NETHERLAND, SEWELL & ASSOCIATES, INC.

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Integrating Emerging Well Logging and Core Analysis Technologies for Improved Evaluation of Unconventional Reservoirs

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INTERPRETATION ISSUES AND BASIC EVALUATION APPROACH

Shale Reservoir Interpretation Challenges

- Areal and vertical variations in reservoir properties
  - Lithology, porosity (type and quantity), and permeability
  - Type and maturity of organic matter
  - Relative volume of mobile and immobile hydrocarbons
  - Formation water volume and salinity
- Critical properties are not fully resolvable with log measurements
- Rigorous evaluation requires integration of well log and core data
- New logging and core analysis technologies provide data that can improve the accuracy of reservoir evaluation; these technologies are currently under-utilized in shales

Core Acquisition Strategy

- Conventional cores provide the most reliable reservoir description data and should be acquired periodically in key reservoir intervals.
- It is not operationally or economically feasible to conventionally core every interval in every well.
- Use rotary sidewall cores (RSWCs) to evaluate intervals not sampled with conventional cores and to resample cored intervals to evaluate invasion effects.
- Many of the protocols carried out with conventional cores can be performed with large-diameter rotary samples.
- Careful planning is necessary to ensure that that the most data possible can be derived from the RSWC samples.
- Multiple measurements from the same sample are critical for reliable evaluation.

The Sidewall Core is Your Friend: Basic Analysis Protocol for Each RSWC Plug

- Core NMR and helium porosity measurements can be performed just after the plug is removed from the wax and foil.
- Electrical property and then mechanical property measurements (including Vp and Vs) should be performed on trimmed, right-cylindrical samples.
- Perform mechanical property measurements in horizontal orientation to properly characterize the likely hydraulic fracture geometry.
- XRD and pyrolysis analyses can be carried out on end trimmings.
- Crushed rock analysis (Dean-Stark or retort) should be performed to determine fluid content, porosity, and permeability.
- Strict sample weight records should be maintained at each step to quantify evaporation or adsorption during sample handling.

TECHNICAL ADVANCEMENTS

Pulsed Neutron Spectroscopy

- Improvements in acquisition and interpretation technologies have resulted in improved accuracy in mineral identification and quantification.
- The latest tools also deliver estimates of the organic carbon content (TOC).
- More accurate porosity estimates can be derived from bulk density measurements when spectroscopy data is available.
- Measurements are useful for facies identification. Facies can be used for the population of core-derived reservoir properties in non-cored intervals.
- The accuracy of the mineral composition estimates can be improved by calibration with x-ray diffraction and TOC measurements from conventional and rotary cores.

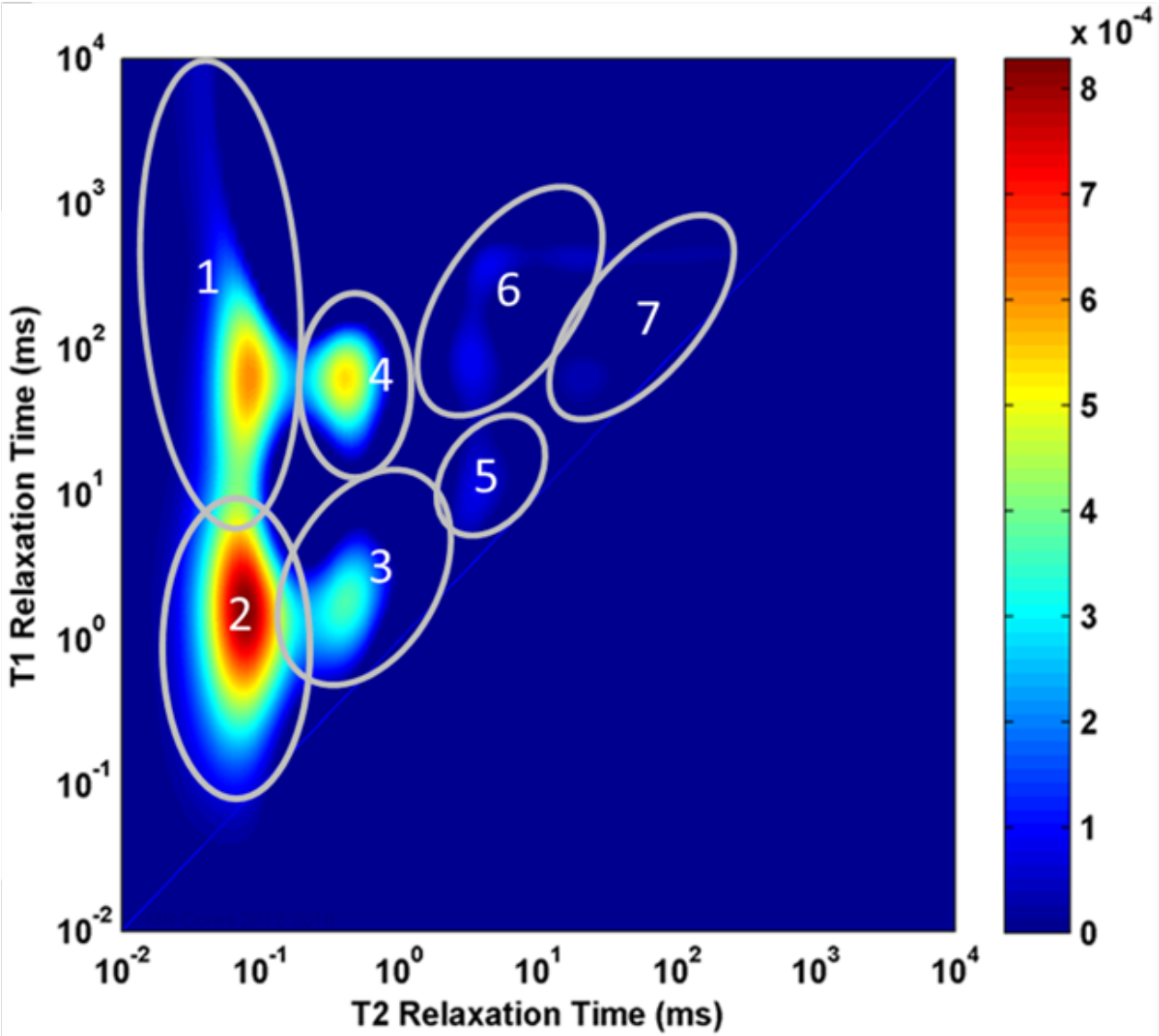
Multiple Frequency Dielectric Dispersion

- Improvements in dispersion modeling have made it possible to obtain accurate estimates of bulk water volume (BVW) in the near-wellbore invaded zone, which are independent of salinity.
- When BVW is reasonably large, the salinity can be estimated as well. This may not be the case in all shale reservoirs.
- Multi-frequency dielectric tools for core analysis have been optimized to obtain accurate estimates of water salinity at low water content.
- Both the volume and salinity of the water in the invaded zone can be determined with well log measurements augmented with salinity measurements from a robust RSWC dataset.
- The importance of these measurements will be discussed later in this presentation.

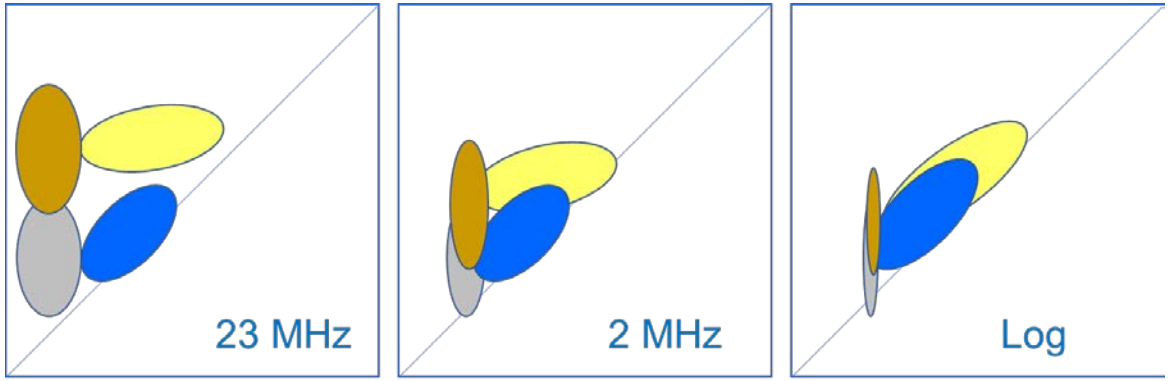
NMR T1-T2 Mapping

- T1-T2 Mapping to identify and quantify reservoir fluids has become increasingly important in shale reservoir evaluations.
- As the result of tool resolution issues causing fluid signal overlap, clustering and principle component analysis techniques have been utilized by logging service companies to provide end users fluid type and volume estimates.
- More distinct fluid signal separation is obtained with the higher frequency measurements utilized for core samples.
- Templates defining the relative positions of the various reservoir fluids on the T1-T2 maps have been developed, allowing the end user to perform independent interpretations of the data.
- Technology is being developed to allow overlapping fluid signals to be individually quantified.

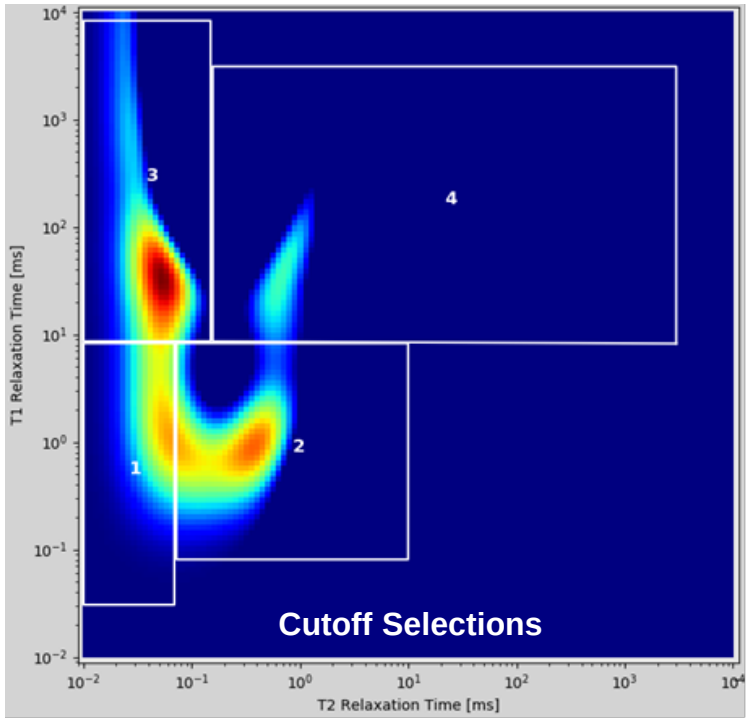
NMR T1-T2 Map Analysis

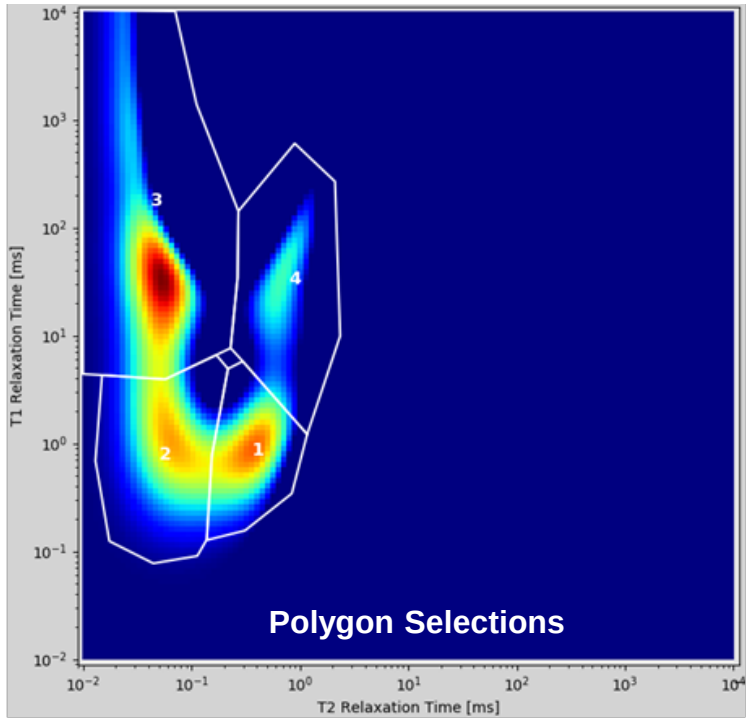


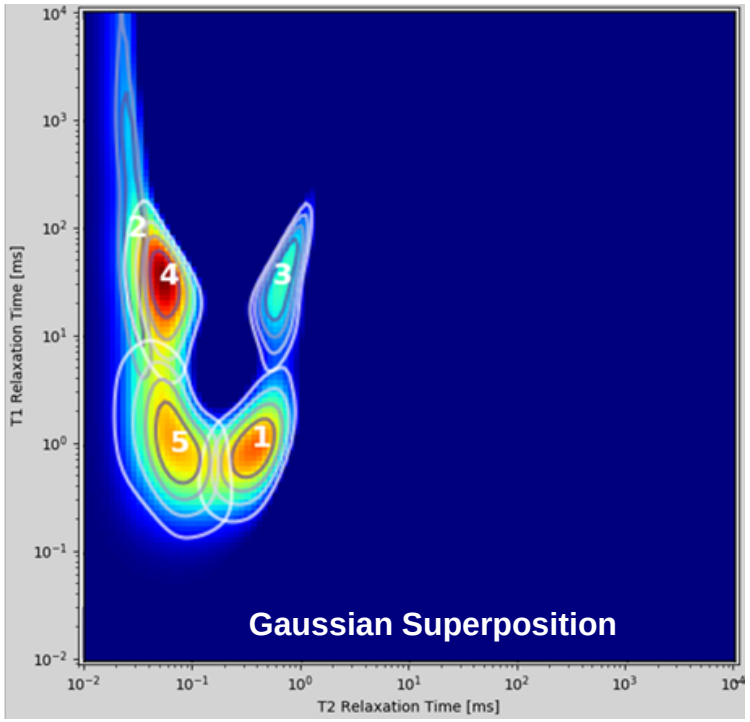
Selection	Fluid Type
1	Heavy Hydrocarbons / Organic Matter / OH
2	Clay Bound Water / OH
3	Clay Bound Water
4	Oil in Organic Pores
5	Capillary Bound Water
6	Oil in Intergranular Pores
7	Bulk Fluid (Oil, OBM, Water)



Handling Overlapping Fluid Signals

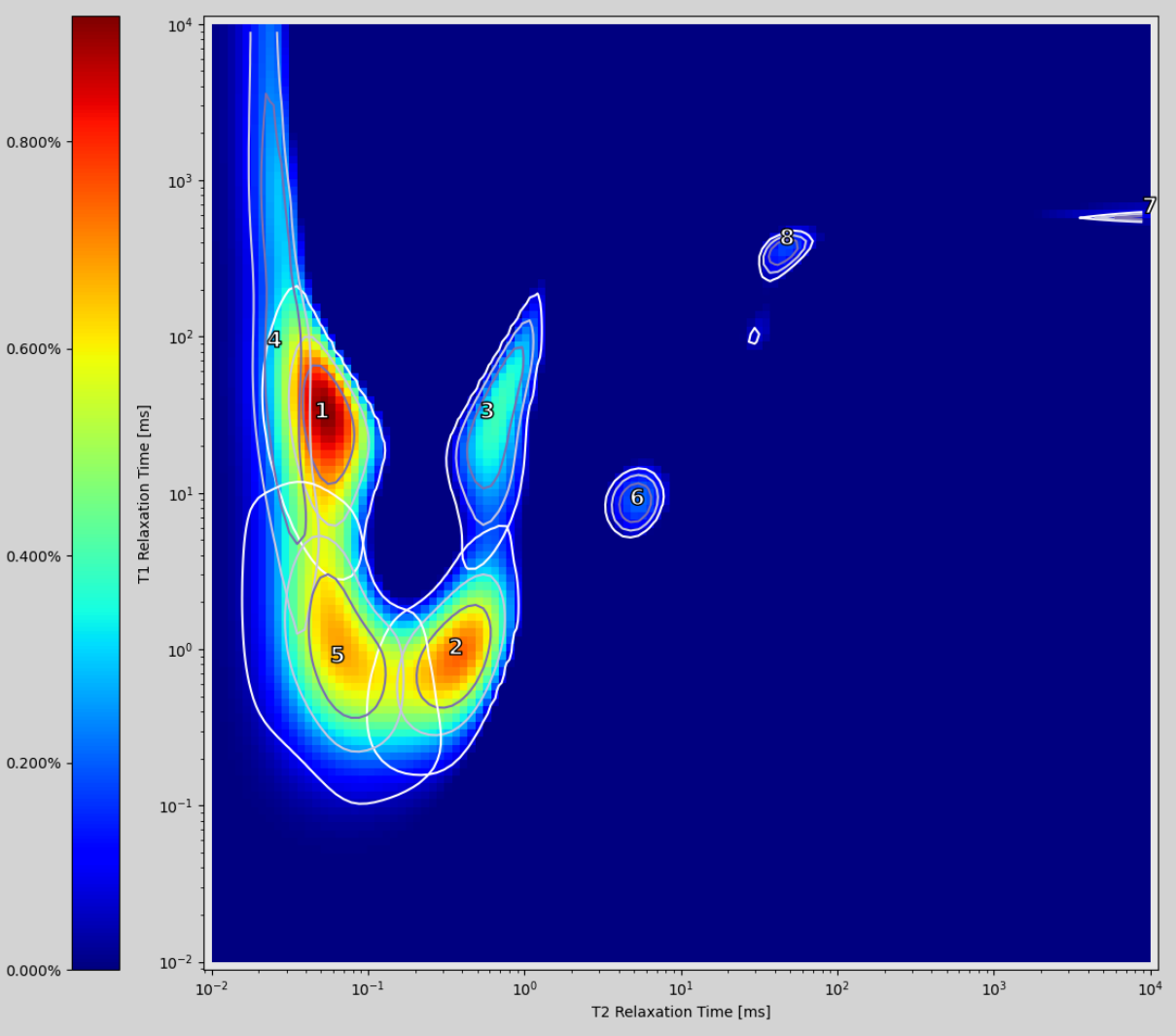






Netherland, Sewell & Associates, Inc. is working on technology to automate the fluid selection and quantification process, which eliminates fluid signal overlap issues.

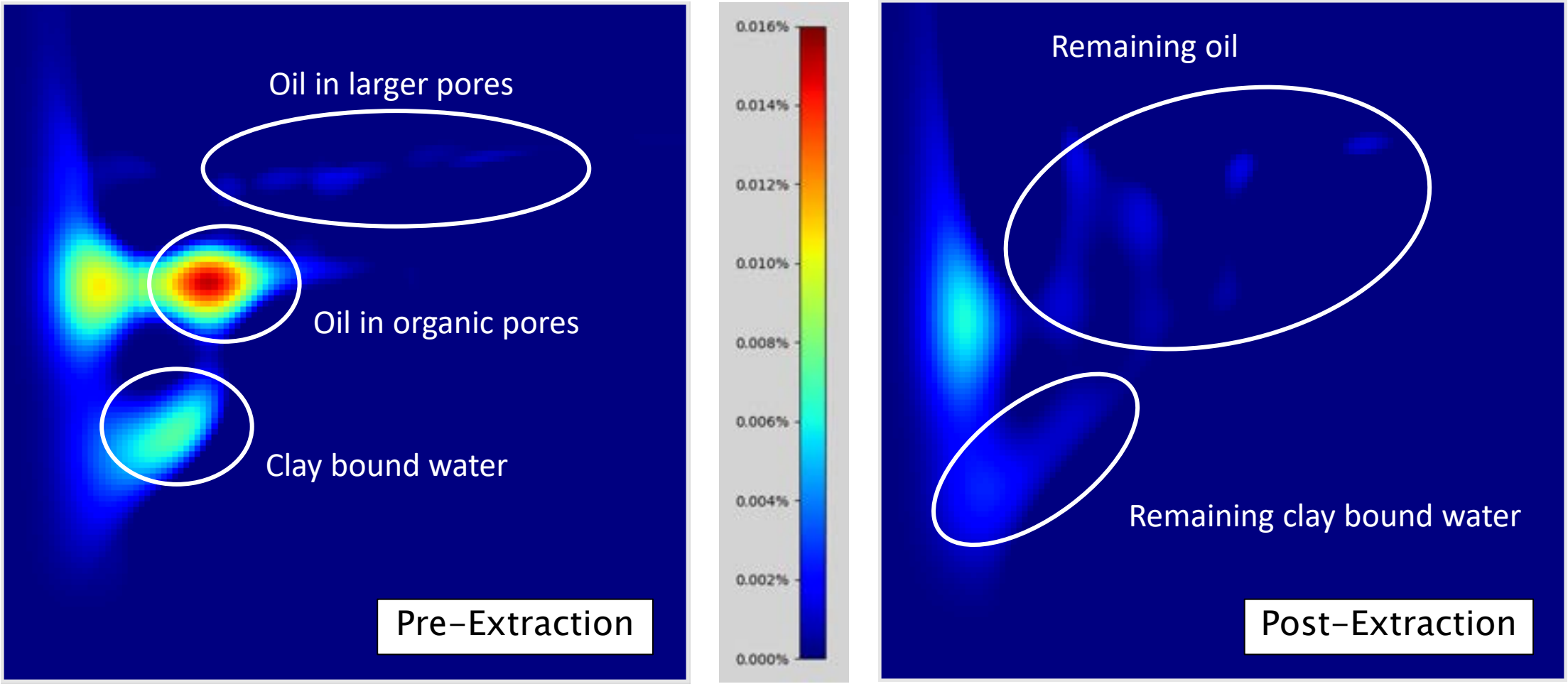
Fluid Type Identification from T1-T2 Map



Region	Fluid Type	Volume [%]
1	Kerogen / Bitumen	1.352
3	Clay Bound Water (CBW)	1.302
4	Oil in Organic Pores	0.509
4	Kerogen / OH	1.457
5	Tightly Bound CBW / OH	1.953
6	Capillary Bound Water	0.070
7	Oil / Water in Larger Pores	0.011
8	Oil in Larger Pores	0.041

OH - hydroxyls associated with clay crystal lattice

T1-T2 Map from Oil Window

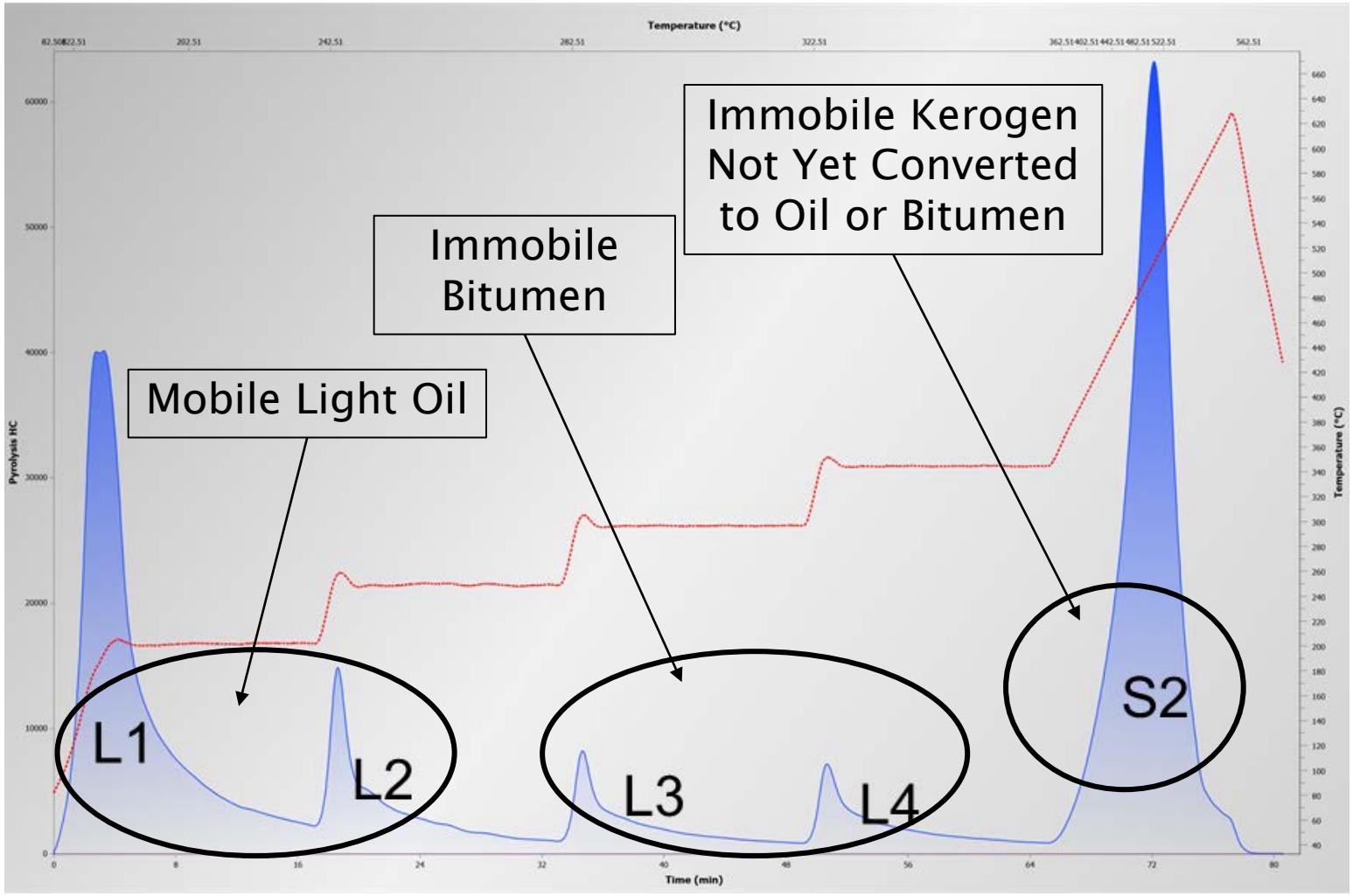


Solvent extraction does not remove all of the oil and water.
HFNMR helps to describe the hydrocarbon pore space (mobile vs. potentially capillary-bound oil).

Multiple Heating Rate Pyrolysis

- With standard Rock-Eval pyrolysis, it is not possible to accurately differentiate mobile oil from immobile bitumen unless measurements are made on both as-received and solvent-extracted core samples.
- Research has shown that multiple heating steps carried out during the S1 heating period (200 to 350°C) can be used to differentiate mobile, lower-boiling-point oil from immobile, higher-boiling-point bitumens, resins, and asphaltines.
- Recent experience with a commercially available multiple heating rate (MHR) pyrolysis protocol indicates that the relative weight fractions of oil and bitumen can be estimated and that S2 values comparable to those obtained from an extracted sample can be derived from a single pyrolysis experiment on a single non-extracted sample. This permits the estimation of both non-extracted and extracted TOC values.

Multiple Heating Rate Pyrolysis



L1 mg/g	L2 mg/g	L3 mg/g	L4 mg/g
14.95	4.41	2.75	2.73

S2 mg/g	S3 mg/g	Tmax °C	TOC Wt %
19.61	0.16	447	7.21

$$\%TOC_{ext} = \%TOC - 0.083(L_1 + L_2 + L_3 + L_4)$$

Importance of Non-Extracted and Extracted TOC

- Log-derived TOC estimates are more representative of non-extracted TOC and measured using standard Rock-Eval pyrolysis.
- Extracted TOC values are needed for the purposes of calibrating the log-derived porosity estimates to the porosities measured from crushed rock analysis.
- Invasion of oil-base mud filtrate must be considered during interpretation.
- MHR pyrolysis can be used with drill cuttings to provide a reasonable continuous record of immobile hydrocarbon content and extracted TOC, as well as thermal maturity.
- The partition between mobile oil and immobile bitumen can be calibrated with the L1 through L4 peaks using standard pyrolysis and the results of crushed rock measurements.

AN ALTERNATE APPROACH TO SATURATION MODELING

Reservoir Water Saturation

- A comprehensive resistivity-based saturation model has yet to be adopted.
- Most analysts utilize a fit-for-purpose approach based on the Archie equation or a modified shaly sand model where m and n are adjusted to match core-derived water saturations.
- An alternate approach that is based on the Herrick-Kennedy electrical efficiency model is gaining acceptance.
- Electrical efficiency is treated as a property of the rock, taking the place of m and n. The electrical efficiency of each interval is determined using flushed zone measurements, then the water saturation in the uninvaded reservoir is computed from the deep resistivity measurements.
- Et is usually reasonably constant. Variations in water content can be quantified with lab measurements with RSWCs at multiple water contents.

Herrick-Kennedy Model

Determine the electrical efficiency, Et, in the invaded zone.

Invaded Zone

$$BVW_{inv} = \frac{Rw_{inv}}{Et \times Rxo}$$

Multi-frequency dielectric RSWC measurements

Array resistivity measurements

Multi-frequency dielectric log measurements

Apply Et in the reservoir using the deep resistivity measurements.

Reservoir

$$\mathrm{BVW} = \frac{Rw}{Et \times Rt}$$

Low-invasion core measurements

Array resistivity measurements

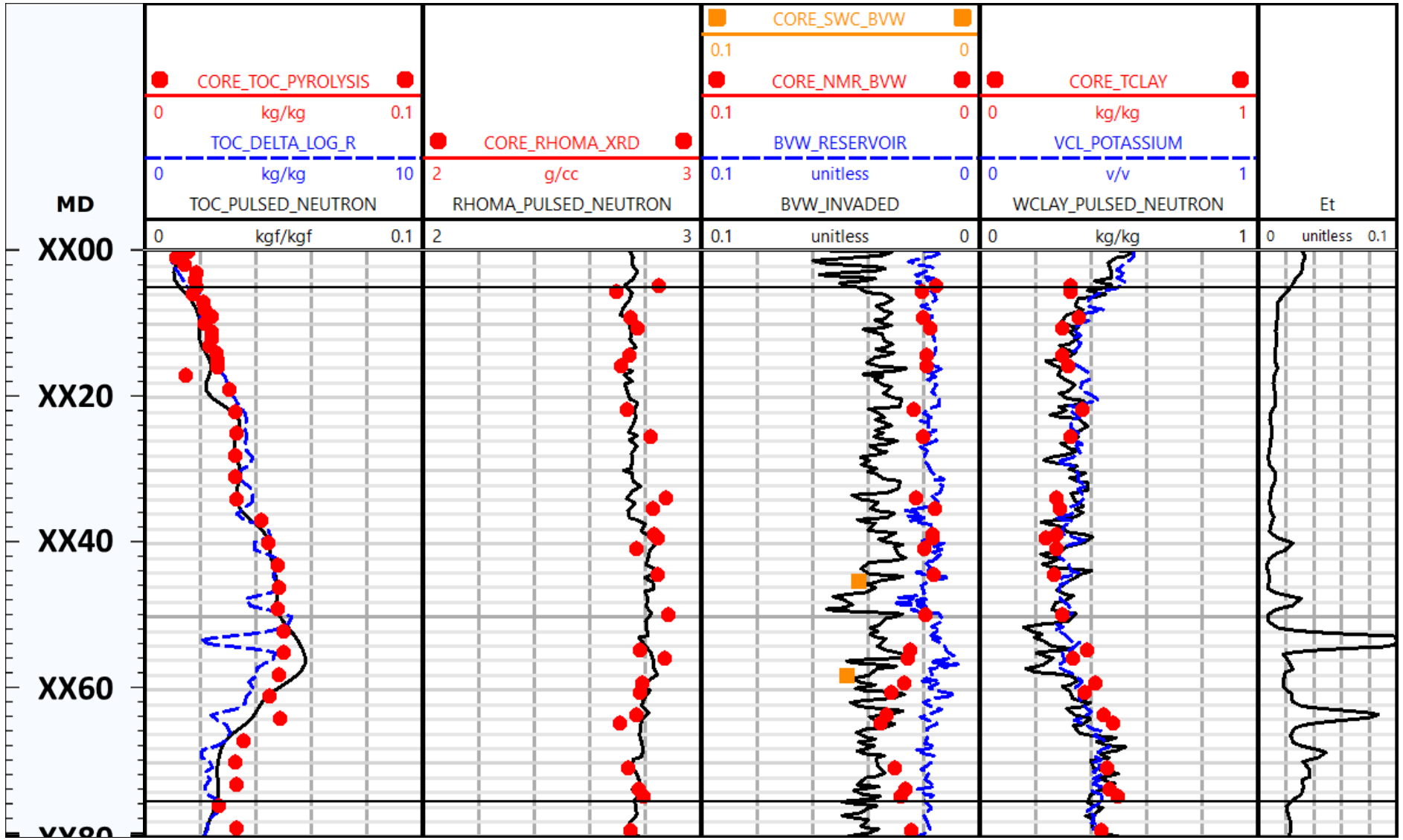
If a core-derived reservoir BVW is known, Rw can be estimated.

INTEGRATED INTERPRETATION

Example Application:
Analog for Unconventional Reservoir in Australia

- Well was drilled with water-base mud, and the source rock interval was cored with a low-invasion, water-base coring fluid.
- Following logging operations, a set of RSWCs were taken through the source rock interval.
- Critical measurements:
  - Pulsed neutron spectroscopy log to determine mineralogy and TOC
  - Invaded zone BVW volume and salinity from log and core measurements
  - Array resistivity measurements
  - Conventional core BVW estimates from crushed shale analysis with well-preserved samples
  - High-frequency NMR measurements on well-preserved RSWCs
- The presence of a highly desiccated clay hydration state was confirmed, and accurate estimates of the true formation water saturation were obtained.

Example Application: Interpretation Results



CONCLUSIONS AND RECOMMENDATIONS

Conclusions

- Advances in well log and core analysis technologies have provided a means to significantly improve the evaluation of unconventional oil and gas reservoirs.
- These technologies are more powerful when they are used in an integrated approach with conventional and RSWC measurements.
- A robust RSWC program should be a part of the formation evaluation program during the exploration and appraisal phases in unconventional reservoirs.

Recommended Data Acquisition

- Gamma-ray – caliper
  - include spectral GR tool to record uranium, thorium, and potassium
- Array resistivity
- Density-neutron with Pe
- Dipole sonic
- Multi-frequency dielectric dispersion
- Pulsed neutron spectroscopy
- NMR
- Mud log
  - Collect cuttings for MHR analysis
- Large diameter RSWCs
- Periodically acquire conventional cores
  - Acquire conventional core using low-invasion fluids with tracers, and carefully preserve conventional cores and RSWCs at the drill site.

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