DEVEX 2017

9 & 10 MAY, AECC, ABERDEEN

BUILDING RESILIENCE, DRIVING GROWTH

Understanding NMR

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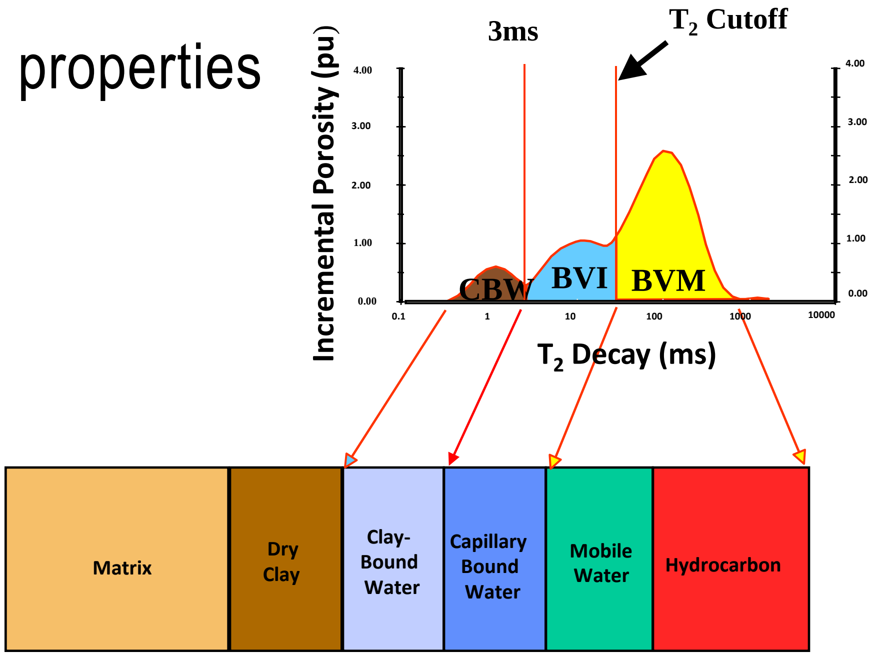
BAKER HUGHES

NMR: Basic Principles

- Measures relaxation of hydrogen nuclei in fluids
  - Electromagnetic: No nuclear sources
- Measures fluid-filled porosity
  - Lithology independent
- Measures fluid type
  - Oil, water, gas: Volumes and properties
- Measures pore size
  - Texture information
- Compartmentalises porosity
  - Productivity

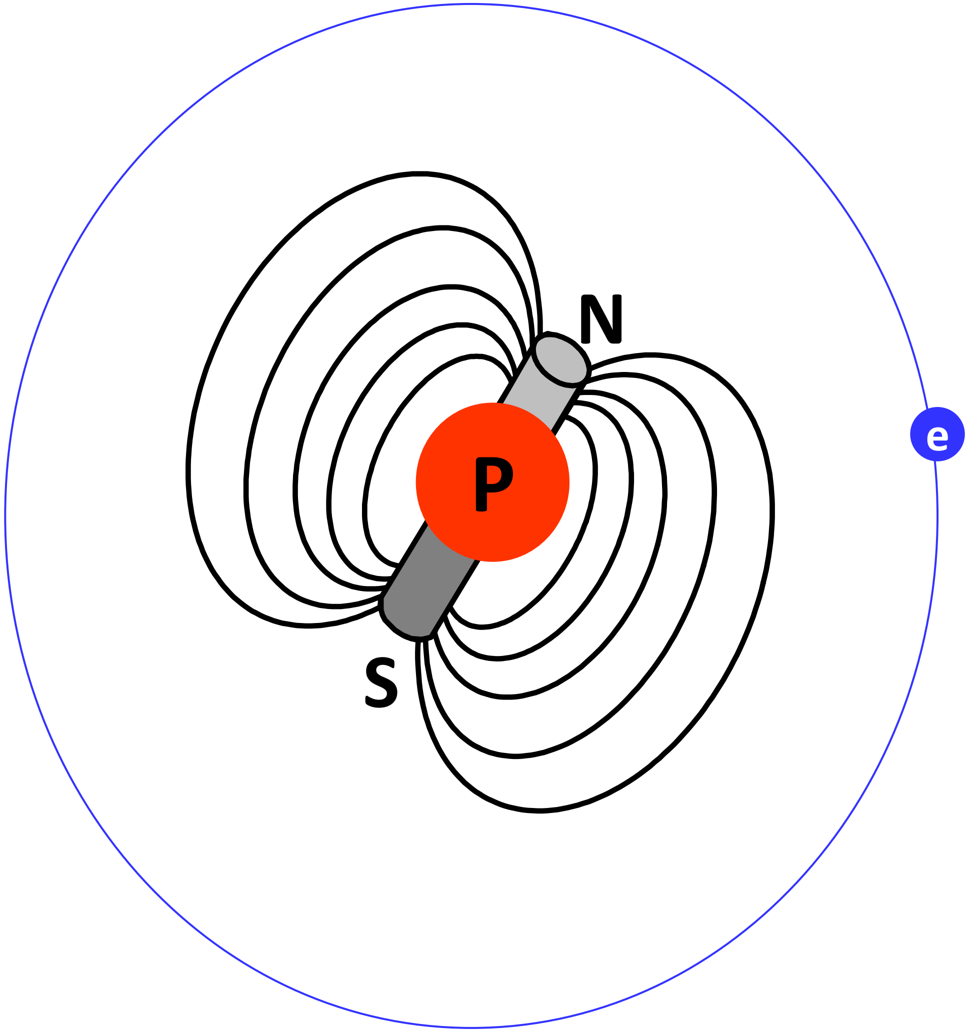


Magnetic Resonance

Hydrogen Atom

Properties

- 1 Proton
- 1 Electron
- Magnetic Dipole
- Spin (1/2)



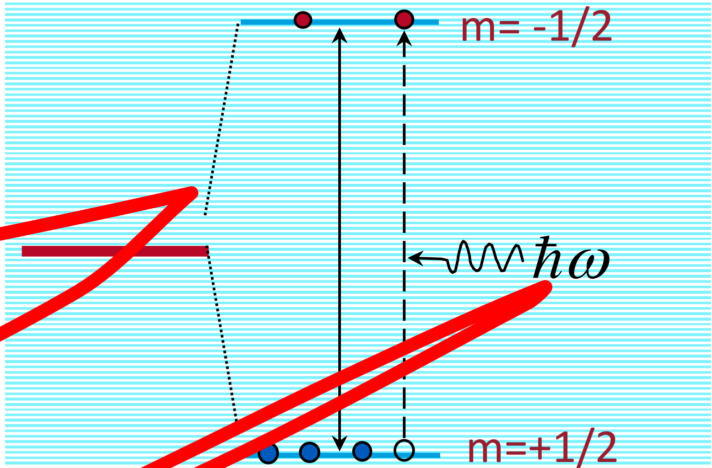
How Does NMR Work?

- Magnetic field produces

$$\Delta E = \gamma \hbar B_0$$

- A time-dependent interaction is needed for proton transitions occurring between Zeeman energy levels.

$$\hbar \omega = \Delta E$$



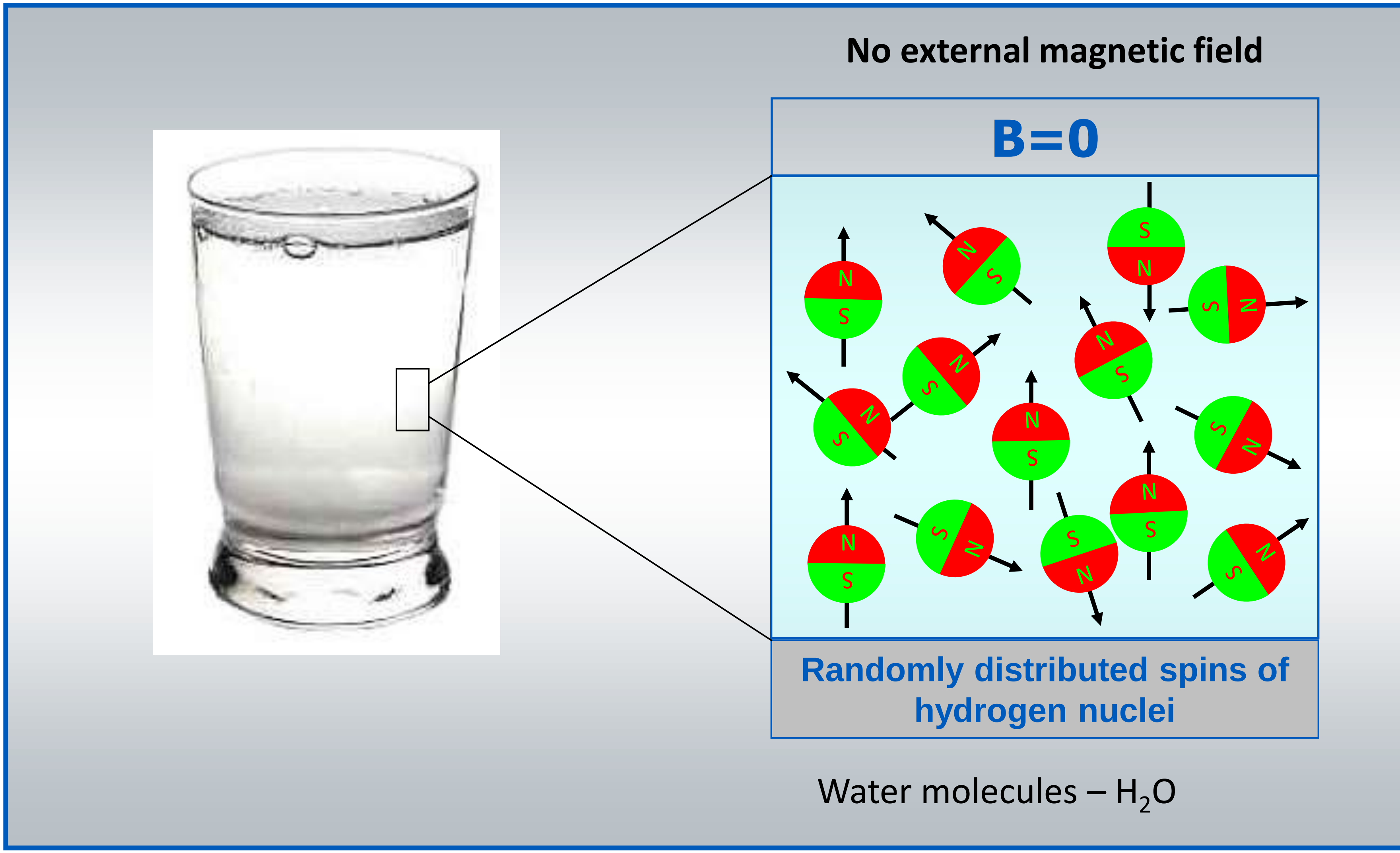
- Resonance condition

$$\hbar \omega = \gamma \hbar B_0 \quad \Rightarrow \quad \omega = \gamma B_0$$

quantum physics eqn.

classical physics eqn.

Hydrogen in Fluids



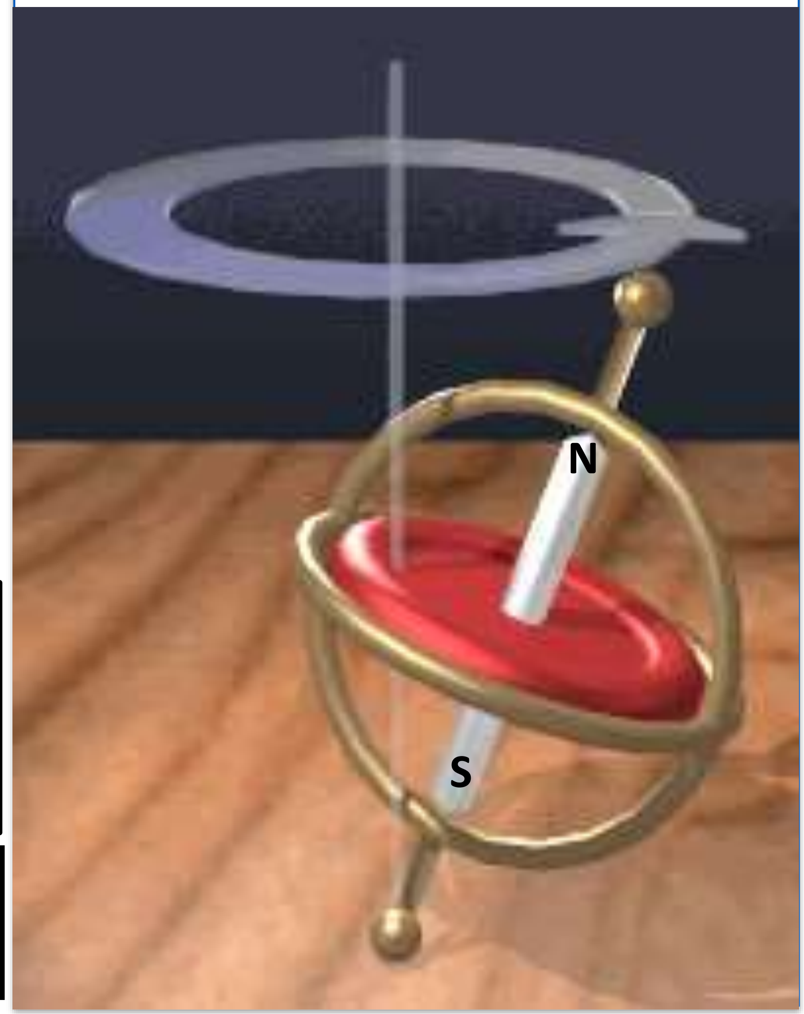
Add External Magnetic Field B_0

Larmor Precession

$$\text{freq.} = 4258 \ \frac{Hz}{Gauss} \ B_0$$

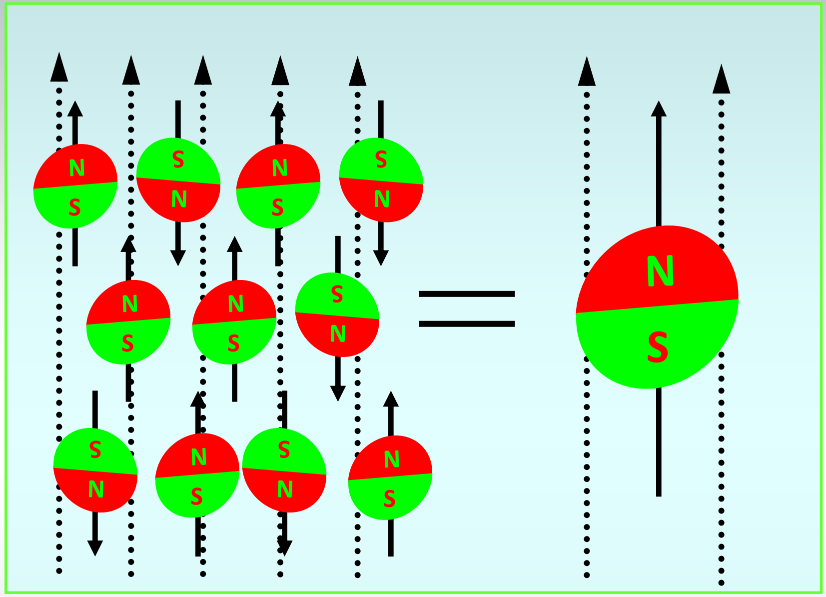
Know the magnet strength
-> Know the frequency

Magnetic Field B_0



Nuclear Magnetization

When placed in a magnetic field, B_0, the ^{1}H protons align parallel and anti-parallel with the field

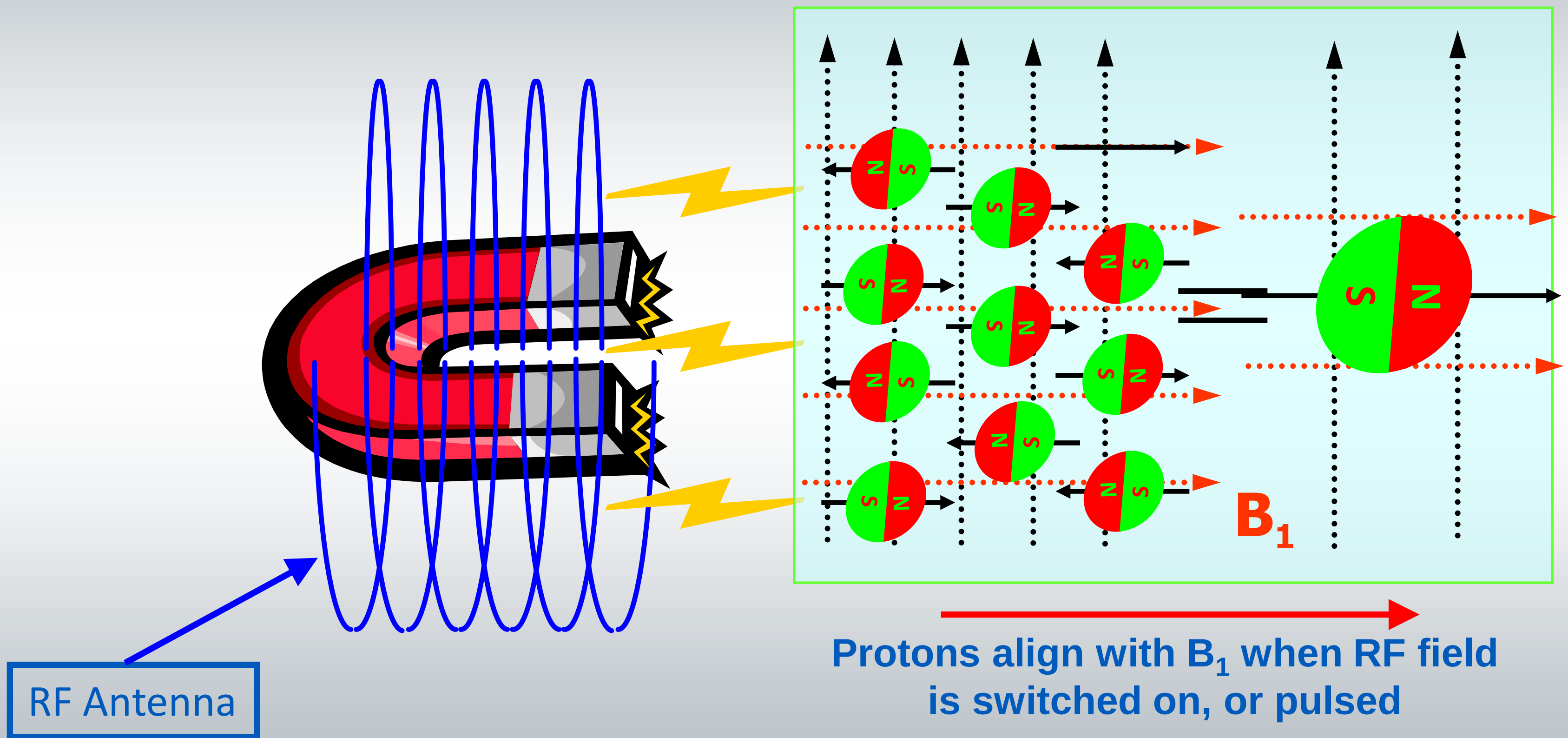


- **The ratio of parallel to anti-parallel is: 100,006 : 100,000....**
- **It is the extra 6 parallel protons that produce the NMR signal that we measure**
- **This is (absolute K) temperature dependent = A calibration parameter**

(0°K = -273°C)

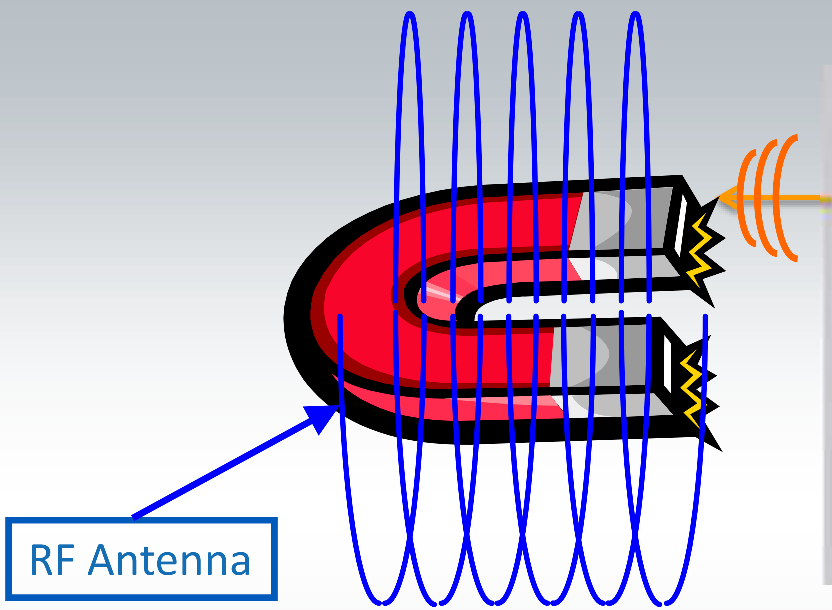
Tipping Pulse

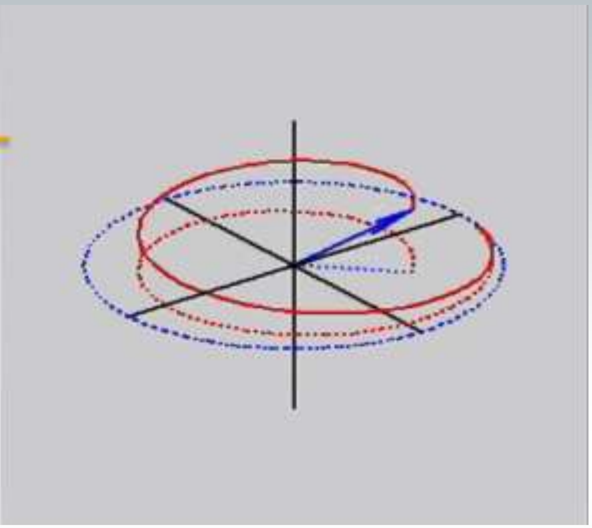
When a pulsed radio frequency field, B_1, is applied , the ^1H protons will realign with the B_1. When B_1 is switched off the ^1H protons begin to precess as they realign with B_0.



Protons align with B_1 when RF field is switched on, or pulsed

Nuclear Magnetization



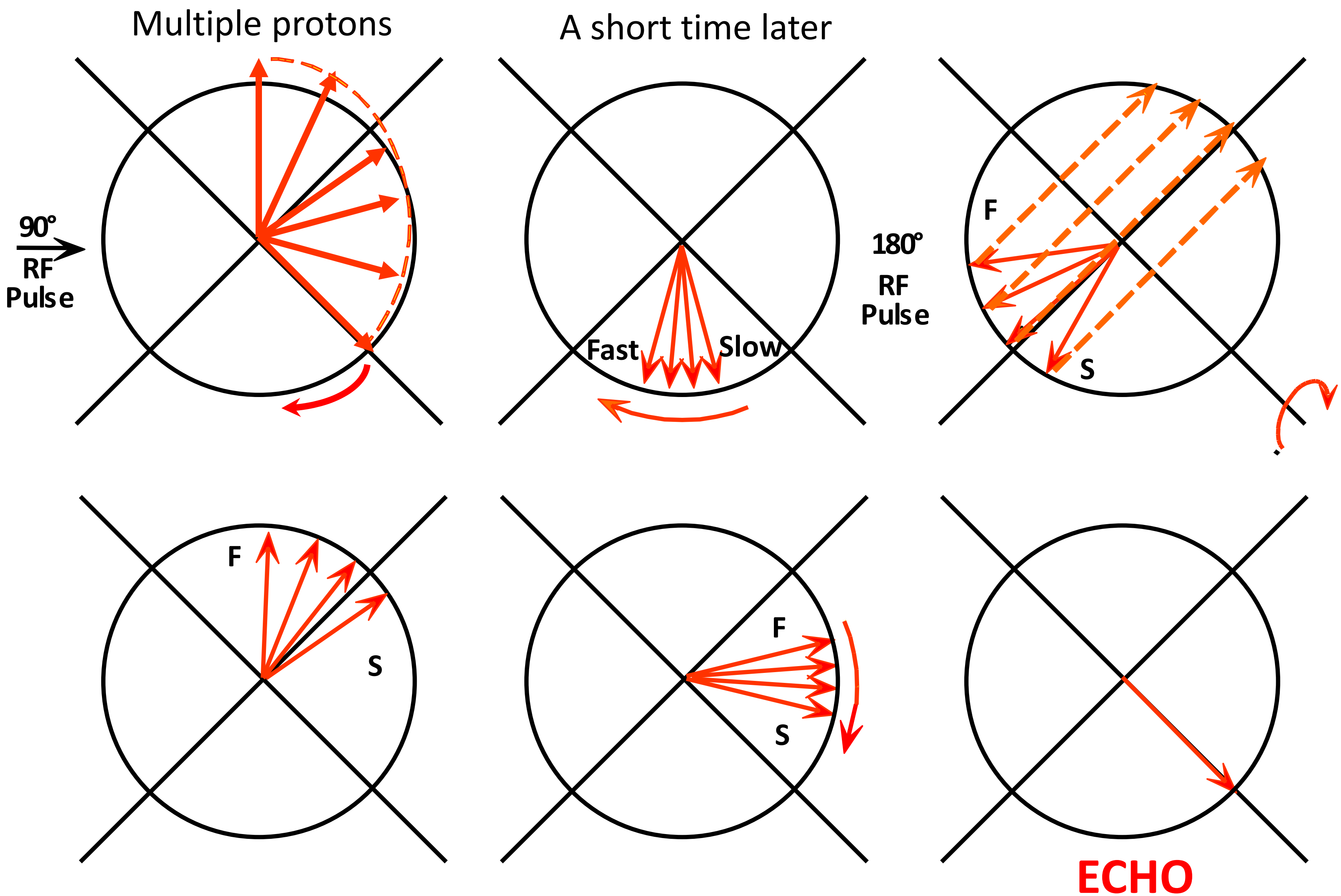


- When the RF field is switched off the protons precess back to realign with B_0
- As they precess $\perp^r$ they emit a small RF signal that is received in the RF antenna.
- This signal decays as they re-align with B_0

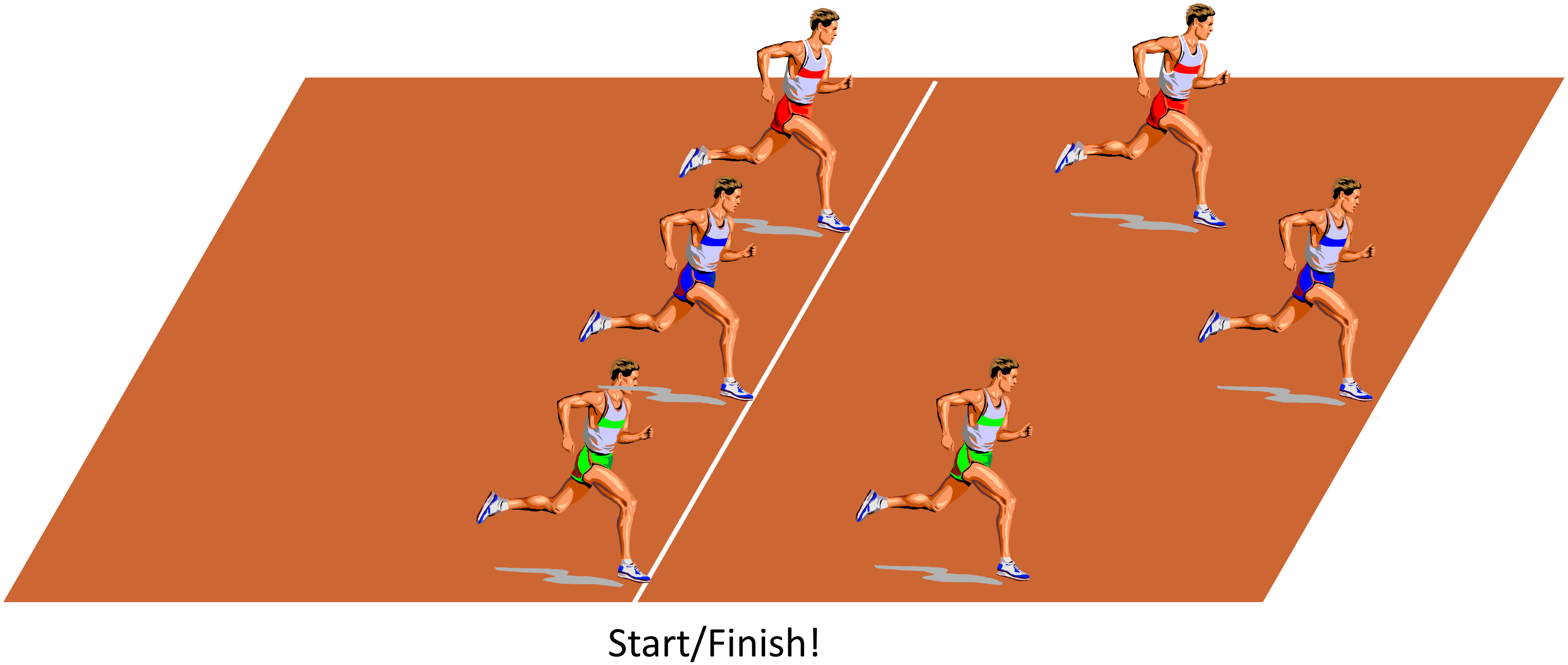
$$\text{Larmor Frequency} = 4258 \times \frac{Hz}{Gauss} \bullet B_0$$

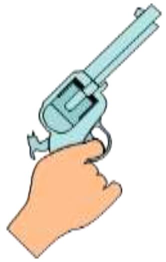
Pulse Sequence

Pulse Sequence

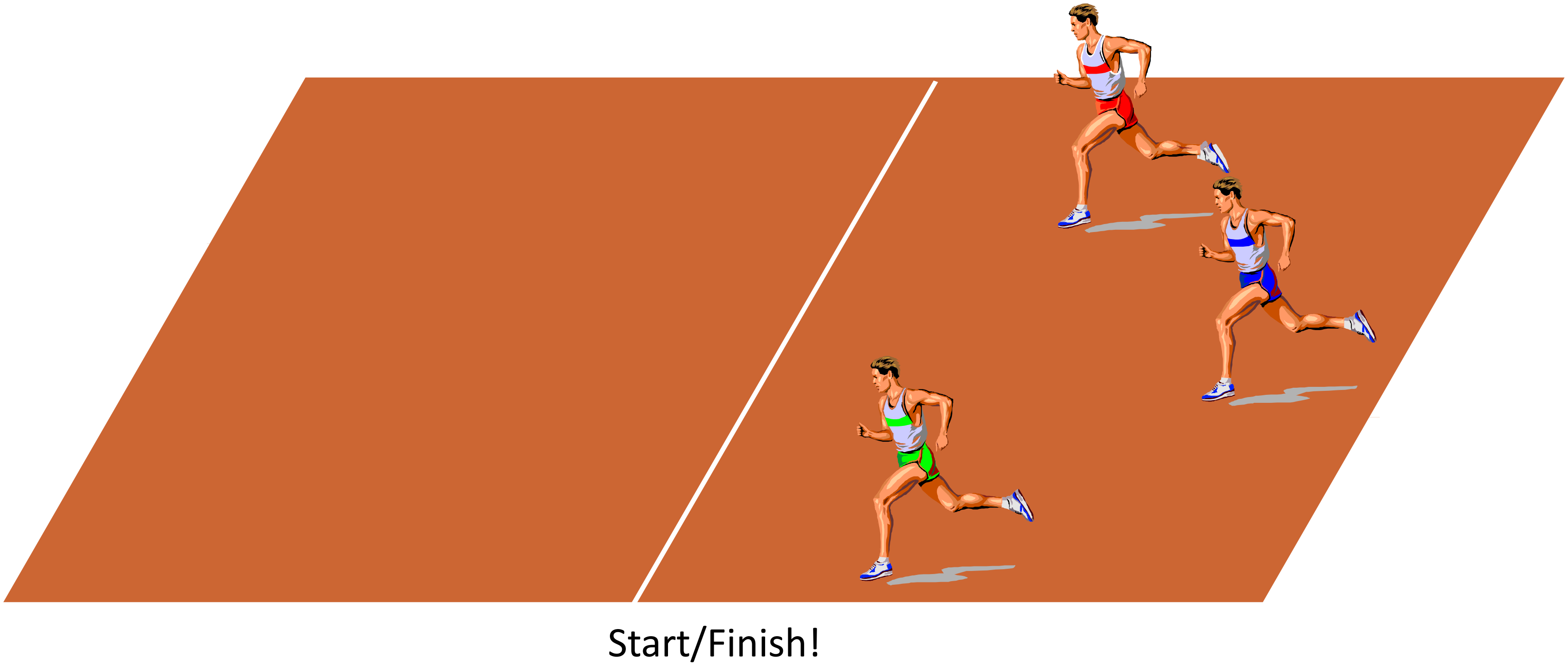


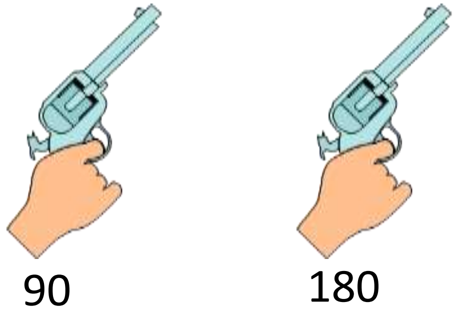
Reversing Race!



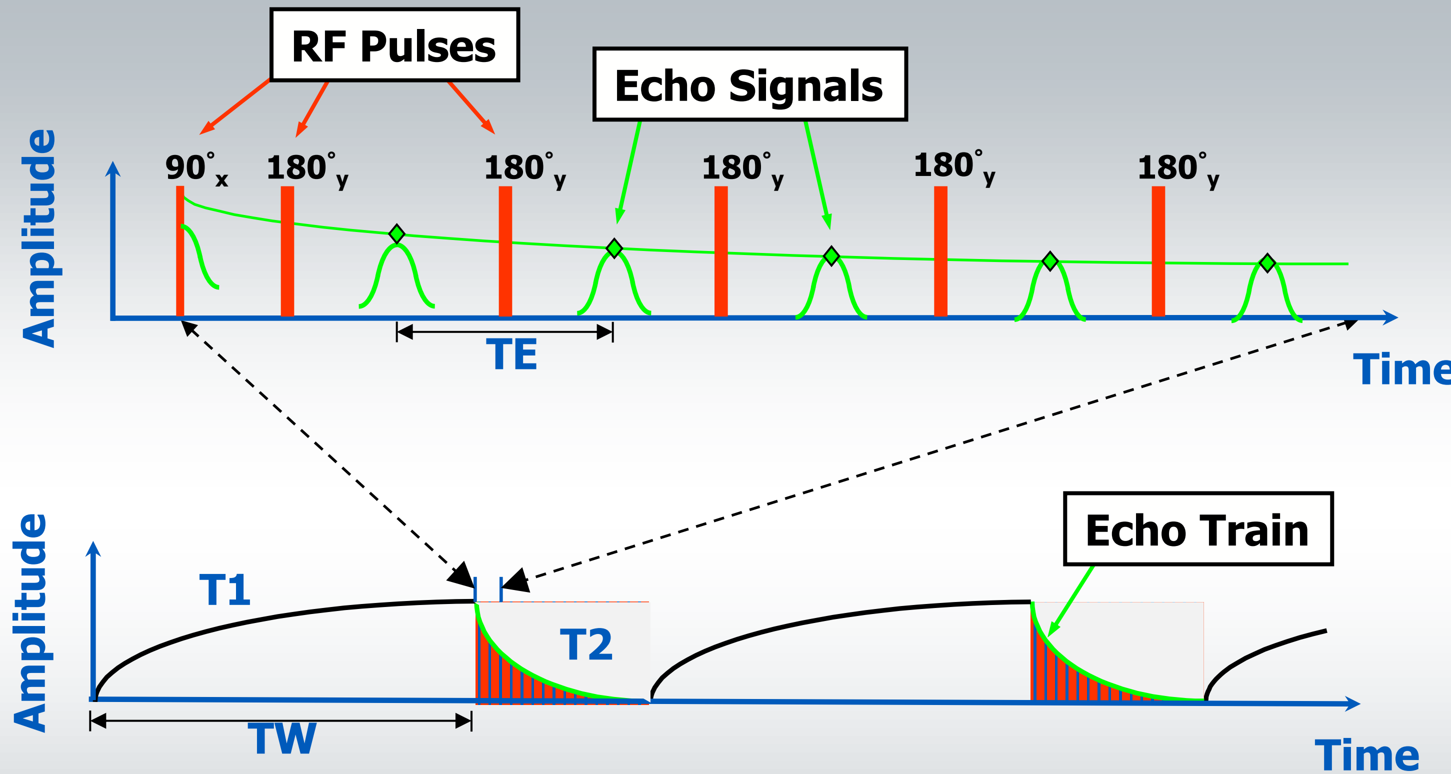


Reversing Race!





Echo Train – CPMG Pulse Sequence

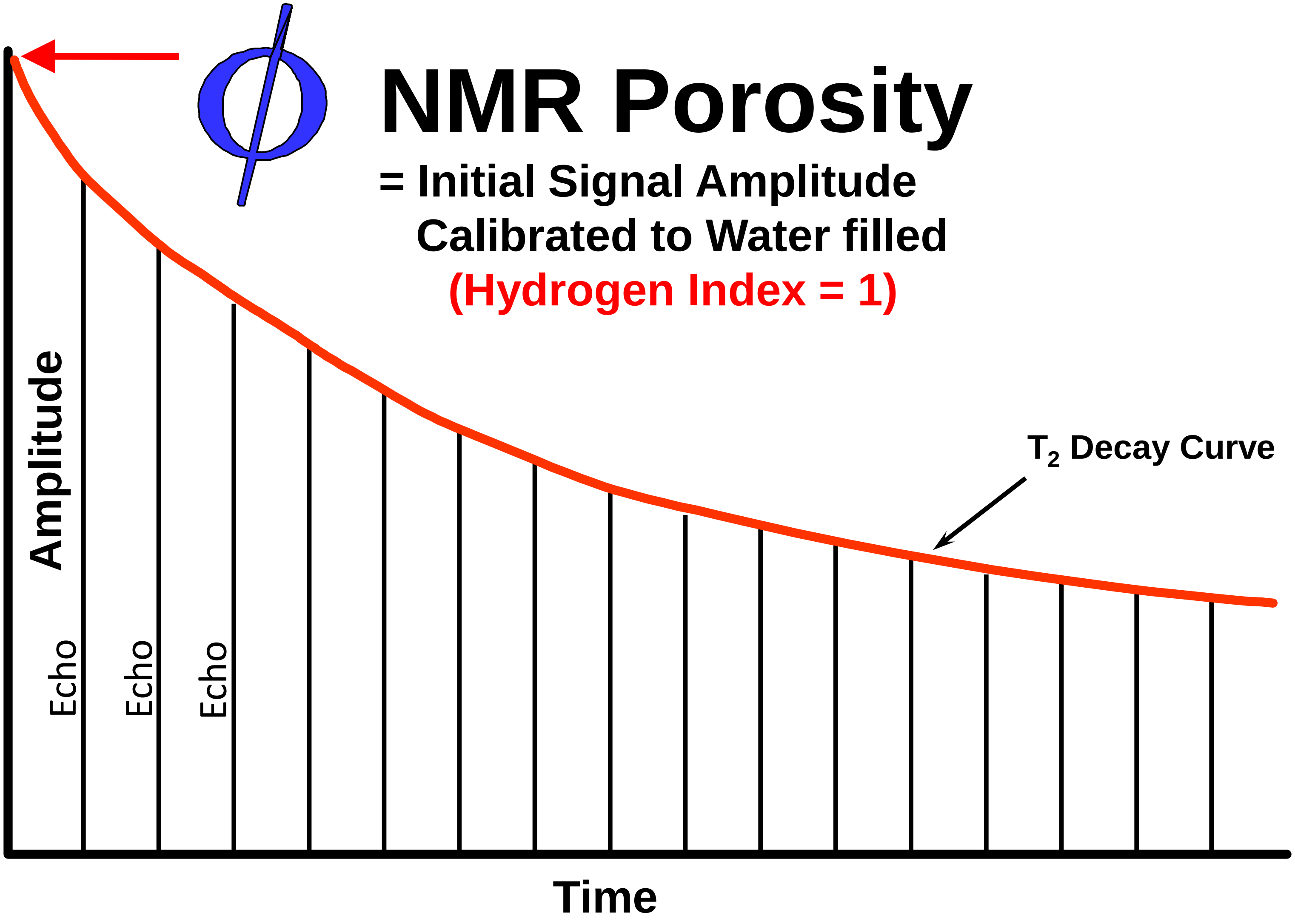


TE : intercho spacing

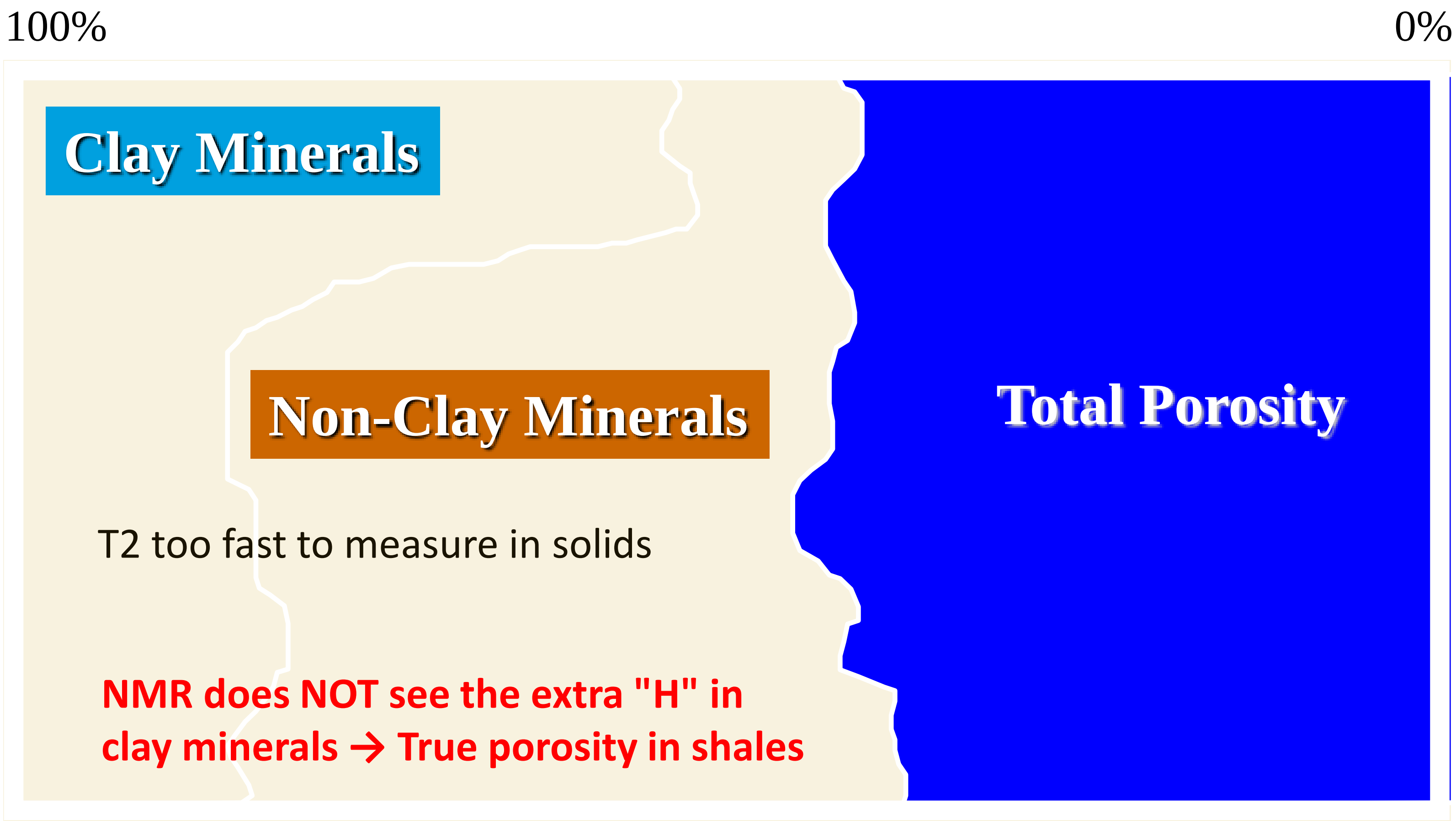
TW : wait time (≥ 3 x T_1 for full recovery)

Porosity

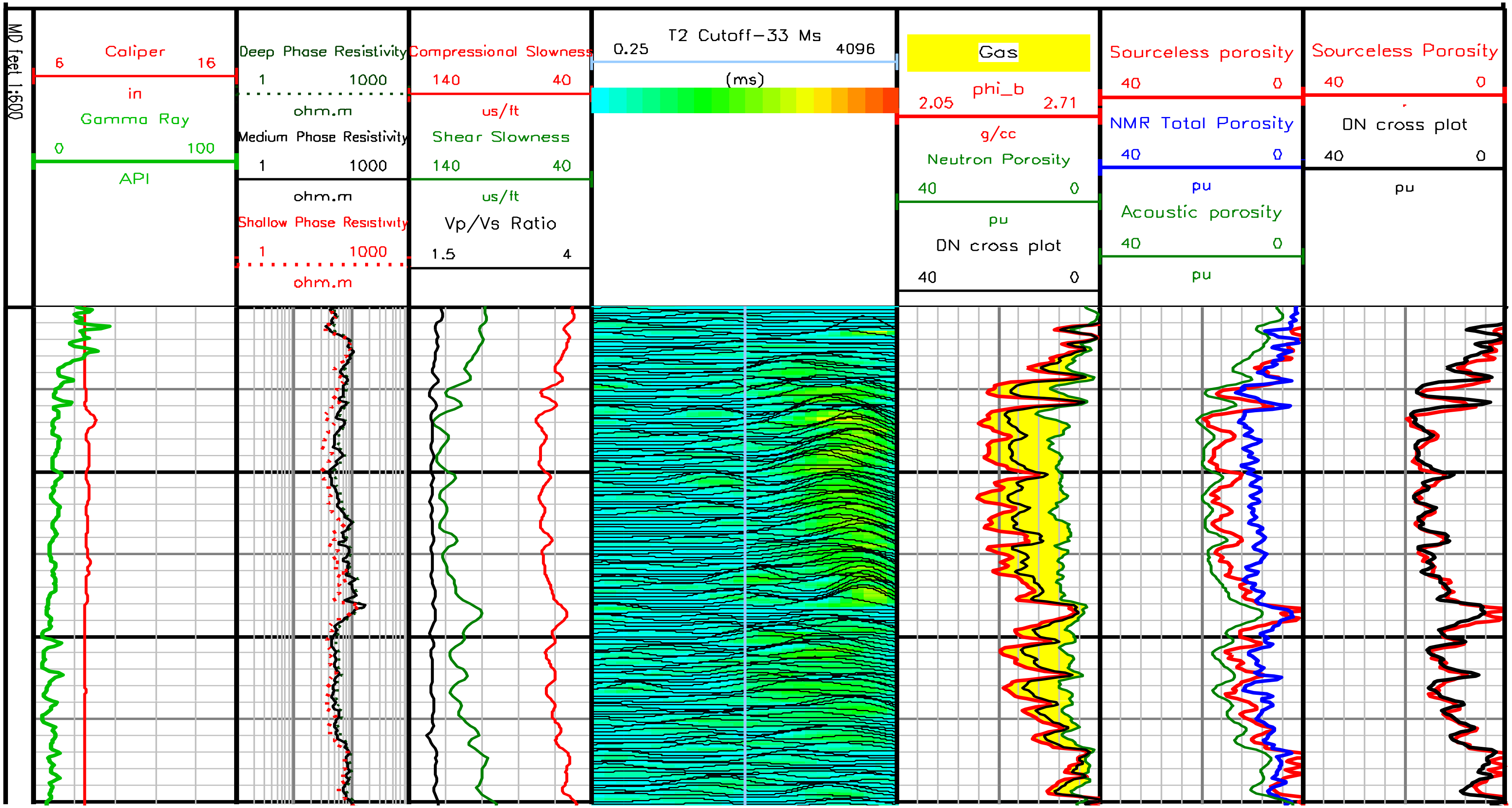
NMR Porosity



NMR Total Porosity = Mineral Independent



Sourceless Porosity

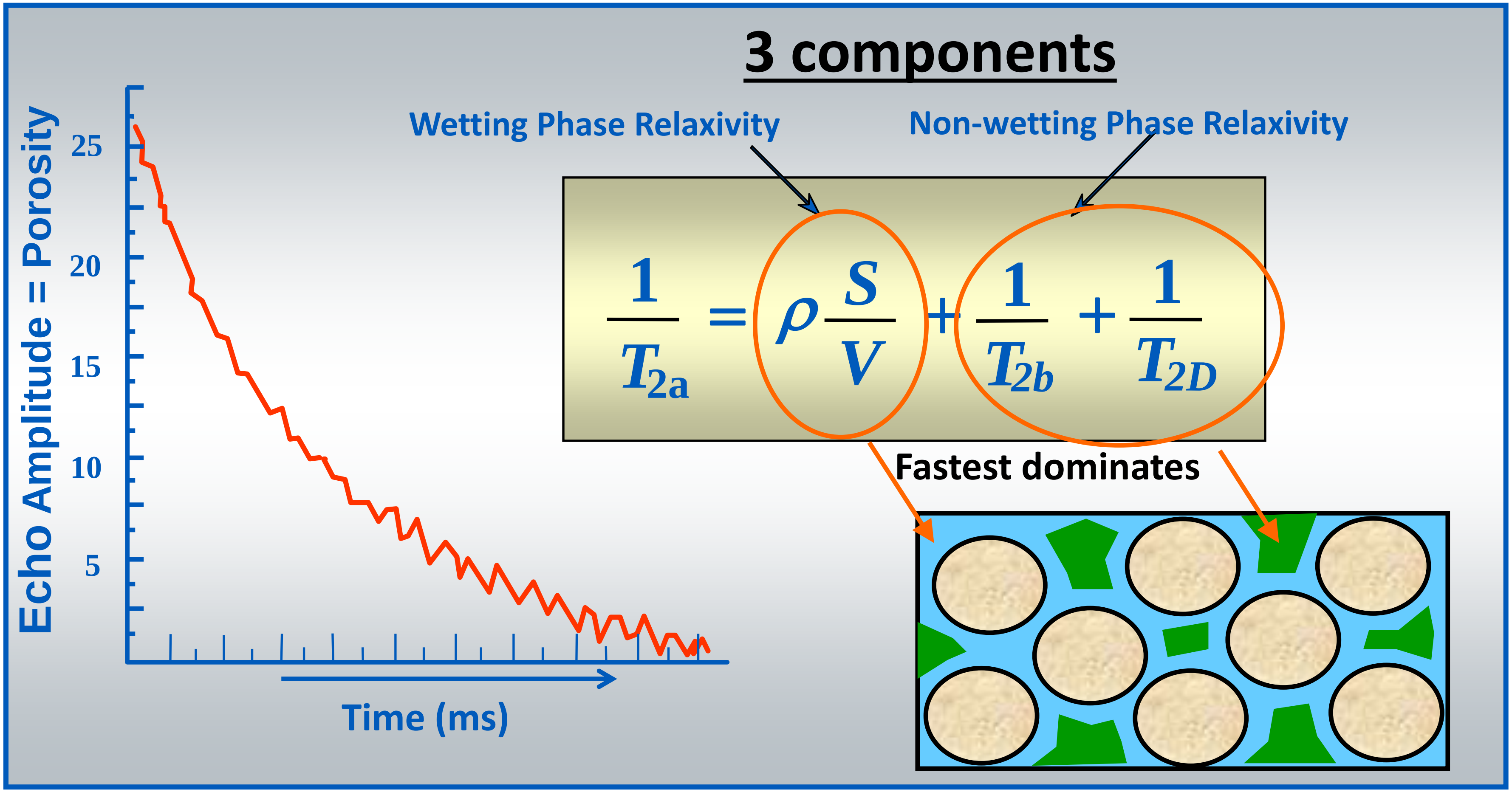


T2 Distribution

T2 Decay Components

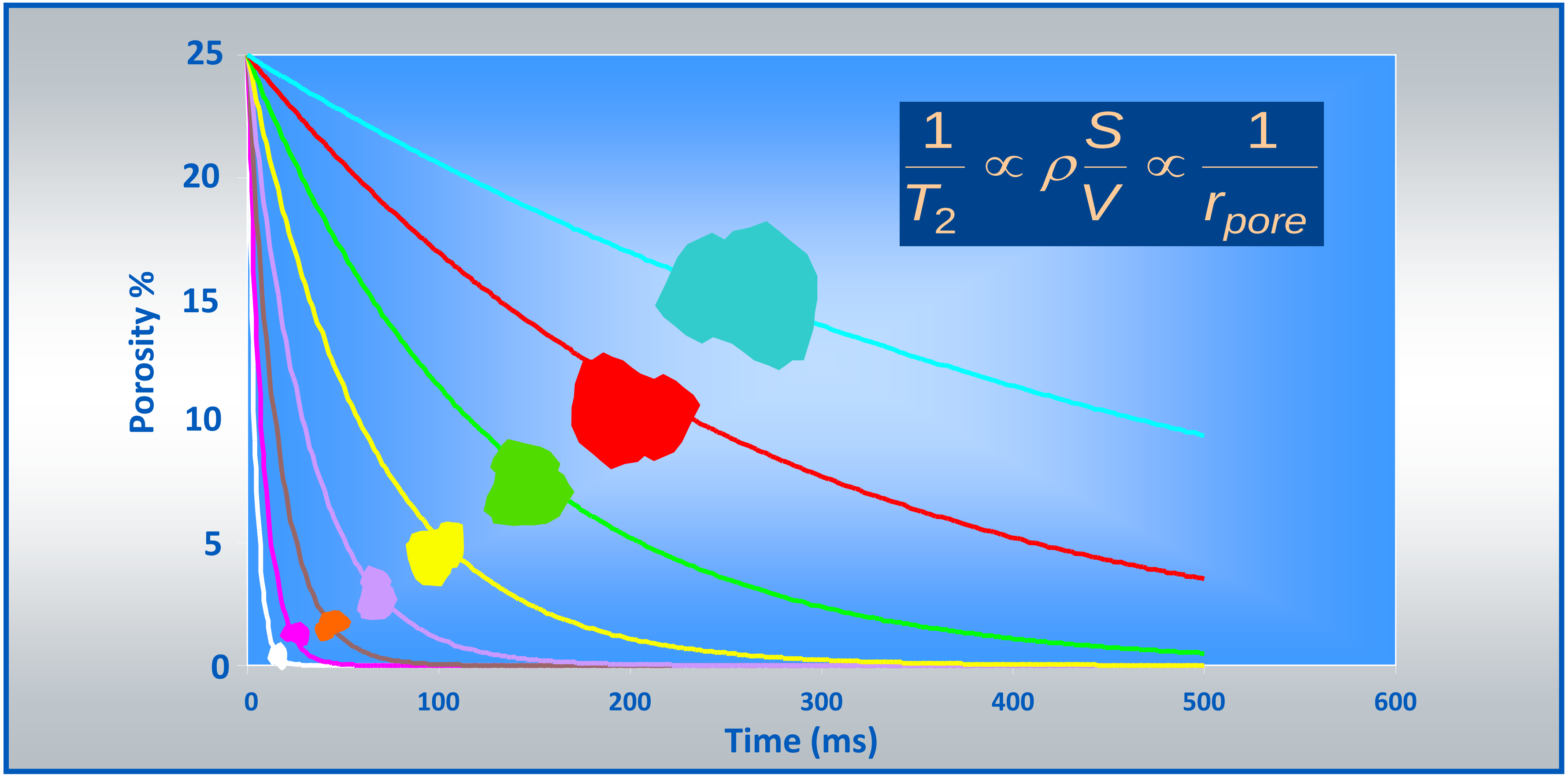
- Bulk T_{2b}
  - Depends on fluid type
  - High viscosity = fast, a few ms.
  - Low viscosity = slow, 1000ms +
- Surface interaction with rock - Surface/Volume ratio
  - Depends on pore sizes, and surface type
  - T2 = .5 – 1000ms
  - Large pores = slower
- Diffusion T_{2D}
  - Depends on viscosity, Magnetic field gradient "G" and TE
  - Gas = fast, fluid = slow

MR Relaxation - T2 Decay Effects



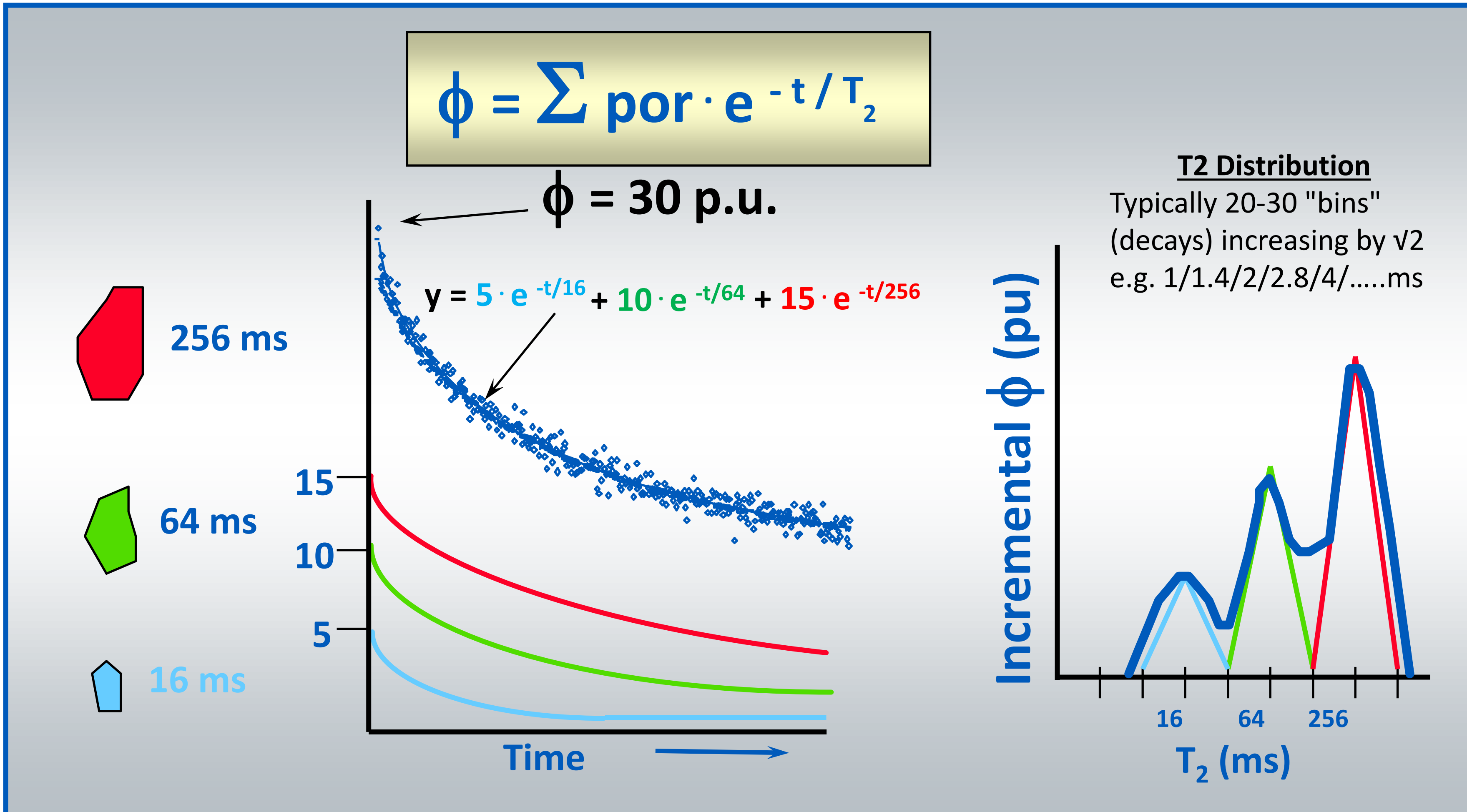
Surface/Volume Ratio → Pore Size

- In a single fluid filled pore the T_2 decay rate is inversely proportional to the surface/volume ratio of the rock being measured and directly proportion to the size of the pore.

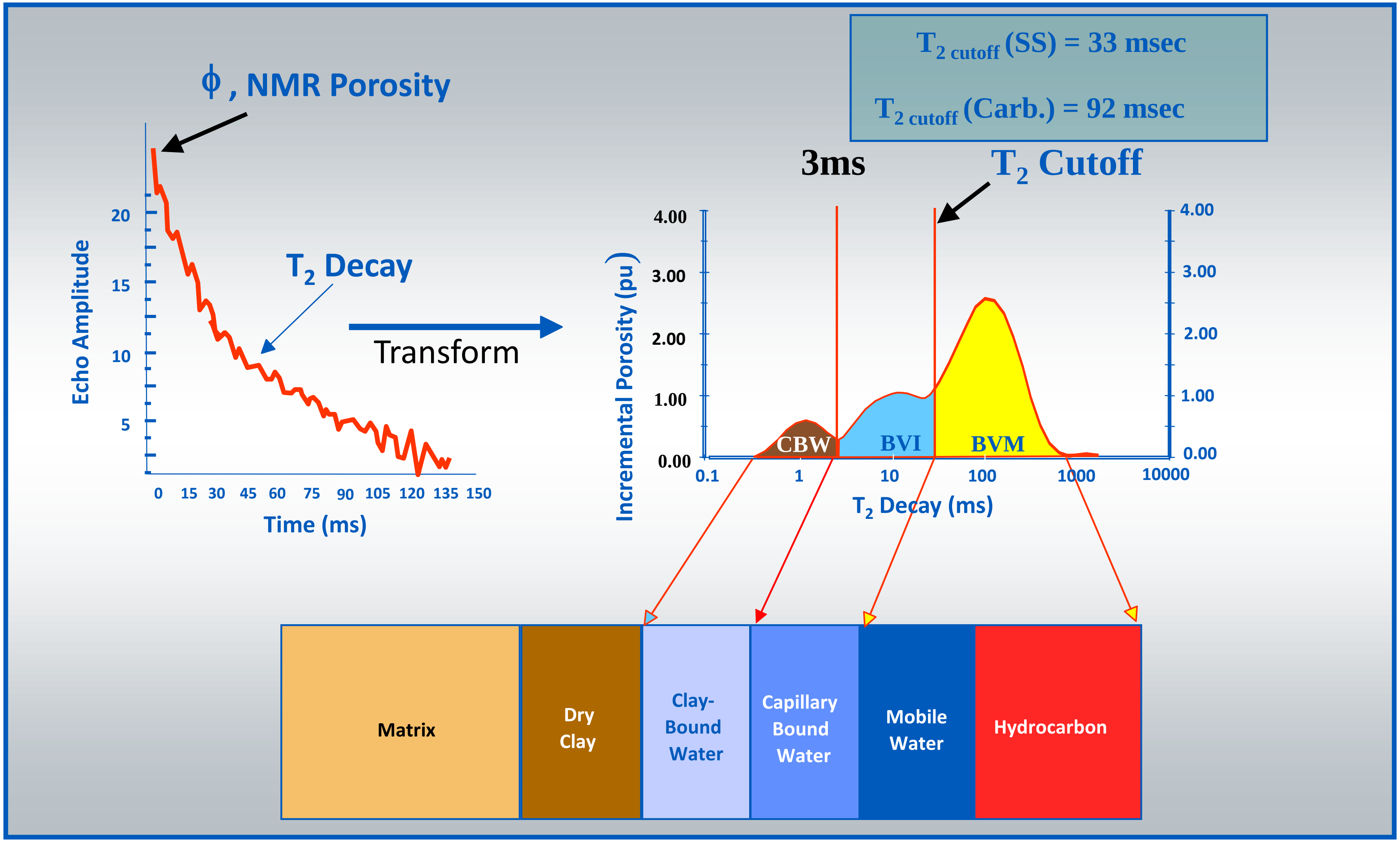


Multi-Exponential Decay

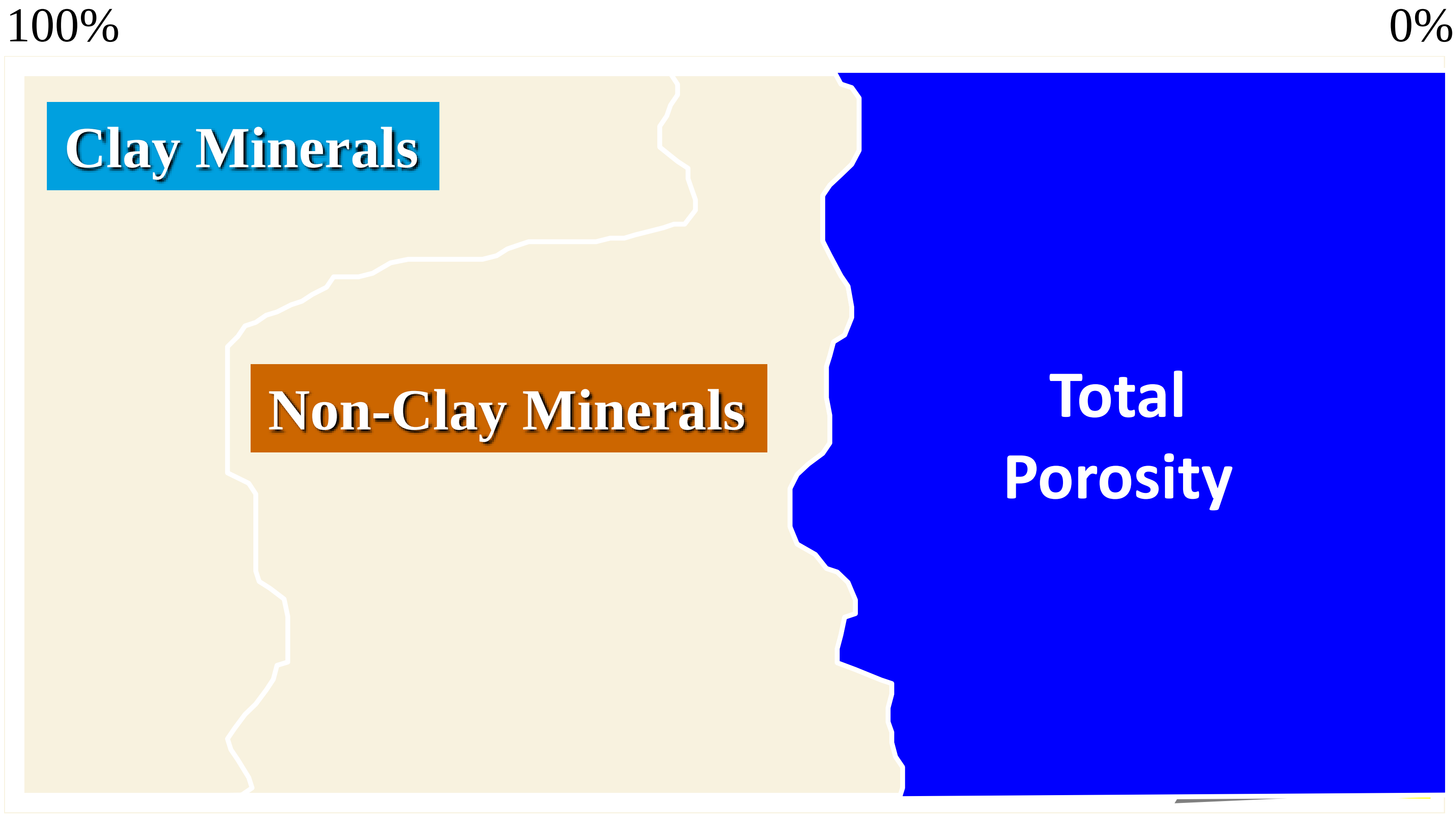
A series of exponential decays are fitted to the data, resulting in the T2 distribution



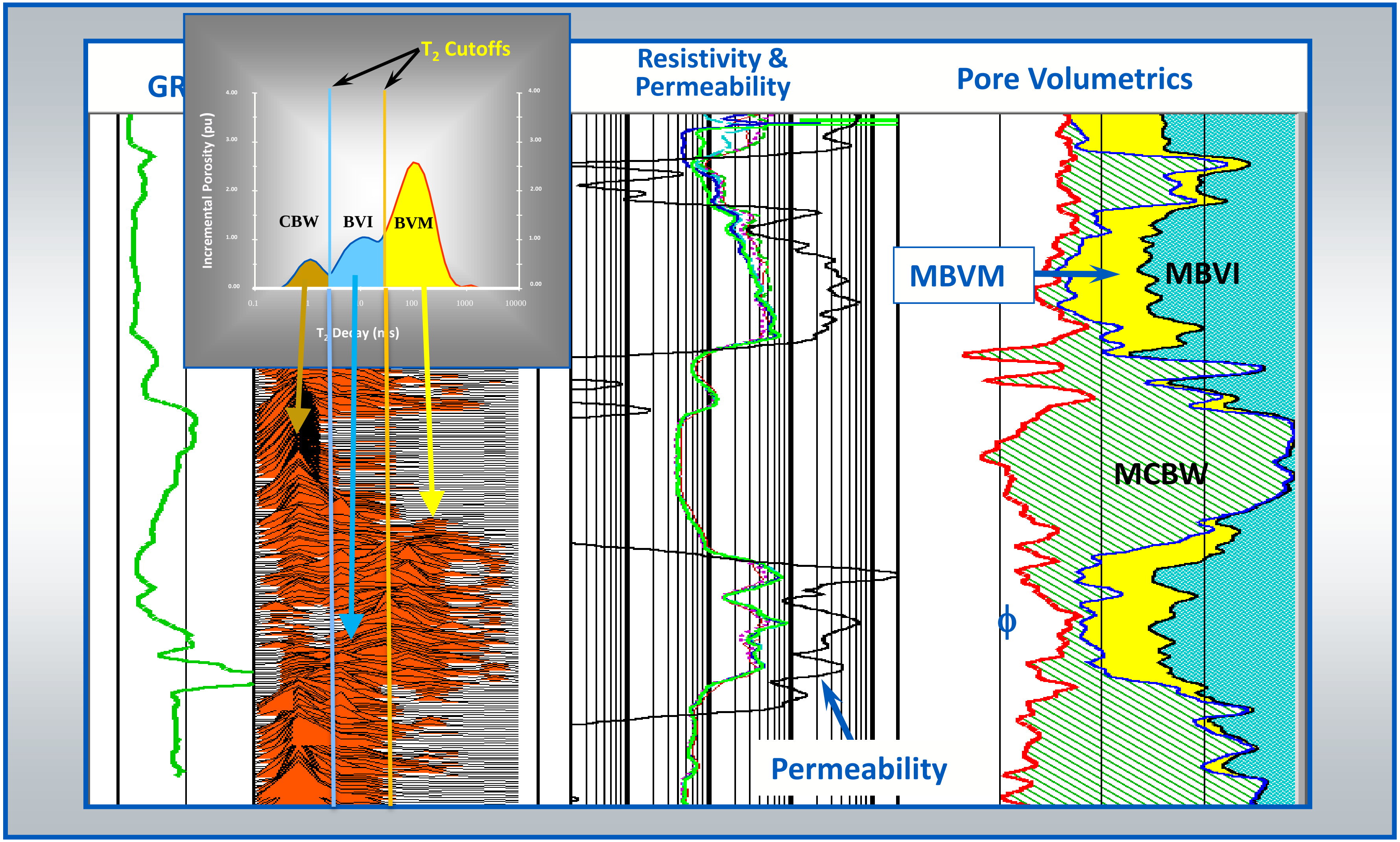
T2 Pore Volumetric Distribution from NMR



Porosity - MR Analysis

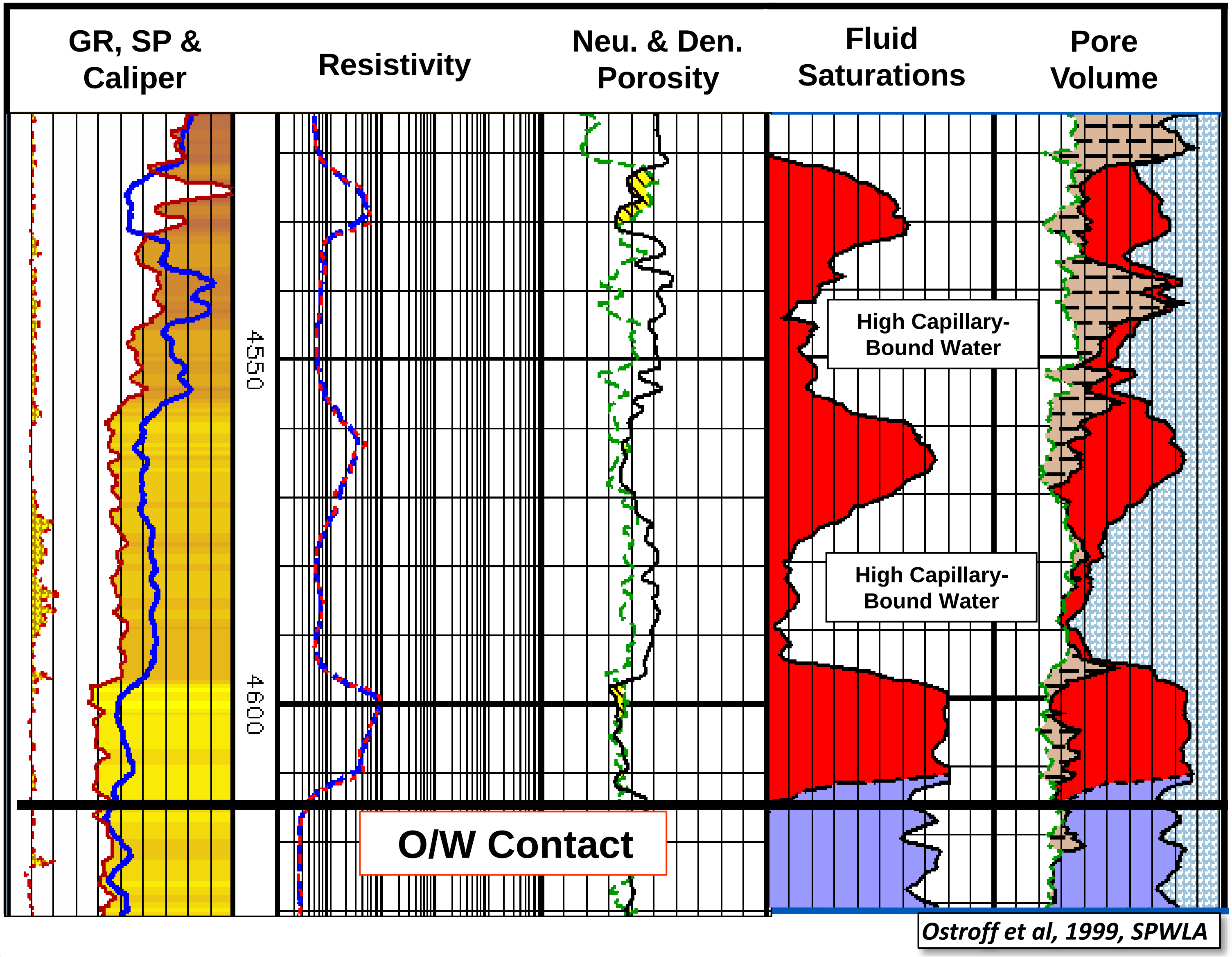


NMR Log Data



GR
Resistivity &
Permeability
Pore Volumetrics
T2 Cutoffs
Incremental Porosity (pu)
CBW
BVI
BVM
T2 Decay (ms)
MBVM
MBVI
MCBW
ϕ
Permeability

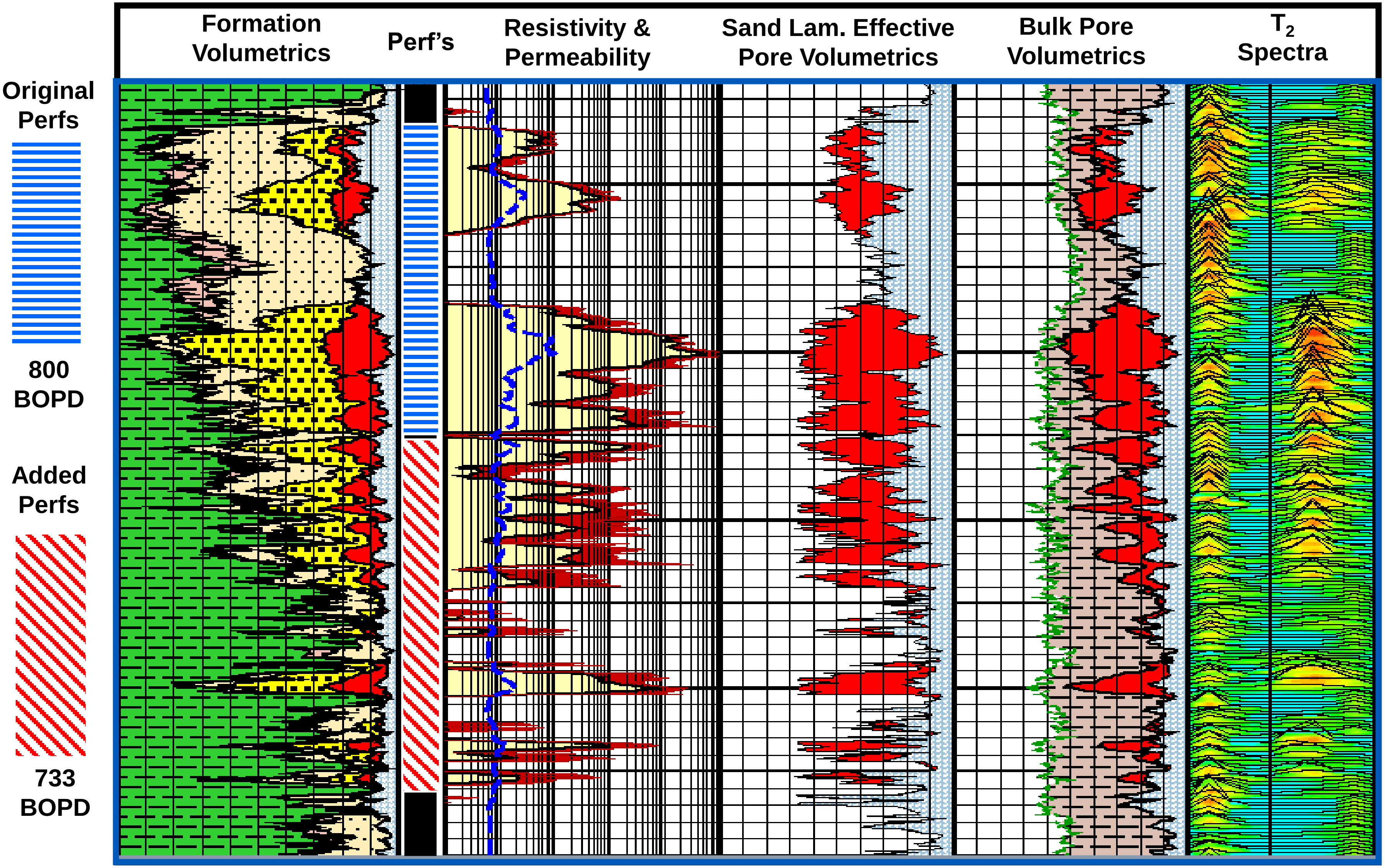
Low Resistivity Pay Example (Non-laminated)



Water-Free Production Correctly Predicted Above Actual Transition Zone!

Transition Zone

Thin Bedded Pay



Permeability

MR Permeability - k_{nmr}

Two **models** in use (Permeability is estimated not measured)

Coates-Timur Model :

$$k_{nmr} = \left(\frac{\phi_{NMR}}{C} \right)^m \cdot \left(\frac{BVM}{BVI} \right)^n$$

SDR/Kenyon Model:

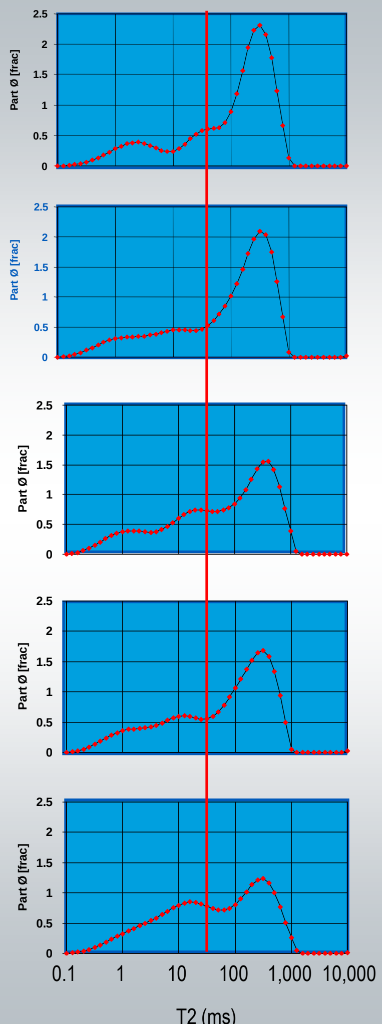
$$k_{nmr} = C \cdot \left(\phi_{NMR} \right)^m \cdot \left(T_{2\,Geo.\,Mean} \right)^n$$

Where assumed default parameters are: C =10, m = 4 & n = 2

Note: k_{nmr} is an estimate of permeability based on a model. For accuracy k_{nmr} should be calibrated to local reservoir data.

Correlation of k and T_2 Distributions

Large pores



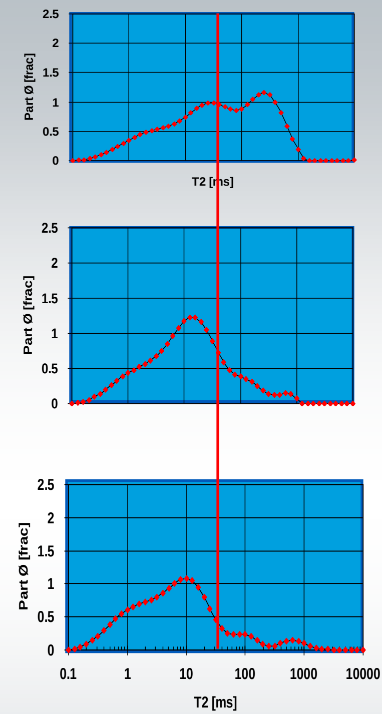
Ø = 25.8
k [md] = 1181

Ø = 25.5
k [md] = 834

Ø = 24.8
k [md] = 737

Ø = 25.1
k [md] = 502

Ø = 24.6
k [md] = 360



Small pores

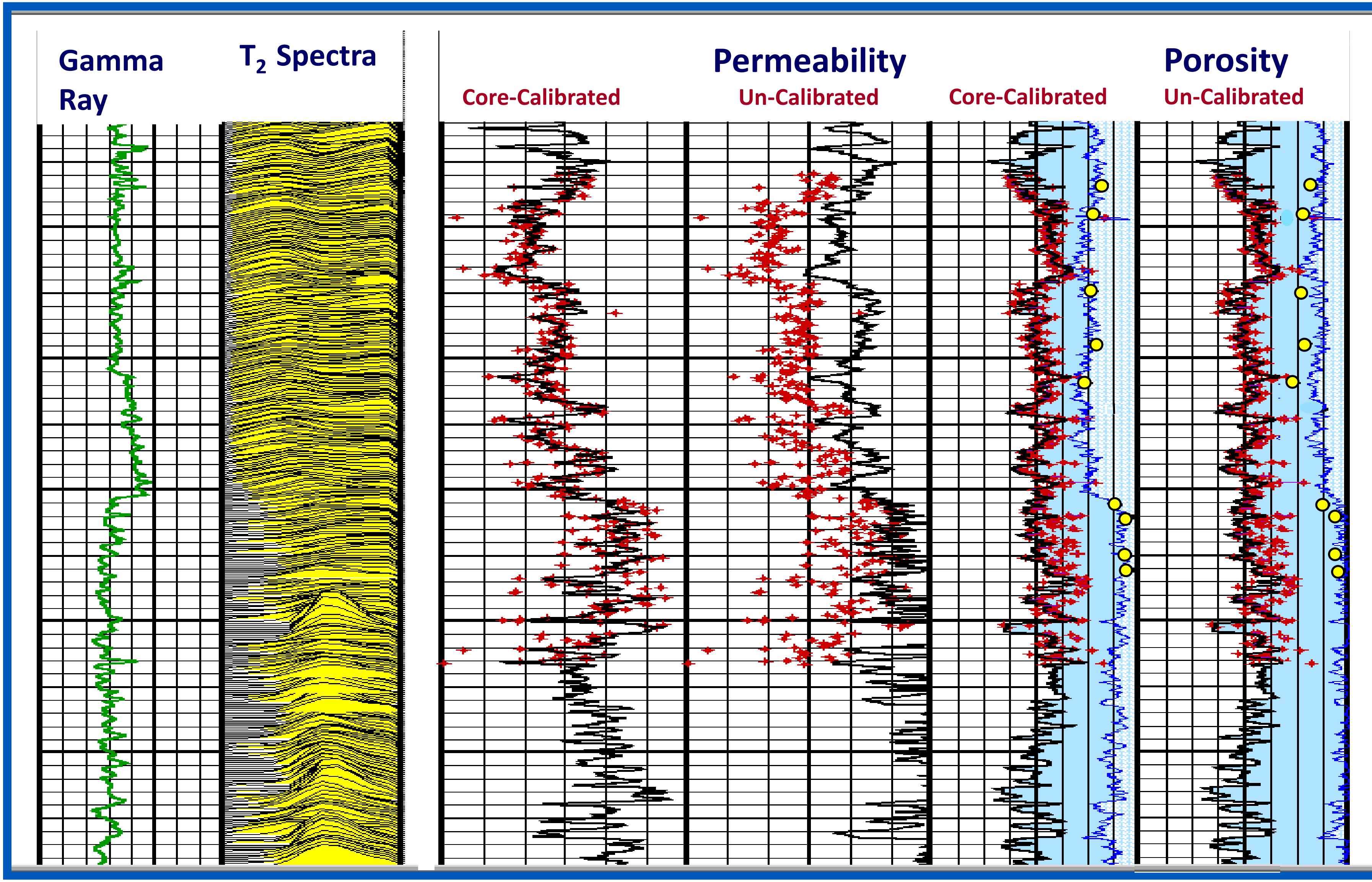
Ø = 24.8
k [md] = 250

Ø = 19.0
k [md] = 1.65

Ø = 18.0
k [md] = 0.14

NB. NMR provides pore size distribution.
Permeability responds to pore throat size!

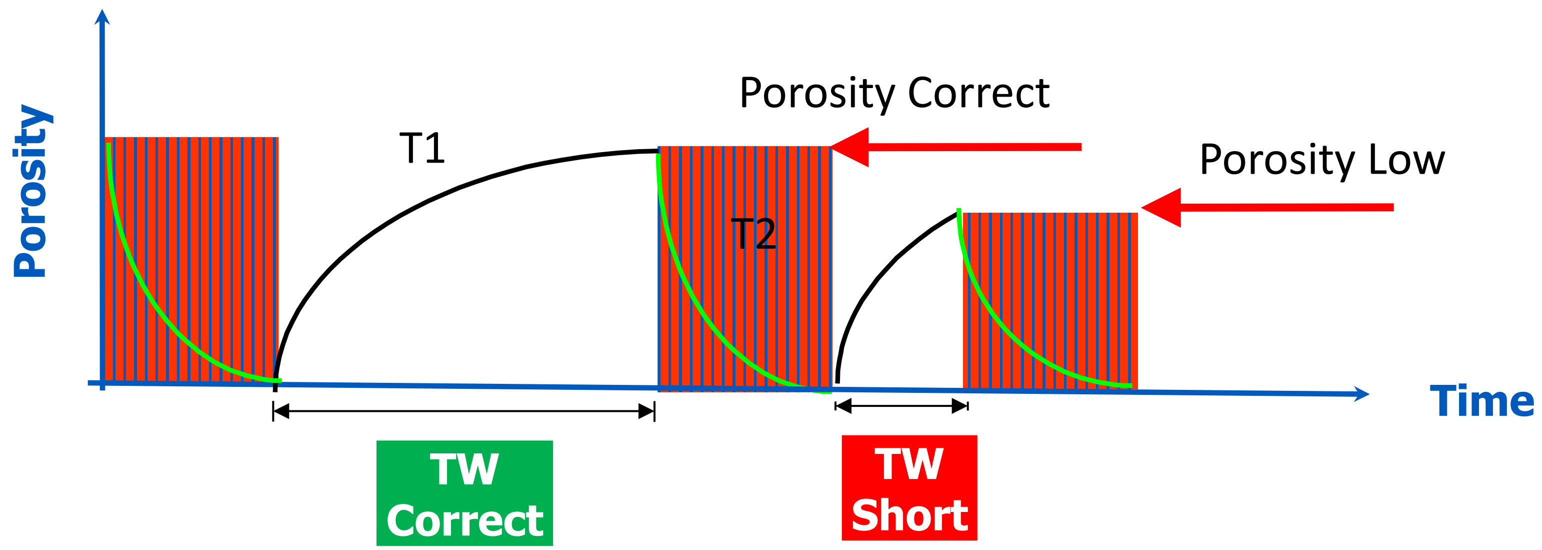
Core-Calibration



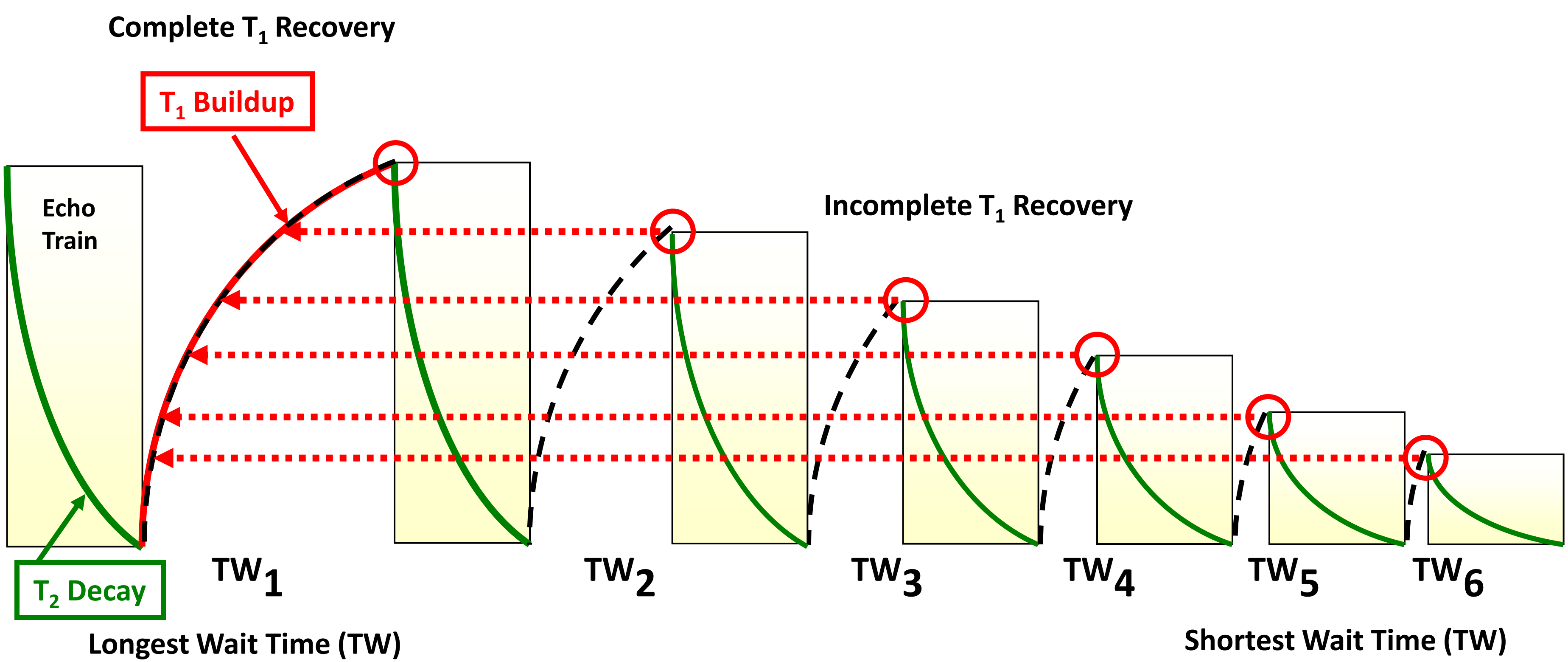
T1 Distribution

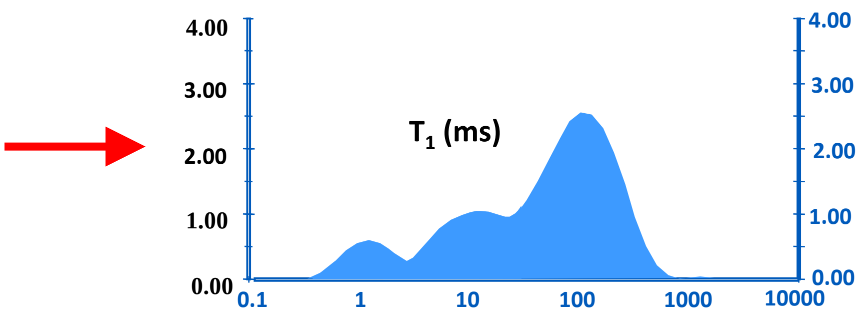
Polarization and TW

- NMR porosity is reduced if sufficient time (TW) is not allowed between "experiments" due to an incomplete polarization of the protons.



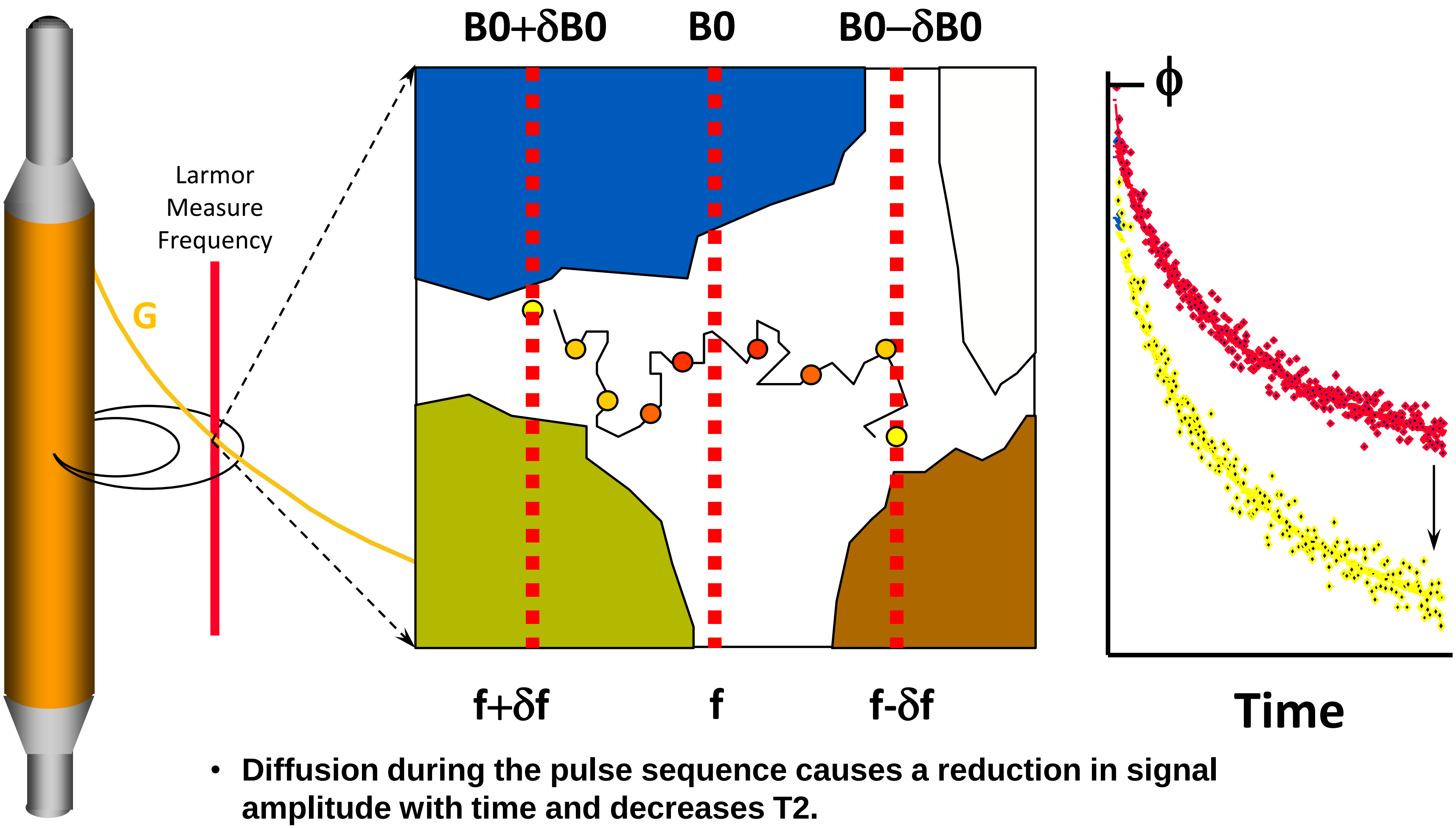
T1 Distribution Determination





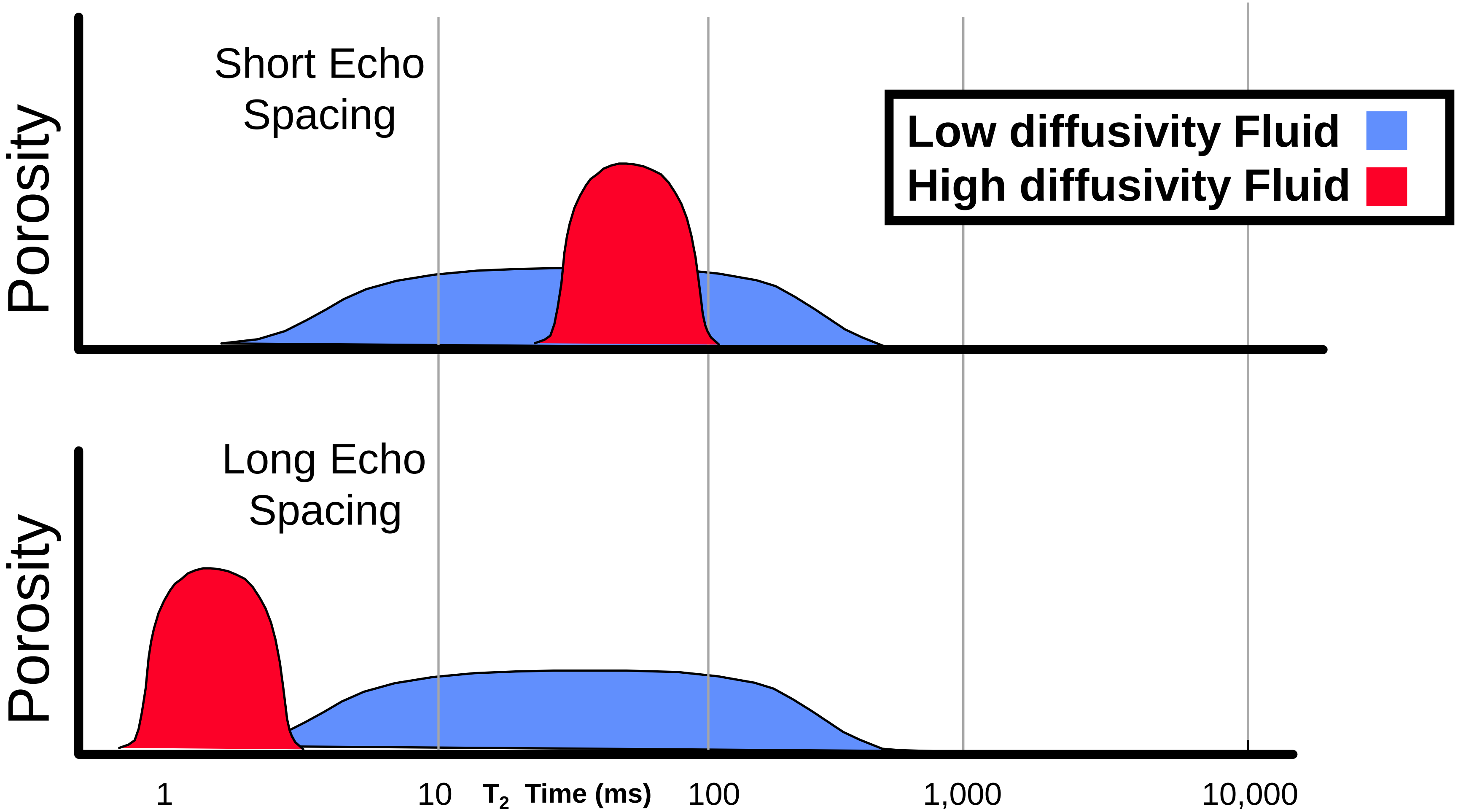
Diffusion

Gradient Magnetic Fields and Diffusion



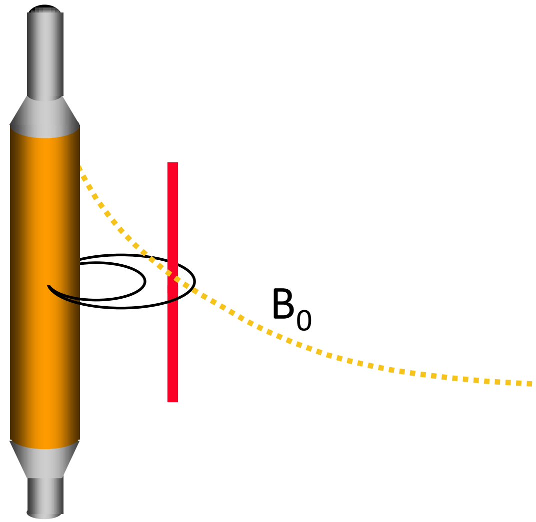
- **Diffusion during the pulse sequence causes a reduction in signal amplitude with time and decreases T2.**
- **A longer TE or higher gradient increases the effect.**
- **Multiple TE Measurements → Diffusivity distribution**

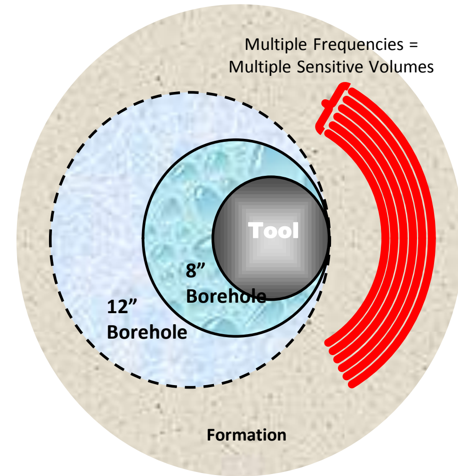
T2 Shift due to Diffusion



Instrument Magnetic Field Gradients

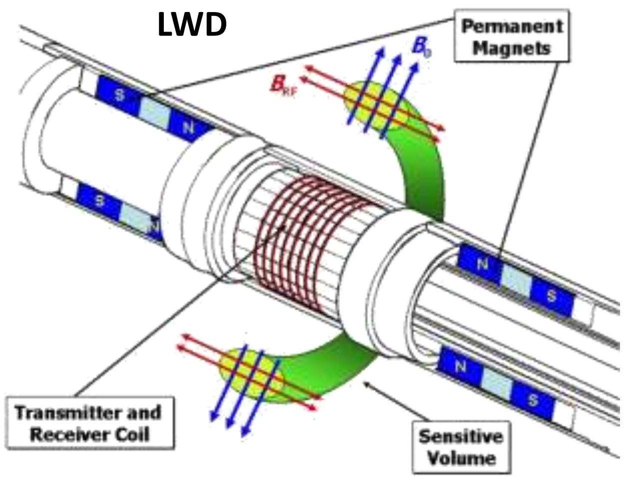
Gradient field tools:
- **Measure Diffusion**



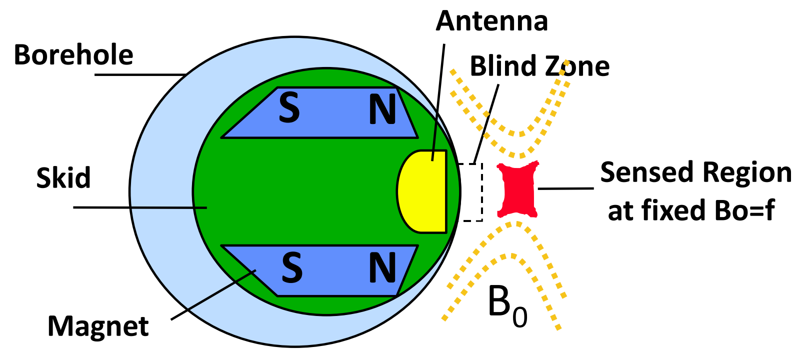


Low gradient field tools:
- **Minimal Diffusion**

LWD

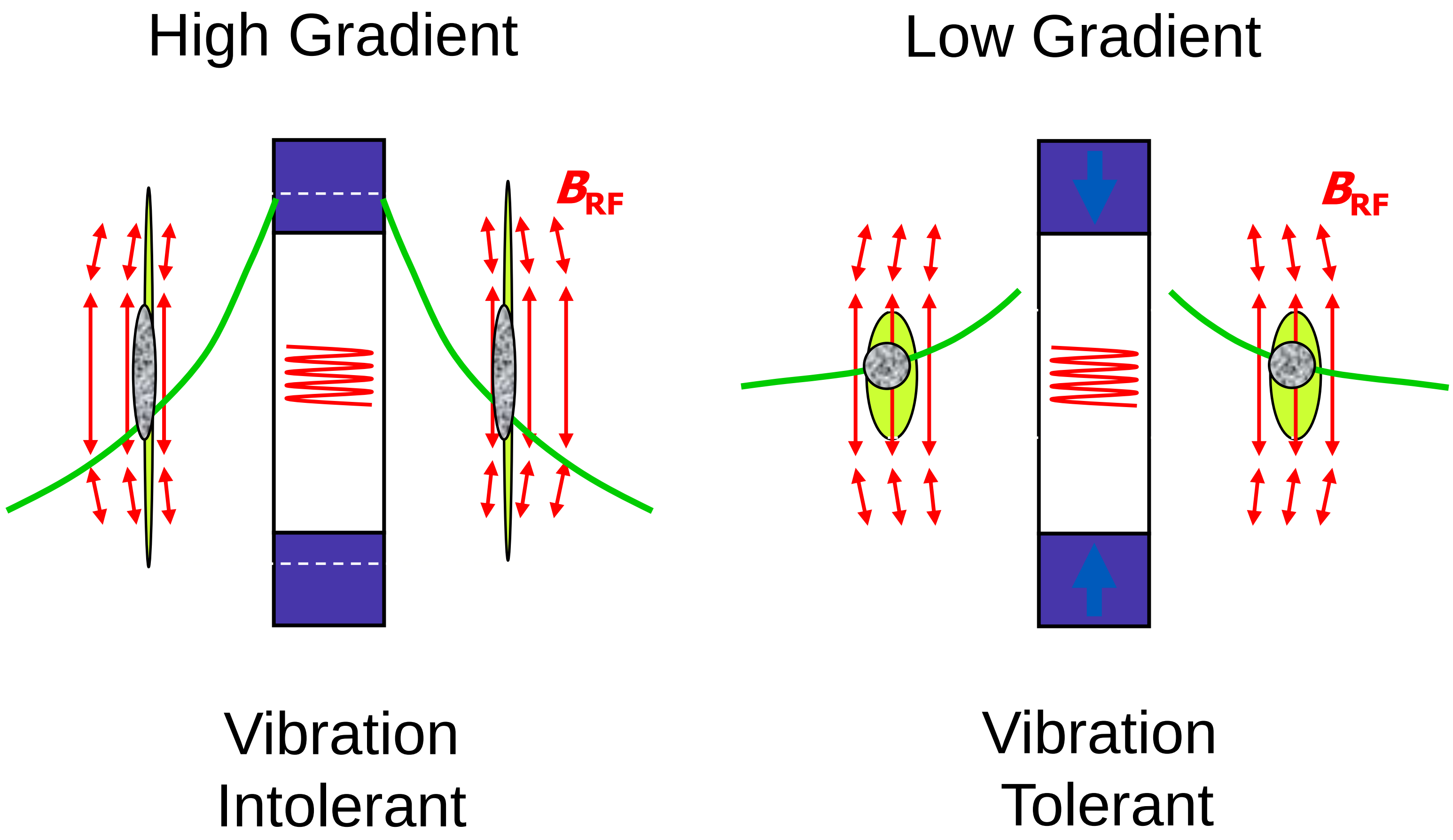


Wireline



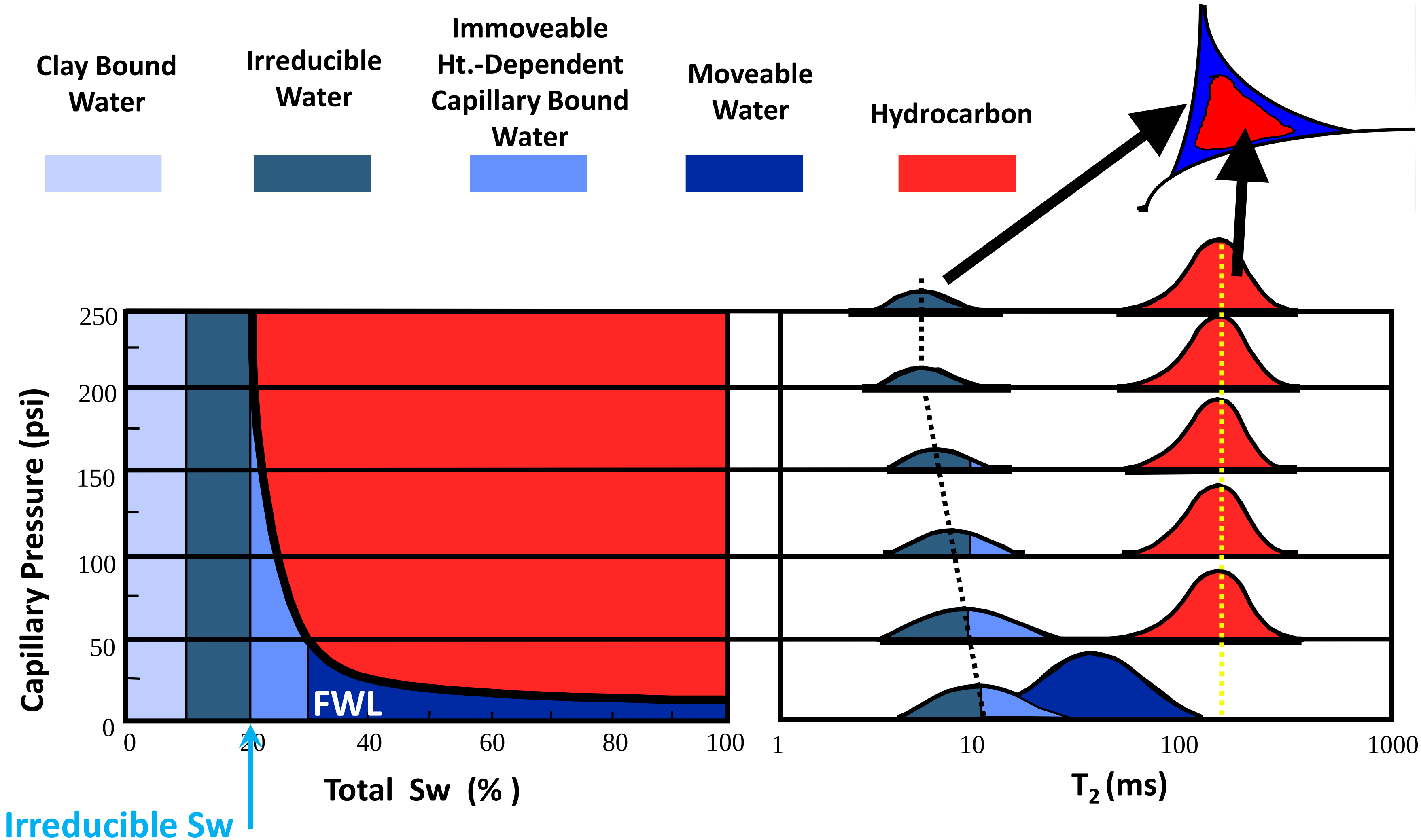
N.B. All measurements are shallow 1-4" depth

LWD NMR in Drilling Environment



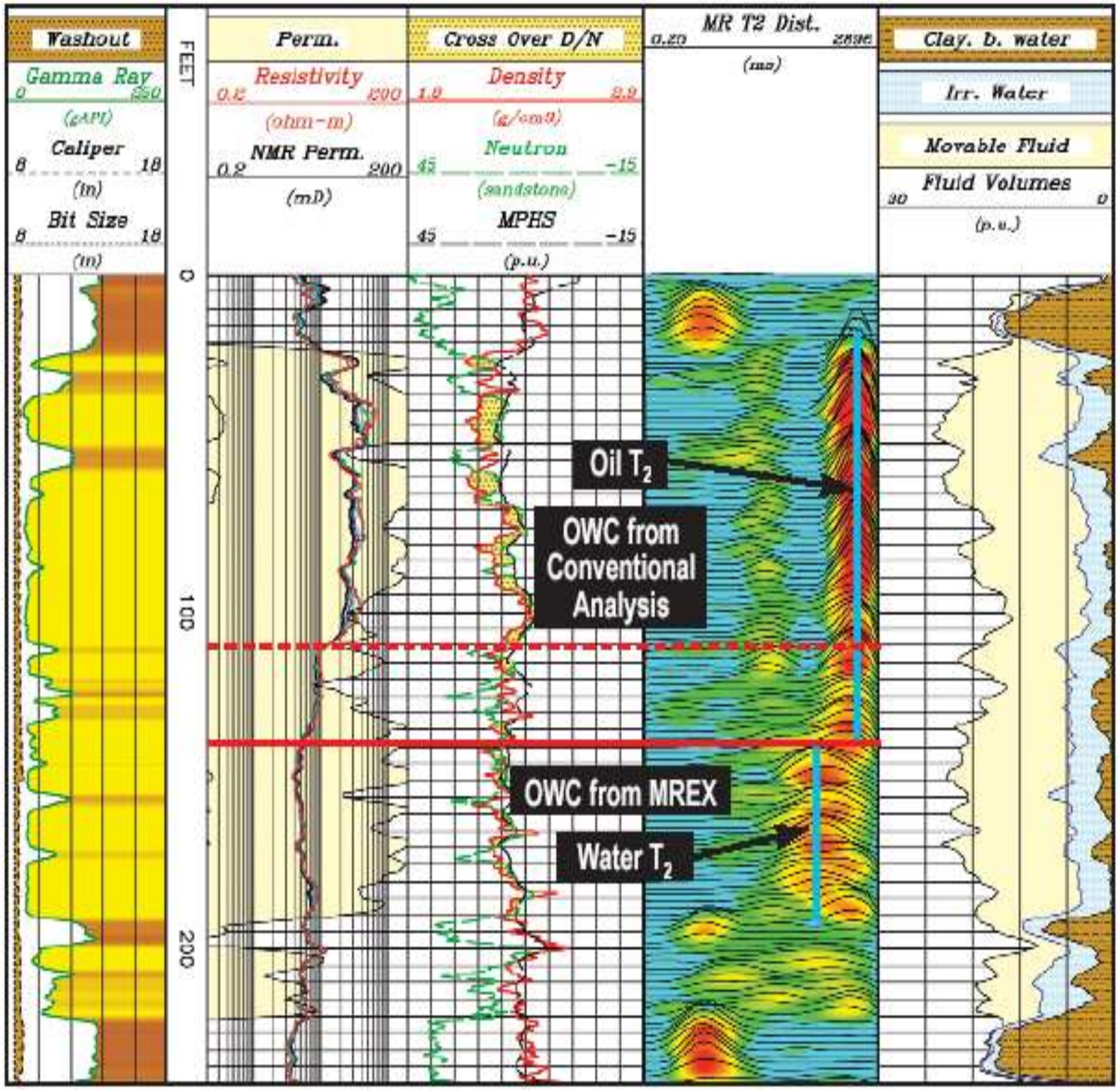
Fluids

Hydrocarbon Affects

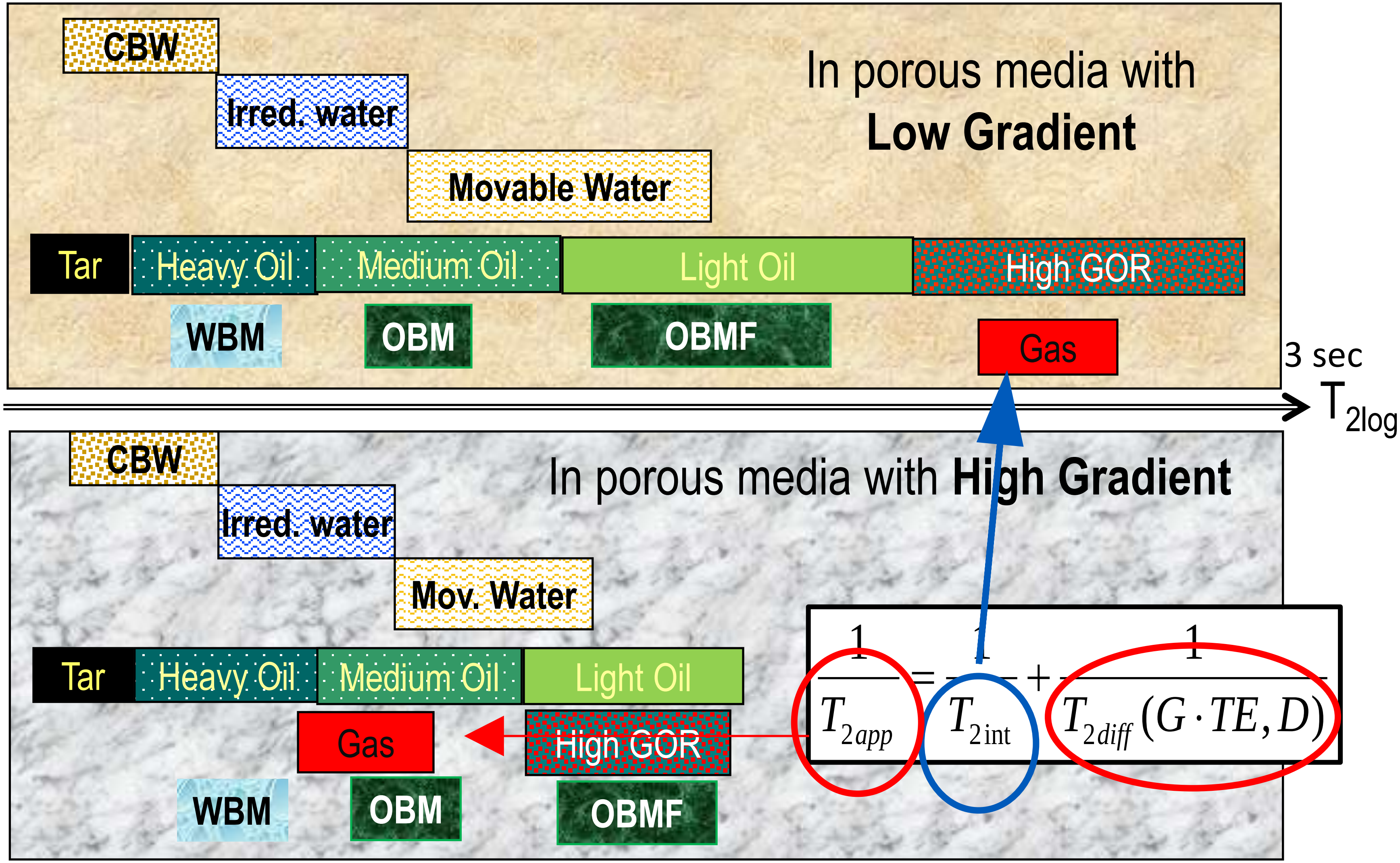


N.B. Techniques available to re-calculate 100% water saturated T2 from mixed fluids → Pore size Distribution

1D NMR – Simple Analysis of T2



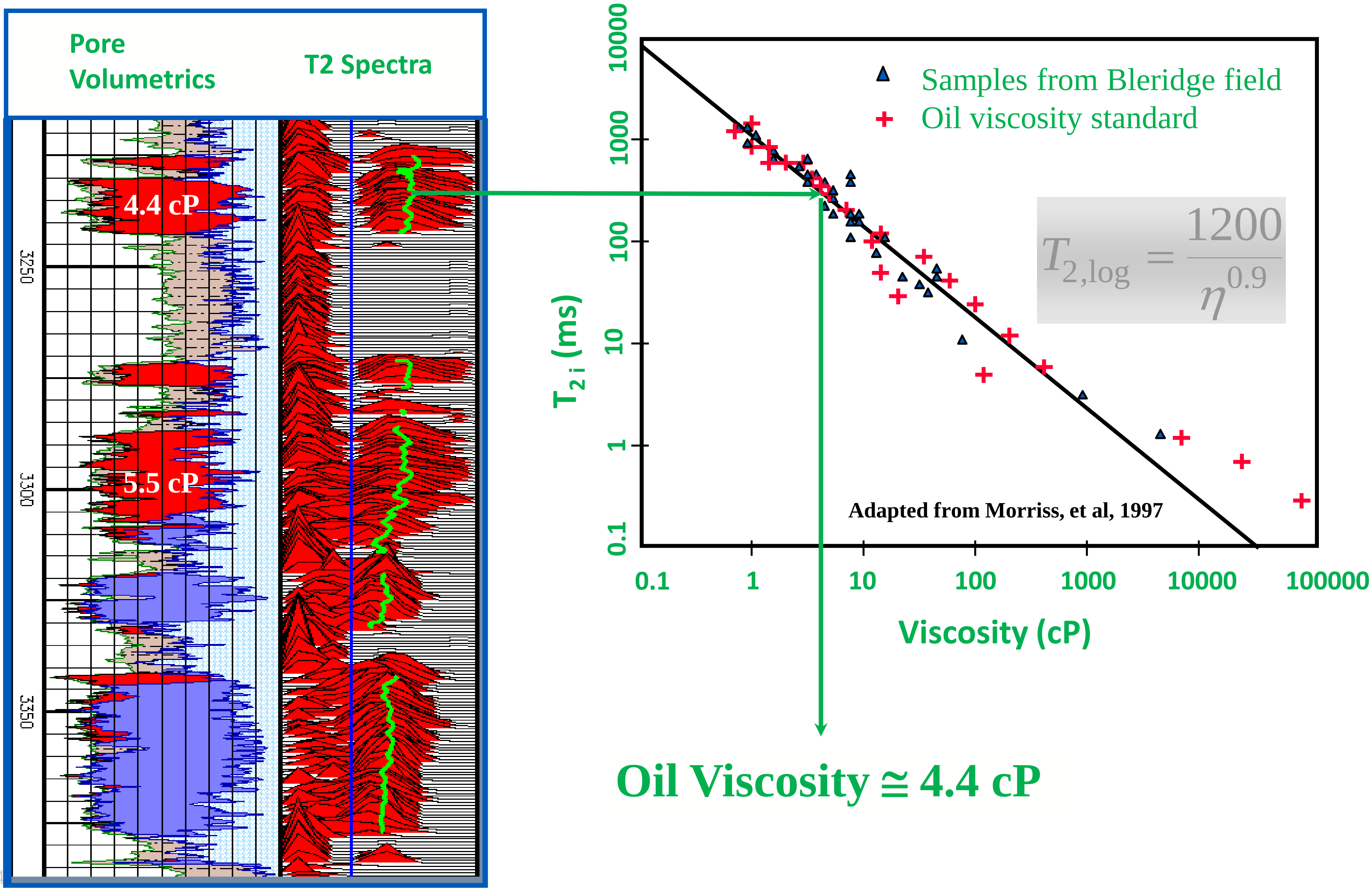
NMR Fluids Response



$$\frac{1}{T_{2app}} = \frac{1}{T_{2\mathrm{int}}} + \frac{1}{T_{2diff}(G \cdot TE, D)}$$

N.B. T2 apparent can be corrected back to Intrinsic.

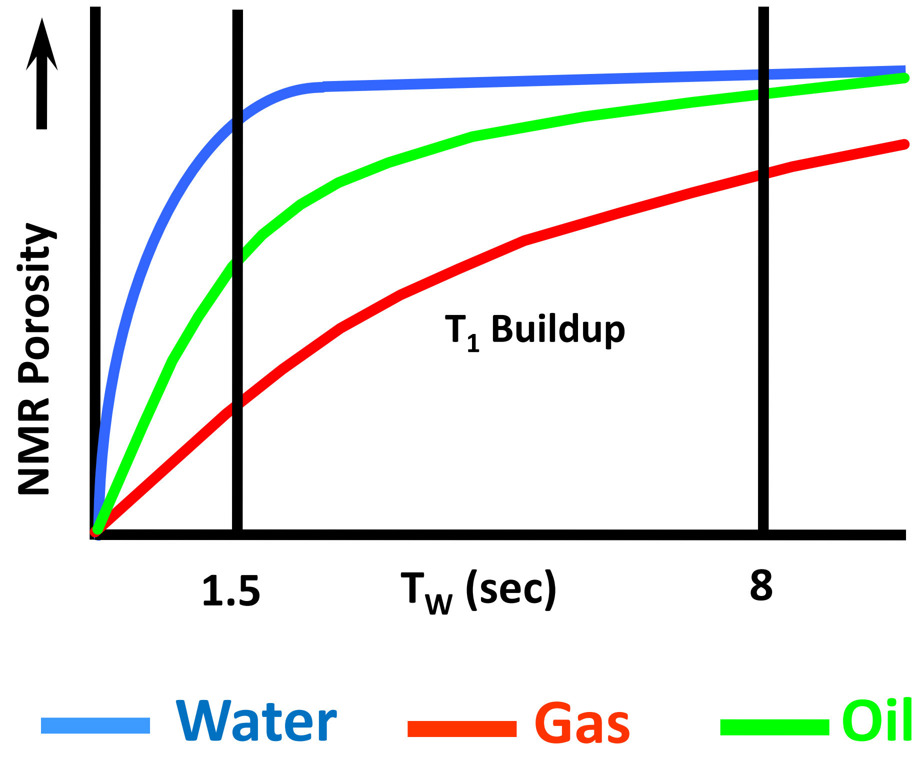
Estimated Oil Viscosity from MR



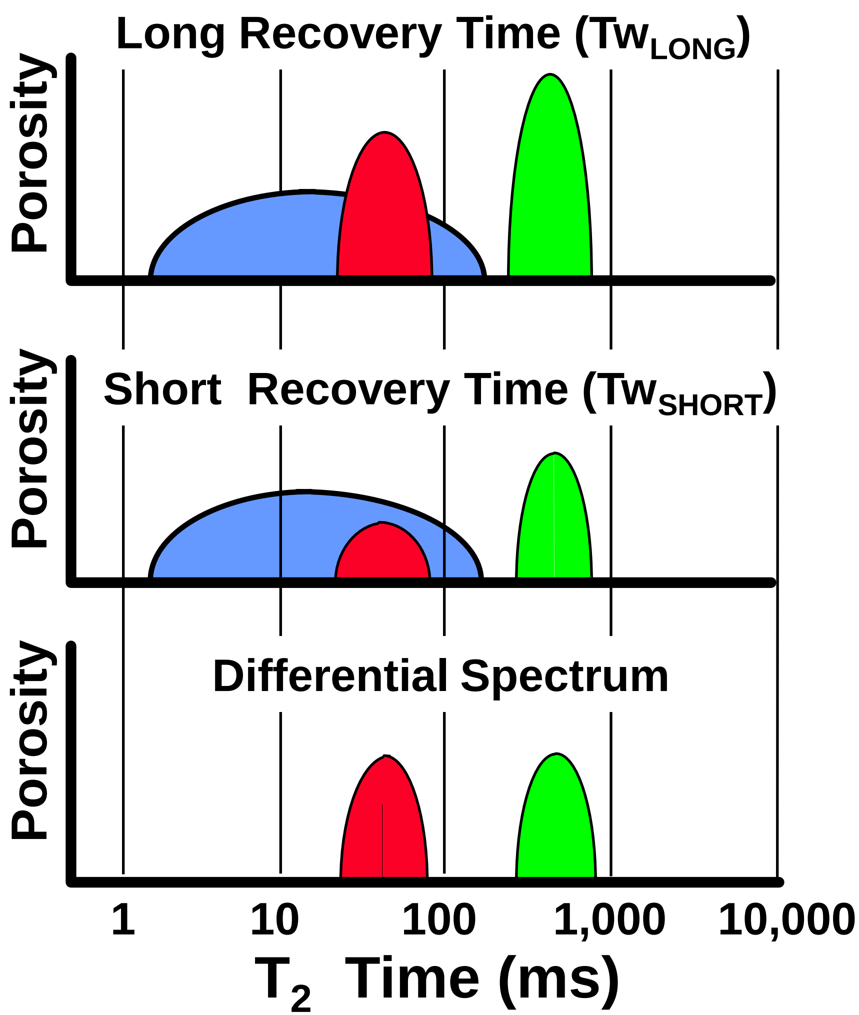
Oil Viscosity ≅ 4.4 cP

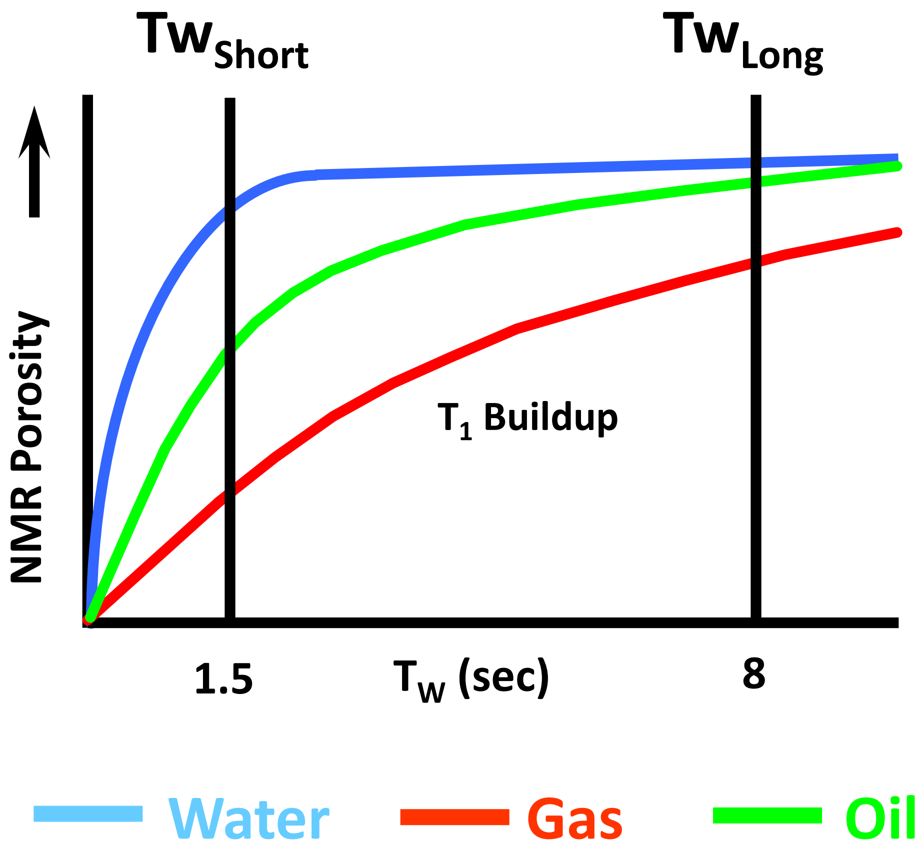
T1 for Various fluids

- Water T1 depends on pore sizes (wetting phase)
  - Typically need 1-2sec
- Oil depends on API
  - Typically 5-6sec
- Gas depends on pressure, temperature
  - Typically 10-15sec

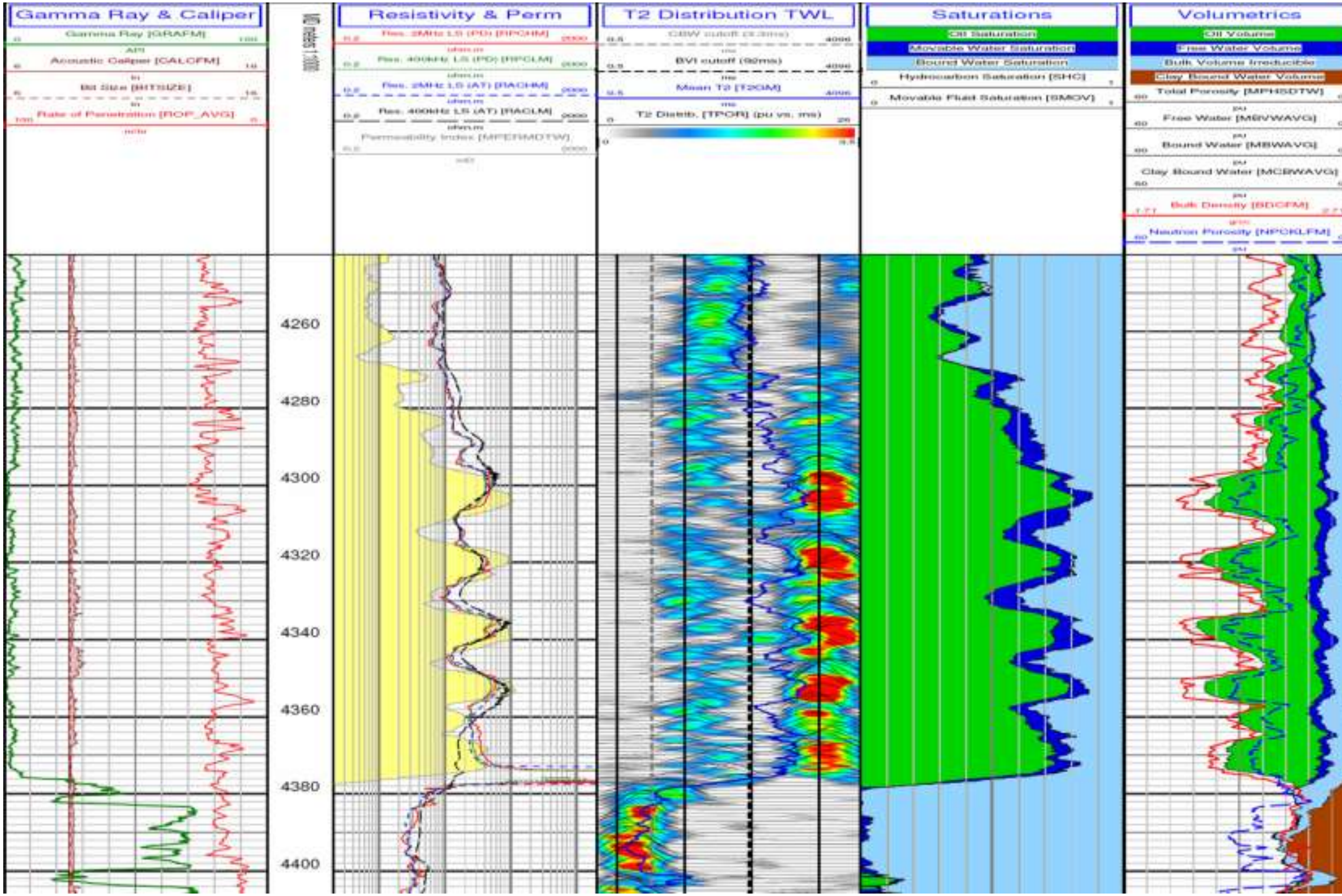


Delta Tw - Differential Spectrum





Dual TW Porosity & Saturation (LWD)



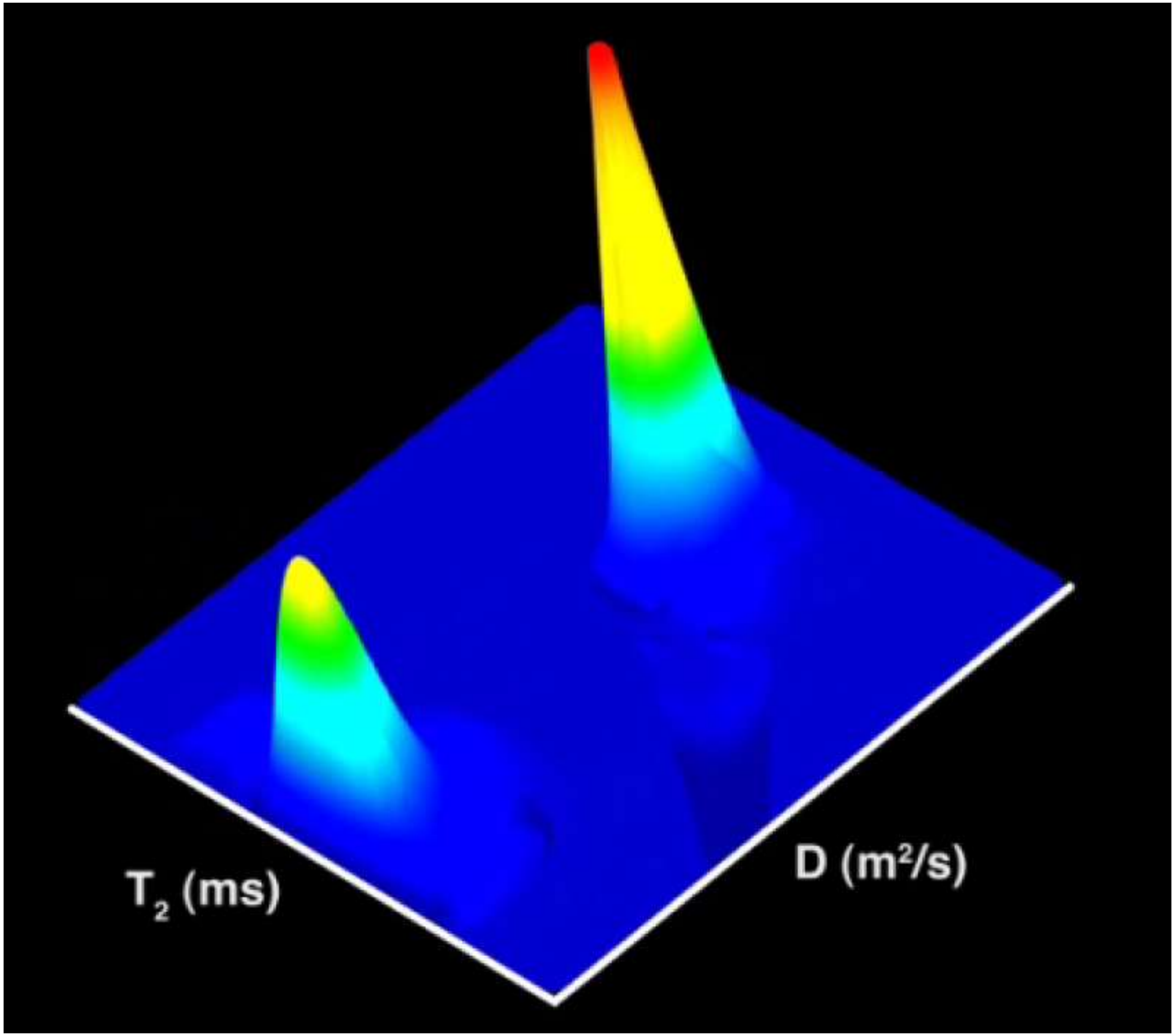
N.B. Shallow measurement

Fluids - T1/T2 Ratio and Diffusivity

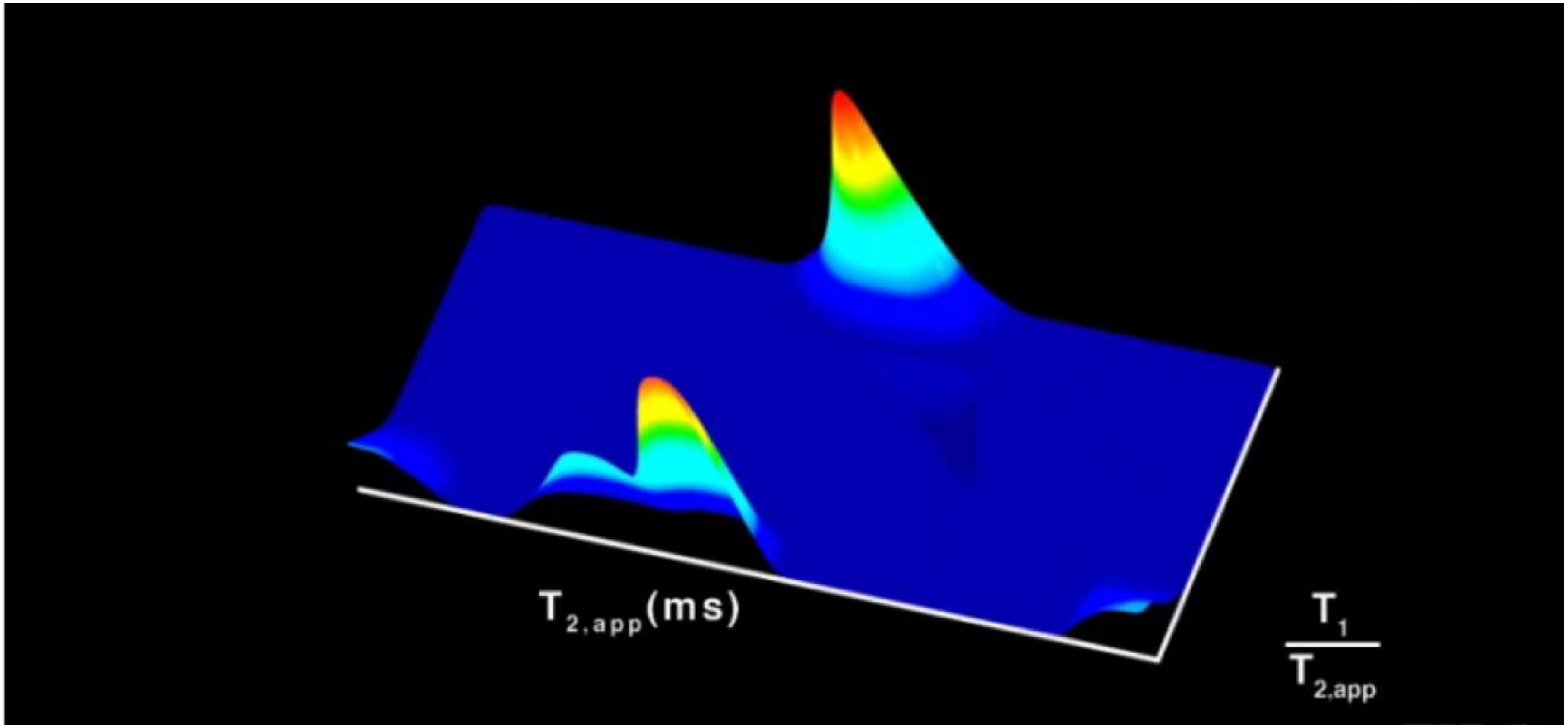
- Non-wetting oil phase: T1/T2~1-1.5
- OBM filtrate: T1/T2~1-2
- Dry Methane: T1/T2~100
- Richer gas: < T1/T2 of methane
- Wet gas, dissolved, condensates: < T1/T2 of dry gas

	Bound Water	Moveable Water	Heavy Oil	Light Oil	Gas
T1	Very Short	Medium	Short	Long	Long
T2	Very Short	Medium	Short	Long	Short
D	Slow	Medium	Slow	Medium	Fast

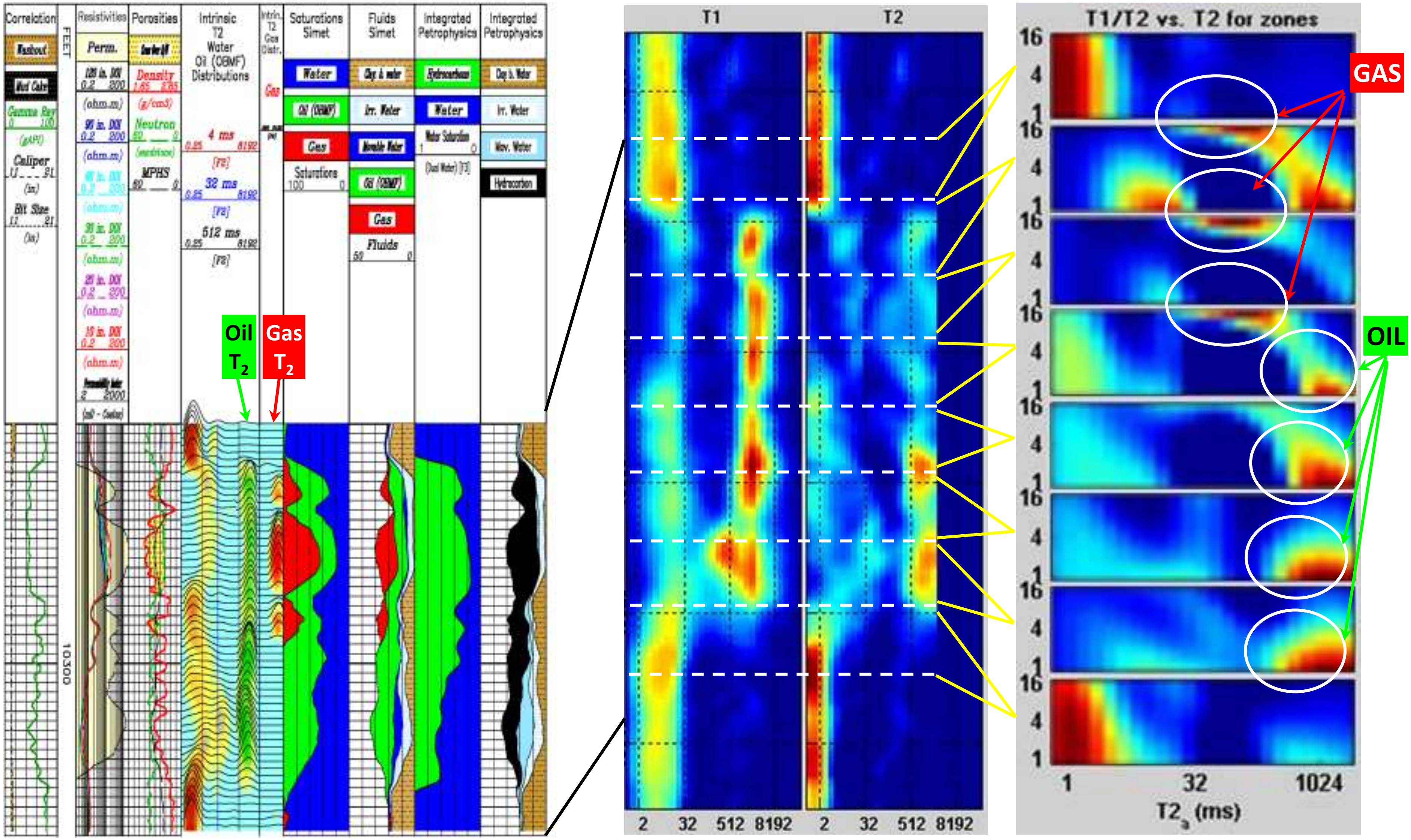
2D NMR Maps - Oil or Water?



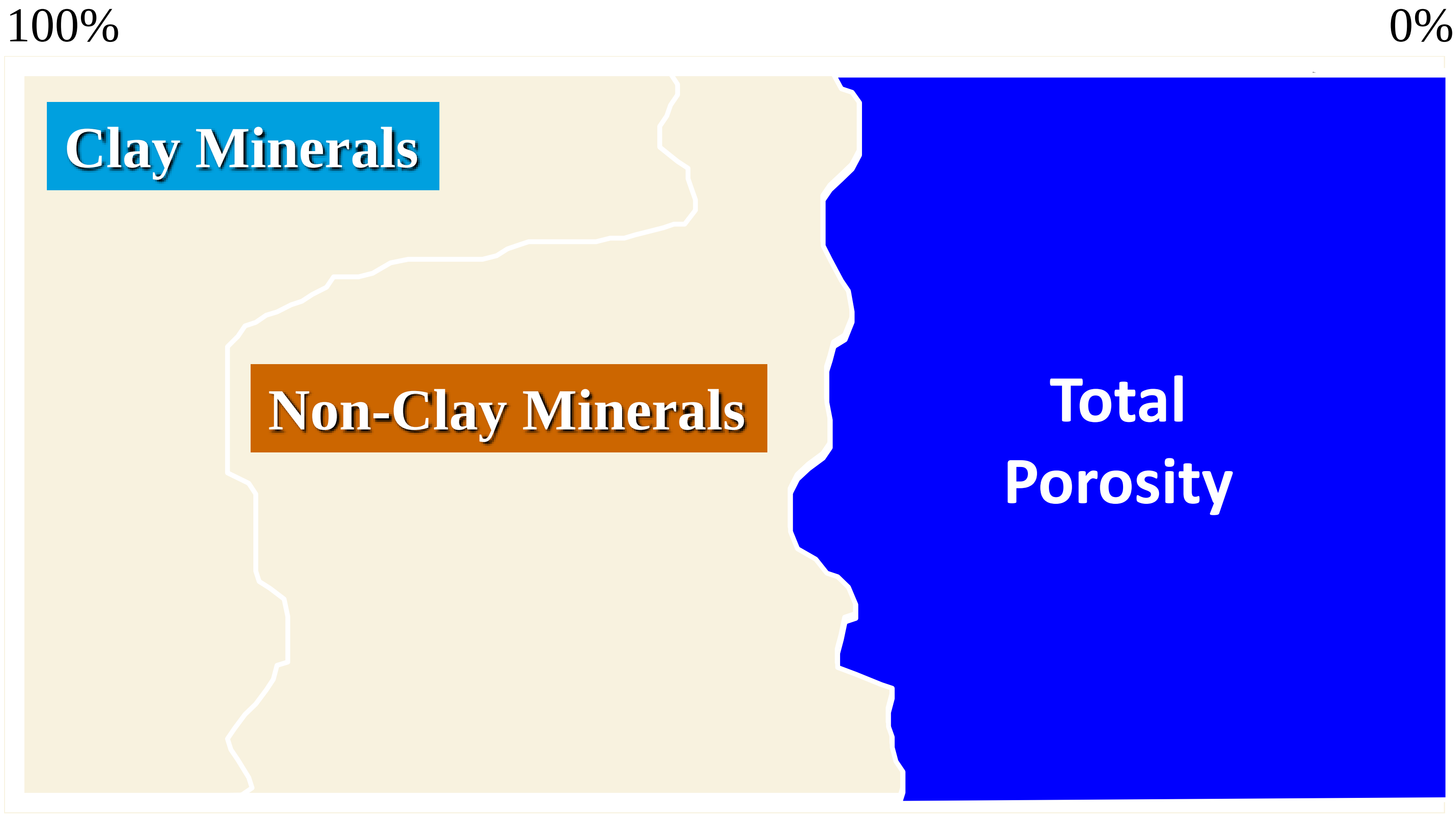
2D NMR Maps – Liquid or Gas?



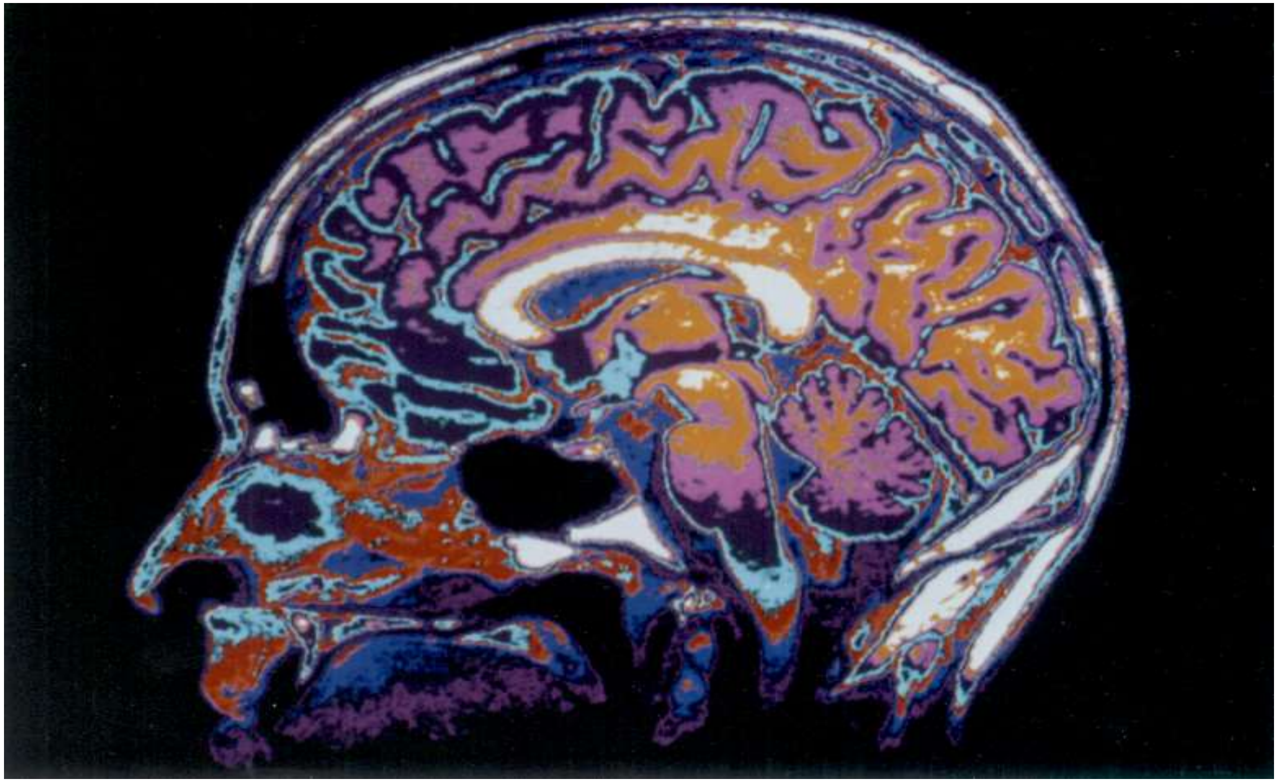
2D NMR Results – Oil & Gas Reservoir



Porosity - MR Analysis



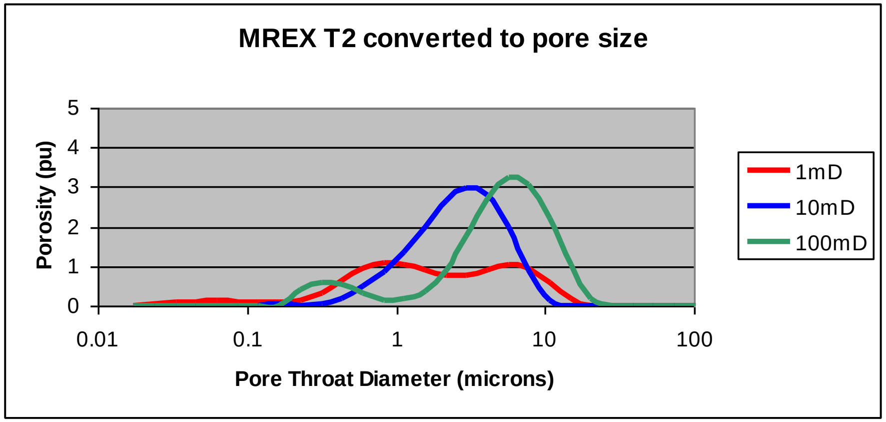
Magnetic Resonance Imaging

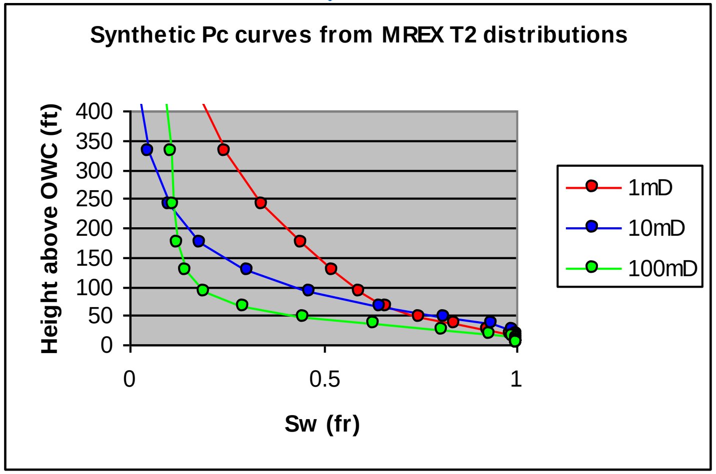


- Clinical MRI images are determined from -
  - Quantity of ^{1}H present in the specimen
  - Relaxation times present in the tissue

Other Applications

Pore size & Capillary pressure





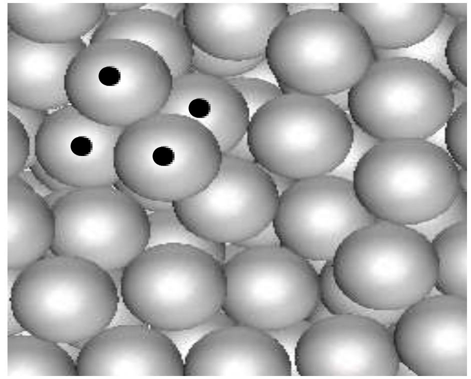
N.B.

NMR responds to pore size

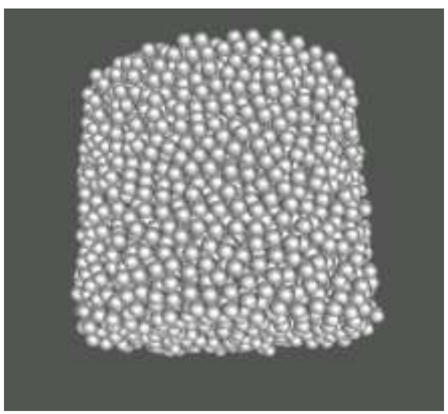
Pc responds to pore throat size!

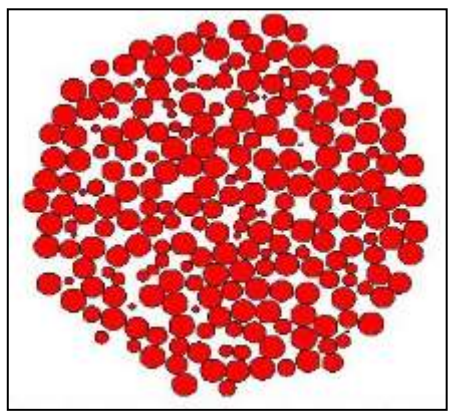
Micro Scale Rock Model

Fontainebleau sst

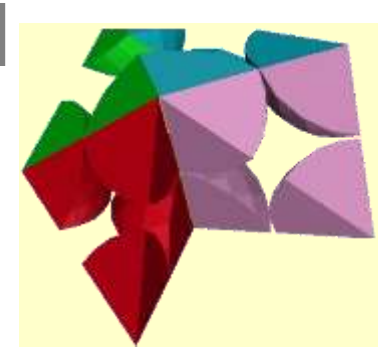


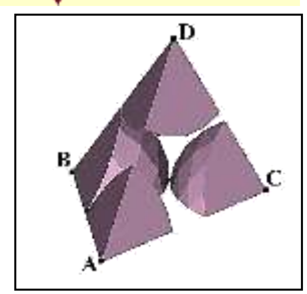
Random, dense packing of equal spheres





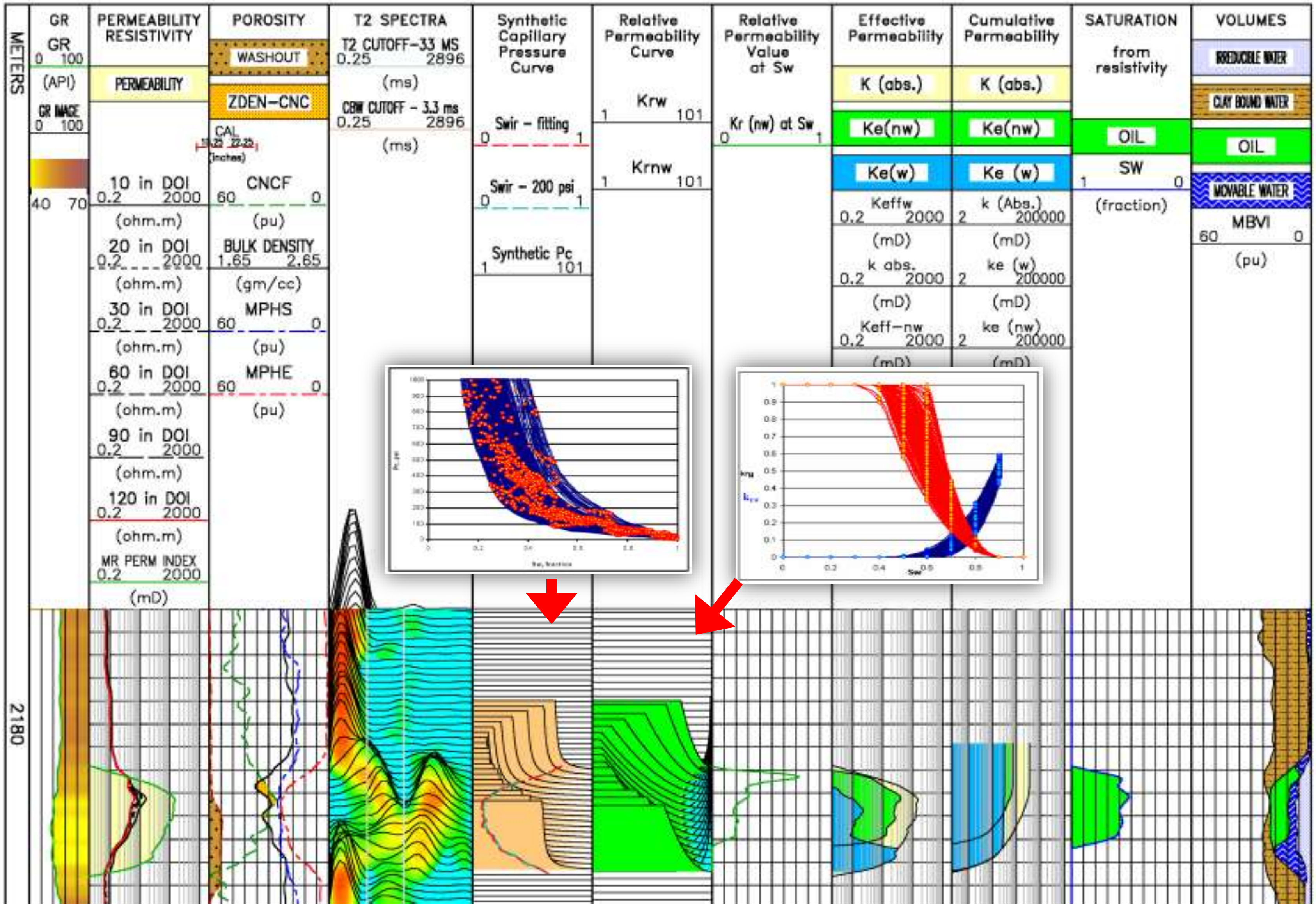
Creating a numerical model and cross-section



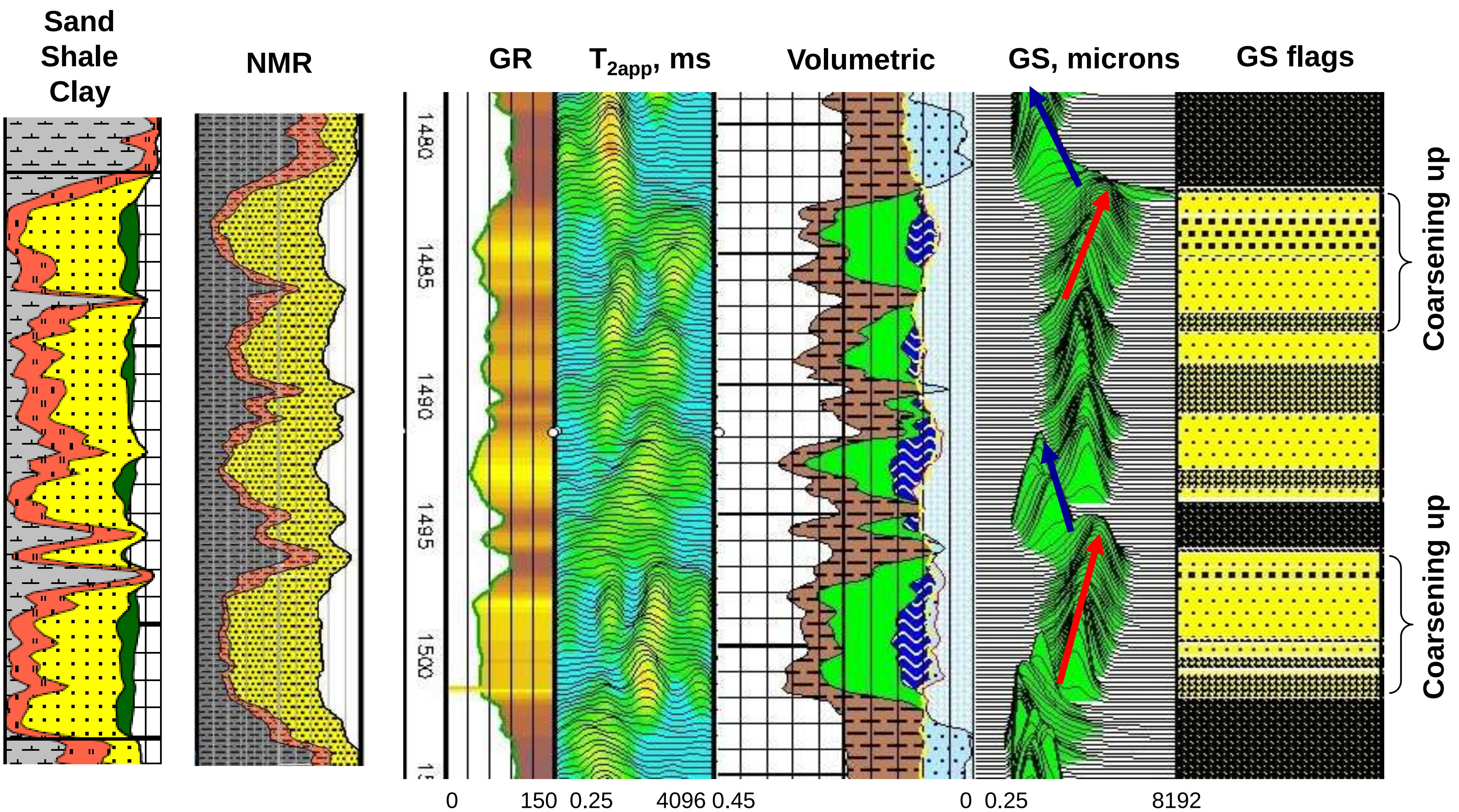


Delaunay cell

Productivity Example: Oil Well



Grain Size – Geology and Completions



Summary

Petrophysics

- Mineralogically-Independent Porosities
- Pore Size Distribution (Single Phase Fluid Saturation) In mixed fluids
- Clay-Bound Water Volume, Capillary-Bound Water & Free Fluid Volumes
- Permeability In carbonates
- Fluid types, volumes, distributions, properties
- Capillary Pressures, Sw_{irr}

Geology

- Grain size distribution
- Rock Fabric/Facies Characterization
- Mineralogy changes
- Cross-Correlation

Reservoir Engineering

- Capillary Pressures
- Fluid changes
- Relative permeabilities
- Effective permeabilities
- Fractional flow
- Cumulative production prediction

Drilling and Completions

- Grain size
- Sand production
- Screen sizes
- Completion intervals
- Completion type
- Perforation modeling