Lecture Presentation

Nuclear Magnetic Resonance Logging

PGE385(M,K)

Petrophysics of Nuclear Magnetic Resonance Measurements

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Petrophysical Applications of NMR Data

- **Mineralogically-Independent Porosities (Total & Effective)**
- **Clay-Bound Water Volume**
- **Capillary-Bound Water & Free Fluid Volumes**
- **Pore Size Distribution (Single Phase Fluid Saturation)**
- **Permeability (With calibration to core or test data)**
- **Shale Volume & Distribution**
- **Flushed Zone Fluid Saturations (DTW analysis)**
- **Hydrocarbon Viscosity (DTE analysis)**
- **Electrical Properties & Water Saturation (Integrated Products)**

Basic NMR Data

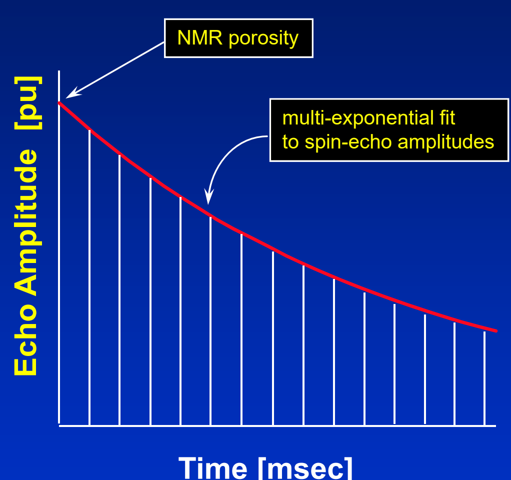
NMR measurements provide:

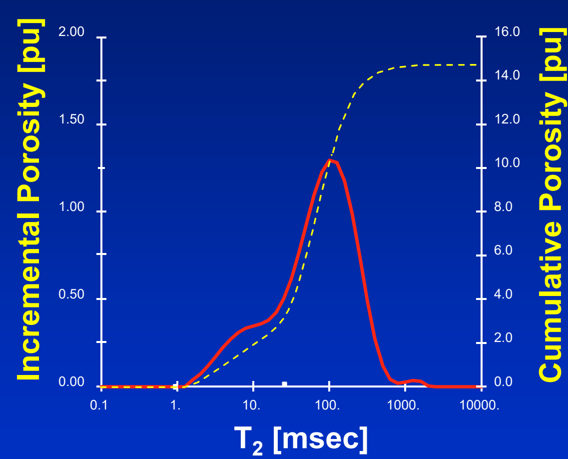
- Echo Amplitudes
- Echo Decay Rates

Calibrated transforms provide:

- Mineralogically Independent Porosities.
- Clay Bound Water
- Capillary Bound Water & Free Fluid Volumes
- Permeability

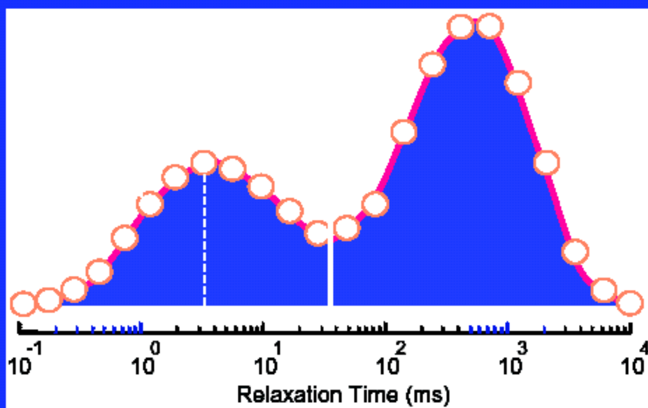
Echo Train Inversion Processing





Acquisition Time Domain → Inversion Processing → T_2 Relaxation Time Domain

Calculation of Petrophysical Parameters from the NMR T2 distribution



$$\phi = \sum_{j=1}^{N} a_j$$

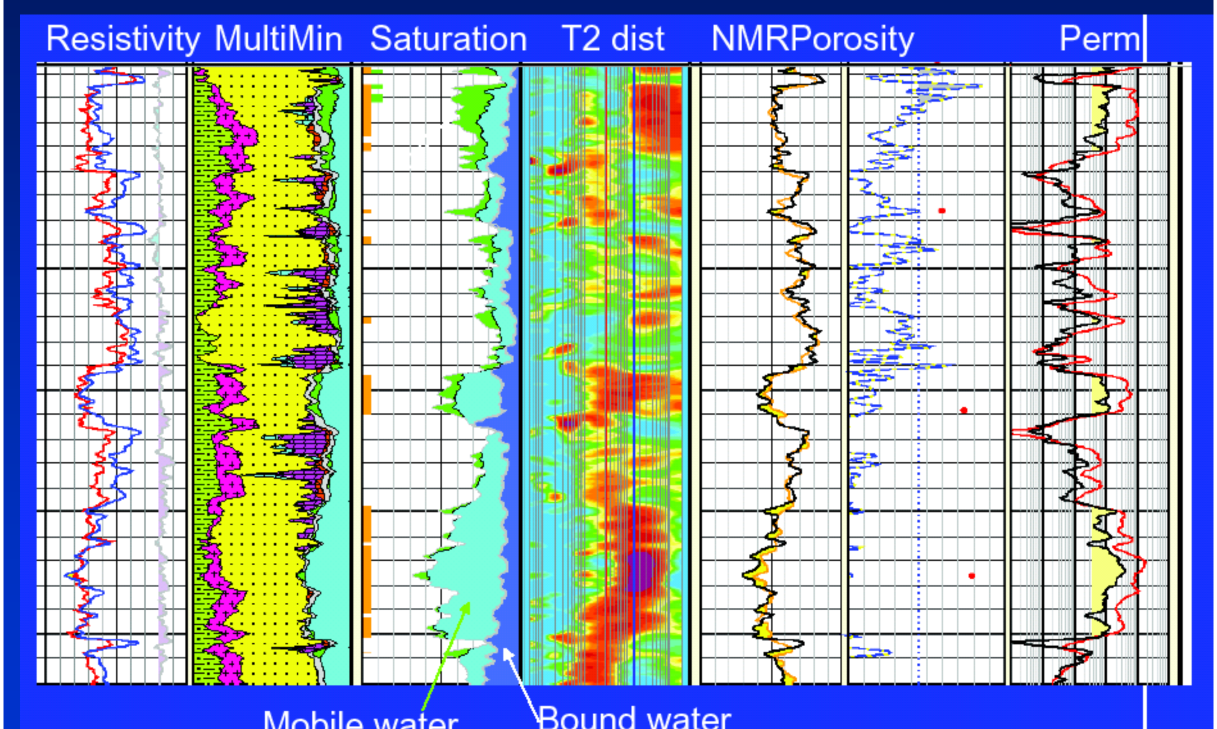
$$BVI = \sum_{j=1}^{N_{cut}} a_j$$

$$FFI = \sum_{j=N_{cut}+1}^{N} a_j$$

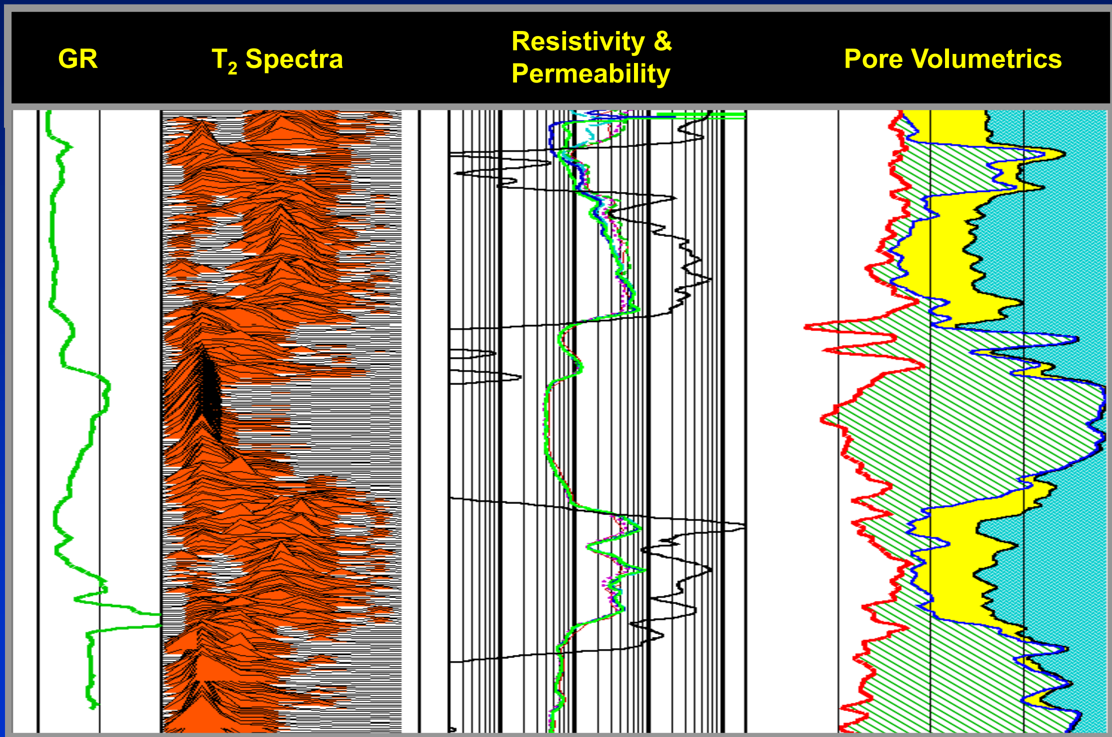
$$\kappa = \left[\left(\frac{\phi}{10} \right)^2 \frac{\text{FFI}}{\text{BVI}} \right]^2$$

$$\eta = \mathrm{aT}/\mathrm{T}_{2G}^{\mathrm{oil}}$$

EXAMPLE



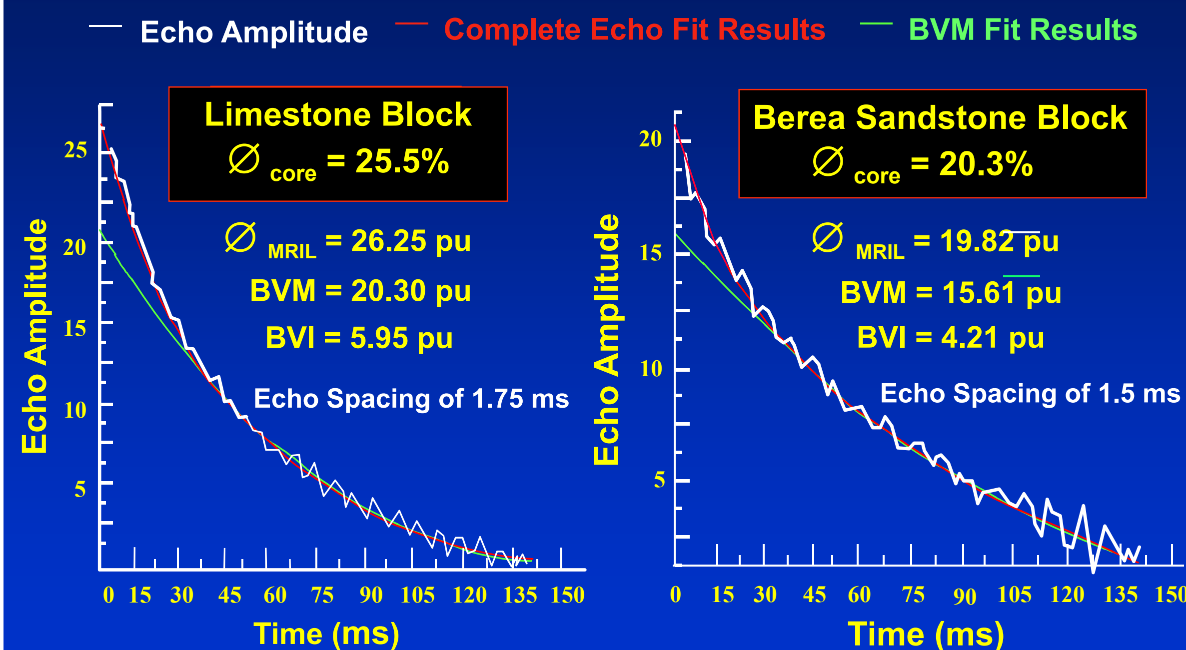
Basic NMR Field Deliverable



NMR Porosity Definitions

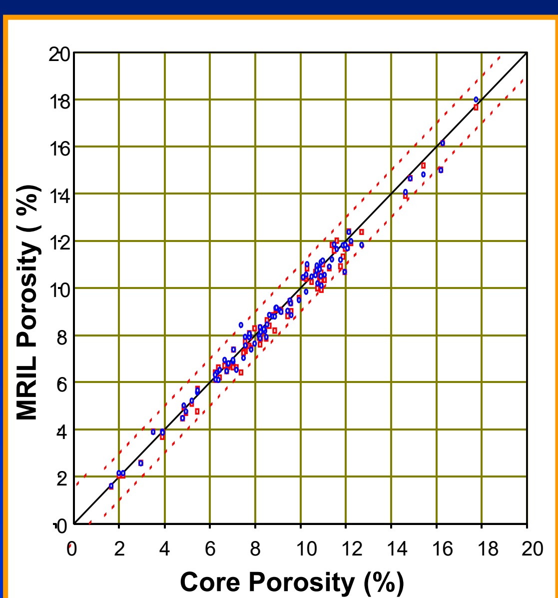
- **Effective ∅ - Pore volume excluding clay bound water.**
- **Total ∅ - Pore volume including clay bound water.**
- **CBW - Clay bound water, which represents anion-free water adsorbed within clay inter-layers.**
- **BVI - Bulk volume irreducible water which includes water retained by capillary forces in small pores, and water wetting pore surfaces.**
- **BVM - Free-fluid volume which is available for hydrocarbon storage and fluid flow.**

MRIL Porosity - Test Pit Verification

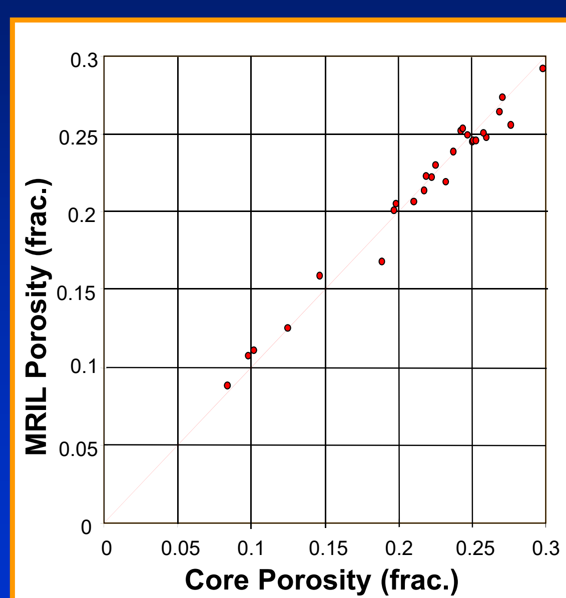


Mineralogy-Independent Porosity

Gulf of Mexico Sandstone



Middle East Carbonate



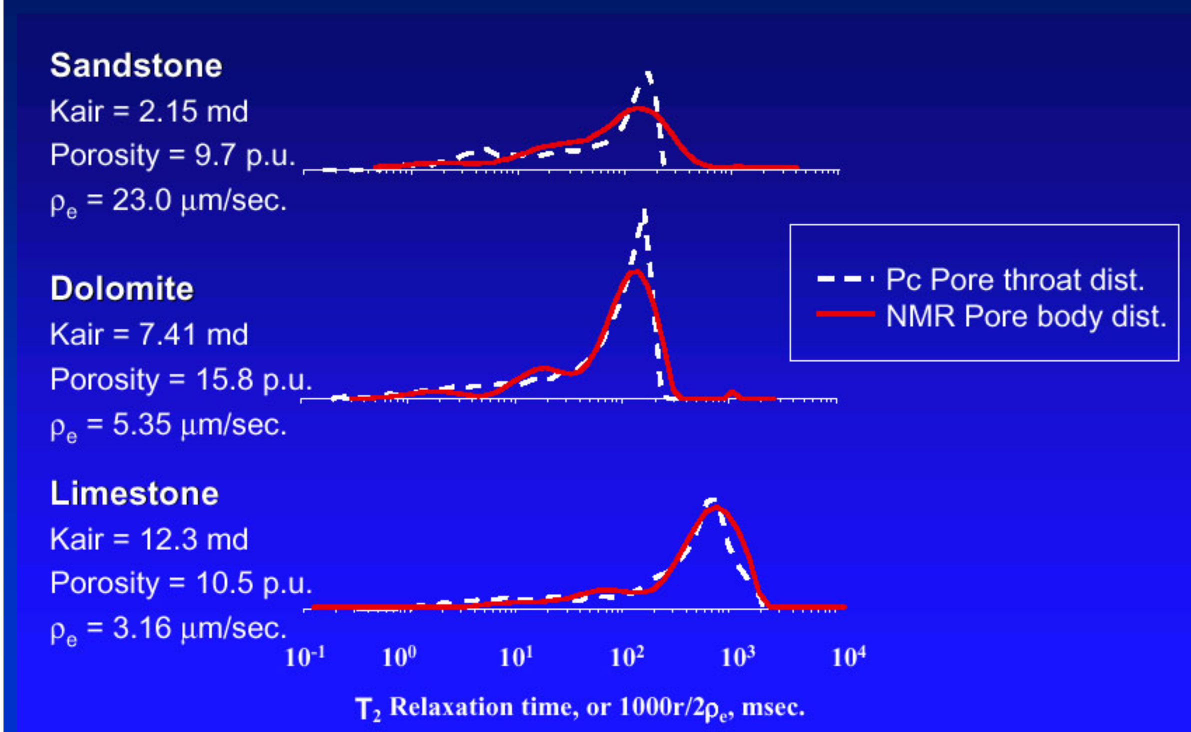
Porosity Considerations

Although NMR porosity is mineralogically Independent, it is not fluid independent.

NMR porosity can be too low when :

- Hydrogen Index of reservoir fluids < 1.0
- Reservoir fluids with long T1 are only partially polarized due to insufficient acquisition wait time (TW)
- "Solid hydrocarbons" (tar) are present with relaxation rates faster than the measurement time window
- Internal gradients caused from magnetic minerals accelerate NMR echo decay to below measurement time window

COMPARISON OF DISTRIBUTIONS

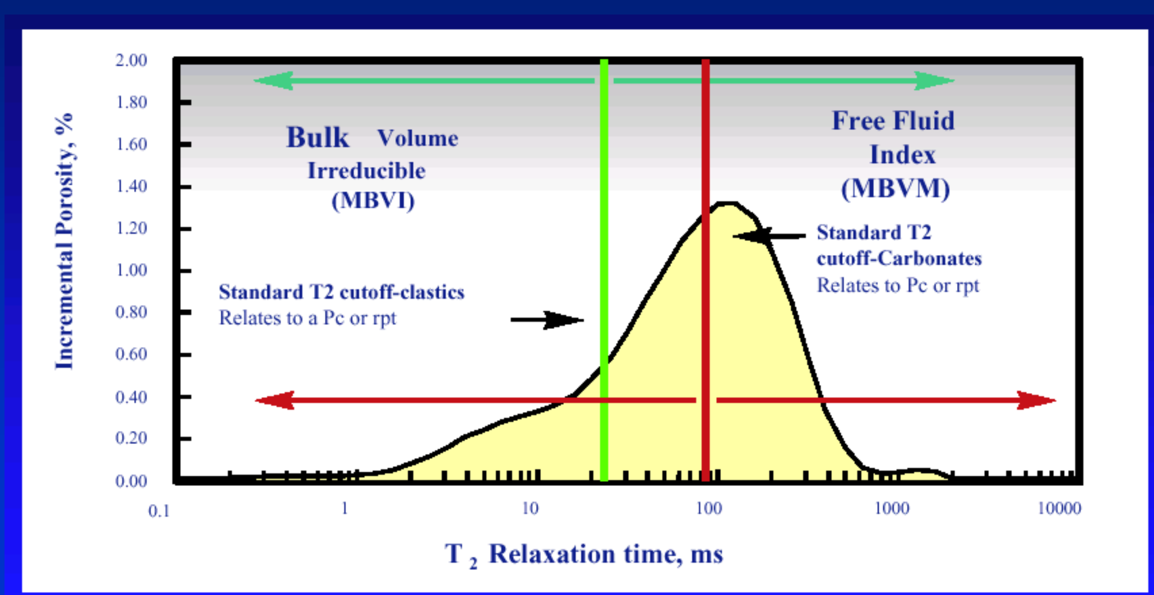


FLUID SATURATION DATA

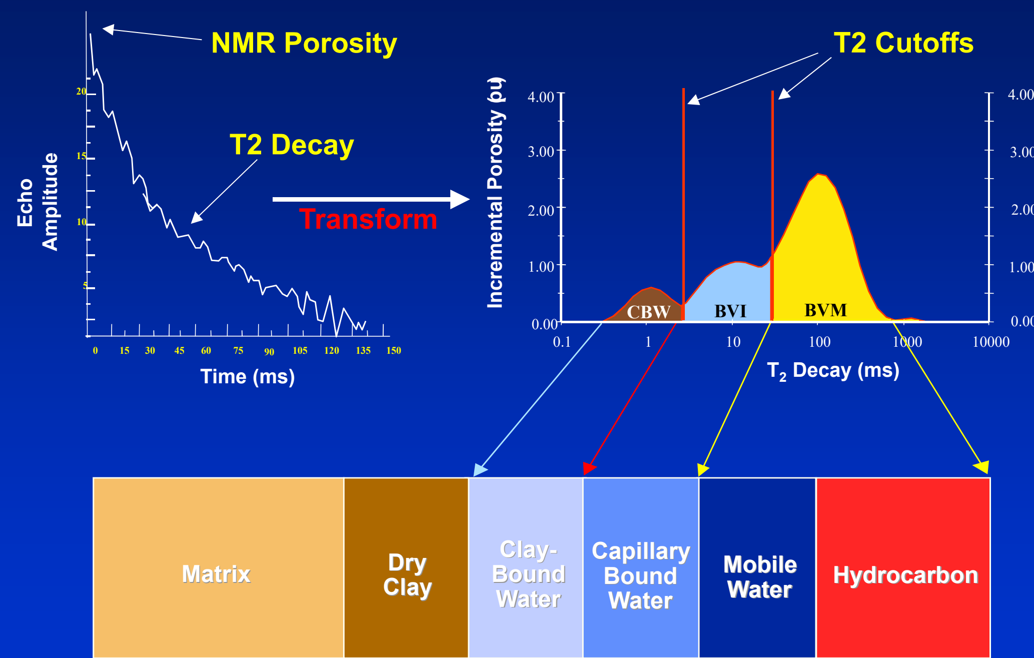
AND

NMR MEASUREMENTS

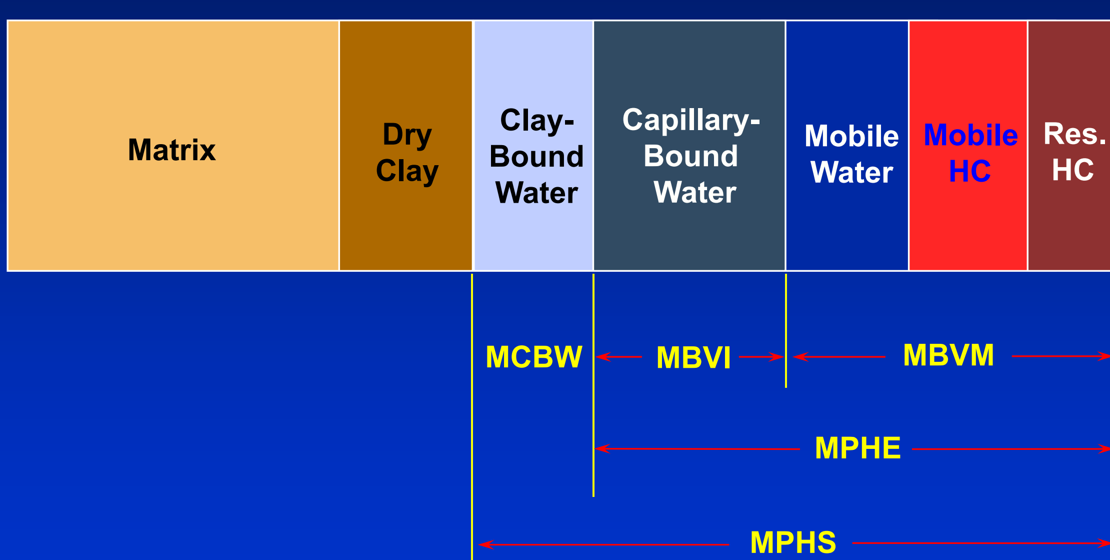
STANDARD METHOD TO DETERMINE MBVI



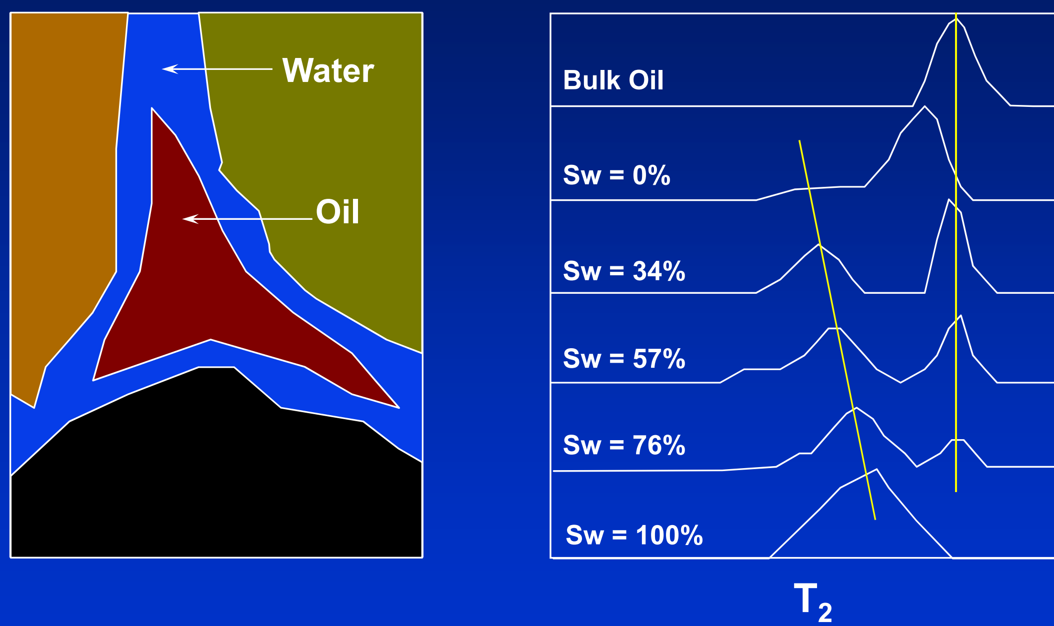
Pore Volumetric Distribution



Bulk Volumetrics - Light HC



Effect of Oil Saturation & T_2 Spectra



Adapted from Straley et al, Log Analyst (Jan. 1995)

T2 Decay in a 2-Phase System

Wetting Phase Relaxivity

$$\frac{1}{T_{2b_{\text{water}}}} = \rho \frac{S}{V} + \left(Sw - \lambda \frac{S}{V}\right) \frac{1}{T_{2b_{\text{water}}}} + \frac{1}{T_{2D_{\text{water}}}}$$

Non-Wetting Phase Relaxivity

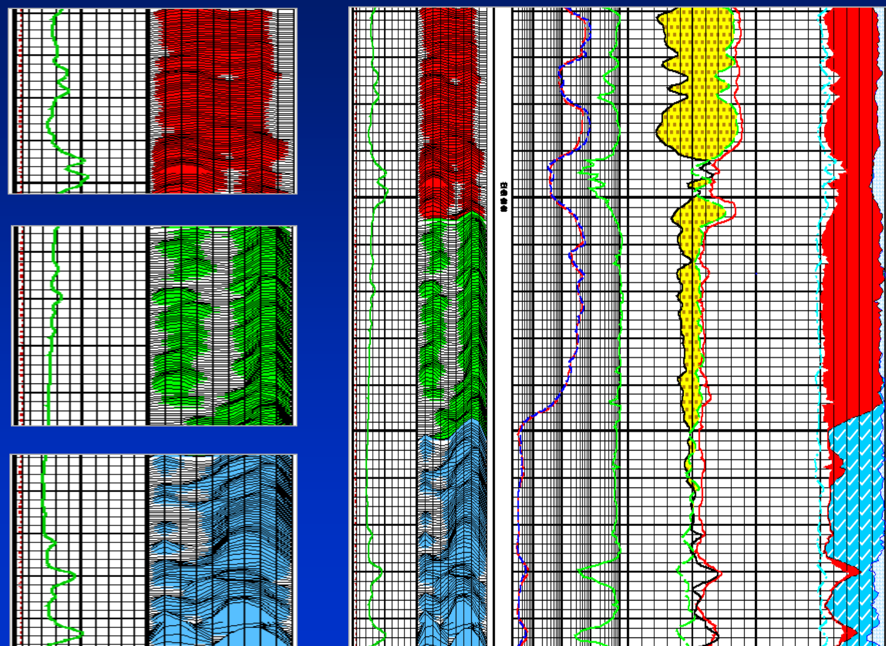
$$\frac{1}{T_{2_{hc}}} = \frac{1}{T_{2b_{hc}}} + \frac{1}{T_{2D_{hc}}}$$

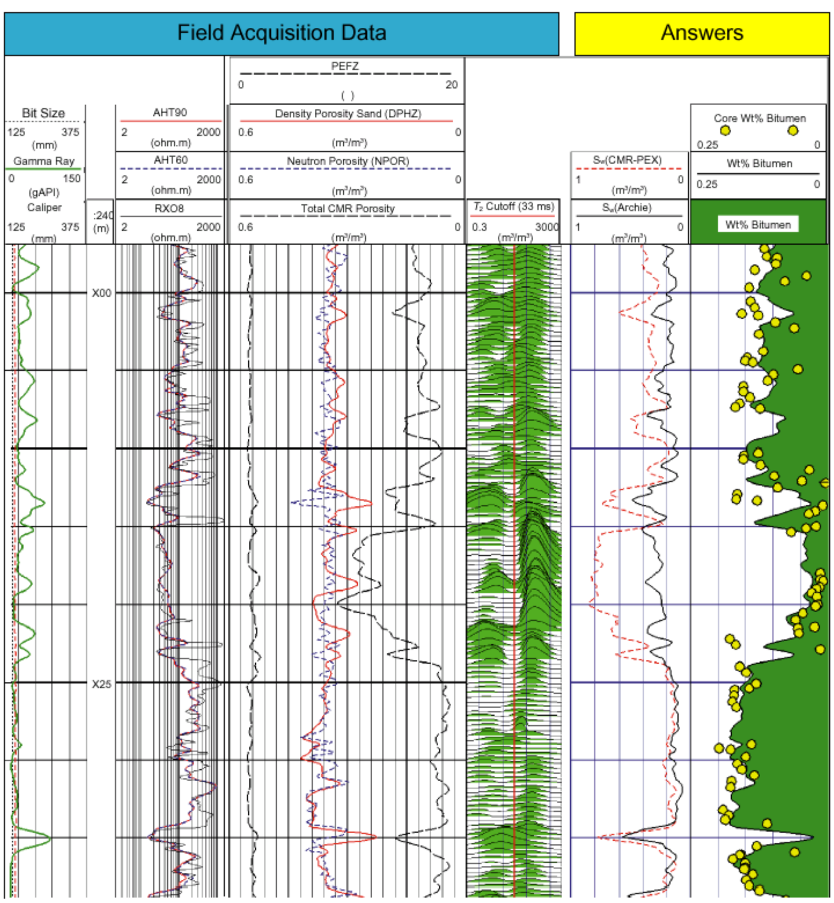
T2 Spectra for Various Fluid Types

Gas

Oil

Water





HYDROCARBON VOLUME

CORE DATA

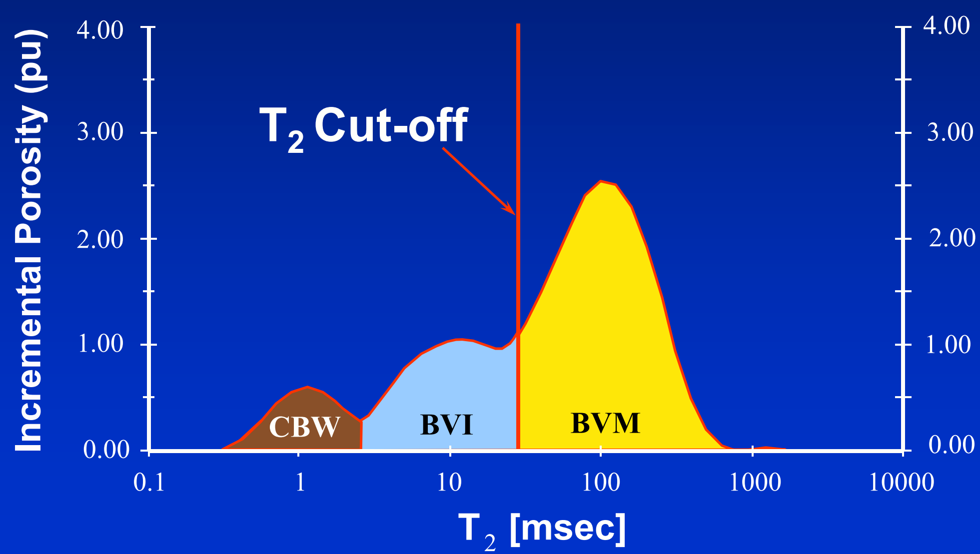
AND

NMR MEASUREMENTS

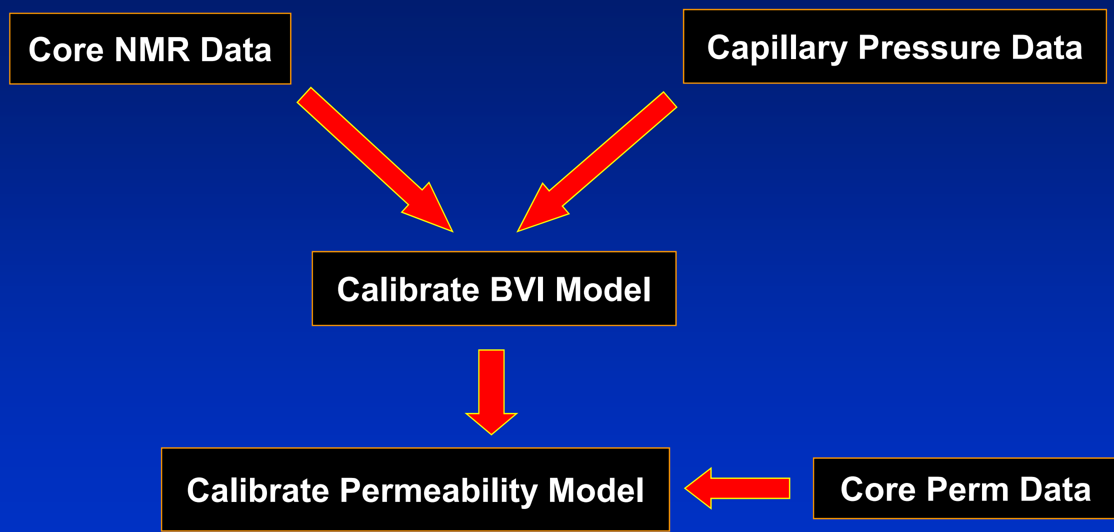
Default T_2 Cut-off Values

Sandstones : 33 msec

Carbonates : 92 msec



Core - Calibration Process



Core BVI Considerations

$$BVI_{core} = Swir_{core} \bullet \varnothing_{core}$$

- If $\varnothing_{core}$ was determined after humidity drying:

$$BVI_{core} \approx BVI_{effective}$$

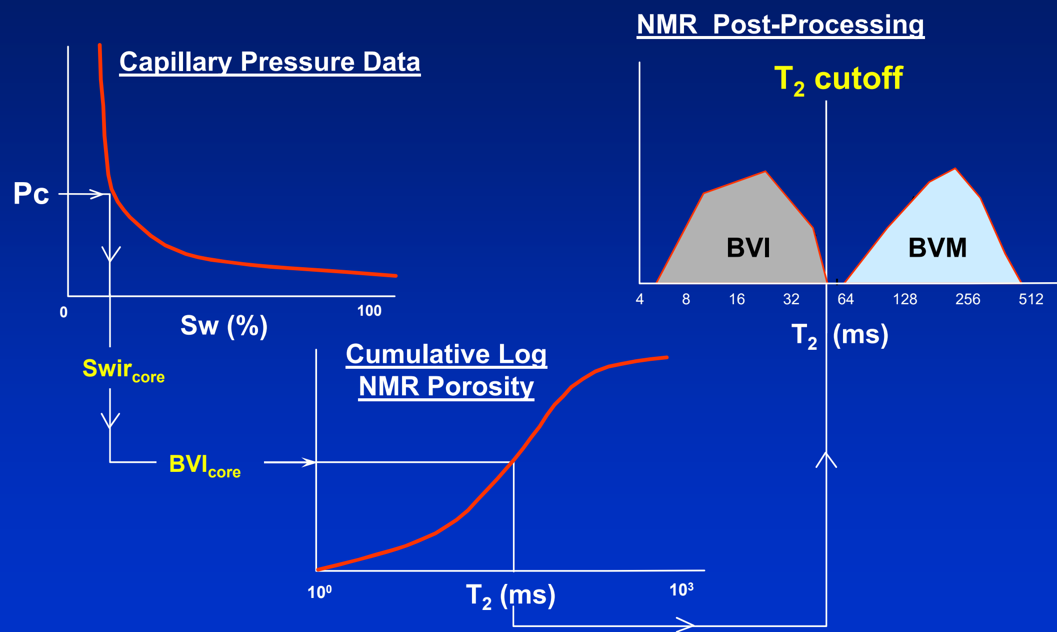
- If $\varnothing_{core}$ was determined after oven drying:

$$BVI_{core} = BVI_{total} = BVI_{effective} + \text{Clay Bound Water}$$

Core NMR BVI Model Considerations

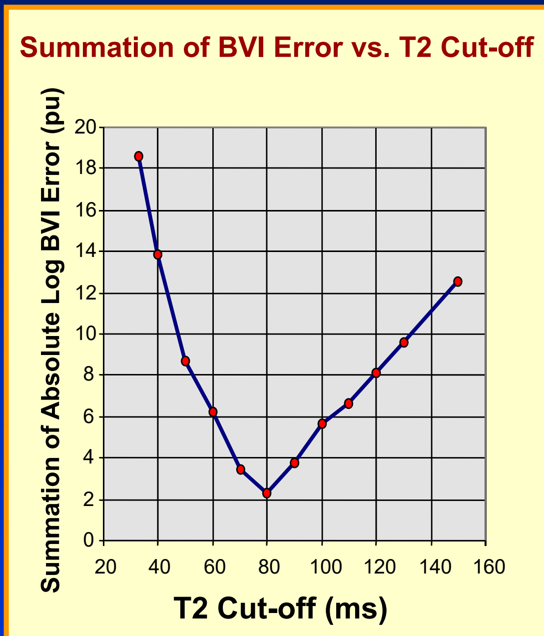
- Standard T_2 cut-off and SBVI models are constructed based on a correlation of T_2 spectra at irreducible water saturation to T_2 spectra at 100% water saturation. These these BVI models are only appropriate for application to T_2 spectra which reflect flushed zone conditions of Sxo = 1.0.
- If an oil-based mud filtrate in present in the flushed zone, then an oil-based mud filtrate de-saturation should be performed and used as the reference to construct the T2 cut-off or SBVI model. These BVI models are only appropriate for application to T_2 spectra reflecting flushed zone conditions of Sxo = Swir.
- T_2 cut-offs and SBVI models determined from core NMR may be inappropriate for application to NMR logs due to noise-induced positive shift of log T_2 spectra.

T_2 Cut-off from Pc & Log NMR Data

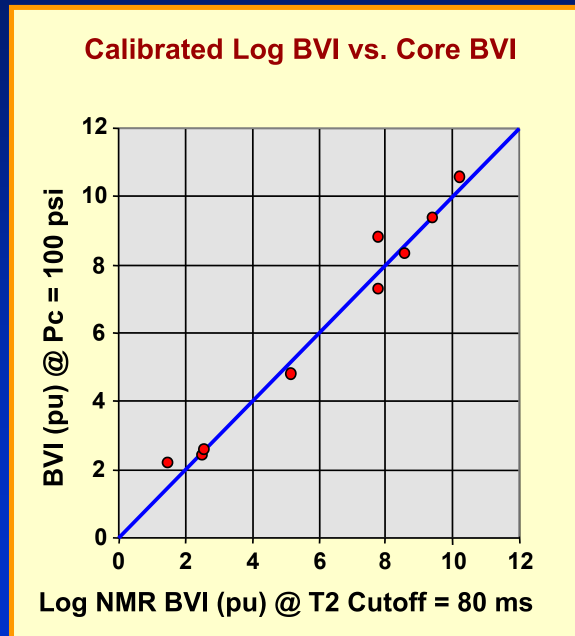


T_2 Cut-off from Pc & Log NMR Data

Error Minimization Plot

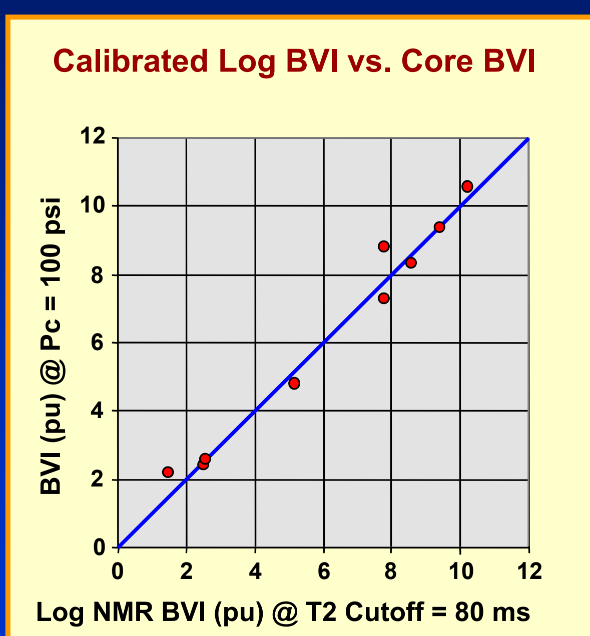


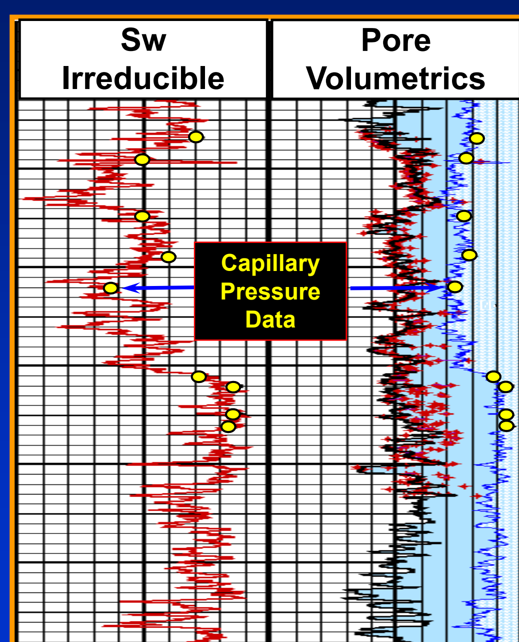
Core- Calibrated Results



T_2 Cut-off from Pc & Log NMR Data

Core- Calibrated Results





NMR Connection to Capillary Pressure

Model Assumptions:

- T_2 is related to pore size
- P_c is controlled by pore throats
- Pore body radius and pore throat radius are proportional
- P_c can be approximated by T_2

$$P_C = \frac{2\sigma \, \text{Cos}\,(\Theta)}{r_{throat}}$$

$$r_{throat} = \frac{106.4}{P_C}[micron\ /\ psi]$$

$$\frac{1}{T_2} \cong \rho \frac{S}{V} \cong \rho \frac{F_s}{R_{body}}$$

where

$\rho =$ killing strength

$F_s =$ Shape Factor

$$R_{body} = T_2 \rho F_s$$

$$\Gamma = \frac{r_{throat}}{R_{body}}$$

$$r_{throat} = \Gamma F_s \rho T_2$$

$$P_c = \frac{106.4\,[\text{microns/psi}]}{\Gamma F_s \rho T_2} \approx (7\text{ - }50)\frac{1}{T_2}$$

where T_2 is in seconds

Pseudo-Pc curves from NMR T_2 Spectra

Model Core-Calibration

$$\frac{1}{T_2} = \frac{1}{T_{2b}} + \rho_2 \frac{S}{V}$$

$$P_c = \frac{2\sigma\cos(\theta)}{r_{pt}}$$

$$\frac{S}{V} = \frac{F_s}{r_b}$$

$$\frac{1}{P_c} = \frac{\rho_2}{2\sigma\cos(\theta)} \frac{r_{pt}}{r_b} F_s T_2$$

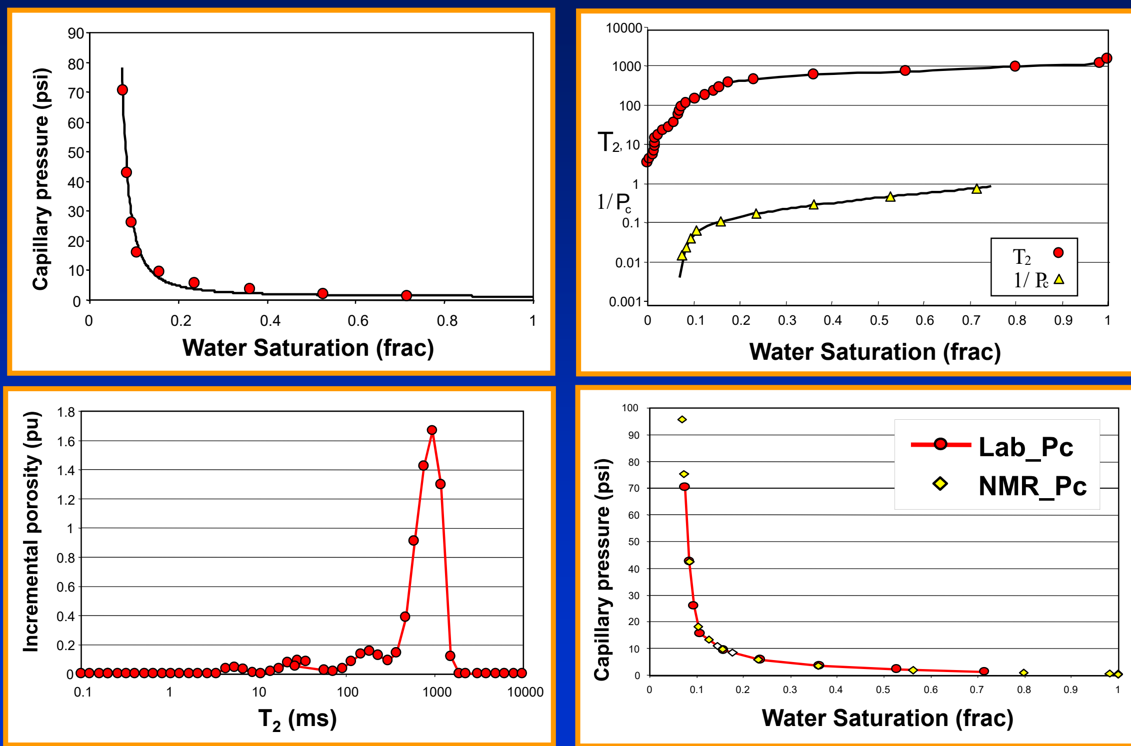
$$C = \frac{\rho_2}{2\sigma\cos(\theta)} \frac{r_{pt}}{r_b} F_s$$

$$\left(\frac{1}{P_c}\right) = CT_2$$

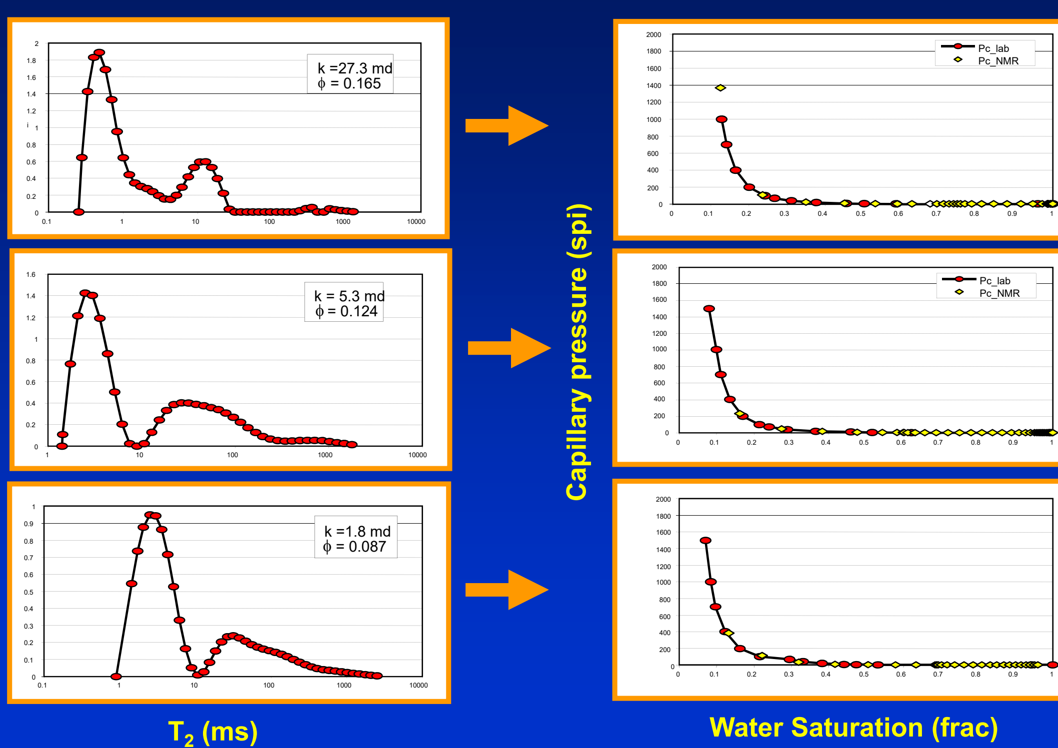
$$Log\left(\frac{1}{P_c}\right) = Log(C) + Log(T_2)$$

$$Log(C) = Log\left(\frac{1}{P_c}\right) - Log(T_2)$$

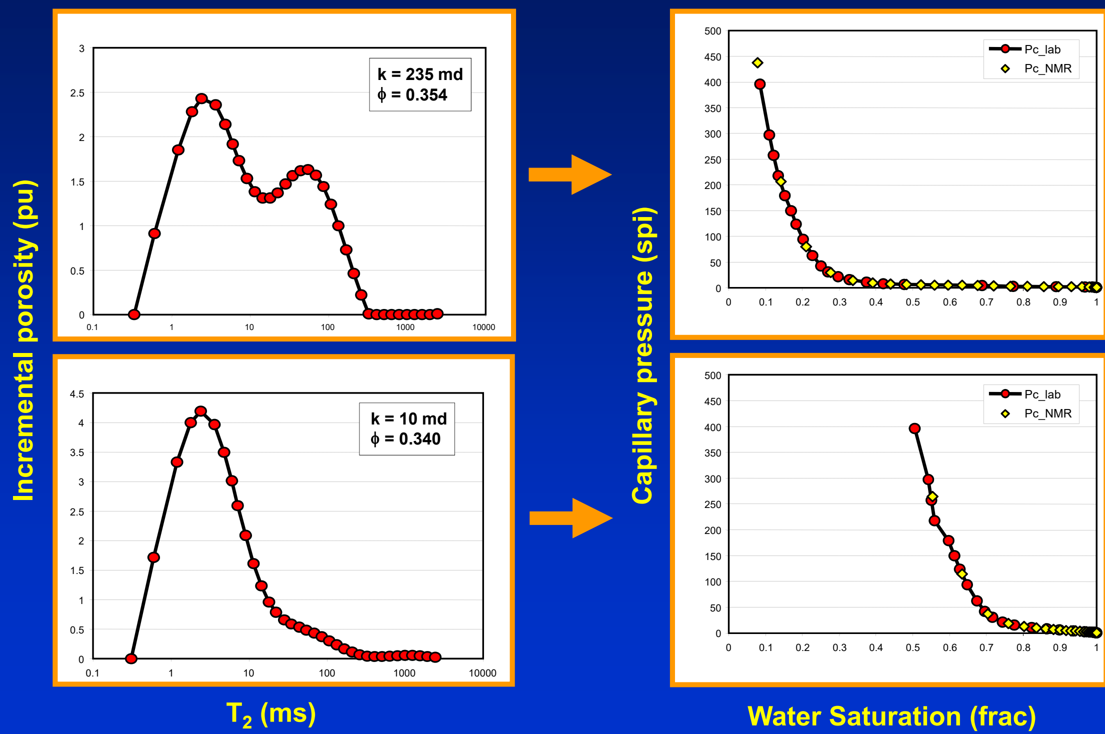
Pseudo-Pc curves from NMR T_2 Spectra



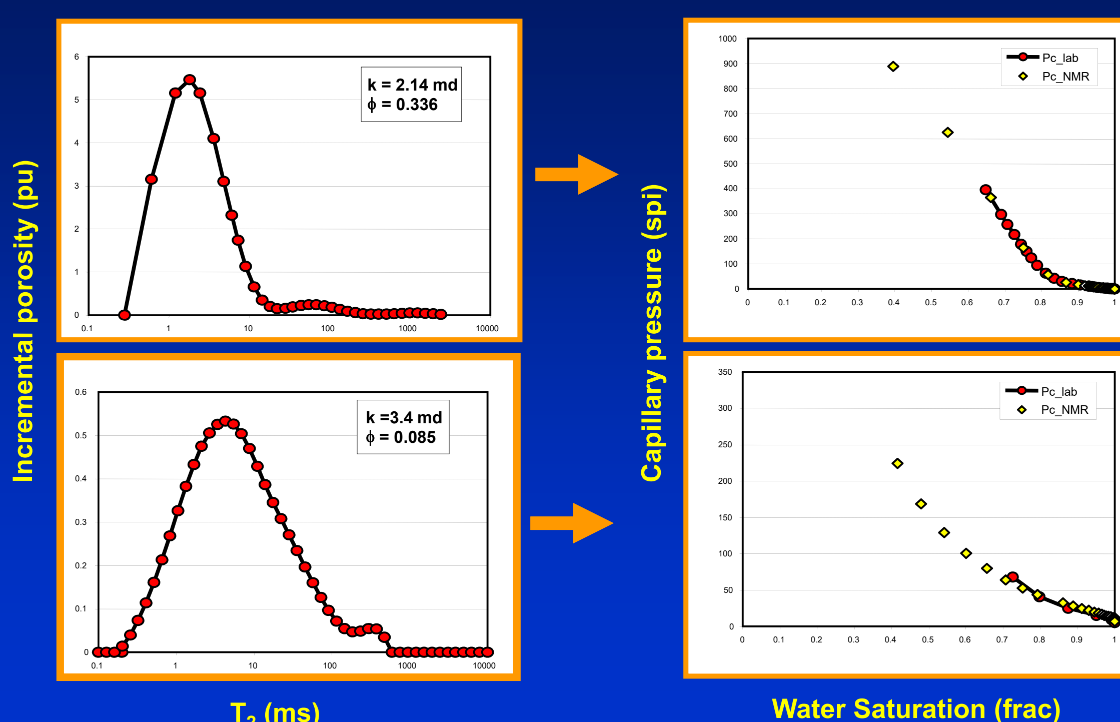
Pseudo-Pc curves from NMR T_2 Spectra



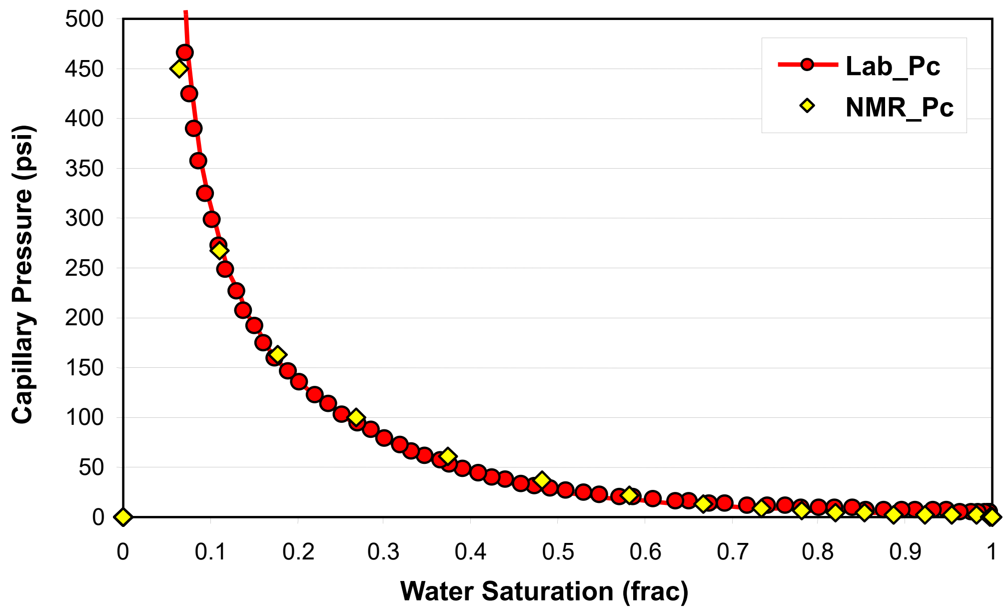
Pseudo-Pc curves from NMR T_2 Spectra



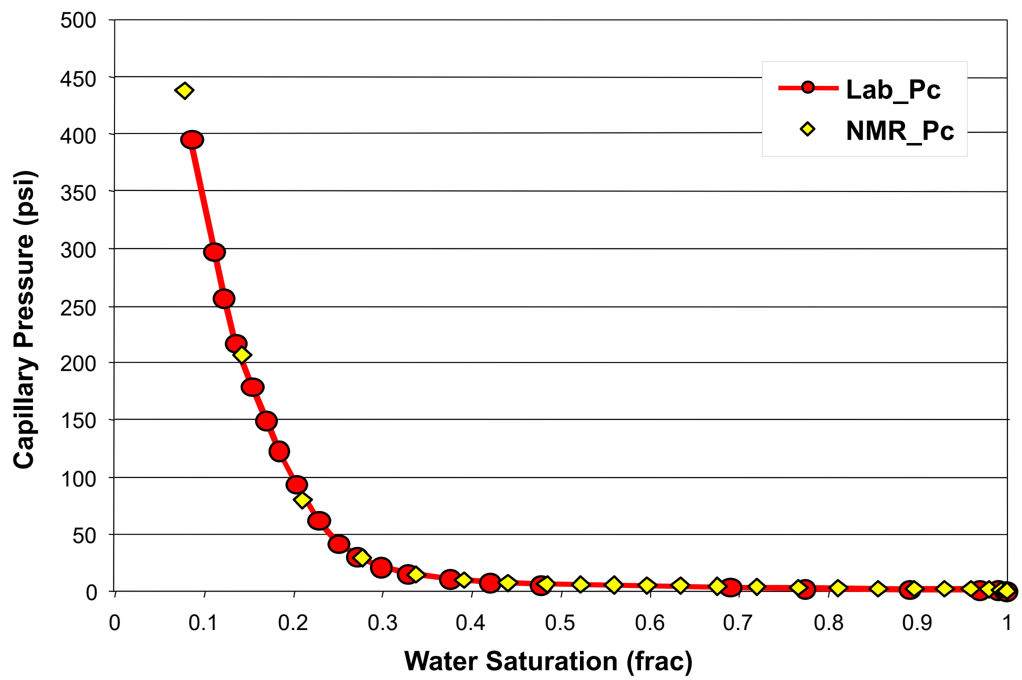
Pseudo-Pc curves from NMR T_2 Spectra



Pseudo-Pc curves from NMR T_2 Spectra



Pseudo-Pc curves from NMR T_2 Spectra

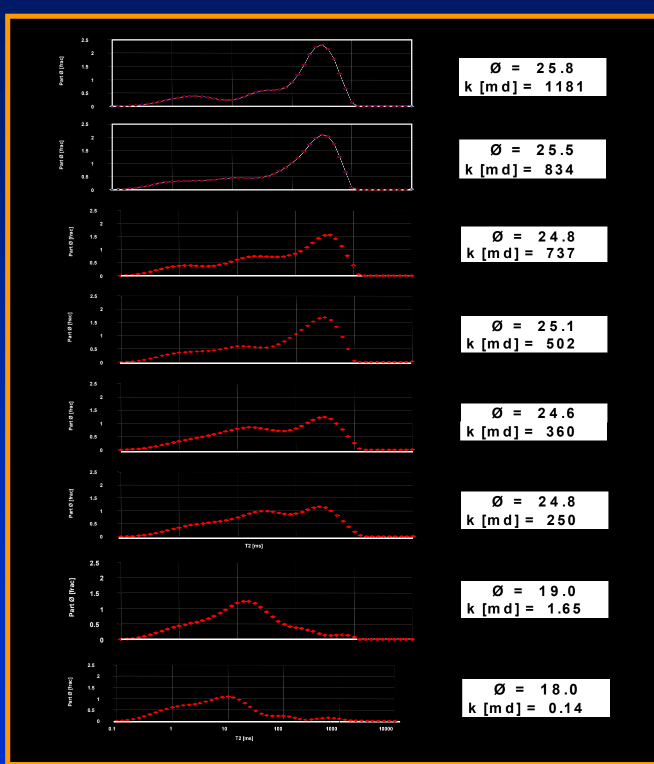


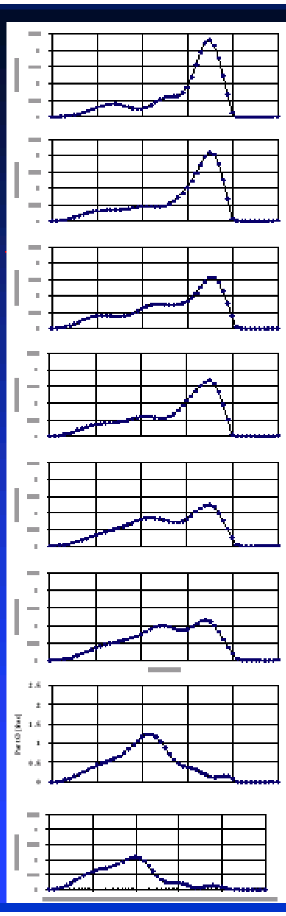
PERMEABILITY DATA

AND

NMR MEASUREMENTS

T_2 Distribution & Permeability





k = 1180 md
Ø = 25.8 p.u.

k = 830 md
Ø = 25.5 p.u.

k = 740 md
Ø = 25.8 p.u.

k = 500 md
Ø = 24.8 p.u.

k = 360 md
Ø = 24.6 p.u.

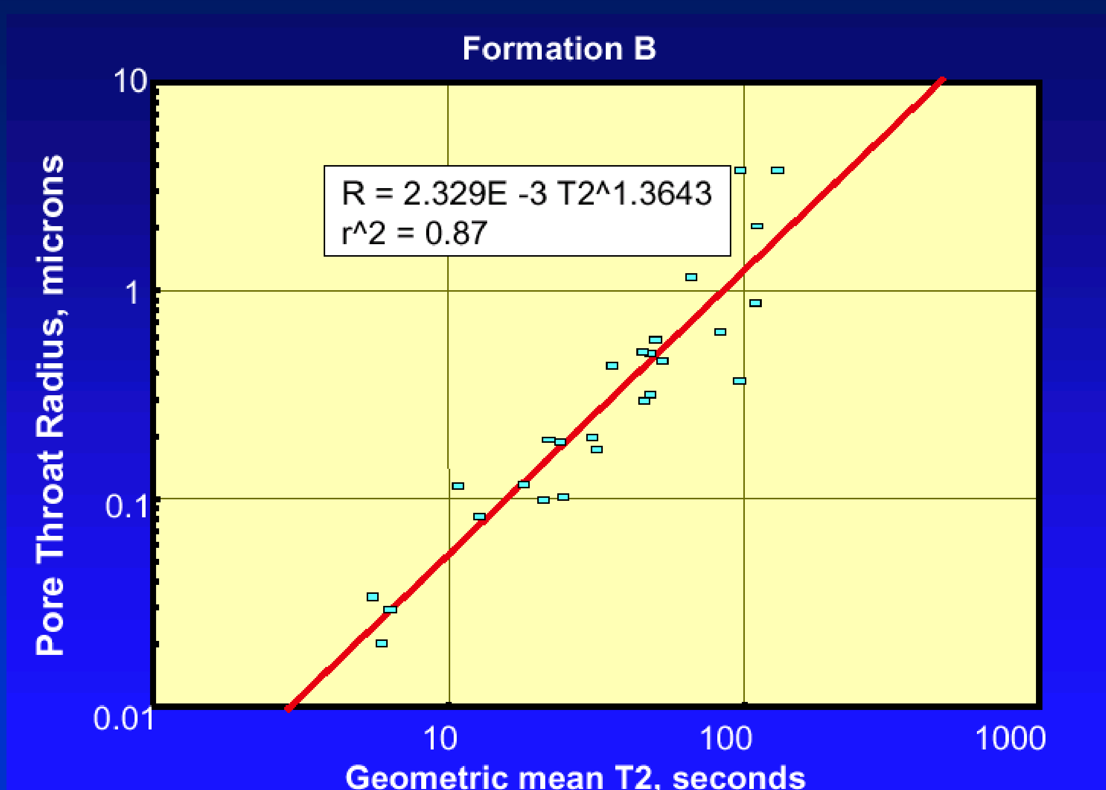
k = 250 md
Ø = 24.8 p.u.

k = 1.65 md
Ø = 19.0 p.u.

k = 0.14 md
Ø = 18.0 p.u.

T2 DISTRIBUTION AND PERMEABILITY

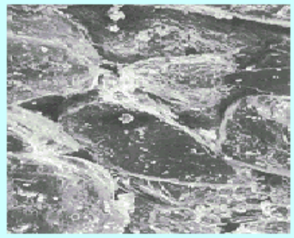
PORE SIZE AND T2



TWO PERMEABILITY MODELS

BVM/BVI concept

looks on pore surface



T_2 concept

looks on pore radius

$$k \propto \frac{1}{S_{por}^2} \propto \frac{1}{S_{w,irr}^2} \propto \left(\frac{BVM}{BVI}\right)^2$$

$$k \propto (\text{"average" pore radius})^2 \propto (\text{average } T_2)^2$$

- Best overall model, sensitive to accuracy of BVI
- high viscosity can increase BVI and lower k

- Sensitive to residual fluids in measurement volume
- work best in zones that have been completely flushed

BVM/BVI CONCEPT: Empirical Equations for k

Pore properties empirically expressed in irreducible water saturation terms (Timur 1968, Coates & Dumanoir 1974):

$$k = \left[100 \cdot \frac{\phi^{2.25}}{S_{w,irr}}\right]^2$$

--> permeability determination from NMR measurements:

$$k = \left[\frac{\phi}{C}\right]^4 \cdot \left[\frac{MBVM}{MBVI}\right]^2$$

MBVM - bulk volume moveable fluids

MBVI - bulk volume irreducible fluids

BOUND WATER MODELS

Timur 1966

$$k \propto \phi^{4.4} = \frac{1}{S_{wir}^{2}}$$

Coates Equation for Permeability

$$k,md = \left[\frac{\phi}{10}\right]^4 \left[\frac{BVM}{BVI}\right]^2 = \left[\frac{\phi}{10}\right]^4 \left[\frac{1 - S_{wir}}{S_{wir}}\right]^2$$

$$k,md = \left[\frac{\phi}{c}\right]^4 \left[\frac{BVM}{BVI}\right]^2 = \left[\frac{\phi}{c}\right]^4 \left[\frac{1 - S_{wir}}{S_{wir}}\right]^2$$

Benefits:

- Effective permeability = 0 for BVM = 0
- No hydrocarbon effects

Determination of the scaling factor c:

$$c = \left(\frac{1}{n}\sum_{1}^{n}\left[\frac{\phi^4}{k}\right]\left[\left(\frac{BVM}{BVI}\right)^2\right]\right)^{0.25}$$

Generalized Coates:

$$k = \left[\frac{\phi}{c}\right]^m \left[\frac{BVM}{BVI}\right]^n$$

Note - 3 parameters: c, m, n, and T_2 cutoff

T2 CONCEPT

T_2 relates to pore body radius

Permeability controlled by pore throats

Pore body radius and pore throat radius are proportional

We remember: $k \sim r_2$

Permeability can be approximated by T_2

$$k = C\langle\phi\rangle^4 \langle T_2\rangle^2$$

where C is a variable

COMPARISON BETWEEN BOUND WATER AND AVERAGE T2 MODEL

Bound Water Model

$$k = \left[\frac{\phi}{c}\right]^m \left[\frac{BVM}{BVI}\right]^n$$

- Best overall model
- Sensitive to accuracy of MBVI (T_2 cutoff determination)
- High viscosity crude can increase BVI and reduce k.

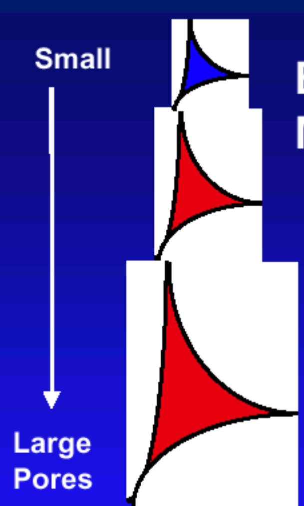
Average T_2 Model

$$k = C\langle\phi\rangle^4\langle T_2\rangle^2$$

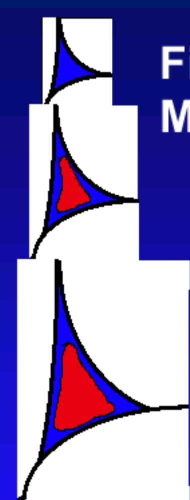
where C is a variable

- Sensitive to residual fluids in measurement volume
- These models work best in zones that have been completely flushed.

TWO VIEWS OF BVI



Bimodal Model



Film Model

Bimodal - Fixed T_2

- Small Pores Contain Irreducible Fluid
- Large Pores Contain Moveable Fluid

Film (Spectral) Model

- Small Pores Contain Irreducible Fluid
- Large Pores Contain Both Irreducible (Film) and Moveable Fluids
- Water Films Appear Like Small Pores

WHICH BVI MODEL TO USE?

- **Bimodal - Fixed T_2**
  - Hydrocarbon-bearing intervals
  - Shaly sands
  - Bimodal porosity systems
- **Film (Spectral) Model**
  - 100% water saturated homogenous sands
  - Oil-based mud
- **Variable T_2 Cutoff**
  - Carbonates
  - Mixed lithologies

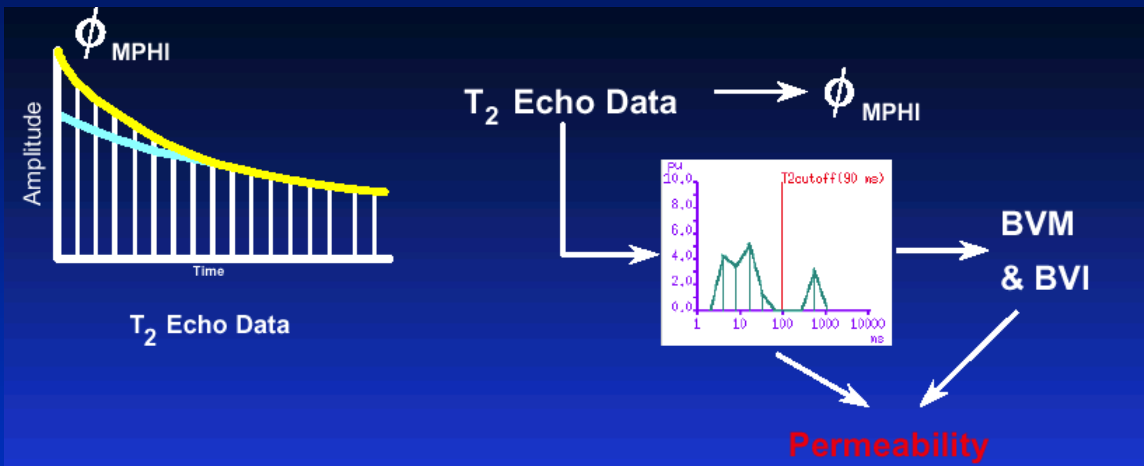
NMR POROSITY/PERMEABILITY SUMMARY

- **Mineralogy Independent ϕ**
  - no interpretation constants required
- **Effective and Total ϕ and BVI and BVM**
- **T_1 and T_2 depends on S/V and ρ**
- **NMR echo decay is related to S/V**
  - pore-size distributions
  - grain-size distribution
- **S/V related to k**

T_2 relates to pore body radius.

Permeability is controlled by pore throat radius !

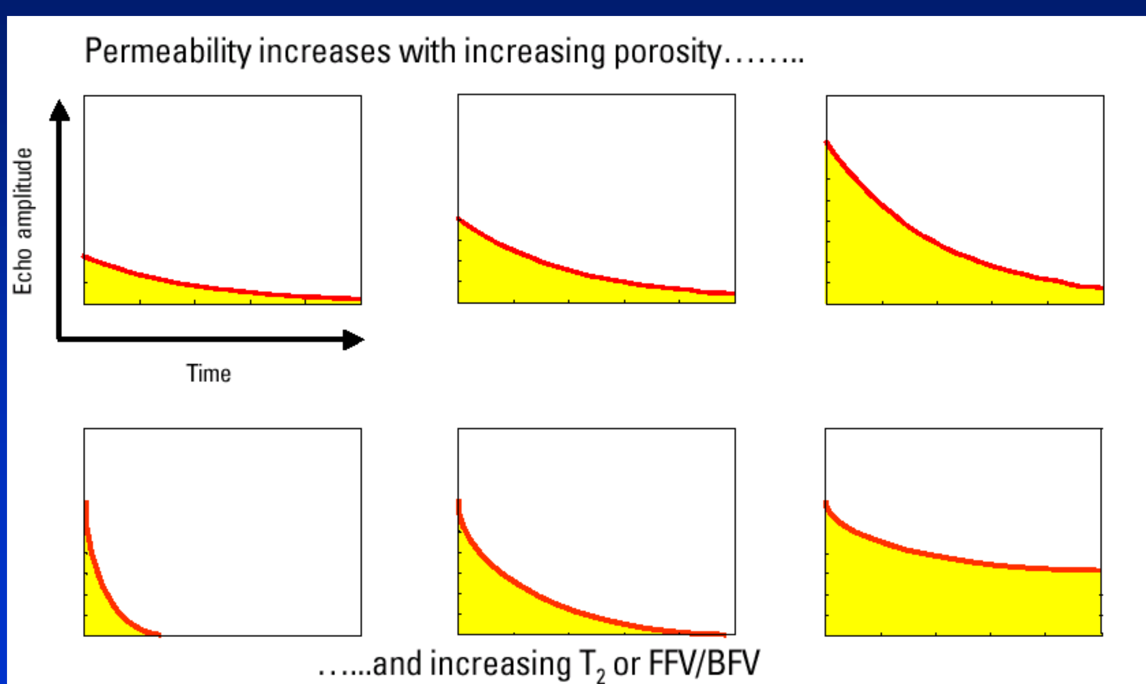
NMR POROSITY/PERMEABILITY SUMMARY



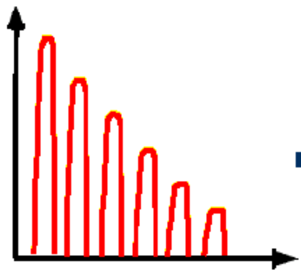
Coates Formulation

$$k = a\,\phi^4 T_2^{\,2} \quad \text{or} \quad k = \left(\frac{\phi_{MPHI}}{10}\right)^4 \left(\frac{BVM}{BVI}\right)^2$$

NMR POROSITY/PERMEABILITY SUMMARY



NMR POROSITY/PERMEABILITY SUMMARY



→ $\sum_{n=1}^{N} \text{echo}(n)$ → Permeability indicator

NMR Permeability Models

Kenyon Model:

$$k = C \bullet \left(\phi_{NMR}\right)^{a} \bullet \left(T_{2\ Geo.\ Mean}\right)^{b}$$

Coates-Timur Model :

$$k = \left(\frac{\phi_{NMR}}{C}\right)^{a} \bullet \left(\frac{BVM}{BVI}\right)^{b}$$

Where assumed default parameters are: C =10, a = 4 & b = 2

Note: These models will produce a <u>permeability index</u> unless explicitly calibrated to local reservoir data.

NMR Permeability Models

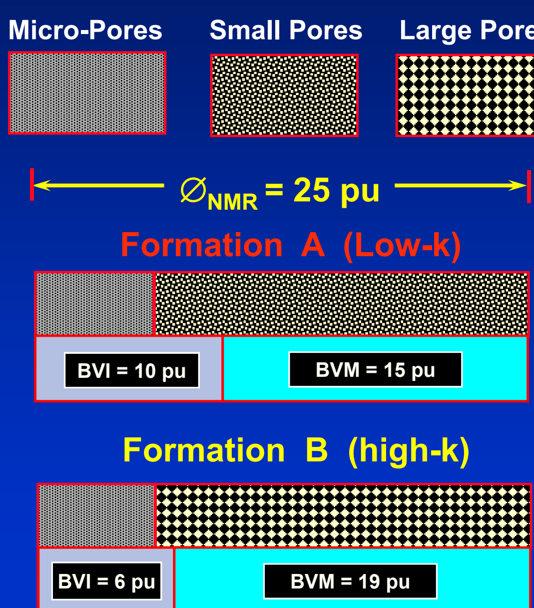
Kenyon Model:

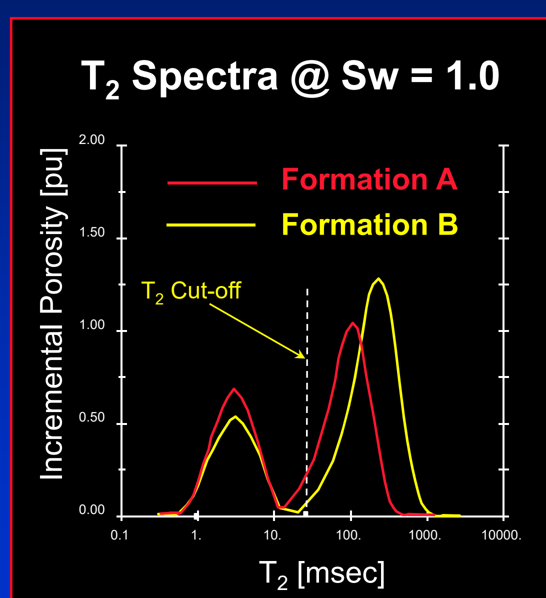
$$k = C \cdot \left(\phi_{NMR}\right)^{a} \cdot \left(T_{2\,Geo.\,Mean}\right)^{b}$$

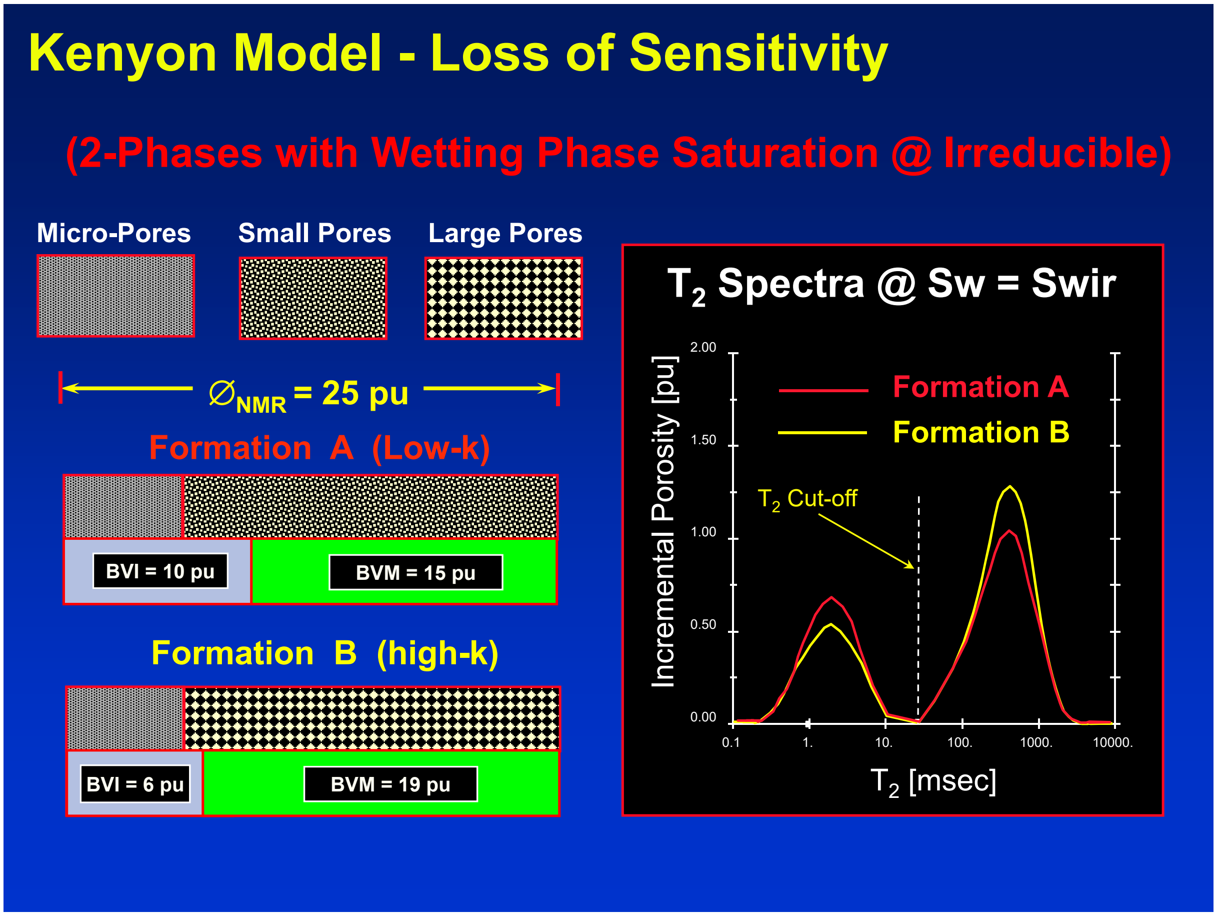
Where default parameters are: C =10, a = 4 & b = 2

Kenyon Model - Ideal Conditions

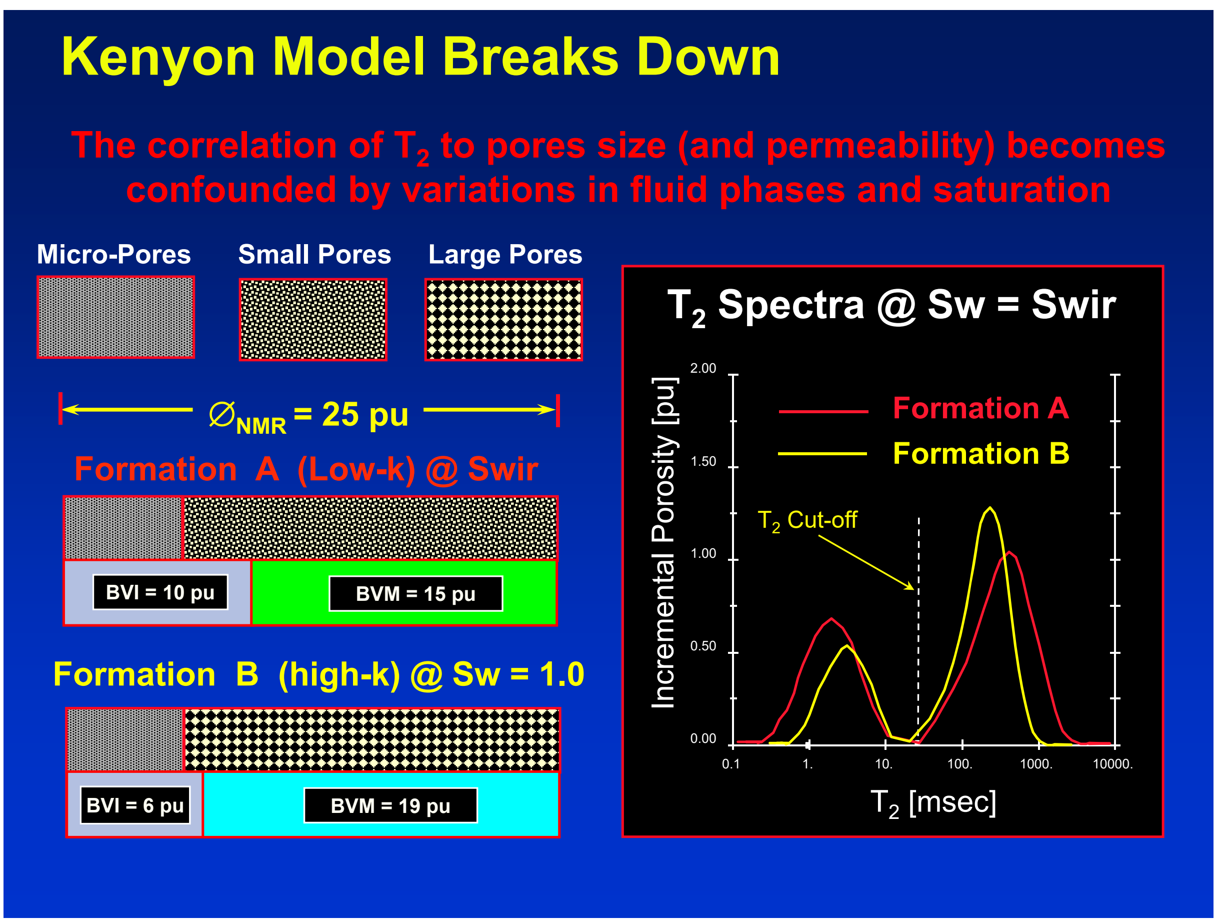
(Wetting Phase Saturation = 100%)







Kenyon Model - Loss of Sensitivity
(2-Phases with Wetting Phase Saturation @ Irreducible)
Micro-Pores
Small Pores
Large Pores
$\varnothing_{NMR}$ = 25 pu
Formation A (Low-k)
BVI = 10 pu
BVM = 15 pu
Formation B (high-k)
BVI = 6 pu
BVM = 19 pu
T_2 Spectra @ Sw = Swir
Incremental Porosity [pu]
2.00
1.50
1.00
0.50
0.00
Formation A
Formation B
T_2 Cut-off
0.1
1.
10.
100.
1000.
10000.
T_2 [msec]



Kenyon Model Breaks Down
The correlation of T_2 to pores size (and permeability) becomes confounded by variations in fluid phases and saturation
Micro-Pores
Small Pores
Large Pores
$\varnothing_{NMR}$ = 25 pu
Formation A (Low-k) @ Swir
BVI = 10 pu
BVM = 15 pu
Formation B (high-k) @ Sw = 1.0
BVI = 6 pu
BVM = 19 pu
T_2 Spectra @ Sw = Swir
Incremental Porosity [pu]
2.00
1.50
1.00
0.50
0.00
Formation A
Formation B
T_2 Cut-off
0.1
1.
10.
100.
1000.
10000.
T_2 [msec]

Limitations of Kenyon Permeability Model

- T2 spectra will only reflect pore size distribution when fully 100% saturated with wetting phase fluid.
- Application of the model is predicated on assumption that pore size (as reflected in the T2 distribution under above conditions) has an implicit relationship to pore throat diameter and pore connectivity.
- The model loses sensitivity when T2 spectra become dominated by non-wetting phase bulk relaxivities.
- A model calibrated in a hydrocarbon leg cannot be applied to a water legs (and visa versa).

Permeability from NMR

Generalized Coates-Timur Model:

$$k = \left(\frac{\phi}{C}\right)^{a} \bullet \left(\frac{1 - S_{wir}}{S_{wir}}\right)^{b}$$

This model is designed to compute the effective (non-wetting phase) permeability model based on the lower permeability boundary condition which is controlled by the ratio of non-wetting phase (1-Swir) to wetting phase (Swir) saturation .

Permeability from NMR

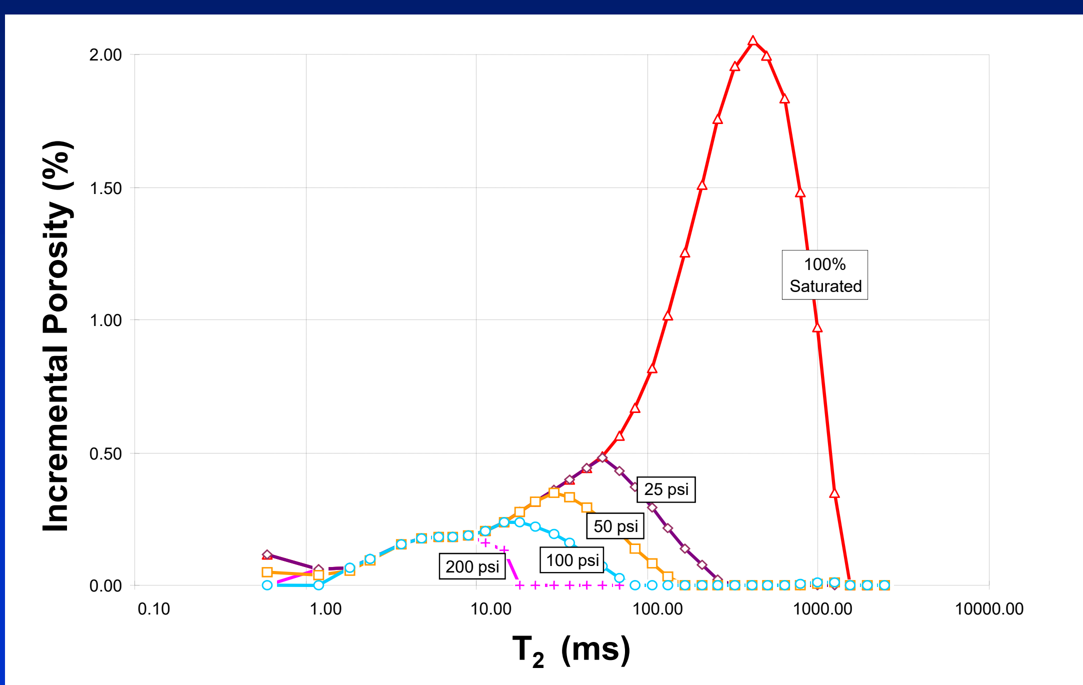
Coates-Timur Model (NMR version):

$$k = \left(\frac{\phi_{NMR}}{C} \right)^a \bullet \left(\frac{BVM}{BVI} \right)^b$$

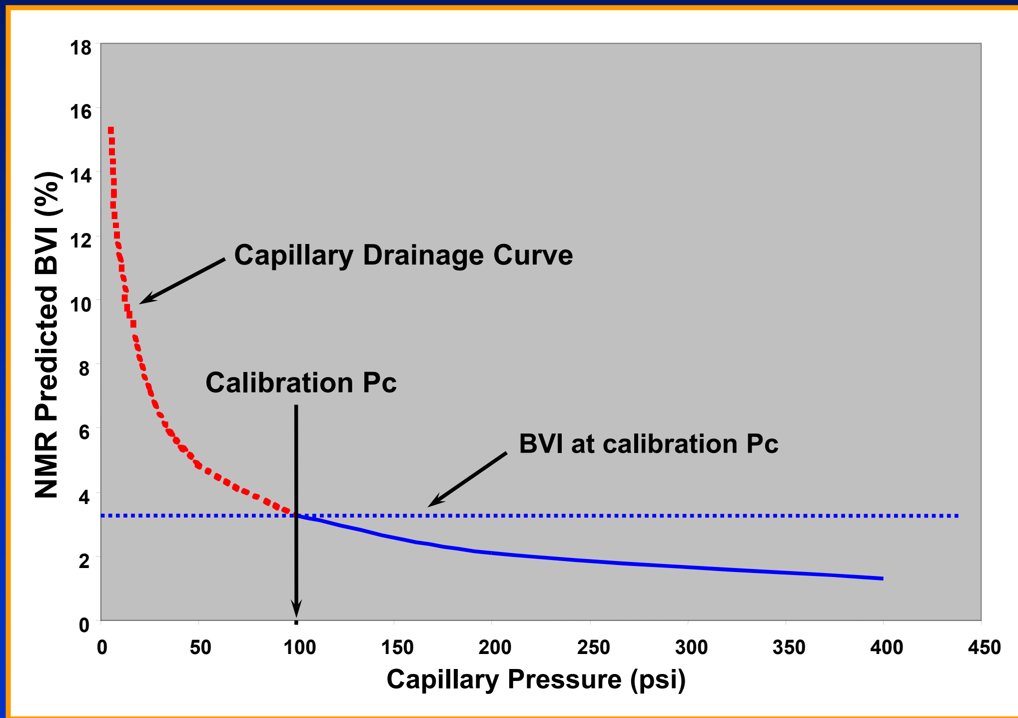
Where default parameters are: C =10, a = 4 & b = 2

BVI Dependence on Capillary Pressure/Height above FWL

T2 Distributions at Partial Saturations



BVI Dependence on Capillary Pressure/Height above FWL

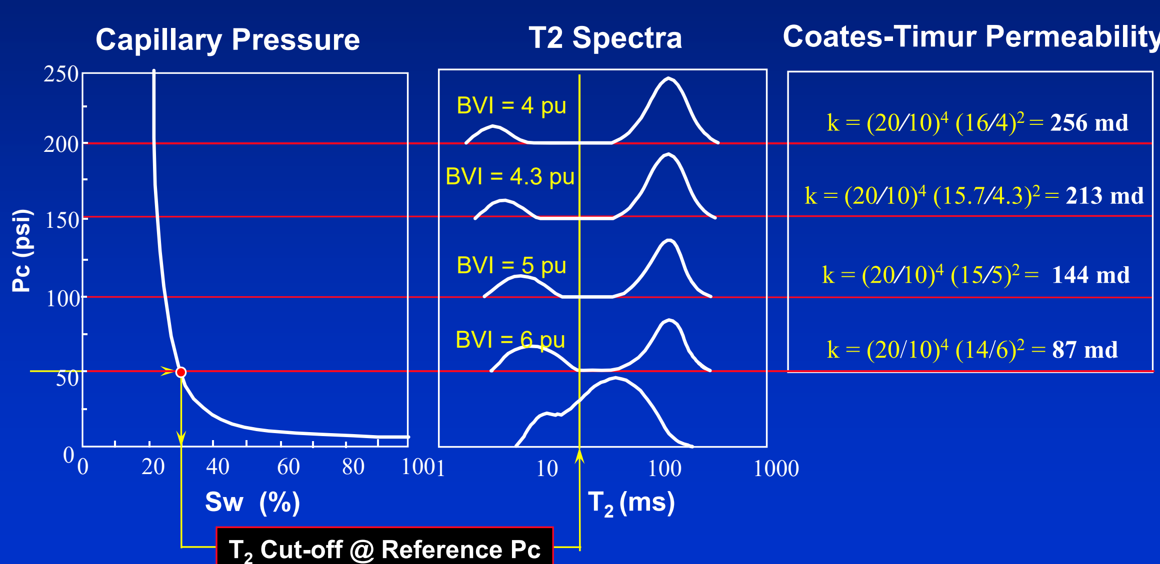


Coates-Timur Permeability vs. Column Height

$\varnothing_{NMR} = 20$ pu

$k_{absolute} = 256$ md

$$k = \left(\frac{\phi_{NMR}}{10}\right)^4 \bullet \left(\frac{\phi_{NMR} - BVI}{BVI}\right)^2$$



Limitations of Coates-Timur Permeability Model

- Application of the model is predicated on assumption that the porosity is all interconnected, and that pore throat diameter sytematically increases proportional to an increase in the magnitude of the bulk free fluid volume (BVM).
- Computed permeability may systematically increase as a function of increasing height above free water level. This effect is most likely to occur for lower quality reservoirs with highly sloped capillary pressure curves, but should not be an issue for very high permeability reservoirs where capillary presure curves are near-asymptotic.
- Model Losses sensitivity at very high permeabilities where irreducible water saturation is on the asymptote of the capillary pressure curve, and porosity doesn’t increase relative to increased pore size and/or pore throat size.

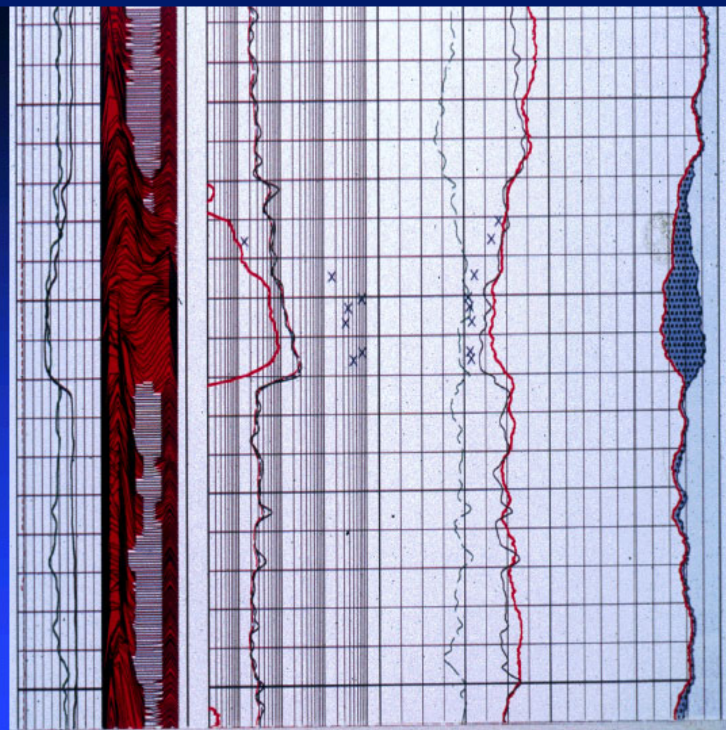
Calibration of Coates-Timur Permeability Model

- Local calibration of model fitting parameters (C, a & b) are necessary to account for variations in the complexity and connectivity of the pore system, which control the permeability and it’s correlation to the bulk pore volumetric elements of which model is strictly comprised.
- Multi-linear regression can be employed to solve for the the formation-specific fitting parameters (C, m & n) when reference permeability data from core or formation tests are available.
- Minimum error analysis can also be employed to solve for an optimum value of the porosity denominator C” while holding parameters “a” and “b” constant at default values.

UNCALIBRATED PERMEABILITY

Coates' Constant

$$k = \left(\frac{\phi_{MPHI}}{C}\right)^4 \left(\frac{BVM}{BVI}\right)^2$$

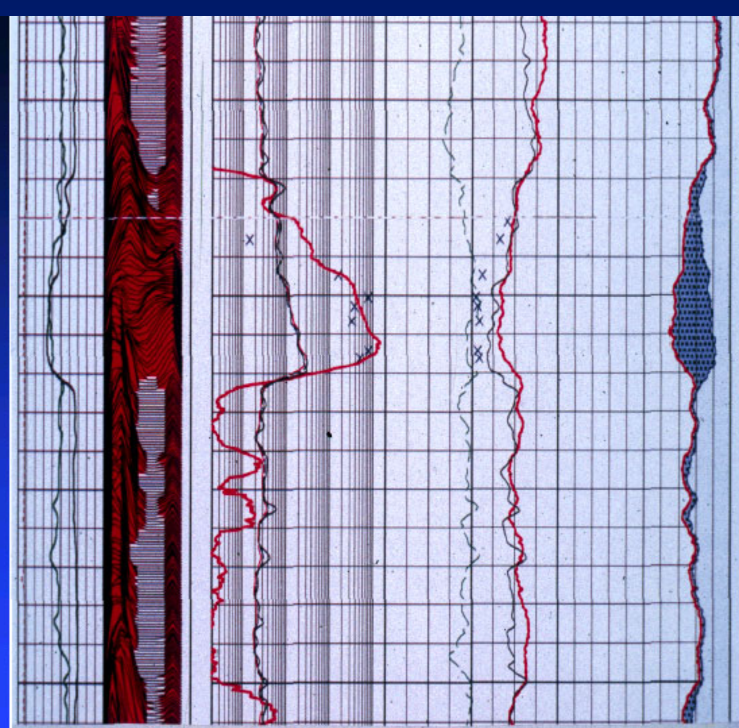


CALIBRATED PERMEABILITY

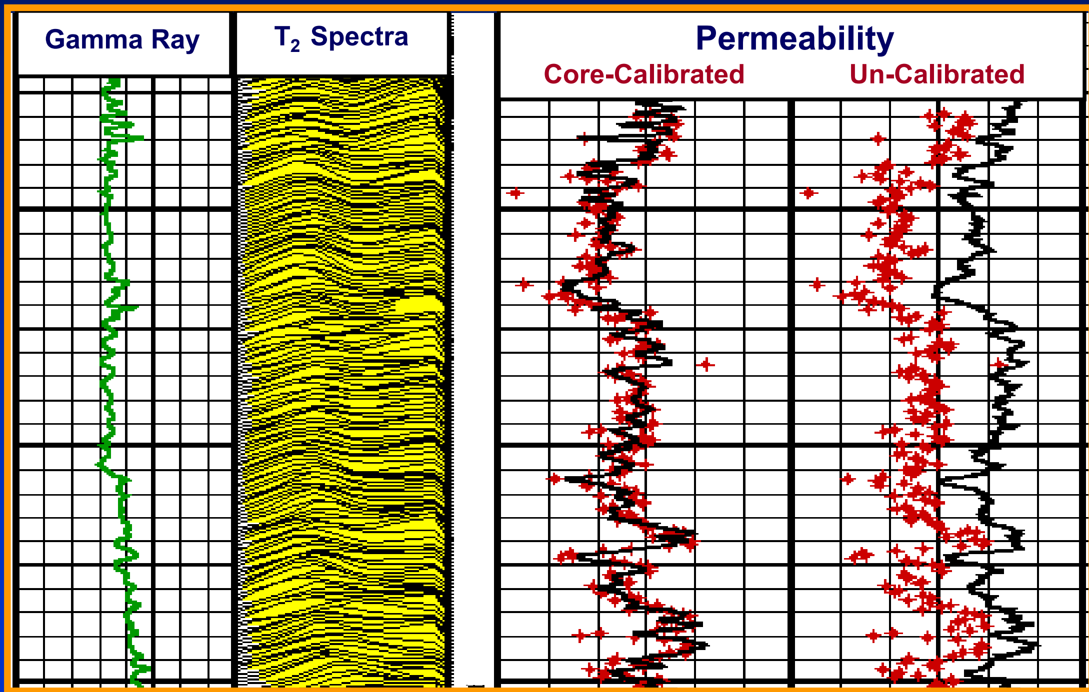
Calibrated Permeability Model

Coates' Constant

$$k = \left(\frac{\phi_{MPHI}}{4}\right)^4 \left(\frac{BVM}{BVI}\right)^2$$



MRIL Permeability Index versus Core-Calibrated MRIL Permeability



Permeability - Frames of Reference

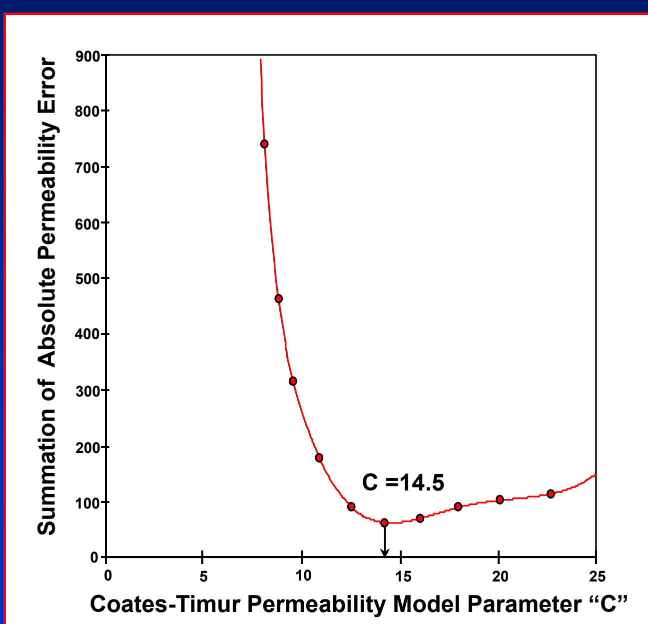
- $k_{air} > k_{\infty} \sim k_{liquid} > k_{effective}$
- $k_{\text{ambient stress}} > k_{\text{reservoir overburden stress}}$

Reference Permeability Sources

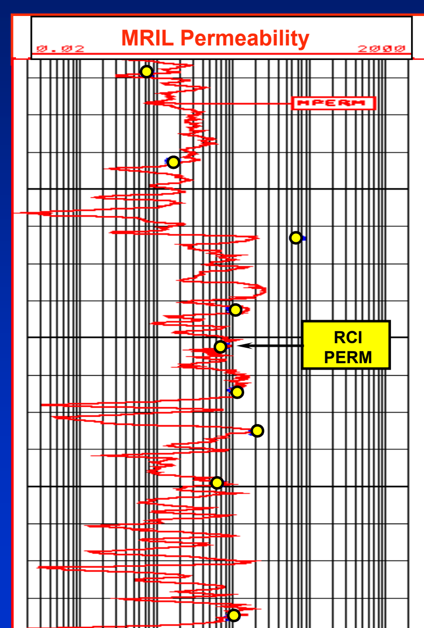
- Conventional Cores
  - Whole Core
  - Core Plugs
  - Probe Permeameters
  - Thin Section estimates
- Rotary Sidewall Cores
- Well Production Tests
- Drillstem Tests
- Wireline Formation Testers

NMR Permeability Calibration

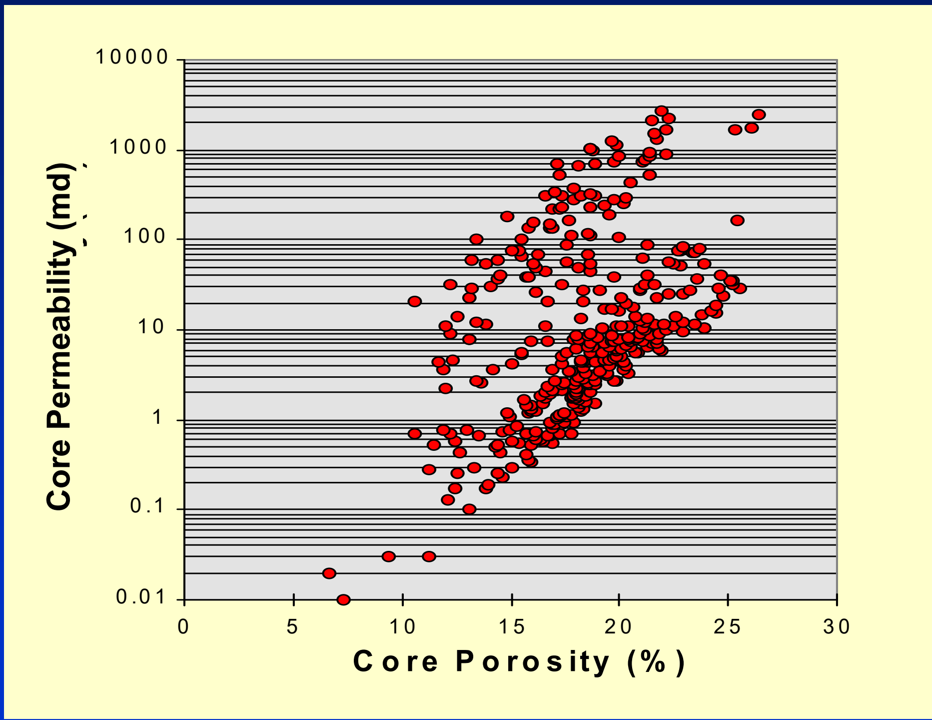
Coates-Timur Model Optimization Plot



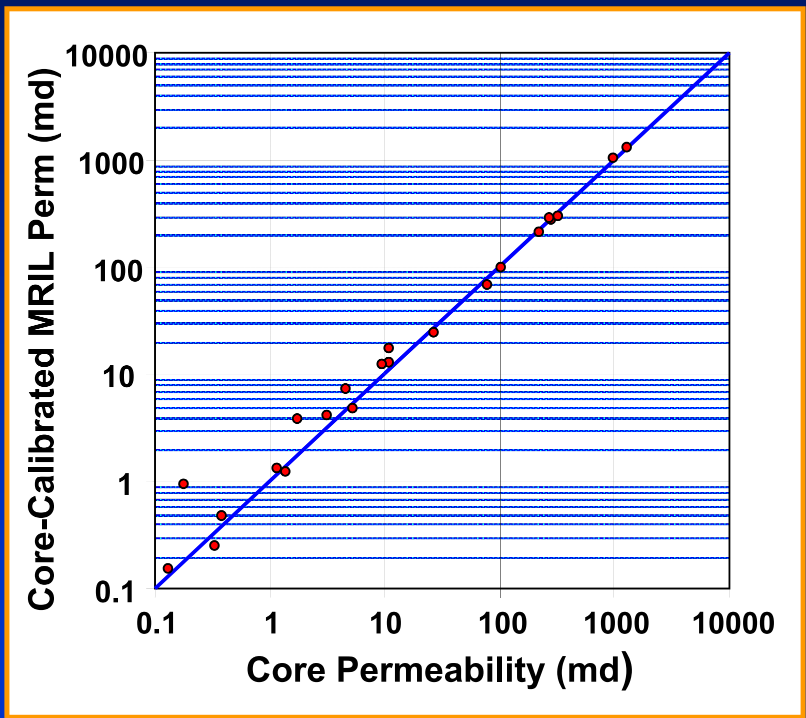
Core- Calibrated Results



CASE STUDY: Well A



Core-Calibrated MRIL Permeability
Carbonate Example

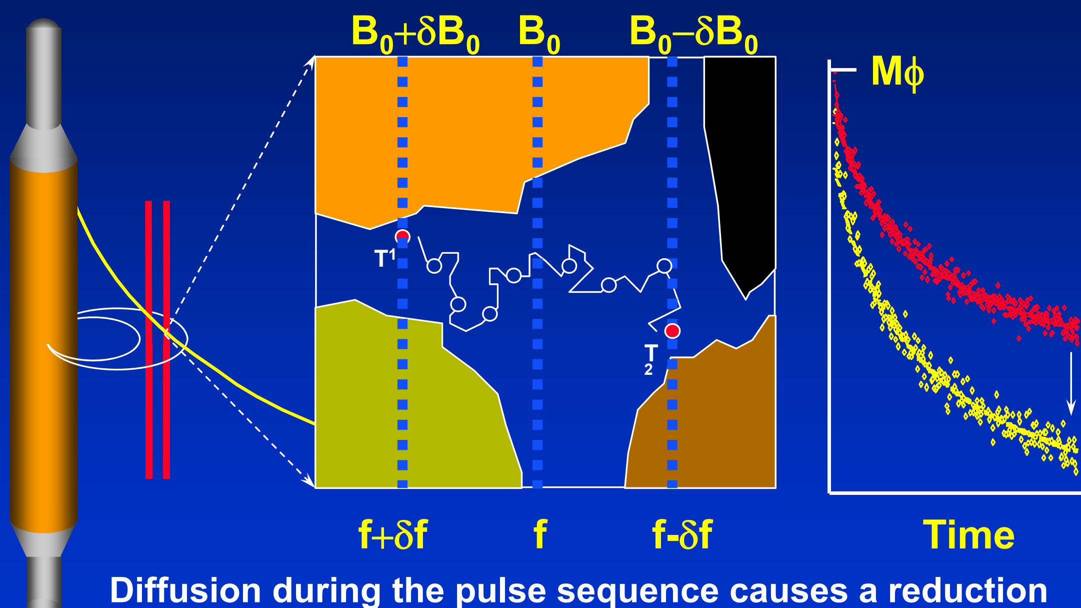


NMR

GRADIENT DIFFUSION

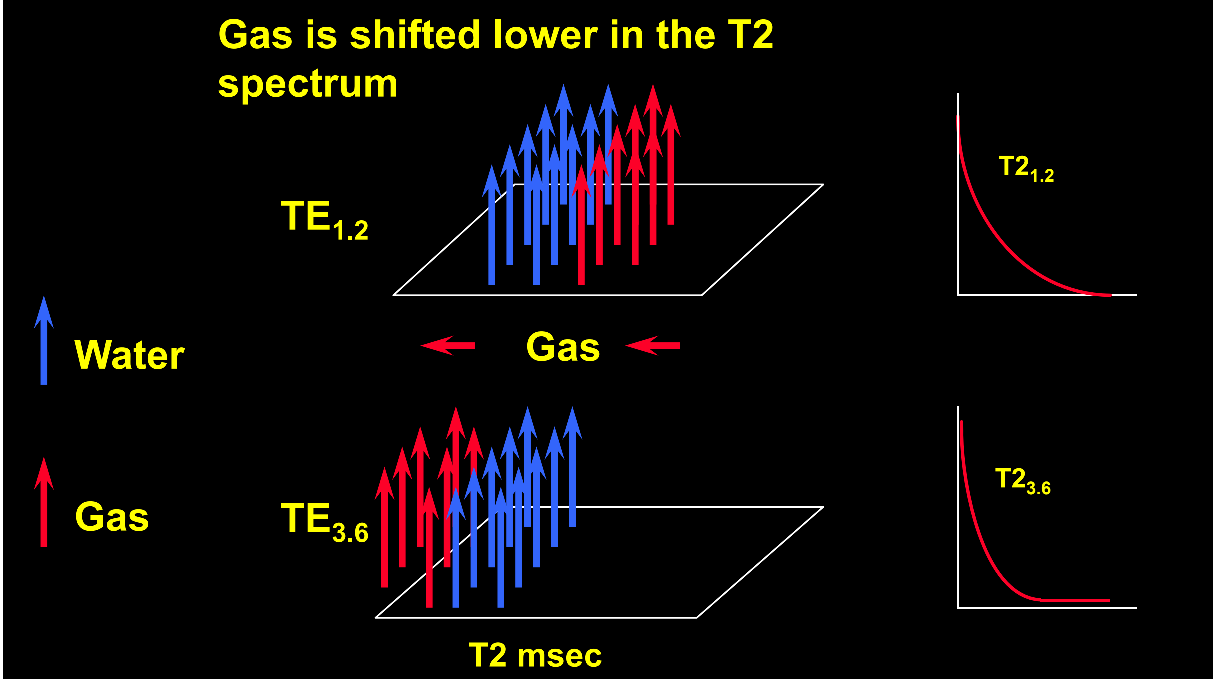
MEASUREMENTS

MRIL Gradient Field and Diffusion

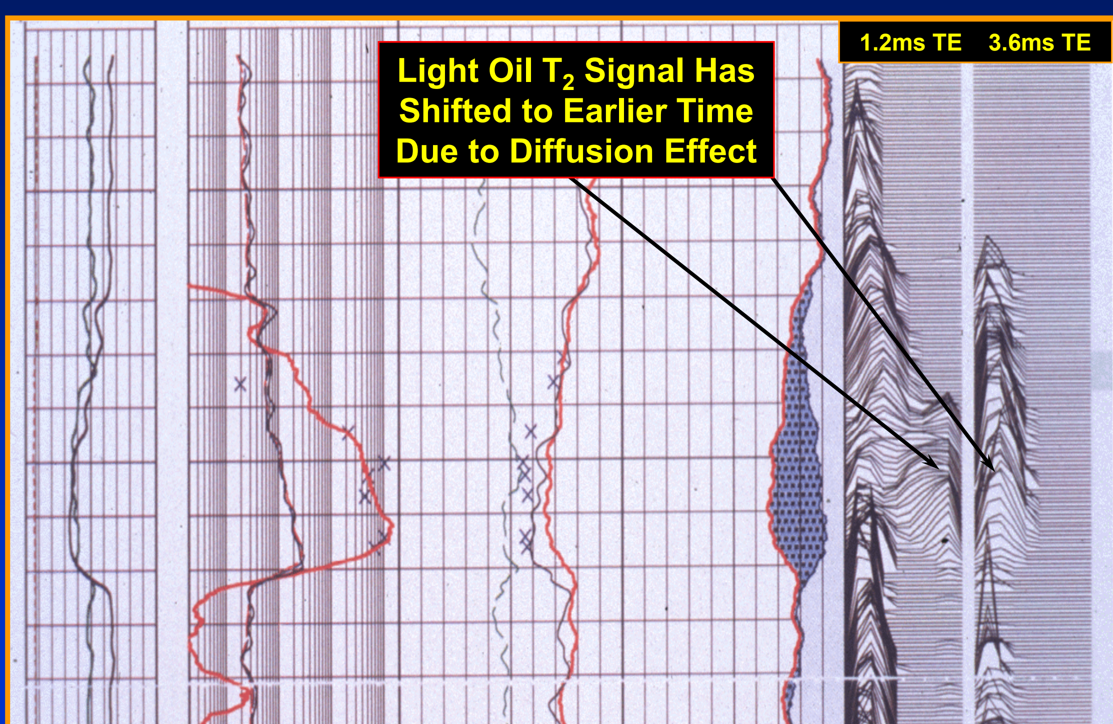


Diffusion during the pulse sequence causes a reduction in signal amplitude with time and decreases T2.

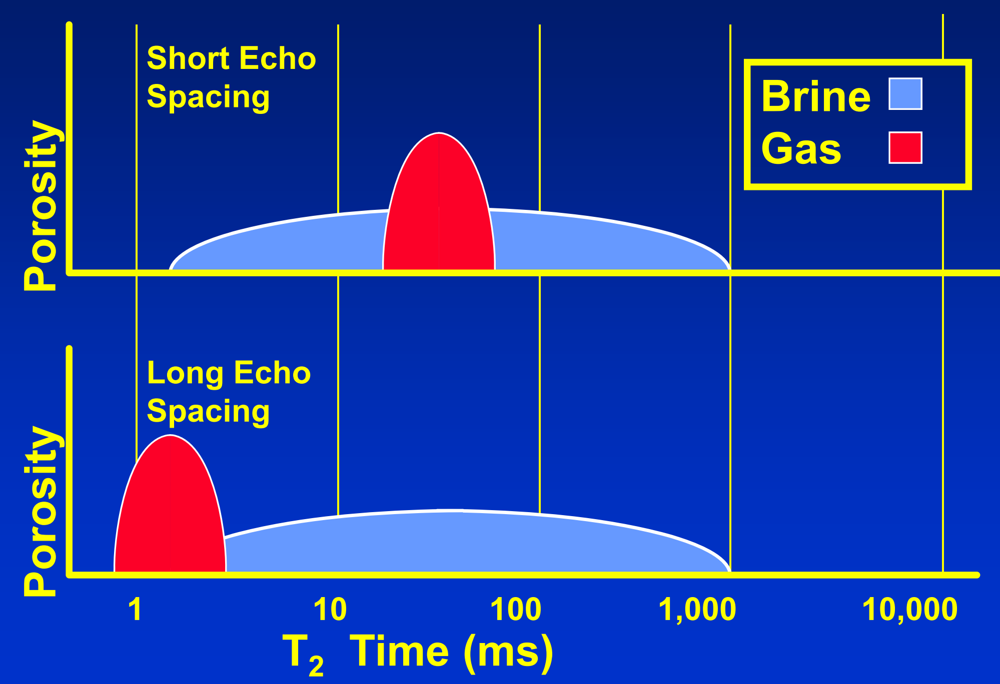
Shifted Spectrum - Gas Detection



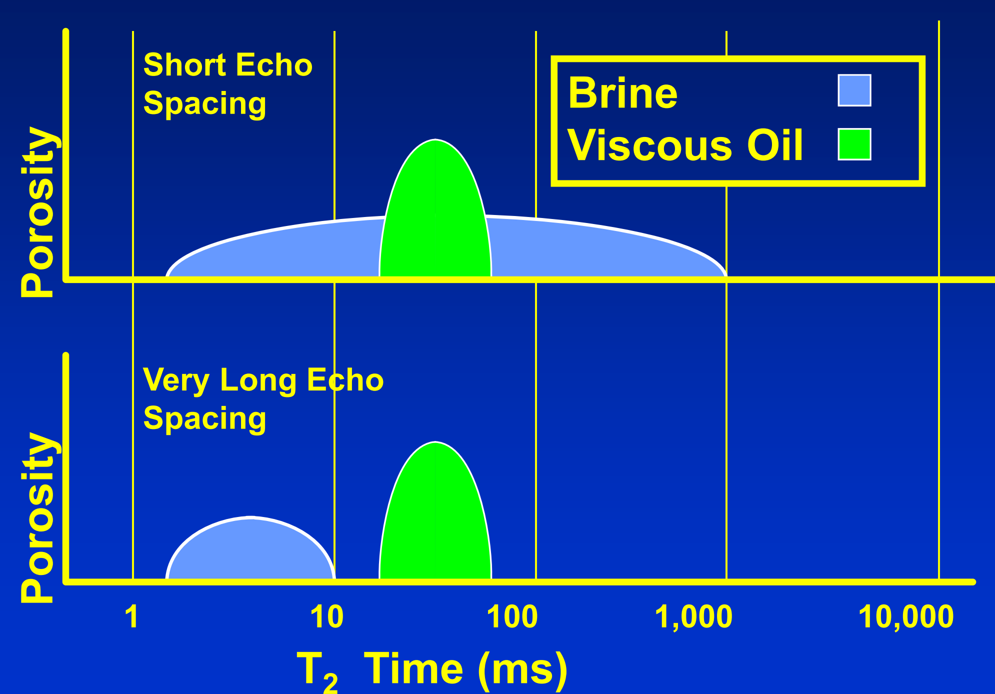
Delta TE Log



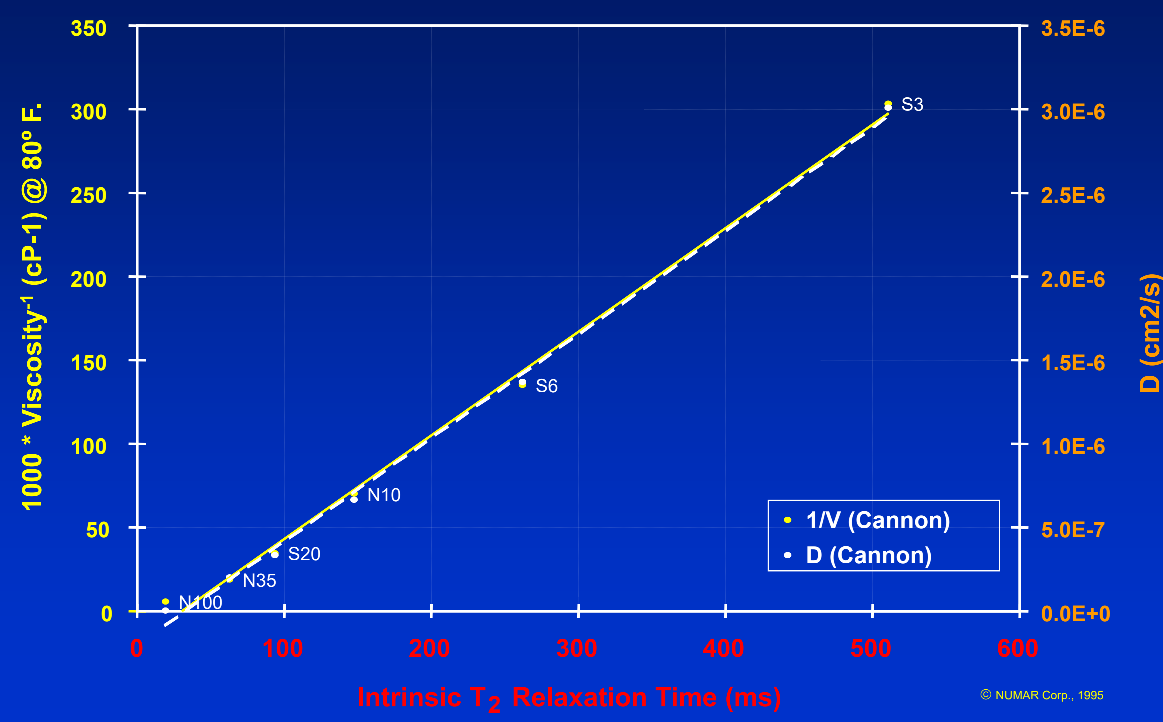
Shifted Spectrum - Gas Detection



Shifted Spectrum - Viscous Oil Detection

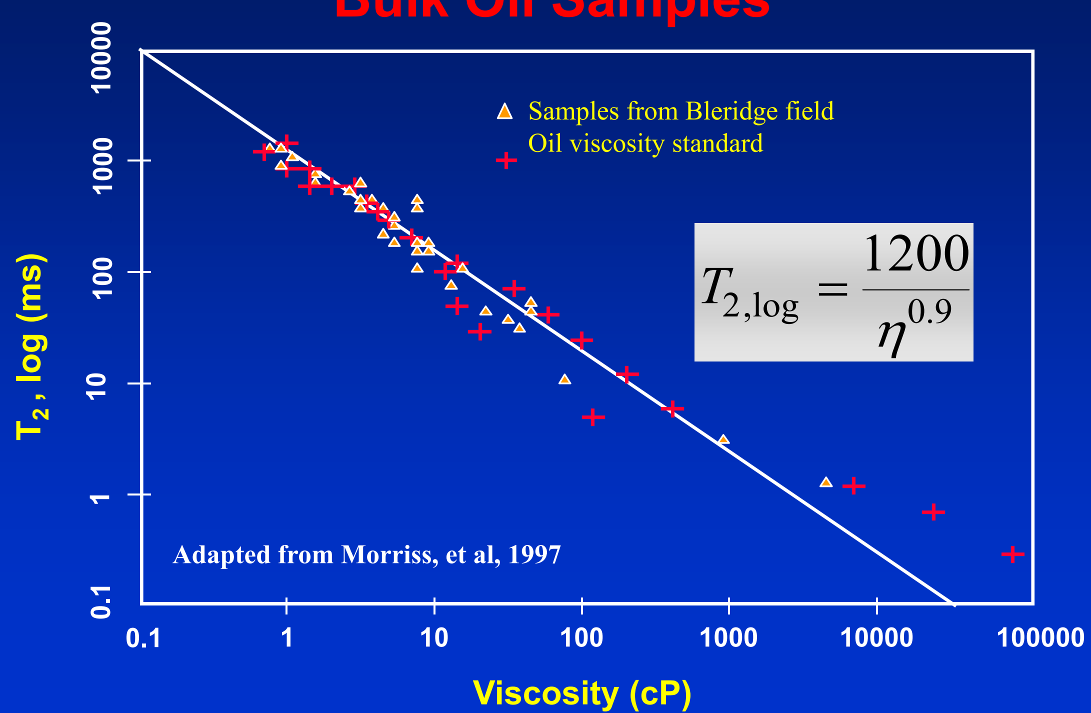


Viscosity, Diffusivity & Intrinsic T_2

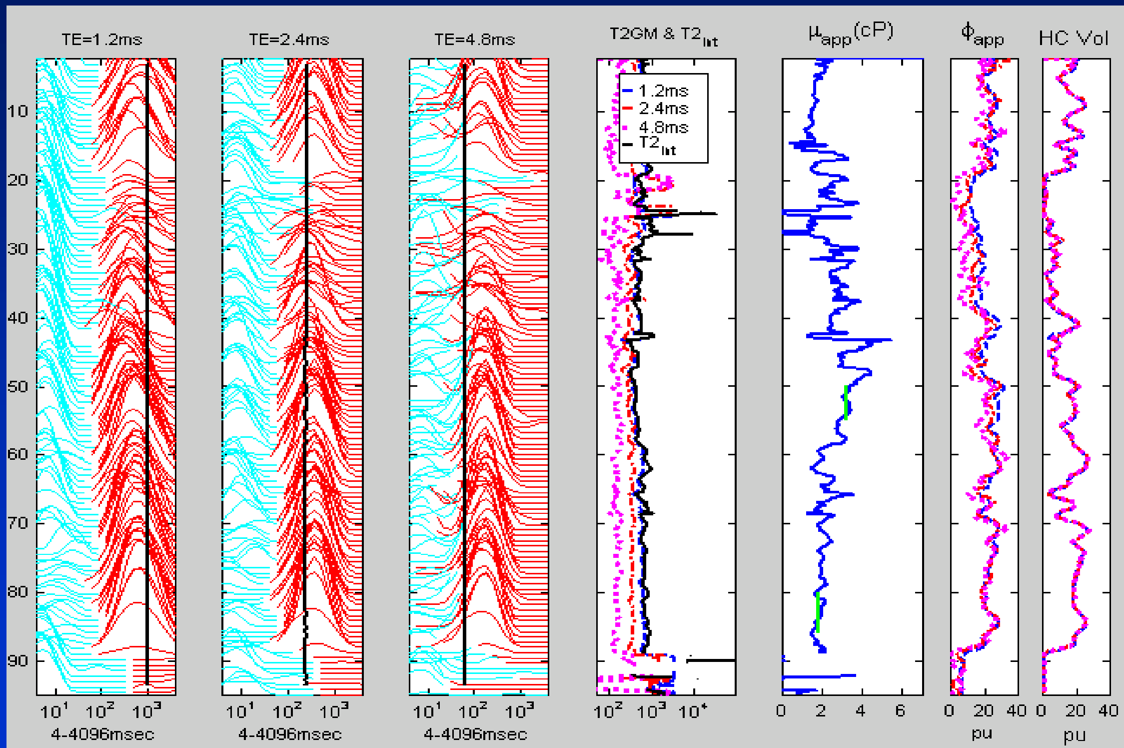


Intrinsic T_2 vs. Oil Viscosity

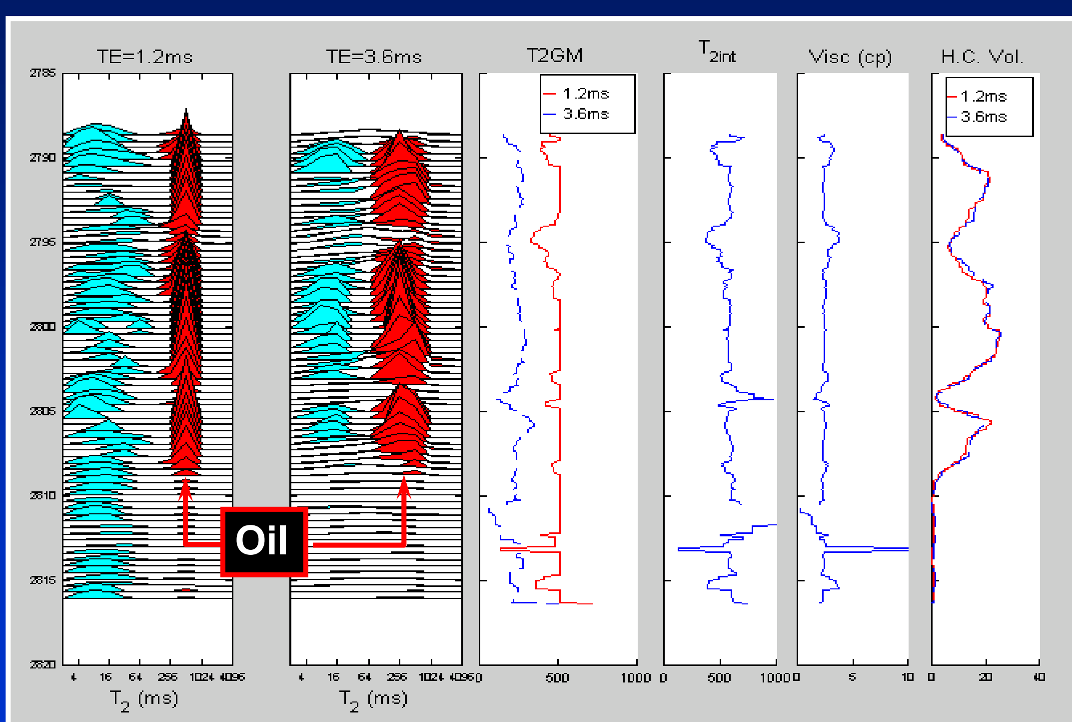
Bulk Oil Samples

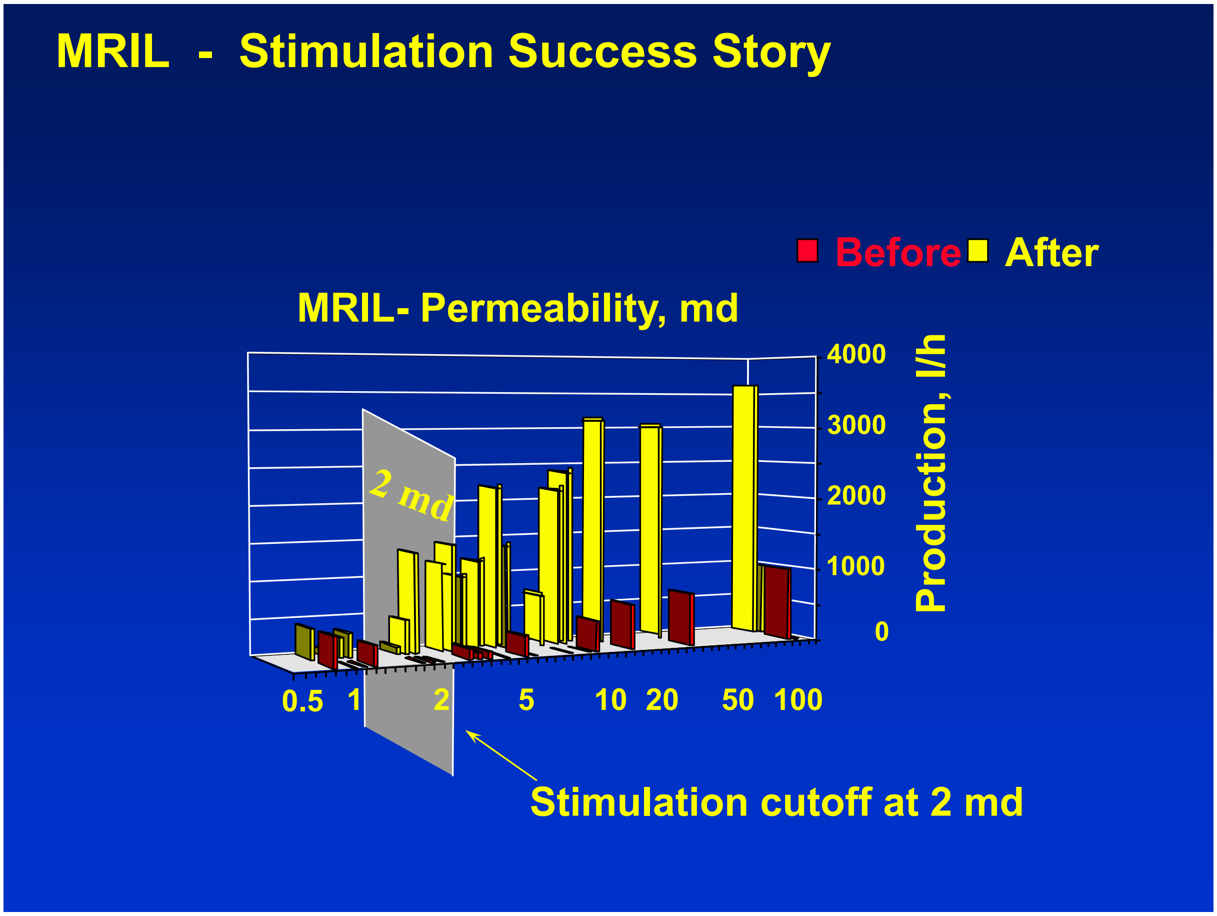


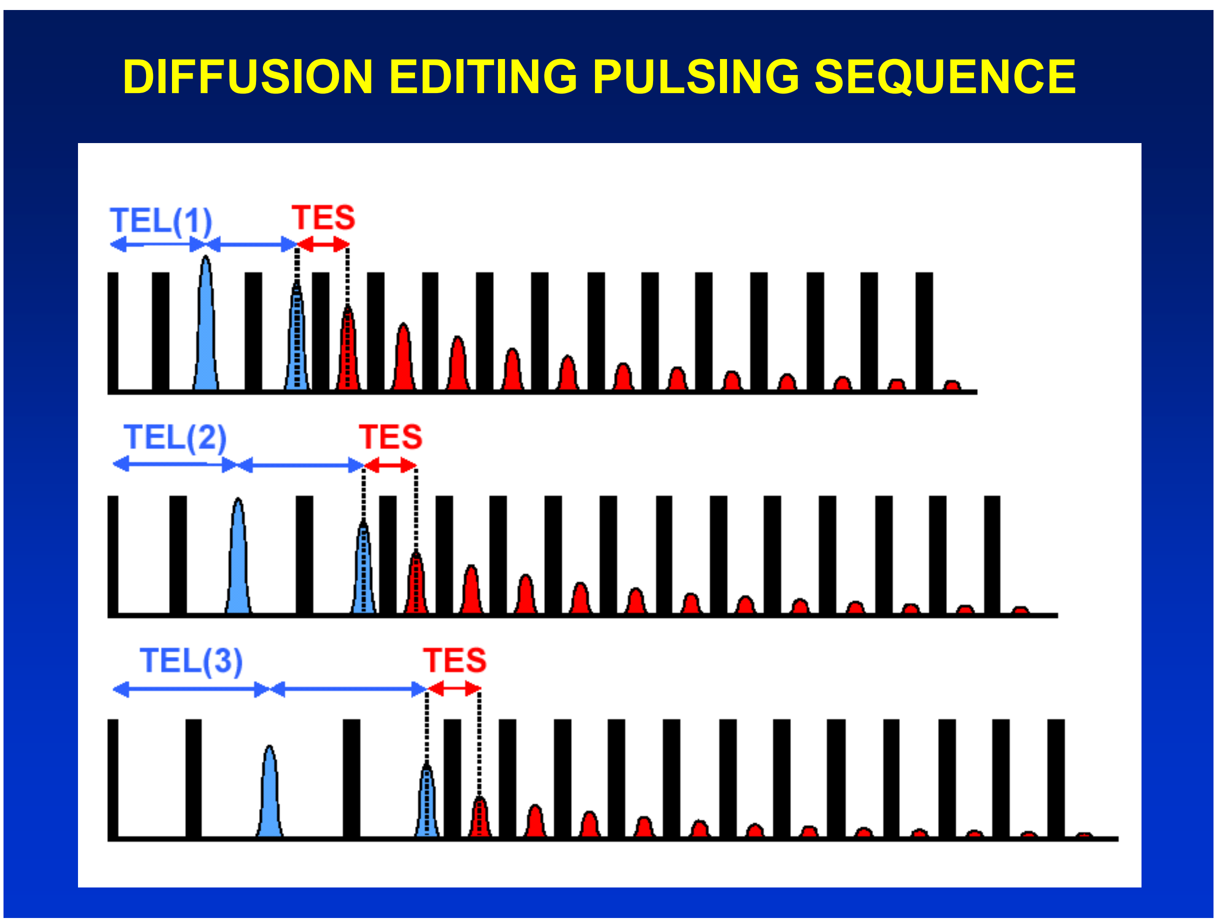
Multiple TE Analysis Deliverables



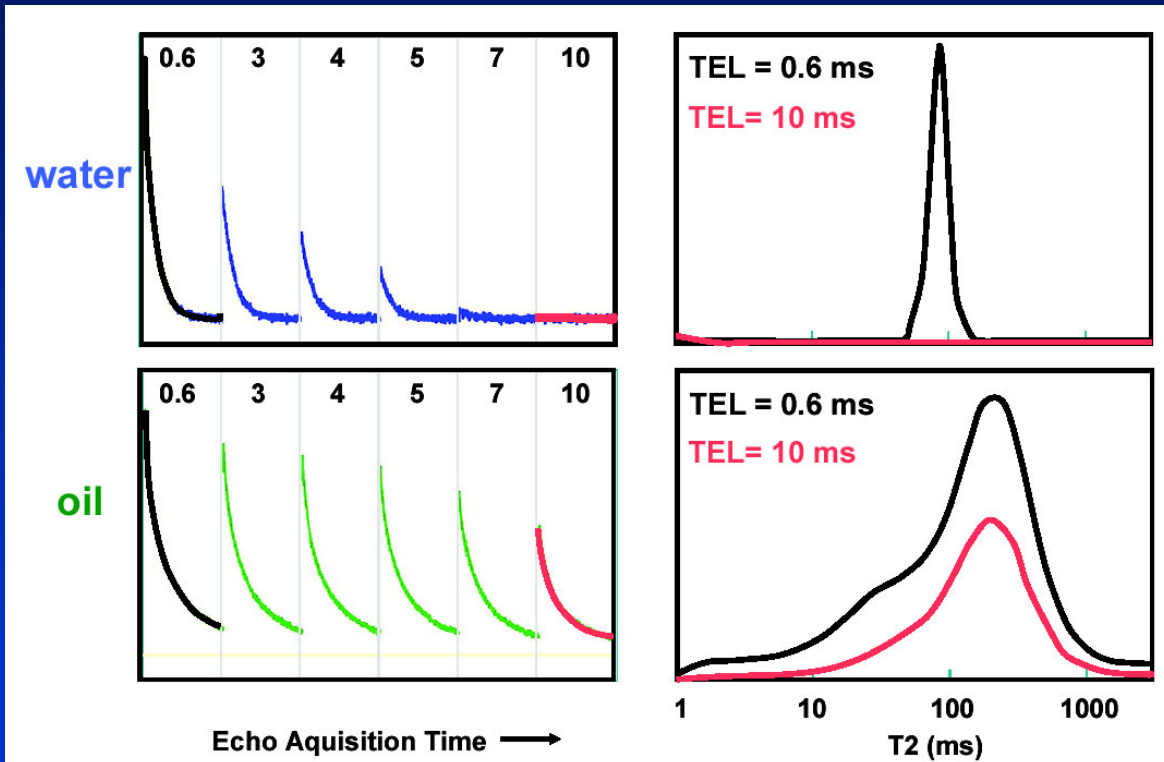
Oil Viscosity Analysis from DTE MRIL Data



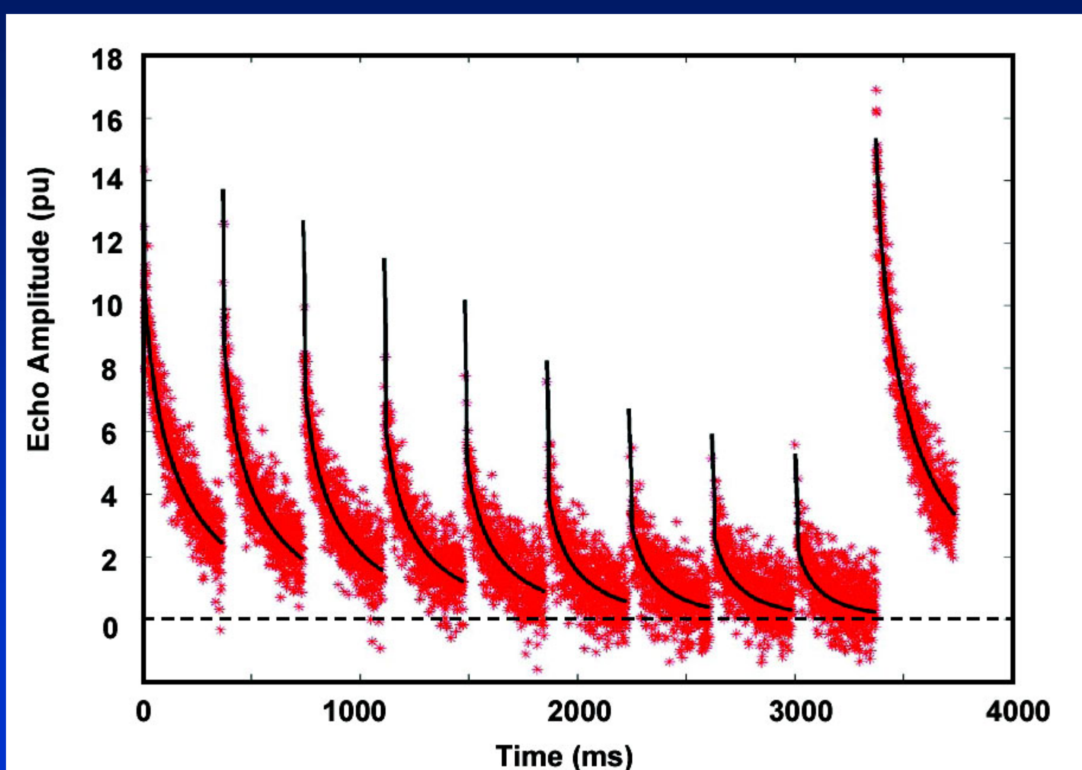

MRIL - Stimulation Success Story
Before
After
MRIL- Permeability, md
4000
3000
2000
1000
0
Production, l/h
2 md
0.5
1
2
5
10
20
50
100
Stimulation cutoff at 2 md


DIFFUSION EDITING PULSING SEQUENCE
TEL(1)
TES
TEL(2)
TES
TEL(3)
TES

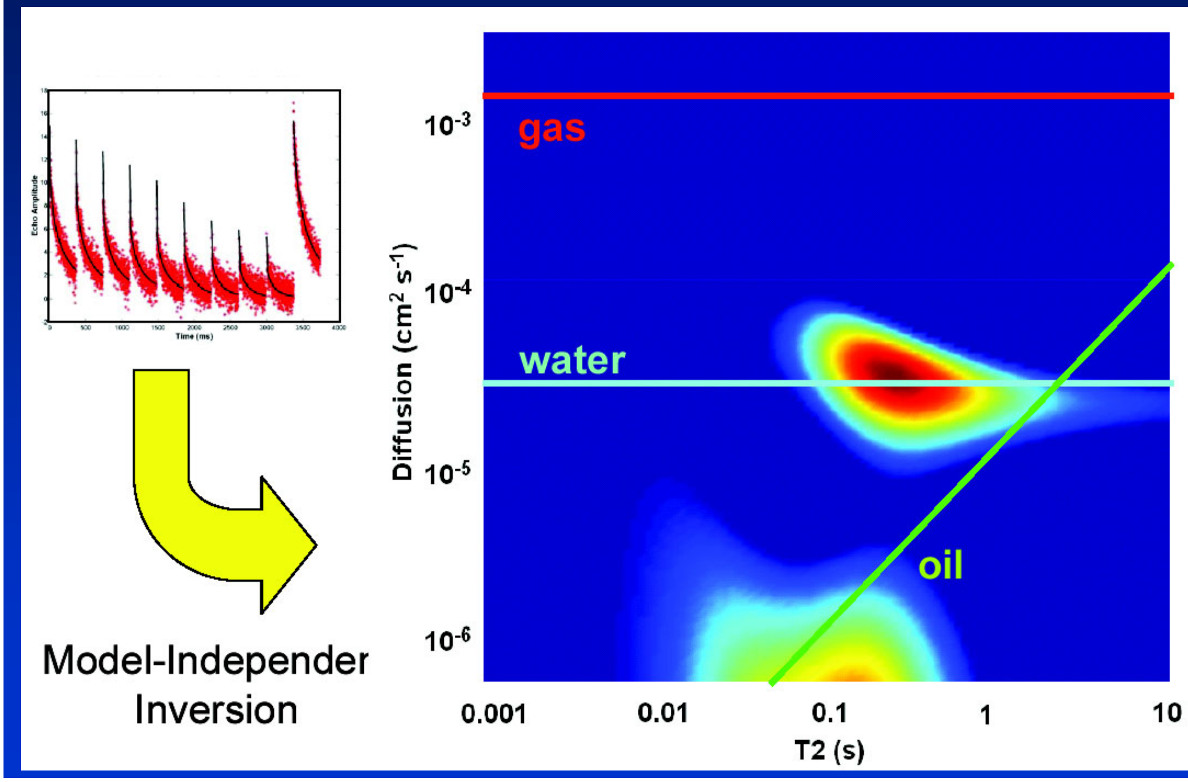
DIFFUSION EDITING MEASUREMENTS



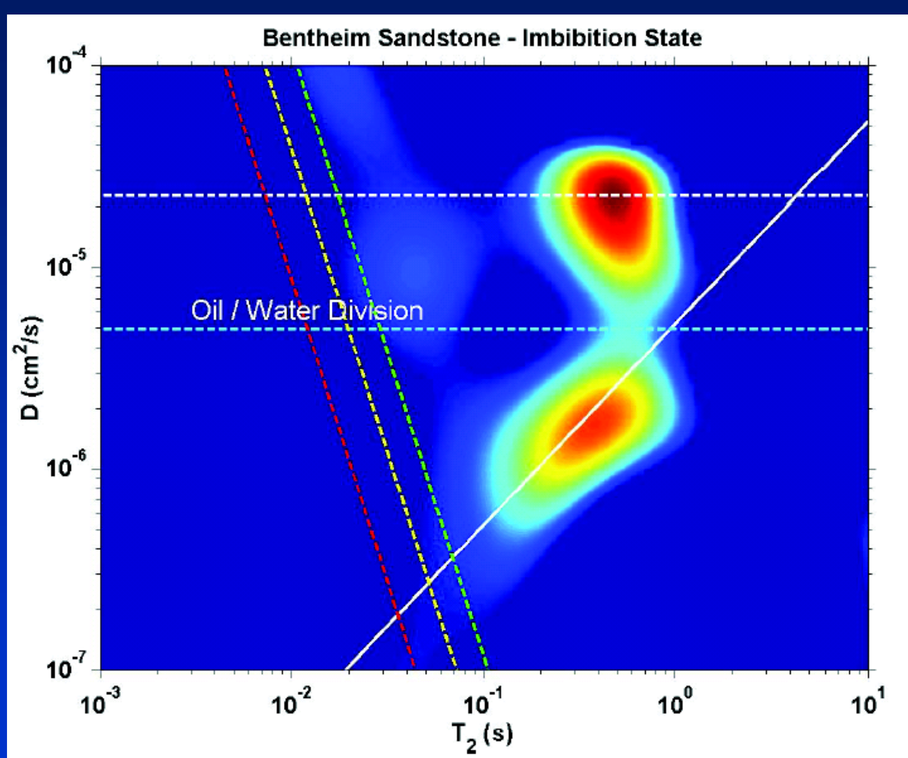
MRX DIFFUSION EDITING DATA



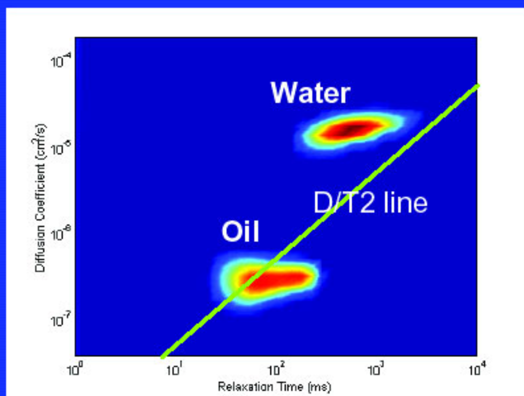
MODEL INDEPENDENT ANALYSIS



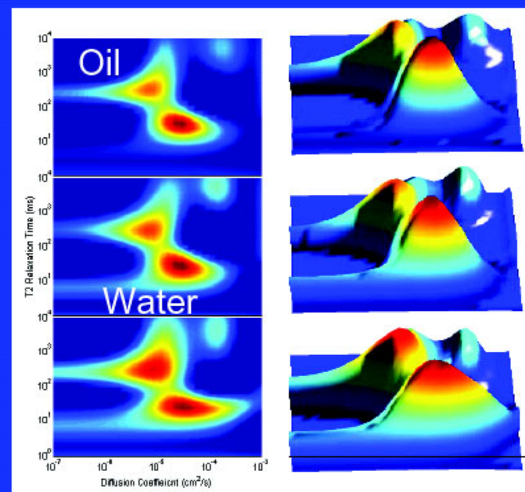
LABORATORY MEASUREMENTS (Hirasaki et al.)



LABORATORY MEASUREMENTS (ChevronTexaco)

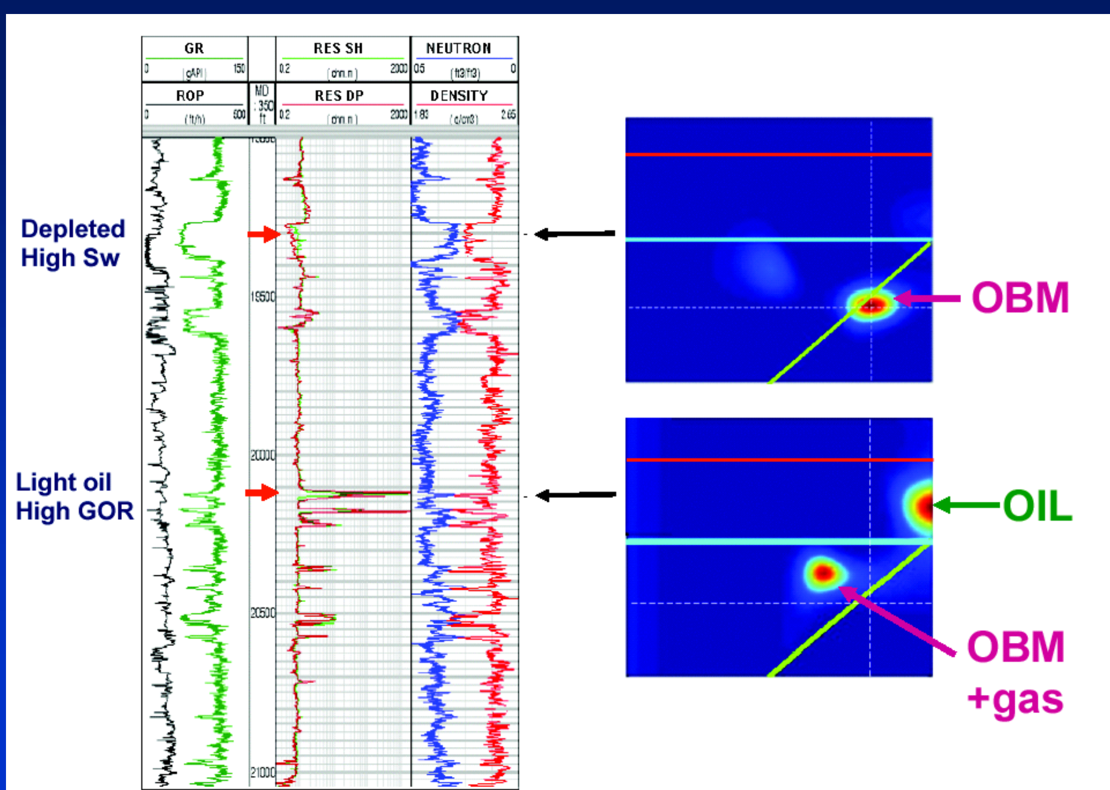


RD2D of Water-oil mixed glass beads measured at laboratory.

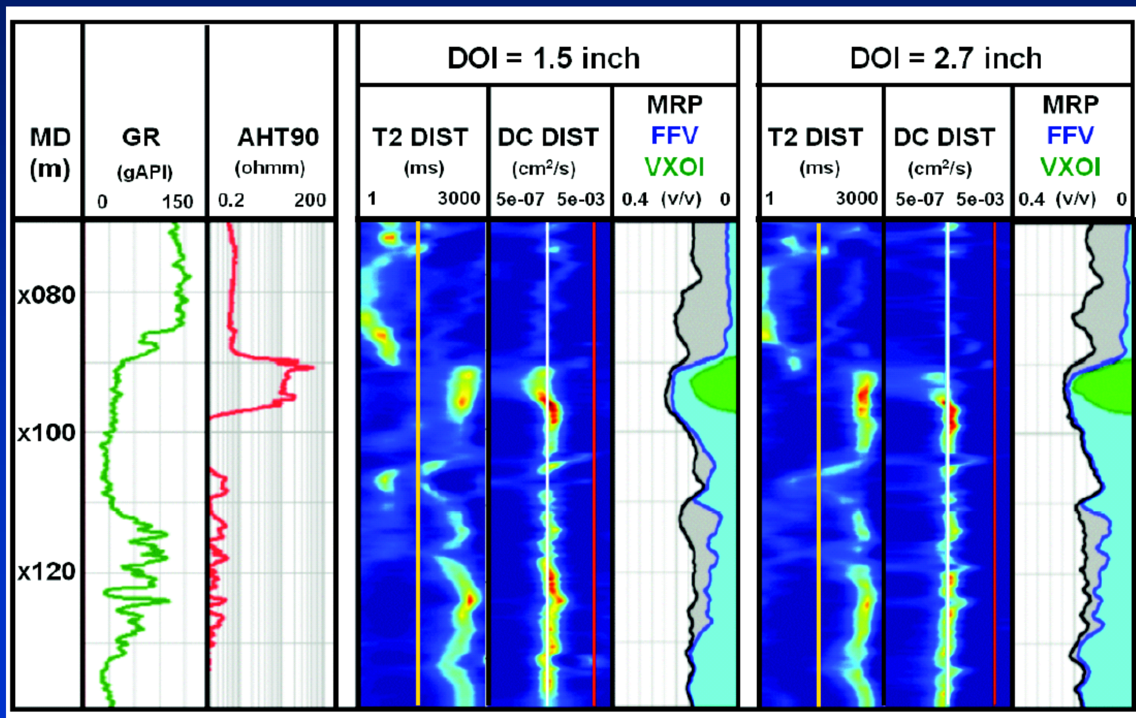


Field example shows resolved oil and water peaks in RD2D map.

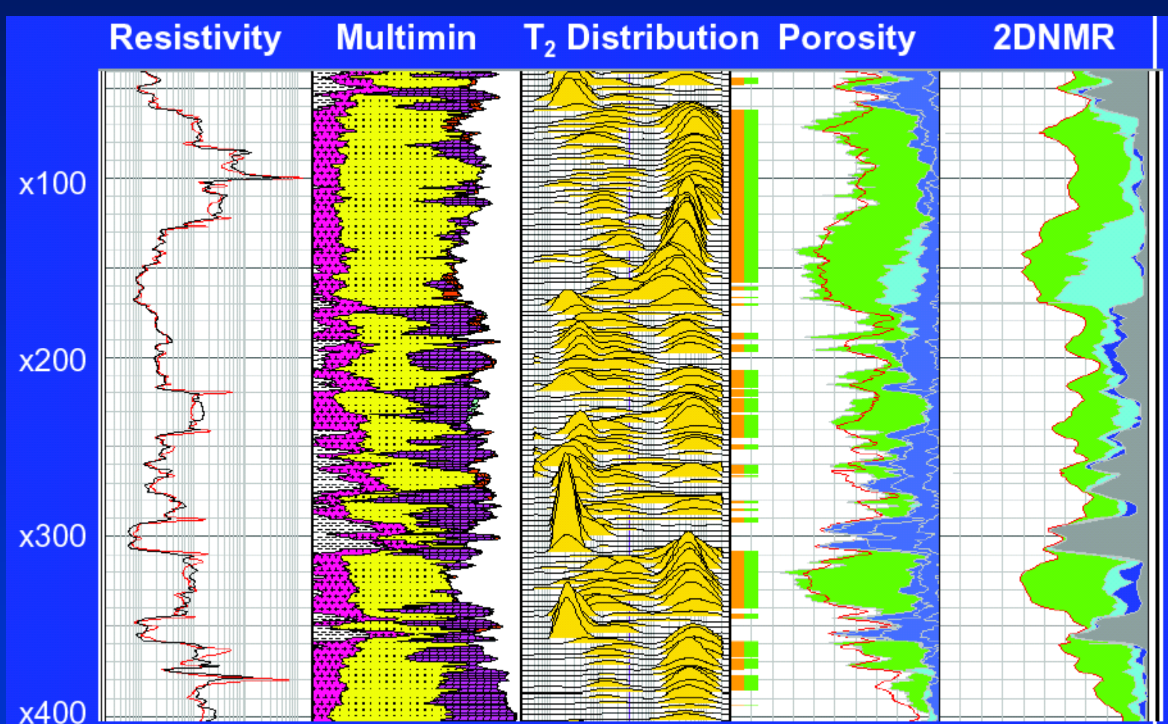
FLUID CHARACTERIZATION: Oil-Base Mud



EXAMPLE



EXAMPLE OF 2DNMR



Acknowledgements:

Baker Atlas
Schlumberger
Halliburton