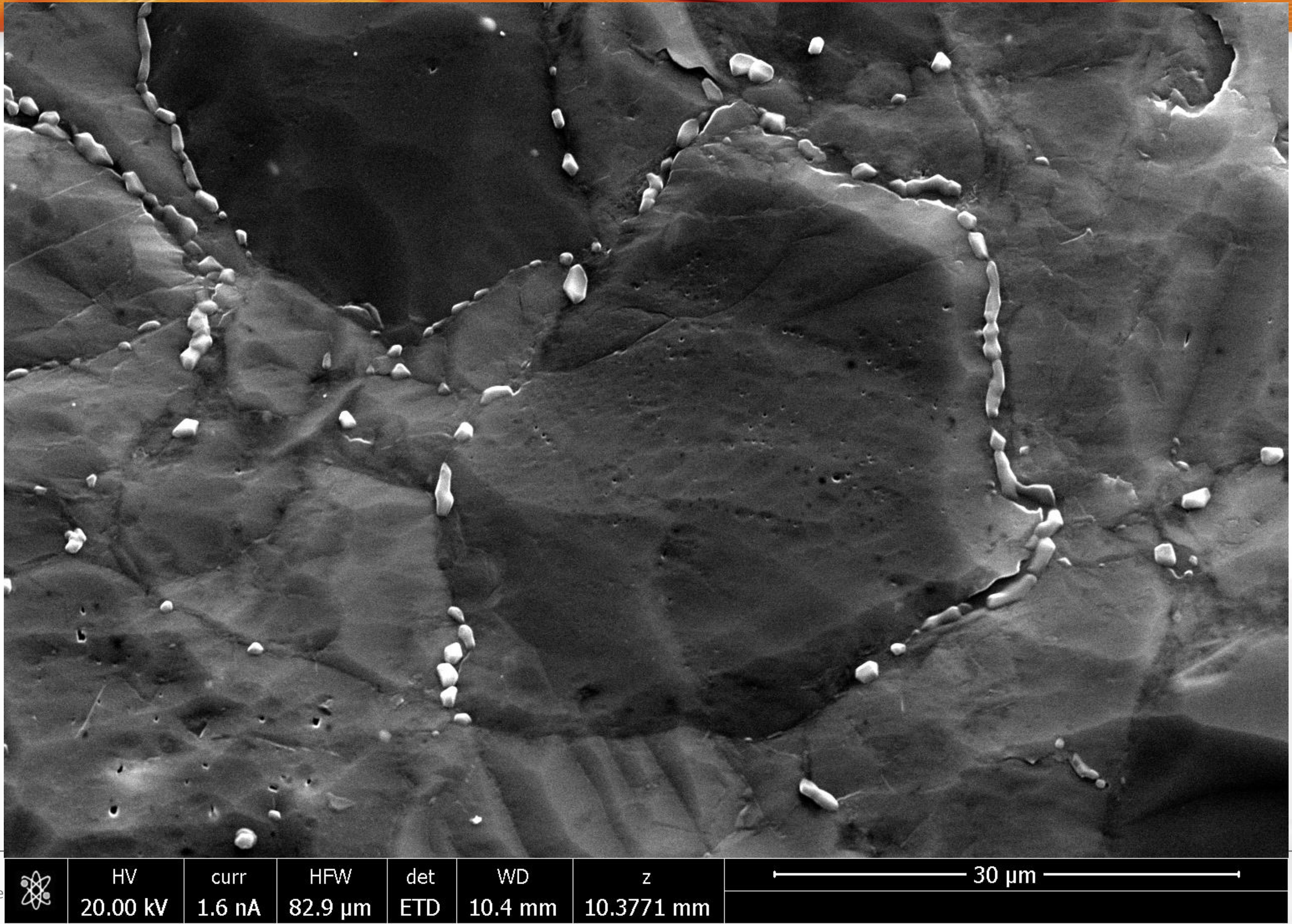
Toluene, Dean Stark$_{Crushed}$ after Dean Stark$_{Plug}$



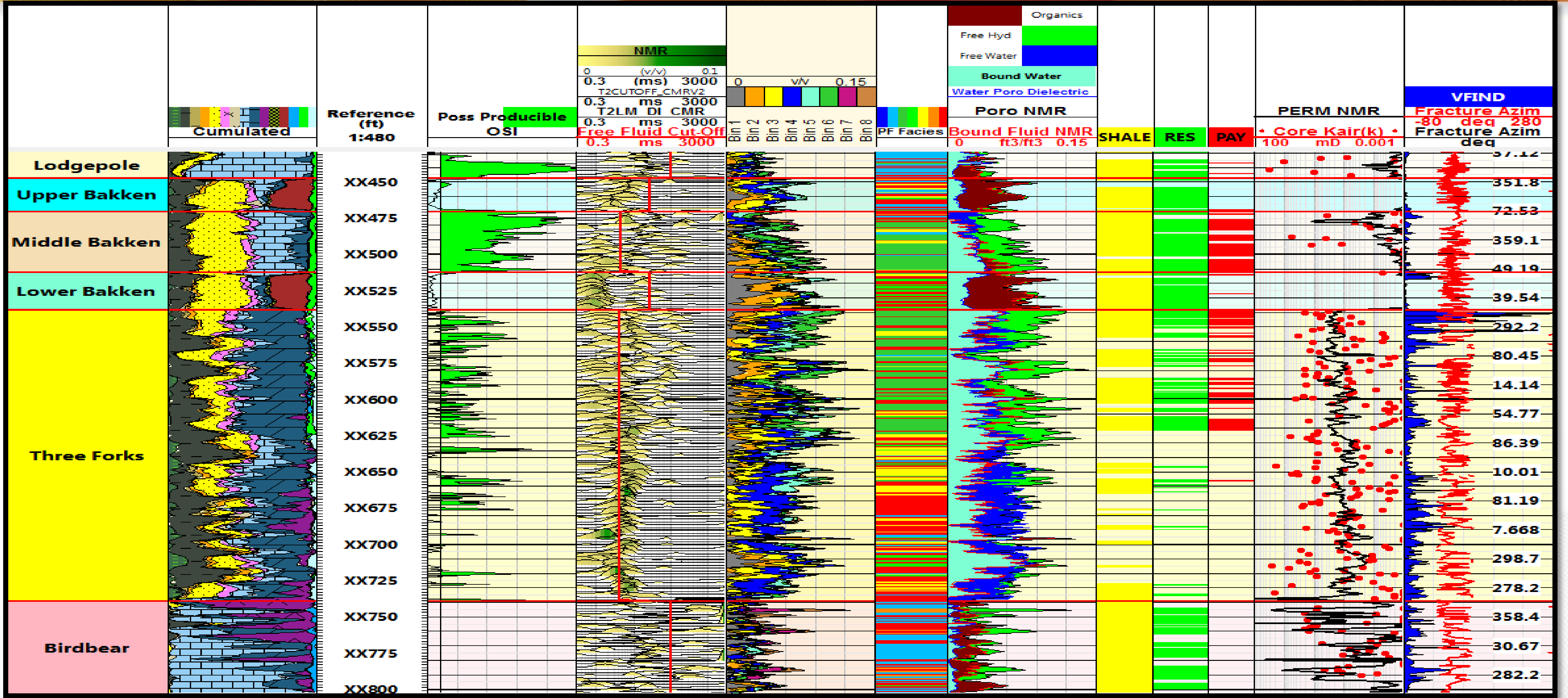
Water, Dean Stark$_{Crushed}$ after Dean Stark$_{Plug}$



Salt Precipitation in Middle Bakken



Producibility



Developing Basin Wide Petrophysical Model

Williston basin

- ~150,000 square miles
- Several thousand wells drilled in the BPS

Log data availability

- Numerous service companies over several generations
- Varying vintages of logging tool technologies

Data Wells

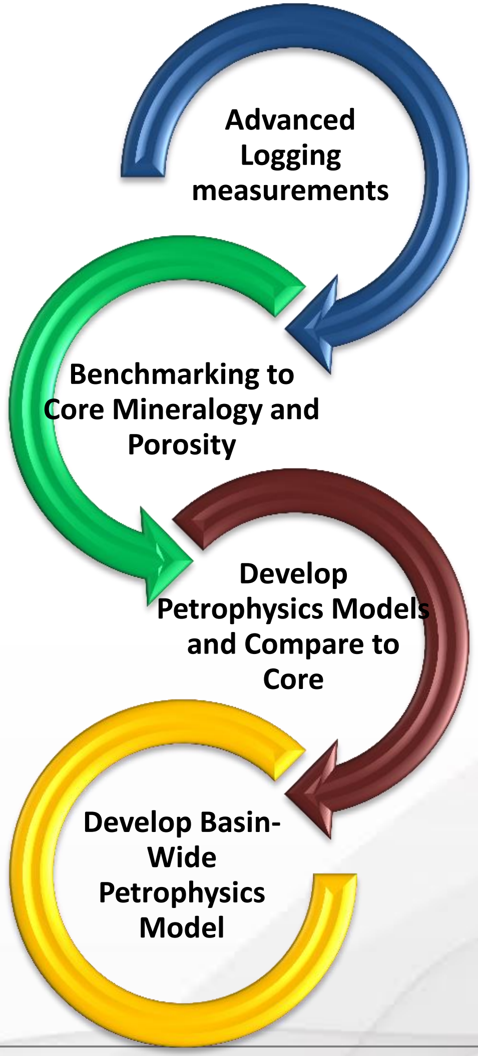
- Advanced technology logging suites, and/or cored
- Sparse subset of the total wells in the basin

Basin-wide petrophysical model

- Using minimum number of logs
- "Data Wells" to calibrate the model
- Currently in development

Advanced Models to Basin-Wide Model

Advanced Petrophysical Model	Advanced Logs
Probabilistic Multi-Mineral Analysis – 14	Induced Elemental Capture Spectroscopy Spectral Gamma Ray Density/Neutron/Pe
Laminated/Thin Bed Saturation Analysis	Triaxial Resistivity High Frequency Dielectric
Porosity	Density/Neutron NMR Total Porosity High Frequency Dielectric Multi-Mineral Analysis Grain Density
TOC	Induced Elemental Spectroscopy
Rock Mechanical Properties	Multi-Component Cross-Dipole
Hydrocarbon Column	NMR High Frequency Dielectric



Calibrated Petrophysical Model	Minimal Logs
Probabilistic Minerals – 6	Density/Neutron/Pe Gamma Ray
Standard Saturation Analysis	Deep Resistivity
Porosity	Density (Using Core & Advanced Petrophysics Model Grain Densities)
TOC	Density (Sonic if available)

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Summary

Integrated advanced downhole logging measurements resulted in defining robust Petrophysical Models

Model results were compared to numerous core analyses

- Increased confidence in the petrophysical models

NMR and dielectric measurements

- Revealed deficiencies in core analysis techniques & methods used for unconventional tight oil

Methods to estimate producibility are possible

- Each BPS reservoirs has its own distinctive set of characteristics that must be recognized and leveraged when evaluating their productive potential

Summary

Basin-wide Petrophysical Models using reduced log data sets are currently under development

"Data Wells" with advanced logging suites are helping to develop and calibrate interpretation techniques for a basin-wide model

Results from the Petrophysical Models provided the basis for:

- Re-calculating STOOIP
- Refining the production type curves
- Characterizing the BPS across the basin and improving agreement with measured production results

Acknowledgments

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We would also like to thank Schlumberger for committing the resources to produce the manuscript.

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